



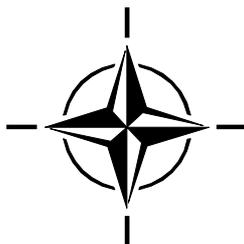
RTO TECHNICAL REPORT

TR-HFM-170

# **Supervisory Control of Multiple Uninhabited Systems – Methodologies and Enabling Human-Robot Interface Technologies**

(Commande et surveillance de multiples systèmes sans pilote – Méthodologies et technologies habilitantes d'interfaces homme-machine)

This Report documents the findings of Task Group HFM-170 (2008 – 2011) that identified and demonstrated several successful supervisory control methodologies and interface design practices for enabling single operator control of multiple Unmanned Vehicles in network-centric operations. Fifteen independent technology demonstrations by member NATO Nations are summarized. In addition, a candidate supervisory control framework is described by which to characterize and communicate research within the supervisory control domain.



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Edited by:

Dr. Leo van Breda (TNO)

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- SCI Systems Concepts and Integration Panel
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# **Supervisory Control of Multiple Uninhabited Systems – Methodologies and Enabling Human-Robot Interface Technologies**

## **(RTO-TR-HFM-170)**

### **Executive Summary**

Uninhabited Vehicles (UVs) are at the forefront of current operations and future thinking. With increasingly automated UVs, the operator's role will become more supervisory in nature, overseeing the automated activation of planned events and managing unexpected changes that impact the automated mission plans. Future vehicles will also have the capability to make certain decisions independent of operator input and pre-defined mission plans. This capability of the UVs to 'decide' (i.e., be autonomous) constitutes a whole new set of challenges for UV operators, as they will be required to rapidly judge the appropriateness of certain UV decisions and assess their impact on overall mission objectives, priorities, rules of engagement, etc. Moreover, there is a vision for a new control paradigm whereby a single operator will simultaneously supervise multiple autonomous UVs. Unfortunately, there is a dearth of information as to how best to support the coupling of this intelligent autonomy with the unique capabilities and decision-making responsibilities of the operator so as to maximize mission effectiveness across a wide range of mission contexts. New interfaces are required that take into account issues associated with this automation management as well as potential negative automation-induced impacts on the operator.

Given the possibility that future operators may likely control many UVs simultaneously, additional human factors challenges will include how best to maintain situation awareness, a reasonable workload level, and high system performance and safety across several managed assets. New principles for supporting the operator in such scenarios, which focus on supervisory control design methodologies, adaptive automation, and novel situation assessment/decision support aids, need to be developed and evaluated. Additionally, standard operator interface design guidelines associated with UV supervisory control need to be identified so as to facilitate interoperability across unmanned platforms.

HFM-170 developed and demonstrated pertinent supervisory control human-system interface design practices and concepts for UV network-centric operations through 15 specific technology demonstrations. These demonstrations focused on many critical issues including multi-vehicle control, manned-unmanned teaming, human-automation interaction, telepresence interfaces, delegation interfaces, vehicle hand-offs, operator workload adaptive systems, variable levels of autonomy, authority sharing, situation awareness aids, cognitive workload assessment, swarming interfaces, and dynamic mission management. HFM-170 concentrated on the identification and demonstration of successful supervisory control methodologies and interface design practices for enabling single operator control of multiple UVs. The applications addressed varied in degree of autonomy from manual robotic control to highly autonomous, swarming UVs.

This report summarizes in alphabetical order these 15 Technology Demonstrations, including a summary description of the activity, human factors issues involved, results and lessons learned. This report also provides a discussion on the development of a supervisory control framework by which to characterize and communicate research and technology development occurring within the supervisory control domain.

# Commande et surveillance de multiples systèmes sans pilote – Méthodologies et technologies habilitantes d’interfaces homme-machine

## (RTO-TR-HFM-170)

### Synthèse

Les véhicules sans pilote (UV, *Uninhabited Vehicle*) occupent une place de premier plan dans les opérations actuelles et dans les études de prospective. Avec la généralisation des véhicules automatisés sans pilote, l’opérateur aura de plus en plus un rôle de surveillance, qui consistera à superviser l’activation automatisée d’événements planifiés et à gérer les changements imprévus susceptibles d’avoir une incidence sur les plans de mission générés automatiquement. Les véhicules futurs seront également capables de prendre certaines décisions indépendamment de toute intervention de l’opérateur et du plan de mission prédéfini. Cette capacité de décision (autrement dit, cette autonomie) des véhicules sans pilote pose des défis d’un type entièrement nouveau aux opérateurs de véhicules sans pilote : ils seront, en effet, appelés à évaluer rapidement l’adéquation de certaines décisions prises au niveau du véhicule sans pilote et à en apprécier l’impact sur les objectifs généraux de la mission, les priorités, les règles d’engagement, etc. Qui plus est, un nouveau paradigme de commande émerge, dans lequel un opérateur unique aura à surveiller simultanément de multiples véhicules sans pilote et autonomes. Malheureusement, on manque d’informations sur les meilleurs moyens d’assurer le couplage entre cette autonomie intelligente et les capacités et responsabilités décisionnelles uniques de l’opérateur en vue d’optimiser l’efficacité de la mission dans une grande diversité de contextes de mission. De nouvelles interfaces sont nécessaires pour prendre en compte les questions liées à cette gestion de l’automatisation et les effets négatifs sur l’opérateur potentiellement induits par l’automatisation.

Etant donné que les futurs opérateurs risquent de devoir contrôler simultanément un grand nombre de véhicules sans pilote, d’autres problèmes relatifs aux facteurs humains se posent, en particulier la meilleure façon de garantir une connaissance adaptée de la situation, une charge de travail raisonnable, et un niveau élevé de sécurité et de performance du système sur un ensemble gérant plusieurs engins. De nouveaux principes pour soutenir l’opérateur dans de tels scénarios, axés sur les méthodologies de conception de systèmes de commande avec dispositif de surveillance, l’automatisation adaptative et sur les aides à l’évaluation d’une situation nouvelle et à la décision, doivent être développés et évalués. De plus, des lignes directrices pour la conception d’interfaces opérateurs standard associées à un système de commande avec dispositif de surveillance de véhicules sans pilote doivent être définies de manière à faciliter l’interopérabilité entre des plates-formes non habitées.

HFM-170 a mis au point et démontré des pratiques pertinentes pour la conception d’interfaces homme-machine avec dispositif de surveillance et des concepts pour des véhicules sans pilote opérant dans un contexte d’opérations réseautiques dans le cadre de 15 démonstrations des technologies spécifiques. Ces démonstrations ont mis l’accent sur plusieurs points cruciaux, parmi lesquels la commande de véhicules multiples, le travail d’équipe homme-machine, l’interaction homme-automatisation, les interfaces de téléprésence, les interfaces de délégation, les véhicules automatisés sans intervention manuelle (*hand-offs*), les systèmes adaptatifs de charge de travail de l’opérateur, les niveaux variables d’autonomie, le partage d’autorité, les aides à la connaissance de la situation, l’évaluation de la charge de travail cognitive, les interfaces de systèmes en essaim (*swarming*), et la gestion dynamique de missions. HFM-170 a concentré son attention sur l’identification et la démonstration de méthodologies de commande avec dispositif de

surveillance et de pratiques de conception d'interfaces efficaces pour permettre à un opérateur unique de commander de multiples véhicules sans pilote. Les applications concernées correspondaient à un niveau d'autonomie variable allant de la commande robotisée manuelle à des véhicules sans pilote très autonomes et opérant en essaim.

Ce rapport présente un résumé par ordre alphabétique de ces 15 Démonstrations des technologies, notamment une description sommaire de l'activité, les questions relatives aux facteurs humains s'y rapportant, les résultats obtenus et les enseignements qui en sont tirés. Le rapport discute également de l'évolution d'un cadre de commande avec dispositif de surveillance adapté pour caractériser l'évolution des recherches et des technologies dans le domaine du contrôle et de la surveillance et en assurer la diffusion.



## Chapter 1 – INTRODUCTION

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### 1.1 OVERVIEW AND SCOPE

Uninhabited Vehicle systems (UVs) are at the forefront of current battles and future thinking. A number of NATO countries are now using UVs to enhance their manned forces, especially in performing tasks that are dull, dirty, or dangerous. While several projects are focused on increasing the level of autonomy for future UVs (and thus enabling supervisory control), there is a dearth of information as to how best to couple this intelligent autonomy with human decision-making abilities. With highly automated UVs, the operator's role is supervisory in nature, overseeing the automated activation of programmed events (e.g., making sure the appropriate event is activated at the appropriate time) and managing unexpected changes to the automated mission plan. Associated operator interfaces must take into account issues associated with automation management, including vigilance, attention management, clumsy/brittle automation, etc. Continuing this trend beyond the current state-of-the-art, a vision exists for a new interface paradigm for controlling next-generation UVs. This envisioned interface system involves multiple autonomous UVs being controlled by a single supervisor. These UVs will have the capability to make certain decisions independent of operator input and pre-defined mission plans. This capability of the UV to 'decide' constitutes a whole new set of challenges for UV operators, as they will be required to rapidly judge the appropriateness of these decisions and assess their impact on overall mission objectives, priorities, etc.

Given the current progress of technological developments and operational concepts regarding UVs, a strong and combined effort of NATO-countries is essential to resolve the unique human-system issues associated with augmenting the existing force with these vehicles. Since the trend is very clearly on the development of more autonomous UVs, the time is right to address the critical human factors issues involved. Human factors design guidelines will have the greatest impact if they are identified before wide scale NATO design and procurement of highly autonomous UVs occur. Given the possibility that future operators may control multiple UVs simultaneously, additional human factors challenges will be to maintain situation awareness, a reasonable workload level, and high system performance and safety across several managed assets. New principles for supporting the operator in such scenarios, which focus on supervisory control design methodologies and novel situation assessment/decision support aids, need to be developed and evaluated. Additionally, standard operator interface design guidelines associated with UV supervisory control need to be identified so as to facilitate interoperability across unmanned platforms. The ultimate goal of HFM-170 was to increase NATO's successful operations utilizing highly automated UVs; however, the specific goal was to provide a single point of focus for identifying, prioritizing, and addressing human factors challenges associated with UV supervisory control.

HFM-170 team members developed and demonstrated pertinent supervisory control human-system interface design practices and concepts for UV network-centric operations. It directly leveraged HFM Task Group HFM-078/RTG-017 [1], which developed a comprehensive review of uninhabited military vehicle human

## INTRODUCTION

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factors issues across a wide variety of human effectiveness areas and potential military applications. Building off this acquired knowledge, HFM-170 concentrated on the identification and demonstration of successful supervisory control methodologies and interface design practices for enabled single operator control of multiple UVs, with various degrees of autonomy (including highly autonomous UVs).

Several relevant issues and challenges addressed included:

- Supervisory Control Issues and Methodologies:
  - Human-automation challenges and mitigation techniques.
  - Human-automation problem solving/cooperative dialog.
  - Networked telepresence.
  - Manned/unmanned collaboration.
  - Flexible (adaptive) level of automation.
  - Optimization of human/vehicle ratio.
  - Heterogeneous systems.
- Control Station Design – Decision Support Interfaces:
  - Situation assessment aids, augmented feedback of action impact.
  - Task switching, interruption and prioritization methods.
  - Predictive / “look ahead” tools, anticipatory support.
  - Intelligent aiding, time-critical decision making.
  - Multi-modal interfaces, intuitive interfaces, natural language speech enabled interfaces.
  - Commonality of supervisory control interface design components supporting interoperability.
  - Augmented remote world.

A unique aspect of HFM-170 was the process followed. The team was given explicit instruction to operate in a more collaborative manner, with more demonstrations versus discussions of research papers. The next section discusses a novel approach that the group settled on to attempt to maximize collaboration and tech demos without compromising each researcher’s research priorities.

### **1.2 HFM-170 PROCESS: MAXIMIZE COLLABORATIONS AND TECHNOLOGY DEMONSTRATIONS**

Given the direction from the HFM Panel for the Task Group to focus on increasing team collaborative efforts and hosting high-fidelity Technology Demonstrations (TDs) versus strictly discussing lab research findings, the team needed to formulate a new approach to facilitate these objectives. However, the dilemma was how to accomplish true collaboration within the obvious limitations that exist with NATO teams (e.g., no additional resources provided, conflicting schedules, international restrictions, the continuing need for team members to accomplish their own national research agenda). HFM-170 Team Members thus formulated a new process by which to formally identify, develop and ascertain NATO collaboration potential for specific UV-related TDs that would be occurring within each individual country over the time-course of the Task Group. This process is summarized below.

The team first identified a series of TDs that would occur throughout the follow-on Task Group period of performance. Each participating Nation was allotted at least one TD if they so desired. A total of 15 Technology Demonstrations (TDs) were eventually agreed upon across 8 countries. These TDs focused on a broad range of pertinent human factors issues associated with supervisory control of multiple unmanned systems (see next section and the following chapters). Several candidate supervisory control frameworks were subsequently conceived in an effort to integrate these TDs into a common supervisory control framework (see Chapter 2).

After identification of the official list of TDS, each TD was considered in-turn for potential level of NATO collaboration. Since higher levels of international collaboration requires a significant amount of lead time for planning and orchestrating, this discussion of potential collaboration opportunities took place at the initiation of the Task Group. Collaboration among each of the participating TG NATO Nations was considered along a graduated scale (Figure 1-1). This scale defaults at ‘no collaboration’, which is applicable to many situations given constraints placed on programs and costs of collaboration. As collaboration level increases, the scale rises to “coordination” (information sharing, schedule coordinating, witnessing the TD, etc.), then to “cooperation” (structuring similarly focused tech demos to enhance effects, maximize information gathering, data collection) and finally to full “collaboration” (multiple NATO Nations combine resources to produce a truly integrated TD). Full collaboration was achieved in one instance within this Task Group, and is described in Chapter 9.

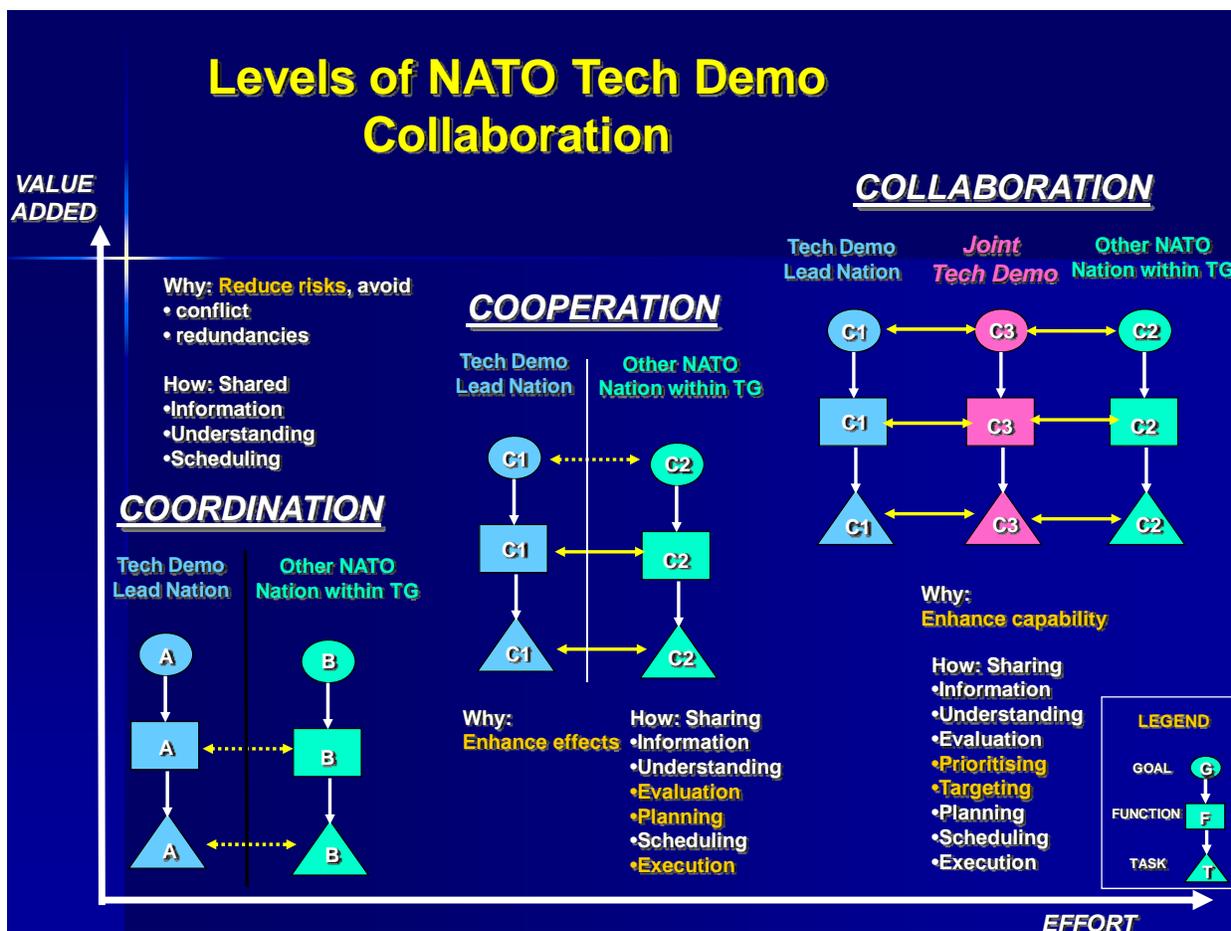


Figure 1-1: Levels of NATO Technology Demonstration Collaboration for HFM-170.

## INTRODUCTION

For each TD, the eventual level of collaboration for each country/representative was dependent upon several variables including level of mutual research interest, availability of resources, alignment of resources, timing, value added, etc. The method for identifying and characterizing instances of collaboration is described next.

Each TD “owner” was required to complete a collaboration matrix (see Figure 1-2 below) that conveyed how much collaboration was desired (and in what area of the TD). One dimension of the matrix consisted of 3 levels of collaboration while the other represented 3 different phases of a TD. For each TD, this completed matrix was presented along with a discussion of the TD (objectives, approach, design, etc.), after which each country was prompted to state their level of interest (using the same collaboration matrix structure) in collaborating with that TD. In this way, the group was able to systematically identify and then track collaborations across a wide spectrum of collaboration levels and groups involved. Some TDs resulted in few to no collaborations while other TDs had much interest from various countries and one resulted in a new joint TD between the Netherlands and the US.

	<i>Planning/Design</i>	<i>Execution</i>	<i>Analysis</i>
<i>Communication</i>			
<i>Coordination</i>			
<i>Collaboration</i>			

**Figure 1-2: Collaboration Matrix for Each TD.**

The follow-on meetings occurred approximately every 6 months, over a three year period. Meetings centered around one or more tech demos associated with the host country. Many TDs were actual live tests using real assets in air or on ground or on water, providing needed realism and hands on experience. The tech demo researchers presented the TD(s), invited specialists as desired, and used the available time to discuss and critique the demo specifics. Contrasting approaches/concepts were also discussed.

As a means to disseminate the results and lessons learned from this Task Group, a NATO “Technology Forum” Workshop (RWS-217) is organized at the end of this effort. This forum presents summaries of all TDs conducted throughout the TG period through posters, videos, and hardware demos/simulations. Discussions center around lessons learned and the way forward regarding multi-vehicle control by a single operator.

### 1.3 SUMMARY

A total of 15 TDs were included as part of HFM-170. These TDs are listed in Figure 1-3, along with the Host country. TDs focused on many critical issues including multi-vehicle control, manned-unmanned teaming, human-automation interaction, telepresence interfaces, delegation interfaces, vehicle hand-offs, operator workload adaptive systems, variable levels of autonomy, authority sharing, situation awareness aids, cognitive workload assessment, swarming interface technology, and dynamic mission management.

<b>Technology Demonstration</b>	<b>Title</b>	<b>Host Country</b>
1	Multi-crew Control of a Single Unmanned Aircraft	Canada
2	Behaviour based Collision Avoidance and Formation Control of Multiple Unmanned Vehicles	Canada
3	Supervisory Control: OmniSense	Canada
4	Interacting with Multi-agent Systems / UAV Swarms	France
5	PEA Human Factors and Authority Sharing	France
6	Cognitive and Cooperative Automation for Aerial Manned-Unmanned Teaming Missions	Germany
7	Remote Auditory Target Detection Using an Unmanned vehicle – Comparison Between a Telepresence Headtracking 3D Audio Setup and a Joystick-Controlled System with a Directional Microphone	Netherlands
8	Supervisory Control: Optimal Distribution of Workload Among Operators for Mixed Initiative Control of Multiple UAVs	Portugal
9	Task Switching for Multi-UGV Control	Sweden
10	Supervisor Control of UGVs for Tactical Reconnaissance	Sweden
11	Dynamic Airborne Mission Management Capability Concept Demonstrator	United Kingdom
12	Multi-UAV Supervisory Control Interface Technology (MUSCIT) Demonstration	United States
13	Delegation Control of Multiple Unmanned Systems (DELCON)	United States
14	Intelligent Agents as Supervisory Assets for Multiple Uninhabited Systems: RoboLeader	United States
15	Unmanned Surface Vehicle Control & Monitoring Human-Computer Interface for Amphibious Operations	United States

**Figure 1-3: HFM-170 Technology Demonstrations.**

The following chapters begin with an extensive review of the efforts undertaken by HFM-170 to identify supervisory control frameworks by which to describe the research being done in this area, including but not limited to the TDs. This is followed by a summary of each TD including its goals, approach, and results/lessons learned.

### 1.4 REFERENCES

- [1] *Uninhabited Military Vehicles (UMVs): Human Factors Issues in Augmenting the Force*. 2007. NATO-RTO-TR-HFM-078. Neully-sur-Seine: NATO-RTO.

## Chapter 2 – FRAMEWORKS FOR SUPERVISORY CONTROL OF MULTIPLE UNINHABITED MILITARY VEHICLES

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### 2.1 OVERVIEW AND SCOPE

Throughout the meetings of HFM-170, we have discussed the possibility and desirability of having a framework for describing and contrasting the various supervisory control systems that each member group has been working with, as well as others we have experienced. We have discussed many different potential frameworks, without coming to consensus about any specific one of them. The purpose of this document is to review those discussions, along with conclusions reached about the nature of supervisory control frameworks and desirable attributes for this application (as distinct from others), as well as to review the different frameworks proposed and their strengths and weaknesses.

### 2.2 FRAMEWORKS AND SUPERVISORY CONTROL

Almost concurrently with Sheridan's defining the term and concept "supervisory control", he proposed a framework for characterizing it – his ten stage model which will be reviewed in Section 2.3 below. In Sheridan's definition, which has remained more or less intact since he coined it, supervisory control is any human-machine relationship in which the machine is in a subordinate state *like* that of a human supervisor-subordinate relationship. "... [S]upervisory control derives from the close analogy between a supervisor's interaction with subordinate people in a human organization and a person's interaction with intelligent automated sub-systems." [1].

But just as there is a huge range of human-human supervisory relationships (from master-slave to parent-child to collaborative work team to president-nation to gang leaders), so there are a wide range of human-machine supervisory control relationships and it would be desirable to be able to characterize and discuss their similarities and differences. If for no other reason, it would be helpful to be able to discriminate one from another, especially when attempting to determine which type works best for which application. So, beginning well before Sheridan, there has been a long history of characterizing the types or stages of a human-machine supervisory control relationship.

But it is worth remembering, after George Box [2], that 'all frameworks are wrong, but some frameworks are useful'. Box uttered that quote, he was talking about models, but a framework is essentially a model – and perhaps a taxonomy. Box meant that a model will never fully capture the details and intricacies of the real world, but that some models may capture interesting or relevant aspects of it – and, in fact, by eliminating excess detail, some models may even make it easier to see relevant relationships and distinctions. Similarly, there are always multiple ways of parsing any complex phenomenon into multiple frameworks or taxonomies. None of these will capture the full richness of the phenomenon, but some of them – indeed, multiple versions

– may be useful because they organize the phenomenon in helpful, insightful ways, highlighting some similarities and differences while obscuring others. There is no single “right” framework for describing supervisory control, but different ones may be more or less useful for different purposes. Therefore, for any framework development or evaluation, it helps to begin with a discussion of the purposes or goals which the framework will serve.

### **2.2.1 Why Have a Framework?**

There are a wide set of possible reasons one might want to have a framework for supervisory control. These include:

- *Training* – A framework can serve as a “mall map” for training users in the specific attributes of a single system, or in training the similarities and differences across multiple systems.
- *Interaction* – The “mall map” attributes of a framework can also serve as a mental model to aid users in understanding and remembering the attributes and behaviors a supervisory control system affords.
- *Organizing Investigation* – For research purposes, a framework can serve as a map to “uncharted territory”, helping to determine what areas have been investigated and what have not – and can aid in generalizing results if it highlights the similarities and differences between “regions” of the space of possible system alternatives.
- *Understanding Alternatives for Design* – As investigation of the space of alternative approaches to supervisory control are completed, they form a set of data about design alternatives – a database that may be organized according to a framework. Thus, the framework may serve as a guide to designers to understand both what alternative design methods are available and what conditions they have been proven to work well in.

The reasons for this working group were related to the later two – to characterize the set of systems and applications we were discussing as a part of our collaboration. To the degree that the framework we created helped us gain insights from the set of supervisory control applications we studied, that would be added benefit. Finally, we also wanted an organizing principle for this report.

### **2.2.2 Framework Attributes and Goals**

Frameworks can be more or less elaborate, and they can highlight or suppress different aspects of the phenomenon they model. Given the goals described above, desirable attributes for our framework included:

- *Brevity and Simplicity* – To serve as an organizing principle for communicating the results of this working group to the outside world, it was important that the framework be simple and brief enough to be conveyed and explained to a reading audience in a limited amount of time. We were willing to make some sacrifices in the coverage or resolution of the model in order for it to be readily comprehensible by our audience. To some degree, the “fame” (or prior knowledge) of a candidate framework could be used to compensate for simplicity, and some frameworks (most notably Sheridan’s [3], [5] and [6]) were already well known in the human factors and engineering world.
- *Emphasis on Domain* – Since this exercise was a part of a NATO RTO working group on supervisory control of unmanned military vehicles, this colored our efforts in three ways:
  - First, “supervisory control” was the focus and topic of our framework development efforts. While many other topics in the domain of human-automation interaction are related to supervisory

control (such as levels of autonomy, adaptive autonomy and user interface and interaction design), these were not directly our focus.

- Second, our emphasis was on developing a framework for characterizing supervisory control of *Unmanned Military Vehicles (UMVs)*. While, as will be seen below, we occasionally discussed other forms of supervisory control (both human-human and other application domains), our ultimate emphasis was on UMVs.
- Third, since supervisory control is, at root, a relationship between human and automation, we focused on characterizing and describing alternate ways in which that relationship could exist. Technology and its application domains, while relevant, were not the primary focus.
- *Coverage* – It was important that the framework developed be able to cover – that is, to represent and describe – each of the applications that were being developed and tested by the various participating members and their countries’ laboratories. Coverage outside that set was nice to have, but deemed less important.
- *Distinction* – While the ability to cover the set of demonstrations being developed by the working group participants was important, it was equally important that our framework be able to make distinctions between them. We wanted to be able to organize and characterize these demonstration systems, identifying their similarities and differences.

### 2.3 ALTERNATE FRAMEWORKS CONSIDERED

In this section, we will describe the various frameworks considered during the course of the working group.

#### Sheridan

Sheridan’s initial “framework” for characterizing supervisory control relations was a spectrum arrayed as a 10 item list whose endpoints are full control autonomy for the human (essentially no role for automation) and vice versa [3]. The intermediate levels in this spectrum, then, represent alternative forms of supervisory control interactions. A version of this list is shown in Table 2-1.

**Table 2-1: Levels of Automation (after [3]).**

1	Human does it all.
2	Computer offers alternatives
3	Computer narrows alternatives down to a few
4	Computer suggests a recommended alternative
5	Computer executes alternative if human approves
6	Computer executes alternative; human can veto
7	Computer executes alternative and informs human
8	Computer executes selected alternative and informs human only if asked
9	Computer executes selected alternative and informs human only if it decides to
10	Computer acts entirely autonomously.

### *Strengths and Weaknesses*

Sheridan's spectrum is very simple and very well known, but it has several flaws as a framework for our needs. It has been criticized (in Parasuraman, Sheridan and Wickens [6], among others) for confounding automation employed in the presentation of information, in the making of decisions and in the executing of actions. Because most military systems are complex enough to employ automation operating on many different tasks and task types concurrently, when one assigns a number using Sheridan's framework, one is forced to either be ambiguous about the task or operational domain being described by the number, to break tasks down to a fine enough level where only one of Sheridan's levels makes sense as a descriptor, or to "average" over the automation levels and the tasks and applications where automation is provided. This argument is made in more detail in Miller and Parasuraman [4],[9].

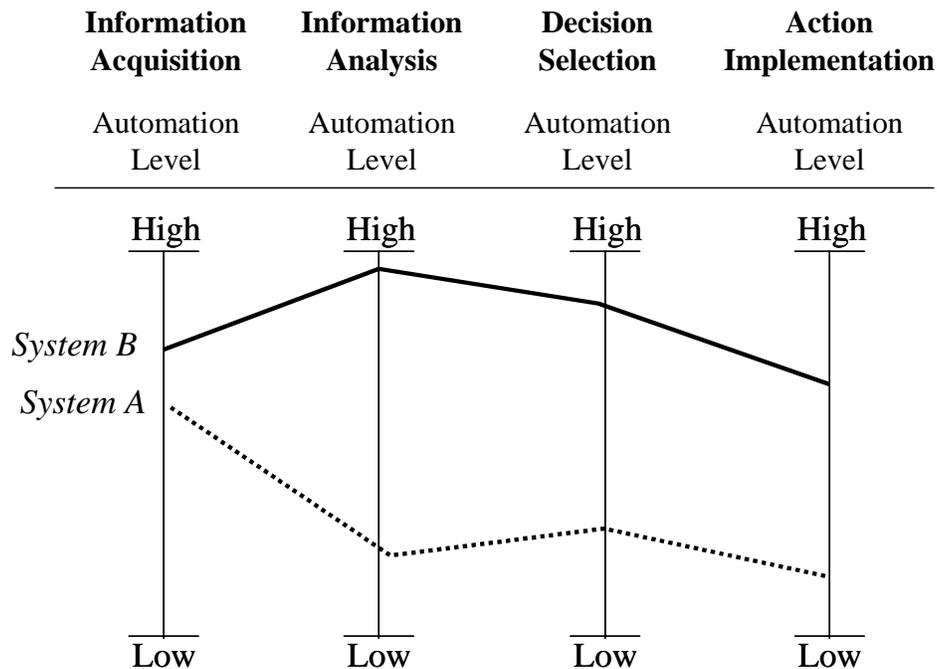
### **Parasuraman, Sheridan and Wickens**

Sheridan's spectrum model is essentially uni-dimensional. As noted above, though, it achieves "unidimensionality" by combining several potential behaviors that automation can perform. While extremely simple and intuitive, this unidimensionality may well be too simple to make the kinds of distinctions between systems and applications which we would like to make.

Another problem with uni-dimensional models of human-automation relationships is that they are ambiguous about what the application domain of the relationship applies to. Parasuraman et al. [6] noted that Sheridan's levels referred mainly to automation that makes decisions, offers suggestions and/or executes actions. There are, however, other jobs automation can do: for example, sensing and analyzing information to detect situations of interest, without necessarily offering any advice on what to do with the information. Parasuraman et al. [6] applied a simple, stage model of human information processing to arrive at four functions that must be accomplished to perform most tasks:

- 1) Information acquisition;
- 2) Information analysis;
- 3) Decision and action selection; and
- 4) Action implementation.

Since these functions can be performed by either human or automation in various mixes, in effect Parasuraman et al., [6] added a second dimension to Sheridan's spectrum – that of the function or task the relationship is defined over. Most human + automation systems can be characterized by a mix of LOAs across these four functions, as in Figure 2-1. One system (A) might be highly autonomous in information acquisition, but comparatively low on the other functions, while a second (B) might offer a high LOA across all four functions.



**Figure 2-1: Levels of Automation by Information Processing Phase for Two Systems (from [5]).**

### *Strengths and Weaknesses*

This information processing stage  $\times$  autonomy level model has gained extensive acceptance in the research community and systems have begun to be developed in accordance with it. Research has shown different effects of automation at the different stages [7]. Nevertheless, it was felt that it too was too coarse grained to provide adequate distinctions between the various supervisory control systems being explored by members of HFM-170. Furthermore, some members of the group had reported prior attempts to use the Parasuraman, Sheridan and Wickens framework to describe and define systems and had encountered difficulties in making clean distinctions between the information processing stages.

### **2.3.1 Miller and Parasuraman**

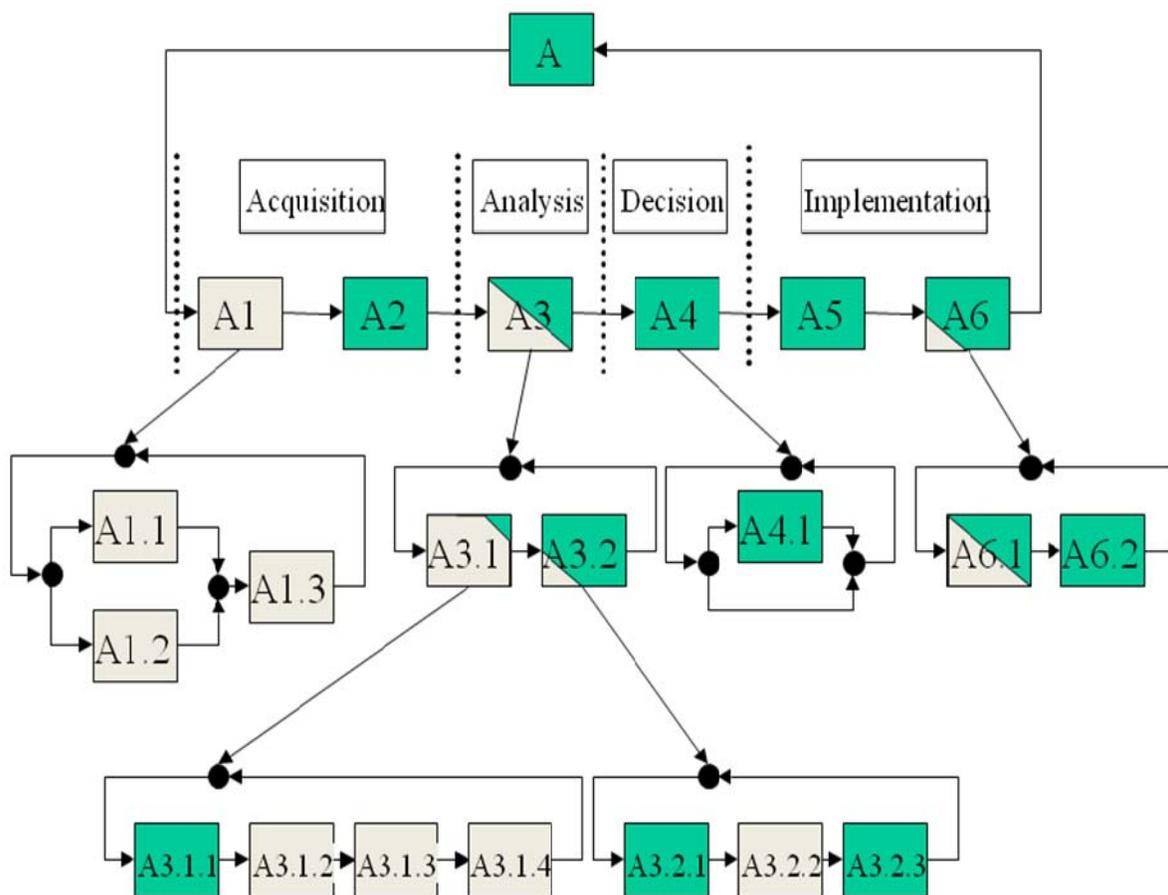
An implication of the Parasuraman et al. [6] levels  $\times$  functions model is that a parent task<sup>1</sup> can be decomposed and that a single automation level need not be applied homogeneously across the sub-tasks. However, in their model a parent task is decomposed into abstract sub-functions based on information processing stages, whereas other decomposition methods might arguably provide more insight into how a task may be performed. In fact, the role of task analysis in Human Factors is to perform exactly such decompositions in a

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<sup>1</sup> Note that in Sheridan's model, as well as in Parasuraman, Sheridan and Wickens, and all of the other models discussed in this document, a decomposition of the functions to be performed by human(s) and automation is important, but it is less important whether the focus of analysis is prescriptive tasks, abstract functions or even the goals which are accomplished by those tasks and functions. Since supervisory control necessarily concerns itself with allocating the work of multiple agents for the accomplishment of a goal, allocation will necessarily include goals, functions and the tasks or methods which accomplish them. Most of the models described in this document apply regardless of whether the supervisor allocates via prescriptive tasks or ecological abstract functions and goals.

hierarchical fashion through any number of levels to some primitive, “stopping” level [8] that may be imposed by biology, physics or, more commonly, the purpose of the decomposition.

In a 2003 paper, Miller and Parasurman [9] argued that while the two-dimensional LOA model offered by Parasuraman et al. [6] represents a major advance over earlier uni-dimensional models, it arguably does not go far enough. The subdivision of a parent task into four information processing phases represents only a single level of decomposition into abstract task categories. In practice, tasks are accomplished by hierarchically decomposable sequences of specific activities – the parent task’s sub-tasks. Automation may be applied differently to each and every sub-task that comprises the parent task. Thus, the profile of automation levels sketched in Figure 2-2 could stretch instead over as many sub-tasks and levels as we want or need to divide a parent task into.



**Figure 2-2: Hypothetical Decomposition of Task A Into a Hierarchical Set of Sub-Tasks – Each of Which May Have Differing Automation Levels.**

In fact, the relationship between automation “level” and task decomposition is more complex still. As is well understood [6], automation does not merely shift responsibility for tasks but can change their nature as well. In a task decomposition, this means that some sub-tasks may be eliminated while others are added. This implies that there will generally be multiple alternate decompositions depending on, among other things,

what LOA is used. Each alternative constitutes a different combination of human and automation sub-tasks and, thus, a different method of accomplishing the parent task.

When one identifies a LOA for a complex system using Sheridan's dimensions, one is in principle identifying something like an average or modal level over the sub-tasks the human + automation system accomplishes. Similarly, when one uses a levels  $\times$  stages model such as in Parasuraman et al. [6], one is performing an abstract and coarse-grained decomposition of the parent task into sub-tasks clustered by information processing stage. Assigning levels by sub-task stages offers more sensitivity than assigning them only to the parent task, but it is still an abstraction. In practice, one could identify the specific sub-tasks to be performed and represent an automation level for each of them.

Figure 2-2 provides a hypothetical illustration of this relationship. A parent task "A" might be said to have a certain level of automation on Sheridan's scale, but in fact, that task is comprised of a series of sub-tasks (A1 – A6) each of which may have a different mix of human and automation involvement (as illustrated by the different shadings of the sub-task boxes). These sub-tasks can be reasonably organized or clustered into Parasuraman, Sheridan and Wickens's information processing stages, but this can obscure both the fact that specific sub-tasks exist and that they may have different mixtures of human and automation involvement. Furthermore, each of the tasks at this level can also, generally, be further decomposed into sub-sub-tasks (A1.1 – A6.2) which may also have different mixes of human and automation involvement... and so on, until some desired primitive level is reached.

Why would one want to perform this kind and level of analysis? More and finer-grained sub-tasks are not necessarily better and, in fact, Parasuraman et al. [6] explicitly state that they chose a four-stage model to simplify design considerations. Precision may be inherently desirable for some purposes (such as training and detailed design), but Miller and Parasuraman's [9],[4] purpose in achieving greater precision and finer granularity was to support flexible task delegation. As we saw above, for any intermediate LOA for a task, there are roles for both humans and automation in its sub-tasks. Yet, someone must coordinate those roles. Insofar as human supervisors are required to manage, or at least be aware of, that division of labor, they must understand the decomposition of the task and of the allocation and coordination requirements among its sub-tasks. Supervisory control is a process of task delegation and delegation requires task decomposition.

### *Strengths and Weaknesses*

That said, while precision and flexibility in stipulating how a task is to be performed is a necessary aspect of powerful delegation relationships, the goals of a framework for this working group were somewhat different. Instead of precisely defining each and every difference in how various systems achieve supervisory control, we wanted to group similar systems – a process that implies some degree of ignoring (or, at least, clustering) differences. Furthermore, prior work with the Miller and Parasuraman [9] approach (as well as the similar LoA<sup>3</sup> and CLAMP<sup>3</sup> frameworks described below) has shown that, while powerful, they are as cumbersome and time consuming to use *for the purposes of description* as most task analytic techniques in human factors [8],[10]. Thus, they were inappropriate for the purposes of briefly and intuitively summarizing the similarities and differences between supervisory control systems being explored in the HFM-170 technology development efforts.

## **2.4 LOA<sup>3</sup>**

During prior work for the U.S. Air Force Research Laboratory and in a proposal to the U.S. Army's Aeroflightdynamics Directorate (AFDD), Miller et al., expanded the concept of hierarchical task decomposition

to describe supervisory control to develop what they called the “LoA<sup>3</sup>” concept. This stood for levels of authority, abstraction and aggregation, and this triumvirate of parameters was advanced as a way of describing and defining delegation relationships. Delegation, in general, was defined as illustrated in Figure 2-3.

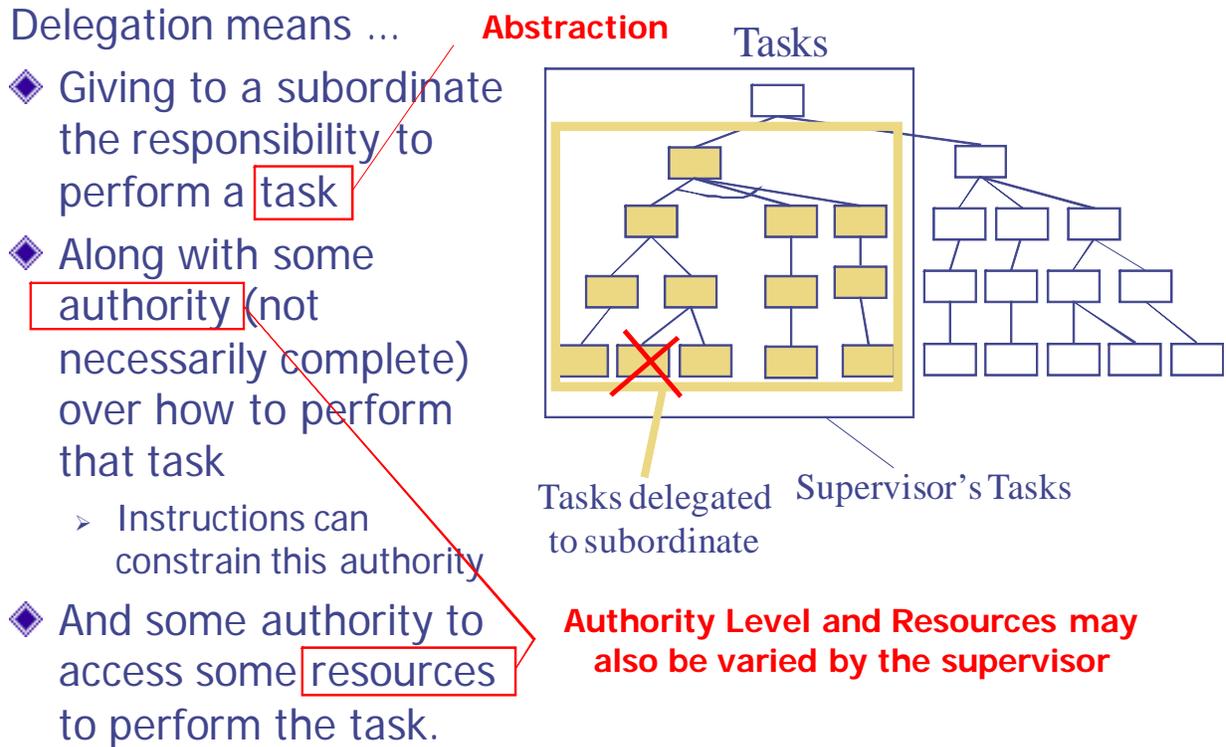


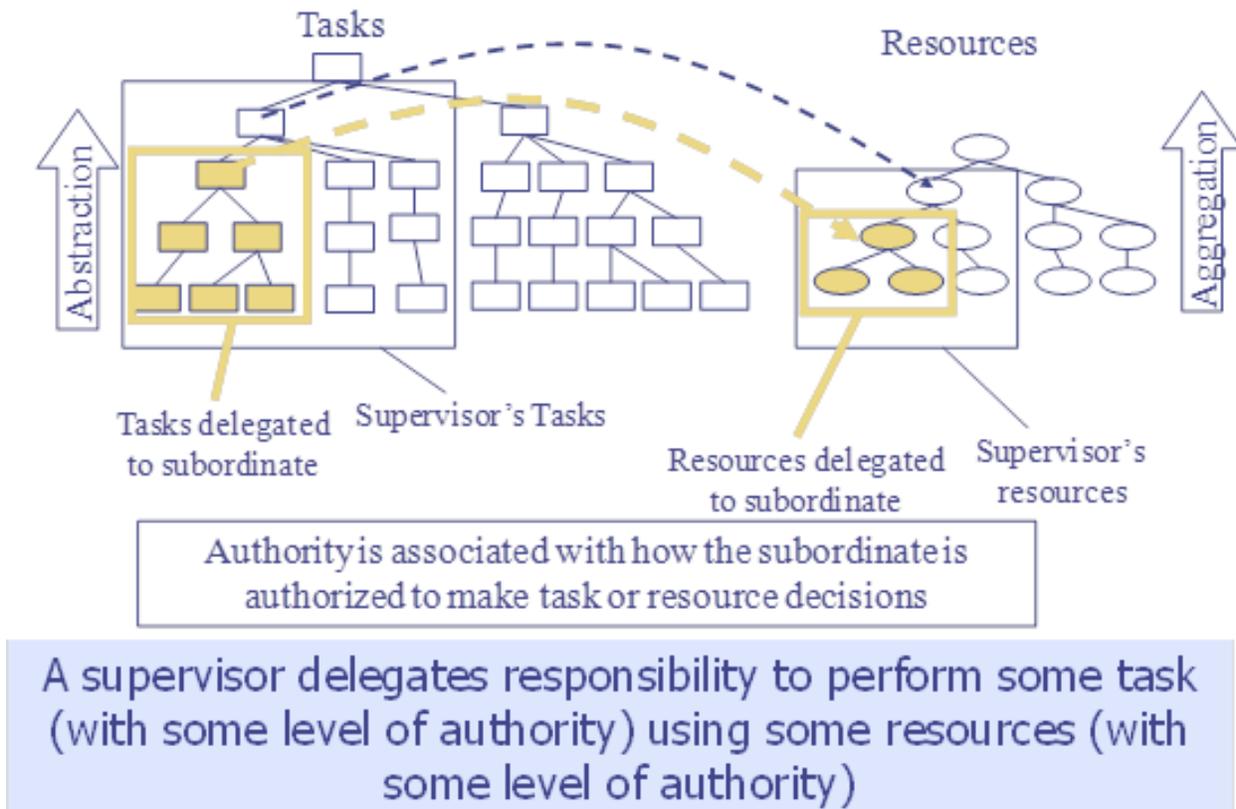
Figure 2-3: A 3-Dimensional Definition and Framework for Delegation Interactions.

The three dimensions were:

- 1) *Abstraction* – This is essentially the means-ends or hierarchical decomposition of a task. Each parent task represents the “ends” or goal of a child (or set of child) tasks; each child task represents the means by which a parent task is accomplished. Delegation means handing over some responsibility for some tasks which themselves are part of larger, parent tasks and which also decompose into smaller child- or sub-tasks. Delegating the task, at any level, means transferring *some* authority to perform that task (if any workload is to be saved) and authority over some resources (at least attentional resources) to perform the task and its sub-tasks and to make the decisions about which sub-task methods to pursue.
- 2) *Aggregation* – This is essentially the part-whole decomposition of resources. Any effective act of delegation must include the delegation of (at least partial) control over resources if it is to accomplish anything – even if the resources delegated are only the attentional and decision making resources of the subordinate. Of the full set of resources which a supervisor controls, s/he will delegate some control over some of those resources to the subordinate.
- 3) *Authority* – Authority represents the degree of autonomy that the subordinate has over the tasks (abstraction dimensions) and resources (aggregation dimension) he/she/it has been delegated.

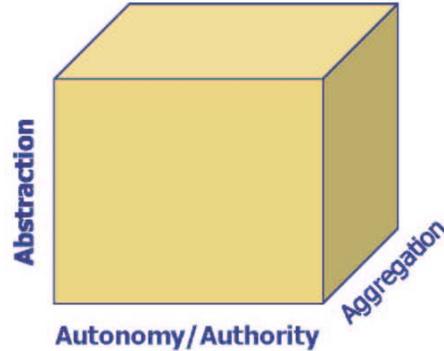
Sheridan’s 10 levels (cf. Figure 2-1 above) can be thought of as a spectrum of autonomy – characterizing a range from “computer has no autonomy” through varying levels of autonomy to provide suggestions only, autonomy to act only if authorized to do so immediately prior, authorized to act only if the action is reported, and ending at “computer has full autonomy”.

These three dimensions, then, let us specify an act of delegation as depicted in Figure 2-4. Any delegation involves the transfer of responsibility for some sub-tasks or tasks for which the supervisor has responsibility, along with some resources over which the supervisor has control. In both cases, the transfer of authority may not be complete, even over these sub-tasks. The supervisor may require the subordinate to coordinate, ask permission, inform, etc.



**Figure 2-4: An Act of Delegation Can Be Specified as a Transfer of Responsibility Along Three Dimensions.**

Note that if the delegation act extends over time and functions, it establishes a *supervisory control relationship* between a supervisory and a subordinate. Therefore, the three dimensions of the LoA<sup>3</sup> model define a three dimensional “space” within which we could place, in principle, any supervisory control relationship (or act) – as illustrated in Figure 2-5.



- ◆ Level of Abstraction– At what level(s) can the human command; in terms of task hierarchy– with what level of authority?
- ◆ Level of Aggregation– what resources (how many agents/systems) can the human command– with what level of authority?
- ◆ Level of Autonomy or Authority– How independently can the automation act? Sheridan’s spectrum

These are dimensions that can be varied in LoA experiments

Figure 2-5: A 3-Dimensional “Delegation Space” Formed by the LoA<sup>3</sup> Dimensions.

### *Strengths and Weaknesses*

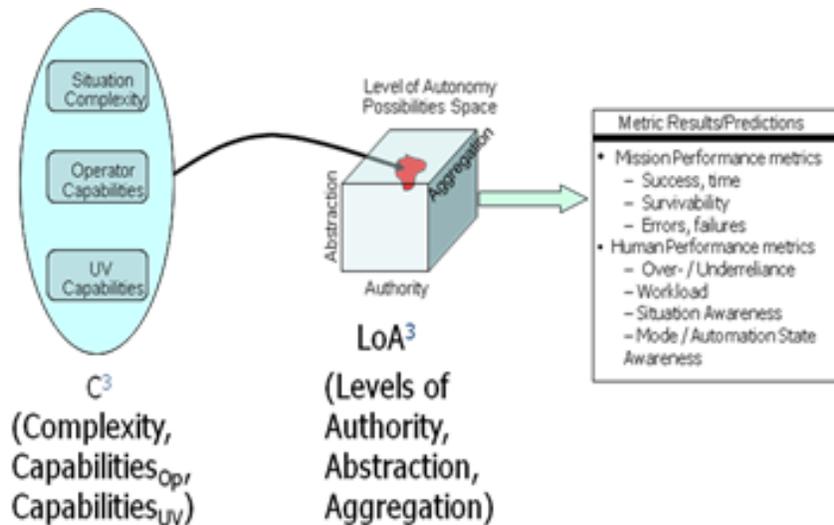
The LoA<sup>3</sup> model provides a rich description of the *act* of delegation, but there were problems with it for the purposes of our technical group. First and foremost, it relies on the same hierarchical task decomposition as the Miller and Parasuraman approach described in Section 2.3.1 above. As discussed there, this approach essentially requires a detailed and complete task decomposition for each alternative considered. While that may be useful for design and for a deep understanding of system alternatives, it is not compatible with the easily understood taxonomic groupings this working group was after. Second, this model was seen as having a failing in that it concentrated *exclusively* on the delegatory act and had nothing to say about the environment or technological context in which that delegation was performed. Since the members of HFM-170 were working on characteristically different technologies and domains (e.g., ground vs. air vs. sea UMVs), it was felt that an adequate framework for the group needed to reflect these differences and similarities as well.

## 2.5 CLAMP<sup>3</sup>

CLAMP<sup>3</sup> was an attempt to remedy the second failing of the LoA<sup>3</sup> model as described above – to embed the LoA<sup>3</sup> model in a broader framework which would include the ability to characterize aspects of the technology and application domains of the supervisory control systems it classified. CLAMP<sup>3</sup> was developed by Harry Funk and used as the framework for a simulation and testing environment for delegation systems which was built and used initially by Jay Shively, Susan Flaherty and Lisa Fern at the U.S. Army’s Aeroflightdynamics Directorate (AFDD) and later expanded and used for additional experiments by personnel at Smart

Information Flow Technologies (a small U.S. business) and George Mason University under funding from AFDD.

CLAMP<sup>3</sup> stands for C<sup>3</sup> (three dimensions of Context) + LoA<sup>3</sup> + Mapping for Predicting of Personnel Performance – as illustrated in Figure 2-6. In other words, CLAMP<sup>3</sup> takes the 3 levels describing the delegation interaction from LoA<sup>3</sup> and “wraps” them in a description of the context in which that delegation action takes place (the three context dimensions) along with a description of the resulting performance metrics for the human-machine system.



**Figure 2-6: The CLAMP<sup>3</sup> Model – Embedding LoA<sup>3</sup> in Context and Performance Outcomes.**

The three context dimensions used were:

- 1) A description of the *Situation Complexity* – That is, for example, is the UAV being asked to fly straight and level at cruising altitude on a clear and windless day, or is it being asked to fly nap of the earth at night, in storms, with enemy radars and small arms fire.
- 2) A description of the *Capabilities of the Operator* – Is s/he a trained fighter pilot (training that might be helpful for operating a UAV, but useless or even counter-productive for operating a UGV) or an untrained infantryman? Is s/he operating in a quiet room devoting full attention to the UMV management task, or is s/he engaged in combat, taking fire and perhaps riding in the back of an armored vehicle in rough terrain?
- 3) A description of the *Capabilities of the Unmanned Vehicle* – These could be any relevant attribute of the UMV, but particular relevance will generally be associated with control and functional capabilities. A vehicle which only ever does one thing (e.g., flies in a circle transmitting images) will impose much less burden on an operator than one that admits many different behaviors and modes. Similarly, one whose performance and stability is unreliable will require much more human attention than one that is highly reliable.

At the “other end” of CLAMP<sup>3</sup> is a description of the outcome or effects of a delegation relationship within the context described – that is, performance measures in terms of both mission and human performance.

### *Strengths and Weaknesses*

While CLAMP<sup>3</sup> has been used as the framework for experimental work sponsored by AFDD, it retains problems for use as a framework for this working group. First, it inherits the problem of LoA<sup>3</sup> and of Miller and Parasuraman [9] in that it is based on a hierarchical task decomposition to describe the delegation relationship between human and automation. While this is rich and detailed, it is likely too rich and detailed for convenient use by this group or easy understanding by others.

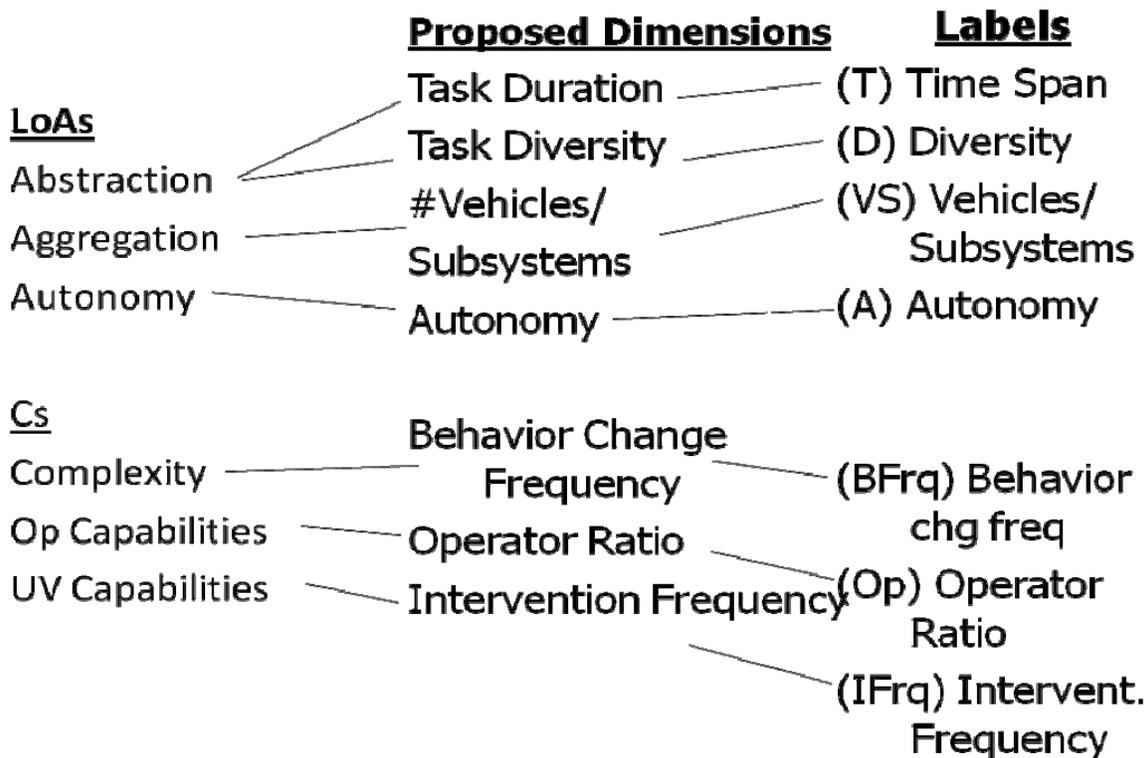
More importantly, while CLAMP<sup>3</sup> calls attention to the need to situate a description of a supervisory control relationship in a context and to describe its effectiveness, methods of representing these dimensions are underspecified. CLAMP<sup>3</sup> tells us, for example, that it's important to consider the complexity of the context, but gives us no metric or even set of factors that might contribute to that complexity. Such would be necessary for comparing applications within and across the members of HFM-170. The main contribution of CLAMP<sup>3</sup> was to remind us to include these dimensions as we moved forward in trying to specify a framework for use by this group.

## **2.6 7D**

There was general consensus that the core ideas of the CLAMP<sup>3</sup> framework were moving in the right direction – that is, particularly the idea that folding a description of a supervisory control relationship into a description of the context in which the relationship was used to describe the resulting system. What was needed, it was felt, was a way of reducing the complexity of the associated dimensions while regularizing and scaling them. It was with these goals in mind that Chris Miller proposed a seven dimensional model at the Stockholm meeting of HFM-170 in June, 2008.

The seven dimensions of this model were formed by returning to the LoA<sup>3</sup> and C<sup>3</sup> (context) dimensions of the CLAMP<sup>3</sup> framework and attempting to characterize and scale them to develop a multi-dimensional description of a supervisory control relationship plus the environment in which that relationship occurred. More specifically, the goal was to use the previously-identified abstract dimensions to form a quantified and specific set of relevant and important dimensions along which the HFM-170 projects and applications varied.

The LoA<sup>3</sup> scales (autonomy, abstraction and aggregation) collectively characterize the *interaction* between the human and automation, as we noted above. The C<sup>3</sup> scales (complexity, operator capabilities, automation/UMV capabilities) collectively characterize the *environment* in which the LoA relationship exists and is exercised. Using this insight, Dr. Miller went through each of the scales and attempted to distill what was “important or significant” about each of them with regard to the supervisory control applications being developed and discussed by this working group. This gave us a means for identifying dimensions to include in our resulting model and, more importantly, for creating a scale for each dimension. The set of dimensions identified are depicted in Figure 2-7 (which also illustrates how they were derived from the LoA<sup>3</sup> and C<sup>3</sup> dimensions) and are discussed along with the scales developed to represent them below.



**Figure 2-7: The Seven Descriptive Dimensions and Their Derivation  
from the LoA<sup>3</sup> and C<sup>3</sup> Dimensions of the CLAMP<sup>3</sup> Model.**

In general, the scales were created to capture the range of variation, yet show interesting degrees of difference, along the dimensions we saw in supervisory control UMV systems under consideration by the group. A secondary motivation was an attempt to synchronize the length and scalar values on each of the scales to facilitate later visualizations. To achieve this later goal, we developed seven point scales for each dimension (as described below) and arrayed each of the scales from “worse” (notionally less competent systems) to “better” (notionally more competent systems). The specific divisions are, of course, somewhat arbitrary and debatable, but the intention was to provide a “chunking” of the dimension into seven significantly different categories:

- What’s important/significant about “Abstraction”? Abstraction, in a task hierarchy sense, captures the number, types and relations of tasks/behaviors the UMV is designed for. If the top level task in a hierarchy for a given UMV can be thought of as “Perform Mission”, then a complete decomposition will represent all the possible tasks that system will perform. The “size” of that hierarchy tells us important things about the mission(s) and capabilities of the UMV and led to proposing two different dimensions:
  - **Mission/Task Duration (T)** – Duration of missions is a reasonable stand-in for “size” of the hierarchy – how much time span does a typical mission or task being analyzed cover? This is not the task that the operator delegates, but rather the operational window for the UMV itself. Length/duration is a simple dimension ranging from seconds to days or weeks. A scale of interestingly different levels on this dimension (for the set of UMV systems we were considering) was proposed as:

- 1) Seconds
  - 2) 1 – 5 minutes
  - 3) 5 – 30 minutes
  - 4) 30 – 90 minutes
  - 5) 1.5 – 6 hours
  - 6) 6 – 24 hours
  - 7) Days
- **Task Diversity (D)** – Task diversity is a necessary second dimension to identify the “complexity” of missions and of UMV roles. How many different *types* of tasks is the UMV involved in? How many conceptually distinct functions<sup>2</sup> are performable by the vehicle(s)?:
    - 1) 1 only
    - 2) 2 – 3
    - 3) 4 – 6
    - 4) 7 – 10
    - 5) 11 – 15
    - 6) 16 – 25
    - 7) 25+
  - What’s important about “Aggregation”? Aggregation refers to the number of vehicles (or vehicle “parts” or sub-functions) being controlled by the user(s) in an application to be characterized by the framework. Some supervisory control systems are being designed to control multiple UMVs simultaneously, while others are controlling at most a single sub-system. This gave rise to the **Vehicles/Sub-systems (VS)** dimension.
  - **Vehicles/Sub-Systems (VS)** – The VS dimension captures how many UMVs and/or UMV sub-systems are typically involved in a mission (in the analyst’s focus of interest):
    - 1) Single sub-system
    - 2) Multiple (2 – 4) sub-systems, but not whole vehicle
    - 3) One whole vehicle or 4+ sub-systems
    - 4) 2 whole vehicles (or parts thereof)
    - 5) 3 – 4 vehicles
    - 6) 4 – 12 vehicles
    - 7) Swarms (12+)
  - What’s important about “Autonomy”? Who’s in charge, who is leading/following? For the mission as a whole, what’s the relationship between human and automation?
    - **Autonomy (A)** – To characterize this dimension, we relied on an abbreviation of Sheridan’s initial autonomy scale which folds in a sense of where, in the hierarchy of tasks which comprise the mission, the control is taking place:

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<sup>2</sup> Of course, determining what a “conceptually distinct function” or task type is will be subject to individual judgment and to the needs and focus of the analysis. This is largely irrelevant as long as the selected level is kept approximately constant across systems to be compared.

- 1) Human is in charge and commands specific, limited, non-integrated functions from automation
  - 2) H sets overall goals, dictates tasks, but delegates moderate decision authority within isolated functions to A, while retaining monitoring and intervention authority
  - 3) H responsible for overall goals, but A is given large tasks which may integrate across functions. A may initiate actions within its functions
  - 4) Balanced responsibilities between H and A
  - 5) As for 3, but switch H and A
  - 6) As for 2, but switch H and A
  - 7) As for 1, but switch H and A
- What's important about environmental "Complexity"? We argued that this could be captured by noting how often the UMV has to change its behaviors (where "behaviors" are significant variations within the tasks or functions defined for "Task Diversity" above). This dimension was called "Behavioral Change Frequency" or BFrq.
    - **Behavioral Change Frequency (BFrq)** – What is the average duration between required changes in vehicle behaviors (either user- or system-initiated) in a typical mission of interest?:
      - 1) Longer than 1 per hour
      - 2) Every 20 – 60 min
      - 3) Every 5 – 20 min
      - 4) Every 1 – 5 min
      - 5) Every 10 – 60 sec
      - 6) Every 5 – 10 sec
      - 7) Once per second or faster
  - What's important about "Operator Capabilities"? Here, we felt that all the required operator capabilities, while significant in their own right for training and selection, etc., could be rolled up and reflected in how many operators are required to control the vehicle(s) in a typical mission on which the analyst is focusing – hence, Operator to Vehicle Ratio (Op).
    - **Operator Vehicle Ratio (Op)** – In the scale developed below, ratio can be calculated – thus, four operators controlling four UMVs yields a ratio of 1:1. Similarly, fractions of an operator's time may be considered if the operator is concurrently engaged in other tasks – thus, an infantry soldier who is spending half his time controlling and monitoring video feed from a UAV while providing covering fire could be represented as .5 operators to 1 UMV or 1:2.
      - 1) 4+ operators to 1 UV
      - 2) 2 – 3 Ops to 1 UV
      - 3) 1 to 1
      - 4) 1 Op to 2 UVs
      - 5) 1 Op to 3 – 4 UVs
      - 6) 1 Op to 5 – 10 UVs
      - 7) 1 Op to 10+ UVs
  - What's important about "UMV Capabilities"? Here, we argued the raw capabilities of the UMV were not as important (and were too diversified for good abstraction in a model), but rather its capabilities

to perform its functions without operator intervention. This, in turn, gave rise to a focus on the frequency with which the operator had to intervene in the functioning of the UMV(s).

- **Operator Intervention Frequency (IFrq)** – This dimension was captured in a scale tied to the required frequency with which the operator had to interact with the system to achieve successful mission behavior. (Note that later thinking, not adopted at the time of presenting and discussing this dimension, suggests that this should not be a simple intervention frequency, but rather a percentage or ratio of clock time which the operator must spend in interaction with the vehicle – similar to “Robot Attention Demand” in Olsen and Goodrich’s (2003) “fan out” metric.):
  - 1) Once per second or faster
  - 2) Every 5 – 10 sec
  - 3) Every 10 – 60 sec
  - 4) Every 1 – 5 min
  - 5) Every 5 – 20 min
  - 6) Every 20 – 60 min
  - 7) Longer than 1 per hour

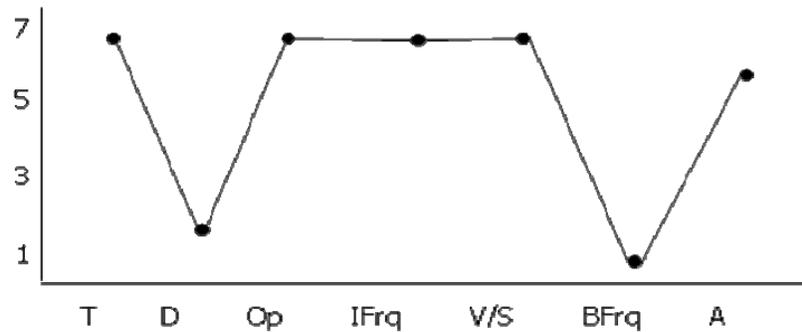
Once these scales had been developed, we sought to illustrate them on a set of examples drawn from significantly different UMV systems. We chose a set of three systems:

- 1) *Unattended Ground Sensors (UGSs)* – These represented a very simple (perhaps degenerate) example of UMV systems. A UGS is a simple sensor which, once installed (or even air dropped), transmits a video or auditory signal only when a stimulus of interest (e.g., a heavy vehicle passing by) is detected. Tens or perhaps hundreds of UGSs can be installed in an area and “controlled” by a single operator. Once installed, they do not move or change their behaviors except transmitting vs. not transmitting.
- 2) *Raja’s RoboFlag* – In 2003 and 2004, Dr. Raja Parasurman and others worked with a simulated robotic platform created by Dr. Mark Campbell of Cornell University to conduct a series of experiments in flexible, delegation-style supervisory control [11],[12],[13],[14]. In this testbed, a single human operator controlled a team of five ground-based robots maneuvering them about a playing field to play a game of “capture the flag” against a fully automated team of five opposing robots. The robots could move, sense other robots, “tag” other robots to disable them and grab the enemy’s flag and return it to their territory. The operator could control these robots (in varying experimental conditions) by either individual waypoint commands, or a series of increasingly aggregated “plays” which might task a single robot or the entire team.
- 3) *Jay Shively’s MUSIM and Delegation Control (DelCon) Environment (a.k.a. “Jaybook”)* – DelCon [15],[16] is a flexible delegation-style supervisory control system being developed by Jay Shively and colleagues at the U.S. Army’s Aeroflightdynamics Directorate. Delcon (or, as it was affectionately known by members of the working group, “Jaybook”) is embedded in the Multiple UAV Simulation (MUSIM) testbed, where it controls three UAVs in the performance of an urban target monitoring, search, tracking and prosecution scenario. Jaybook provides control capabilities that range from waypoint control and joystick-controlled sensor operations to multiple UAV coordinated monitoring and lasing/prosecution plays.

Using the scales defined above, these three example systems can be graphed to illustrate the characteristic differences between them. Figure 2-8 shows a traditional linear graph for each example system. Note that both the RoboFlag and Jaybook examples define regions (rather than simple lines) because they can be operated in

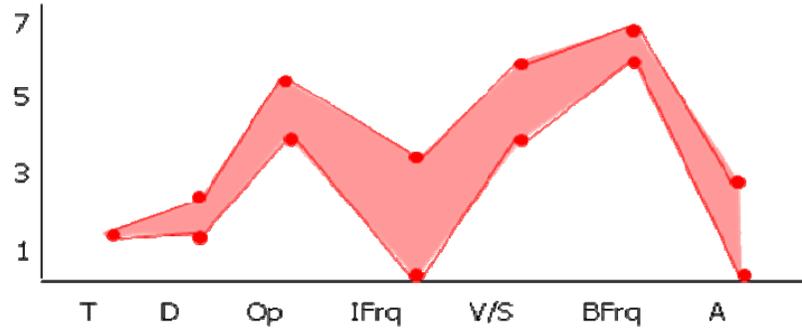
flexible modes and those modes have different implications for dimensions such as how frequently the operator must intervene (IFrq) and how much autonomy is afforded to the system (A).

	<u>UGS</u>
T =	7
D =	2
Op =	7
IFrq =	7
V/S =	7
BFrq =	7
A =	6



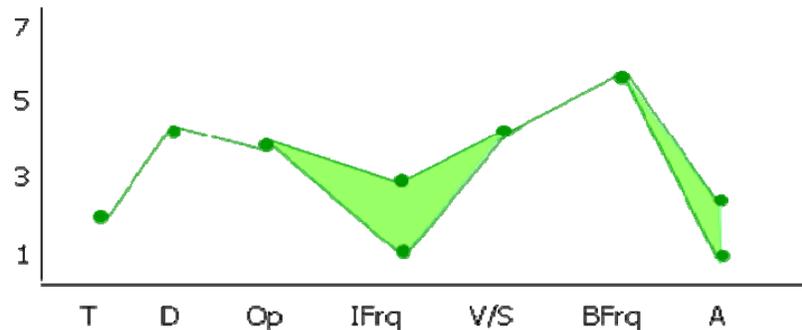
**Raja's RoboFlag**

T =	2
D =	2-3
Op =	5-6
IFrq =	1-4
V/S =	4-6
BFrq =	6-7
A =	1-3



**Jaybook Exp 1**

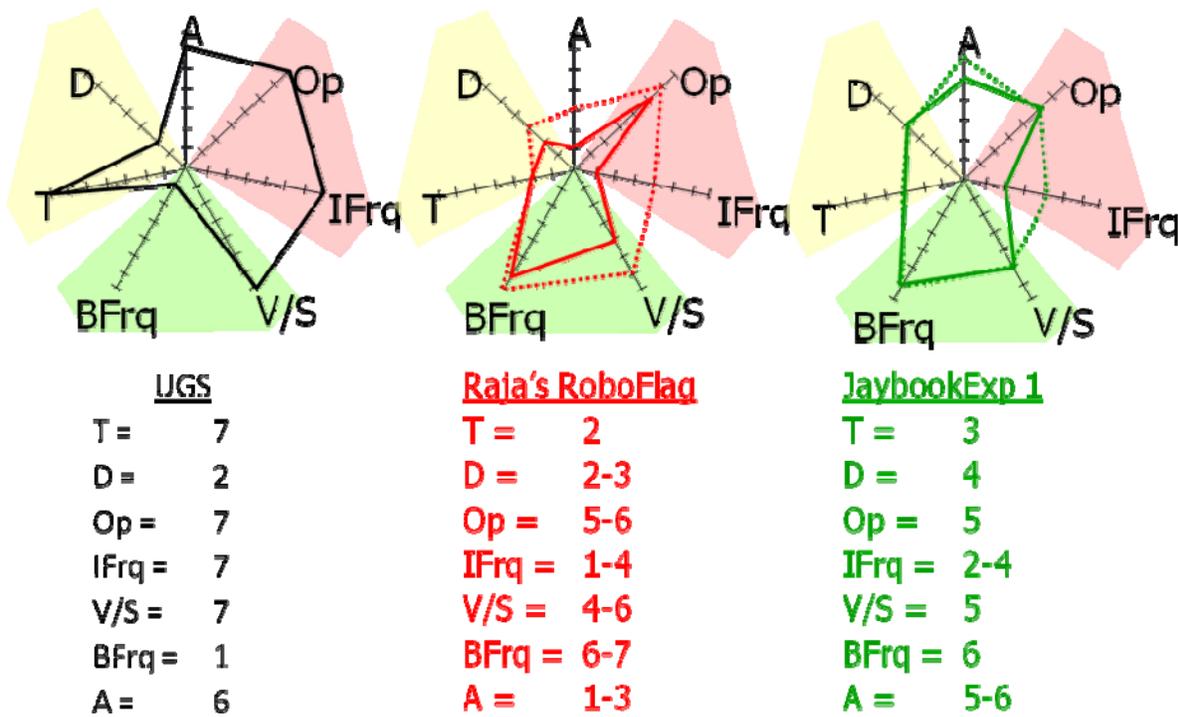
T =	3
D =	4
Op =	5
IFrq =	2-4
V/S =	5
BFrq =	6
A =	2-3



**Figure 2-8: Linear Graphs of Values for Each of the Seven Dimensions for the Three Exemplar Systems.**

These linear graphs make comparisons of the different examples quick and easy. It is obvious that Raja's RoboFlag and Jaybook are both capable of being operated in different modes, while UGSs are not. Furthermore, it is obvious that UGSs are operated in a much longer Typical mission (T) with many more "Vehicles" (VS) and with better (rarer) Intervention Frequency (IFrq), but with much less task Diversity (D) and Behavioral change Frequency (BFrq) than either of the others.

Perhaps more convenient and informative still, because we have structured the dimensional scales to be of equivalent lengths and orientations, we can graph them using a polar star format as in Figure 2-9. Furthermore, the polar star can group the dimensions in interesting categories, for example, task characteristics (Duration (T) and Diversity (D)) are shaded tan, operator characteristics (Operator Vehicle ratio (Op) and Intervention Frequency (IFrq)) are shaded pink, and platform/vehicle characteristics (Behavior Change Frequency (BFrq) and Vehicles/Sub-systems (VS)) are shaded green. Here, again, characteristic patterns are made visible. We can easily see that UGSs are very “good” for the operator in the sense that they require rare interventions and can support a high operator-to-vehicle ratio, but that they achieve this by severely restricting task diversity and behavior change frequency.



**Figure 2-9: Polar Star Depictions of the Values for Each Example System. Note clustering of dimensions into Task characteristics (T and D in tan), Operator Characteristics (Op and IFrq in pink) and Platform or Vehicle Characteristics (BFrq and VS in green).**

*Strengths and Weaknesses*

When initially presented, this 7D model was reasonably well received. It was seen as having the strengths of characterizing environment, vehicle, and operator characteristics, as well as the supervisory control relationship between them – and of doing so in relevant and interesting ways at a reasonable level of aggregation for the group. It was, however, also seen as still too complex for easy comprehension. Furthermore, there was a feeling that many of the dimensions were either poorly defined or confounded (non-orthogonal), or that the scales proposed were sub-optimal in some way. In practice, though, we began work on a simplified version of this seven dimensional model (as described next) to solve the complexity problem instead of concentrating on refining and improving the dimensions and scales.

## 2.7 2D INTERACTION DESCRIPTION

Given the feeling that even the 7D model described above was still too complex for our purposes, we sought to simplify it further. Upon thinking more deeply about the situation, we felt that supervisory control is, at its root, an interaction relationship between a supervisor and one or more subordinates. Everything else is external to that relationship and, while it is not incidental or unimportant, it certainly increases the complexity of a description. We could instead focus primarily and exclusively on the nature of that relationship. This insight led us to the two dimensional model of the supervisory control interaction and relationship described below. Dr. Miller first described and presented this model at the HFM-170 meeting in Paris in September of 2009, and expanded and provided examples of it with developed scales at the Dayton meeting in June of 2010.

After an analysis of various supervisory relationships in human-human interactions (see Figure 2-10), we concluded that they could be reasonably, and usefully, arrayed along two dimensions:

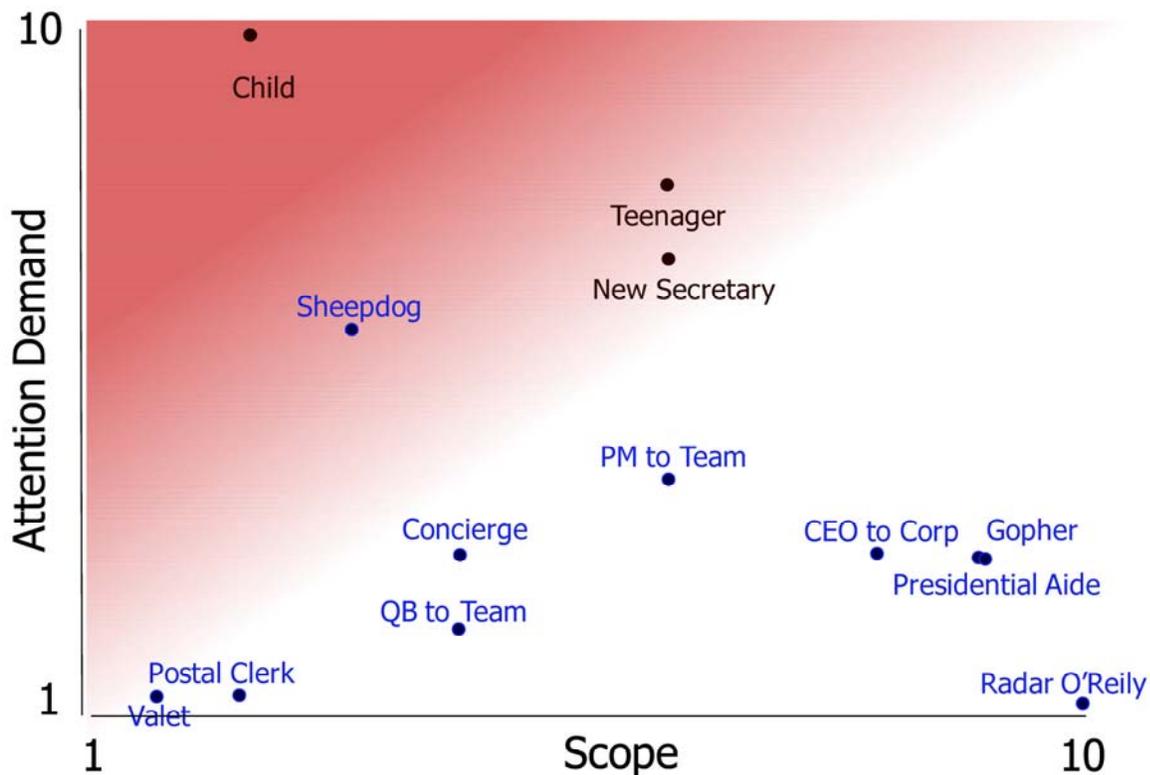
- 1) The attentional demand that the relationship required of the supervisory in order to accomplish any useful work; and
- 2) The “scope” or range of functions and capabilities that the subordinate(s) provide for performing useful work at that level of attentional demand.

	<u>Demand</u>	<u>Scope</u>	<u>Useful?</u>	<u>Ratio</u>
A Parking Valet	1	1	+	1
A Postal clerk/Fast Food Chef	1	2	+	.5
Shepherd to sheepdog	6	3	+	2
A young child (~3 yrs)	10	2	--	5
A teenager (~16 yrs)	8	6	-	1.3
A new secretary/asst	7	6	-	1.1
A concierge	3	4	+	.75
Quarterback (Am.) to team	2	4	+	.5
Project Manager to team	4	6	+	.67
CEO to corporation	3	8	+	.38
Presidential Aide	3	9	++	.33
Movie Director’s Gopher	3	9	++	.33
Radar O’Reilly	1	10	++	.1

**Figure 2-10: Scored Values for Attentional Demand and Performance Scope for Each of 13 Different Human-Human Supervisory Control Relationships.**

At the time this initial thought exercise was performed, we had not developed scales for these dimensions, but we nevertheless took the step of informally rating each relationship on a 10 point scale ranging from low to high<sup>3</sup>. The results of this informal exercise are shown in Figure 2-10.

An interesting phenomena emerged from these ratings. It would seem that when the dimensions were arrayed against each other (see Figure 2-11), one could envision a “utility horizon” which ran roughly along the diagonal. “Useful” supervisory control relationships are those for which the cost to perform useful work is, at most, no more than the usefulness of the work performed. Since the attentional demand dimension we had identified was a fairly direct measure of the “cost” to the supervisor of performing the work and the “performance scope” term was a measure of the range of useful things the subordinate could perform, it served as at least an indirect measure for the benefit or usefulness of the work. Therefore, intuitively, relationships that fell on or below the diagonal were useful, while those which fell above the diagonal tended to be less useful. Such relationships could also be characterized somewhat more quantitatively by taking the ratio of the demand score to the scope score – as illustrated in the rightmost column of Figure 2-10. Here, higher values are indicative of less “useful” relationships (from the perspective of performing work with immediate utility), while lower values are indicative of more productive relationships. To check this intuition, we also provided intuitive ratings (on a five point scale from “- -” to “+ +”) and then calculated a Pearson’s correlation coefficient between the two sets (treating the second scale as -2 to +2). The resulting value was -.765, indicating that demand-to-scope ratio was highly negatively correlated with our sense of the usefulness of the relationship.



**Figure 2-11: Graphing the Demand vs. Scope Scores to Illustrate a Diagonal “Utility Threshold”.**

<sup>3</sup> These ratings are Dr. Miller’s alone.

The results of this initial brainstorming exercise were presented at the Paris meeting in 2009, and were met with general interest as a potentially promising direction. The primary criticism was that both the dimensions and the scales themselves were very informally defined. Thus, Dr. Miller took the step of trying to refine and quantify them, as described below.

*Attentional Demand* – This dimension was meant to capture the amount and frequency of time and attention required by the supervisor to manage the system and achieve the work desired. Our initial thought was that Olsen and Goodrich’s [17] Fan Out metric was a close fit to what was needed. Olsen and Goodrich actually labeled their metric “Robot Attention Demand” (RAD) and defined it by the formula:  $IE / (IE + NT)$ , where:

- IE is “Interaction Effort” – the time (or effort) required to interact with the robot; and
- NT is “Neglect Tolerance” – the robot’s effective performance time without intervention.
- We presume (though this is **not** clearly stated in Olsen and Goodrich) that  $IE + NT = \text{total time}$ .

Thus, RAD is the proportion of time/effort during operation that the supervisor must devote to interacting with the automation. Based on RAD, we proposed “SAD” (System Attentional Demand) – the proportion of supervisor time/effort required to interact with the system in order to perform desired work. SAD is a unitless metric that ranges from 0 (for completely autonomous automation that requires no supervisory input) to 1 (no effectively “free” human time – the supervisory spends 100% of his/her time interacting to achieve the desired work).

To compare multiple systems with SAD, it is important to maintain consistent assumptions and scoring. Important considerations include:

- Whether/what “set up time” to include? The RAD definition was unclear (and, in fact, has been criticized by Crandall and Cummings [18]) for failing to consider pre-mission planning and configuration time, as well as engineering and design time. For using SAD or RAD to compare multiple systems, any set of practices with regards to these non-execution time parameters may be used, but it is important that they are applied consistently across systems that are analyzed.
- What performance context assumptions are used? Again, when assigning time and effort used to control and task the automation, it is also important to maintain consistency in assumptions across different systems rated if the goal is to compare those systems. For example, does the scenario of use represent a “sunny day” where nothing goes wrong or a worst case or factored error assumptions, etc.? Is the user considered a novice, an expert or somewhere in between? What error rates are assumed for the user’s inputs?, etc. Again, the SAD metric can accommodate a wide range of different assumptions, but it is important that the assumptions be applied consistently across systems rated.

*Performance Scope* – There is a problem with using only SAD or RAD as the basis of comparison across supervisory control systems, however. Essentially, both compare systems *only* on the percentage of supervisor time they require; there is no explicit notion of the level of system effectiveness or work accomplished for a given level of SAD. In order to compare system functionality or effectiveness using SAD requires an assumption of homogenous tasks and performance targets – even Olsen and Goodrich’s [18] Fan Out application of RAD presumed a homogenous task: “fanning out” a set of robots searching. That said, there is no explicit notion of the domain or task included in RAD or SAD. Using SAD alone, each of the following examples would have the same “attentional demand” value:

- Telling a fleet of 100 UAVs to “stay put” on the tarmac (that is, to do nothing);
- Telling very highly autonomous UAV to “execute” it’s trip around the world; and

- Telling an efficient secretary to plan your next months' trips (assuming s/he already has access to your required trips and times and knowledge of your needs and preferences).

In each of these cases, the supervisor's attentional demand is one, short verbal interaction. On the other hand, the examples differ radically in the *scope of work performed*. Hence, we felt that a second dimension was needed to reflect the variety of tasks or functions the subordinate automation can perform. The problem is that tasks are inherently hierarchically decomposable and characterizing them across systems and domains is notoriously difficult. Therefore, in order to maintain some consistency in comparing different applications, we would need a *common* task model for the domain of interested which is shared by the applications/relationships. This is not to say that all the systems must perform exactly the same tasks in the same way, but some basis for comparison across tasks was necessary – otherwise we would be stuck simply saying that the systems did different things. One way to accomplish this might be to require that the systems all accomplish a shared function or goal, though perhaps used different methods to do so.

Given such a model (which might, necessarily, be fairly abstract), we thought we could perhaps simply count the tasks (at a given level) that the proposed system performs, and that such a count would itself provide a metric for performance scope. The worked example to be described next was meant as a thought experiment to test whether a simple count of the tasks performed at a common level of a reference model could serve as a reasonable metric for performance scope.

*An Elevator Example* – To test this hypothesis, we conducted an extended thought experiment to compare several versions of a supervisor/subordinate system (which was, in most cases, also a human-automation system), each of which was designed to perform the same basic function: an elevator system in a multi-story building. A “reference model” for the tasks of elevator systems might be:

- 1) Summon/Initiate – call a/the elevator;
- 2) Select Elevator to respond;
- 3) Move to Called floor;
- 4) Control Speed;
- 5) Position Elevator Vertically;
- 6) Open Door;
- 7) Load Passenger(s);
- 8) Select Destination Floor;
- 9) Close Door;
- 10) Move to Destination Floor;
- 11) Control Speed;
- 12) Position Elevator Vertically;
- 13) Open Door;
- 14) Unload Passenger(s); and
- 15) Close Door.

Note that this is intended as a “spanning” model. Not all tasks are pertinent or performed by all systems, and not always in this order. The intent is that alternate elevator systems can be evaluated on whether and how they perform these tasks (with what mix of human and machine).

Next, we defined a set of human-elevator systems to map against the reference model drawn from the variety of elevator systems we had experienced:

- 1) *Old Style* – Completely Manual Operation, single elevator. In this style of elevator, the human (usually a dedicated “elevator operator”) performed door opening/closing, vertical movement and positioning, etc.
- 2) *Freight Elevator* – Here, I was thinking of an elevator in an academic building at the University of Chicago where a button press controlled opening/closing the door but the human controlled the rest (positioning and movement, etc.).
- 3) *English “Moving Carriage”* – This was an elevator which I (and others) had experienced in England – where elevator “cars” ran on a continuous, non-stopping vertical track, there were no doors and riders stepped on/off the car as it passed by the opening on each floor.
- 4) *Current Single* – What we’re all most familiar with: a modern “automated” elevator typical of moderate sized buildings. A button press summons the (single) elevator and which automatically opens its door when it arrives at the appropriate floor and then (usually) automatically closes the door when people board or leave. A different button is pressed for each floor desired and the elevator automatically travels to that floor, positions itself and opens its doors for riders to leave.
- 5) *Current Multiple* – What’s in most big buildings, hotels: a bank of elevators for different floors/regions. A single button is pressed to summon a car, but the automation behind the bank of elevators controls which elevator arrives at your floor. Riders enter and push buttons for their desired floor and the elevator automatically closes its doors and moves to the desired floor, where it opens its doors for disembarking.
- 6) *New York Marriott / HFES ’08* – This was an advanced, optimized bank of elevators many of us encountered at the Marriott hotel in New York City at the Human Factors and Ergonomics Society meeting there in 2008. A user enters the desired floor in a central console and is told which elevator to go to. The elevator arrives, opens its doors and the user enters. There is no need to press a second button to indicate the desired floor, since this has already been done. Instead, the elevator moves to each of the floors users have indicated they want to go to – and supposedly does so somewhat more quickly since it is attempting to route users going to the same floors into a common car.

Given these example systems, we first attempted to determine a SAD metric for each of them. This was accomplished by estimating<sup>4</sup> the time required for each of the tasks in the reference model. The results are presented in Figure 2-12. Note that in order to provide a comparable number across the systems it was necessary to assume a common scenario. We chose a typical, shared task: going up 3 floors as a single passenger. Further, we noted that travel speed increases with more modern systems and, thus, total task time (IE + NT) decreases, tending to drive the SAD value higher than it would otherwise be<sup>5</sup>. In practice, getting there faster enables other work to be done by the human and, thus, perhaps we should have used the highest

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<sup>4</sup> Note that, since this was a thought experiment, each of these estimates is based on the author’s experience, memory, and judgment, not on empirically gathered data.

<sup>5</sup> A further, hypothetical system will illustrate this problem more dramatically: imagine a teleportation elevator system which requires that the user press a button to indicate which floor s/he wishes to go to and then *instantaneously* transports him/her there. Such a system would, in principle, require, say, 2 seconds for the user to press the initial button, but no additional time to get to the appropriate floor. Thus, IE would be 2s and IE+NT would also be 2s and SAD would be  $2/2 = 1$  – a value we associate with a fully manual system above. By contrast, if we took the IE time relative to the total time for the worst case, most manual comparable system (the “old style” elevator), we would have  $2s / 247s = .008$  – a very highly automated system. This seems to mesh with intuition more neatly.

value for total time across the systems which perform the comparable elevator function. This insight is not reflected in the values in Figure 2-12, however.

No.	Task	Alternate Elevator Systems					
		Old Style	Freight	Moving Carriage	Current Single	Current Multiple	Marriott/HFES
1	Summon/Initiate	2s	2s	0s	2s	2s	2s
2	Select Elevator	0	0	0s	0s	0s	0s
3	Move to Called Floor	55s	55s	0s	0s	0s	0s
4	Control Speed	0s*	0s*	0s	0s	0s	0s
5	Position Vertically	15s	15s	0s	0s	0s	0s
6	Open Door	10s	2s	0s	0s	0s	0s
7	Load Passenger(s)	5s	5s	8s	5s	12s	8s
8	Select Destination Floor	--	--	3s	4s	2s	0s**
9	Close Door	10s	2s	0s	1s	1s	1s
10	Move to Destination	90s	90s	10s	0s	0s	0s
11	Control Speed	15s*	15s*	0s	0s	0s	0s
12	Position Vertically	15s	15s	0s	0s	0s	0s
13	Open Door	10s	2s	0s	0s	0s	0s
14	Unload Passenger(s)	5s	5s	8s	5s	5s	5s
15	Close Door	10s	2s	0s	0s	0s	0s
<b>TOTAL (IE)</b>		<b>242s</b>	<b>210s</b>	<b>29s</b>	<b>17s</b>	<b>22s</b>	<b>16s</b>
<b>TOTAL TIME (IE + NT)</b>		<b>247s</b>	<b>247s</b>	<b>220s</b>	<b>150s</b>	<b>150s</b>	<b>150s</b>
<b>SAD (IE/IE+NT)</b>		<b>.98</b>	<b>.85</b>	<b>.13</b>	<b>.11</b>	<b>.15</b>	<b>.11</b>

\* Extra effort beyond continuous commanded movement

\*\* Combined with the summon/initiate act

**Figure 2-12: SAD Estimates for 6 Different Elevator Systems.**

We then created scope values for each of the alternate elevator systems by simply counting which of the tasks each mechanical (subordinate) system performed automatically. We quickly realized that many systems partially automated some of the tasks and we chose to use fractional values to indicate the degree to which, in the scorer’s judgment, the system automated the task. The results are shown in Figure 2-13.

No.	Task	Alternate Elevator Systems					
		Old Style	Freight	Moving Carriage	Current Single	Current Multiple	Marriott/HFES
1	Summon/Initiate	0	0	0	.3	.3	.3
2	Select Elevator	0	0	0	0	.7	1
3	Move to Called Floor	0	0	1	1	1	1
4	Control Speed	.5	.5	1	1	1	1
5	Position Vertically	0	0	.3	1	1	1
6	Open Door	0	.8	0	1	1	1
7	Load Passenger(s)	0	0	0	0	0	.3
8	Select Destination Floor	0	0	0	0	.1	.5
9	Close Door	0	.8	0	.8	.8	.8
10	Move to Destination	0	0	1	1	1	1
11	Control Speed	0	0	1	1	1	1
12	Position Vertically	0	0	.3	1	1	1
13	Open Door	0	.8	0	1	1	1
14	Unload Passenger(s)	0	0	0	0	.1	.3
15	Close Door	0	.8	0	.8	.8	.8
	<b>TOTAL SCORE</b>	<b>.5</b>	<b>3.7</b>	<b>4.6</b>	<b>9.9</b>	<b>10.8</b>	<b>12</b>
	<b>Percent (out of 15)</b>	<b>3.3%</b>	<b>24.7%</b>	<b>30.7%</b>	<b>66%</b>	<b>72%</b>	<b>80%</b>

**Figure 2-13: Performance Scope Estimates for 6 Different Elevator Systems.**

Armed with these sets of quantitative values, we were now able to, again, graph them in various ways to facilitate interpretation. Figure 2-14 shows the two dimensions plotted against each other. Interestingly, in this figure, those systems which are clearly less fully automated cluster in the upper left, while those which are more fully automated cluster in the lower right. This is in keeping with our intuitions that the more modern systems are, in fact, better representatives of “supervisory control” relationships while the older systems are poor examples of the relationship. This suggests that the diagonal in Figure 2-13 may represent a rough definitional boundary: those system which fall above it are not “supervisory control” systems precisely because they require too much effort from the human supervisor for the amount (scope) of work they accomplish. By contrast, those which fall below the line are good examples of supervisory control. The “moving carriage” example, which falls on the diagonal, is an interestingly ambiguous case. It automates some functions but still requires substantial vigilance and attention from the user and we are unsure whether to call it a supervisory control system or not.

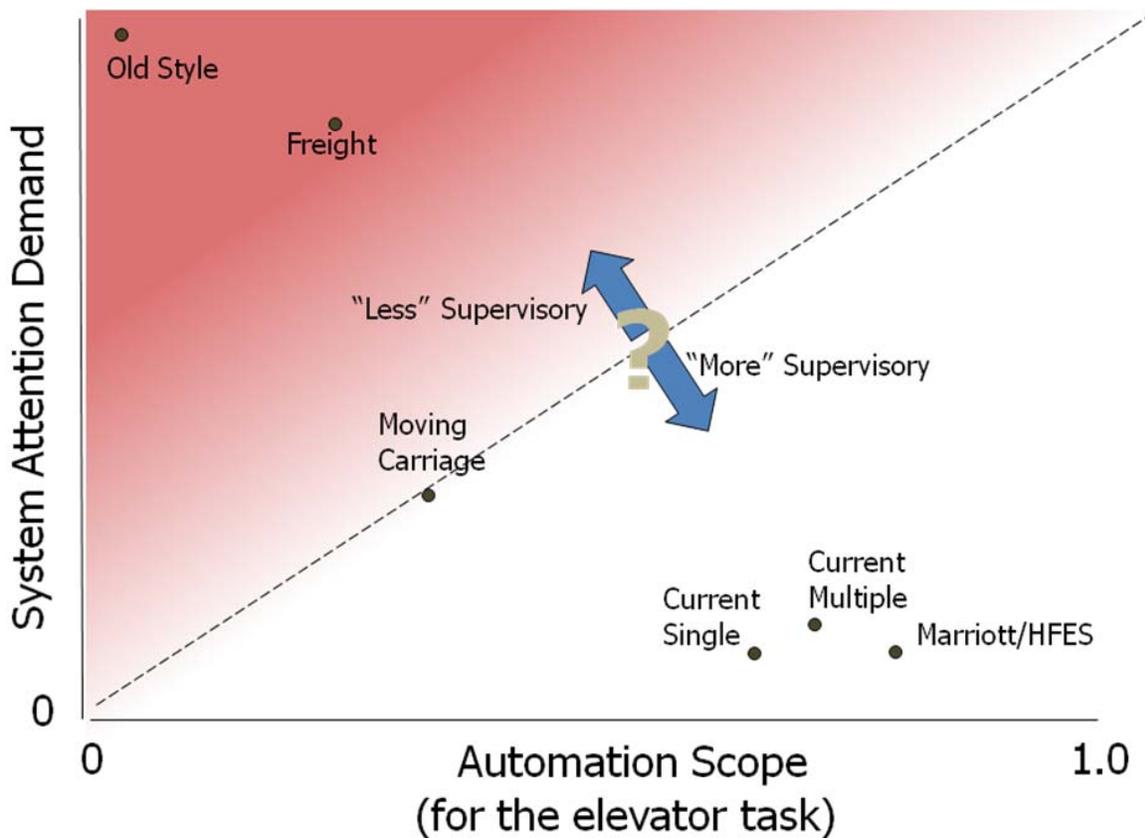
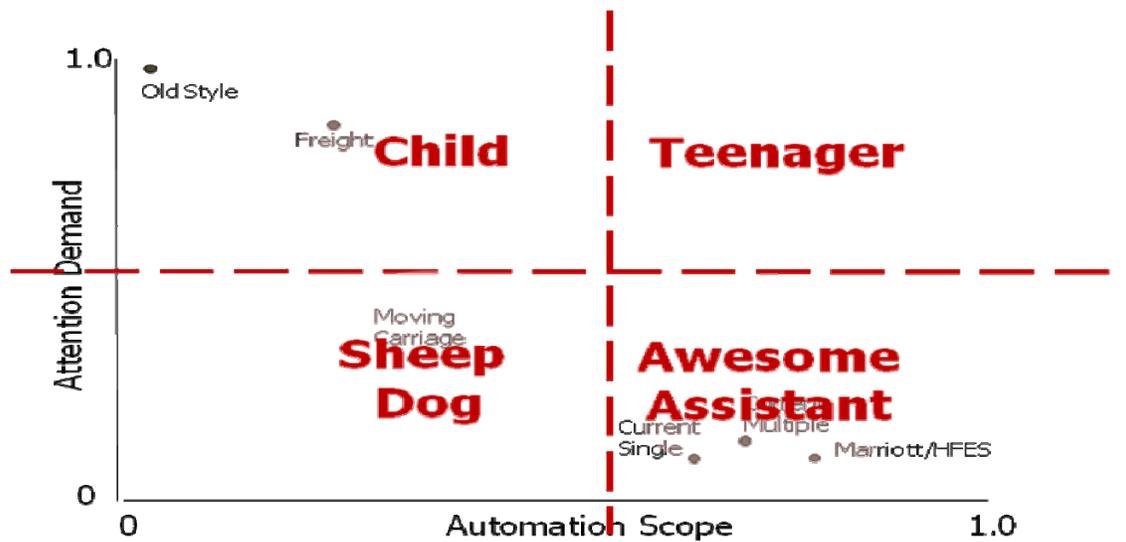


Figure 2-14: Graphing SAD and Performance Scope Dimensions Against Each Other – With a Suggestion of a Definitional Boundary for “Supervisory Control”.

Figure 2-15 provides a slightly richer depiction of the graph by characterizing the different quadrants of it. Here, we might be able to assign labels to suggest the kinds of relationships which characterize the systems which fall into the various sections. For example, the upper left hand quadrant is characterized by comparatively high attentional demand from the supervisor, but comparatively low scope of activities which the subordinate can perform. We might label relationships in this quadrant “child-like” since, like interacting with a child or infant, they require lots of supervision in order to perform little or no immediately useful work. Relationships falling into the upper right hand quadrant might be labeled “teenager-like” since, like interacting with a teenager, substantial supervision is still required, but a surprising range and scope of work can be accomplished if a supervisor is willing to take the time required. The lower left hand quadrant might be characterized as like interacting with a sheepdog since a sheepdog is capable of performing a limited range of behaviors, but can do so with very little supervision from the human supervisor. Finally, the lower right hand quadrant might be characterized as like an “Awesome Assistant” (e.g., a “Radar O’Riley” from the M\*A\*S\*H television series) – someone who has a very wide range of performance capabilities and requires little supervision to perform them.



**Figure 2-15: Labeling the Quadrants to Convey Intuitions About the Types of Relationships Afforded by Systems Which Fall Into Them.**

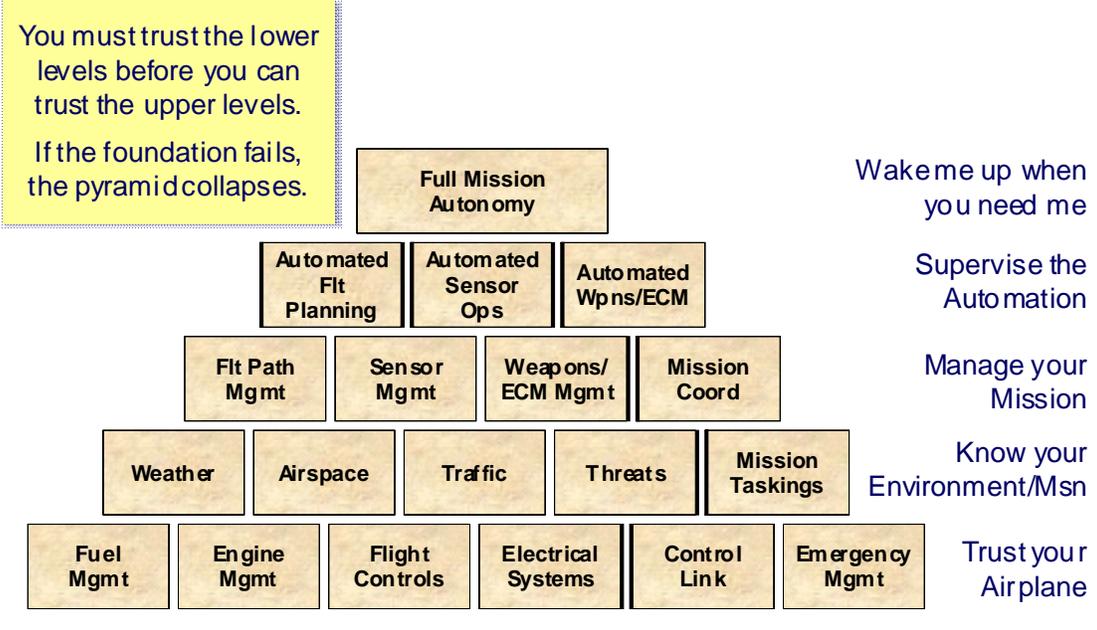
*Moving Beyond Elevators* – The above thought experiment shows promise for this simplified 2D model since it illustrates the model’s ability to capture interesting differences between a set of automation systems and to mirror our intuitions about their effectiveness and the degree to which they exemplify supervisory control relationships. Nevertheless, we realize that we have left open the question of whether or not this framework will prove relevant to real-world systems. Easily the most important challenge would be developing an acceptable “reference model” to evaluate performance scope for a set of realistic UMVs. While we did not perform this task, we were able to point to some characteristics of potential models to serve as starting points:

- It should characterize (and decompose) a common, shared function performed or goal achieved by all systems to be compared.
- Though the model of that shared function can be fairly abstract, it need be concrete enough to support deriving percentage time or effort estimates.
- It is helpful, but may not be required, if there are shared tasks in the decomposition of the shared function. If some systems require a sub-task to perform the function and others do not, the complete list for the reference model can include the union of all of the tasks and scope and SAD assessments can indicate whether or not the alternate systems perform the tasks and the time required.
- The reference model may need to be augmented by a specific, shared scenario (again, as performed by all systems to be compared) to enable temporal SAD computations.

While we did not develop such a model for UMV comparisons, one might be built out of shared vehicle functions such as navigation, propulsion, sensing, etc. One such model for aviation UMVs might be derived from typical functions of aircraft missions- such as those illustrated in the “automation trust” pyramid that Col. Jeff Eggers of the U.S. Air Force has created (see Figure 2-16 for Col. Eggers previously unpublished model). Col. Eggers uses this pyramid to convey the notion that trust in automation must be built from the bottom up, but it also serves as a general task or function decomposition for typical aircraft missions. It is likely that this model, or portions thereof, could serve as the basis for a reference model for at least UAVs for performing the type of SAD and Performance Scope analysis illustrated for elevators above.



# The Automation Trust Pyramid



27-Apr-10

10

**Figure 2-16: Col. Jeff Eggers' "Trust Pyramid" Which Represents a Typical Decomposition of Aviation Functions and Might be Useful as a Reference Model at Least for UAV Comparisons.**

### Strengths and Weaknesses

There was general consensus that this 2D model had done a reasonable job of operationalizing and quantifying the two dimensions and making them reusable across systems and applications to be analyzed. Similarly, this model has the strength of being very simple to explain and convey, thereby making it very suitable for use as an organizing framework for presenting the systems from this working group.

On the other hand, it was, perhaps, not quite as general as would be ideal due to the need for a shared reference model (which would necessarily be at least somewhat task and domain specific). Since we did not have time to complete investigating the development of a reference model for the supervisory control systems under investigation by the HFM-170 members, we cannot say with certainty whether a single, common reference model for all of our systems is possible. Some of us were, in fact, sceptical that a single reference model could encompass the air, sea, and ground applications being investigated, much less the component systems such as alternate visualizations or control systems to support supervisory control systems.

More seriously, though, there appeared to be general consensus that this 2D model may have gone too far in simplifying the characterization of supervisory control relationships, that it had suppressed too much interesting detail between the alternate systems. Having seen the results of this 2D model development, several group participants were interested in returning to (and further refining) the 7D model.

## 2.8 CONCLUSIONS

Clearly, this ongoing discussion of frameworks for supervisory control has illustrated that a very wide diversity of such models are possible, each with different strengths and weaknesses. While no single model emerged with which to present the results of this workshop, we did identify several dimensions that seem relevant to discriminating between supervisory control approaches being examined by this group, and we proposed methods for identifying and characterizing supervisory control relationships – particularly in the 2D model described above.

As has been noted before us (most notably by Parasuraman, Sheridan and Wickens, [6]), Sheridan's original model of levels of autonomy, while convenient, confounds many dimensions of supervisory control relationships and, ultimately, does not give a good sense of how such systems operate and what they do. Several alternate models have been proposed, including some in this document for the first time, which expand and refine our notion of supervisory control relationships as they exist in alternate systems. More importantly, these models have different strengths and weaknesses. Some are very detailed, specific and precise – but that very precision comes at a cost of both greater effort to construct representations of alternate systems within the framework and greater effort to understand the system characterization when it is later presented. Such approaches might be appropriate for design and evaluation of a given system (or, as with Miller and Parasuraman, [9], for conveying specific delegation actions to automation), but they are not particularly convenient for giving a “feel” of the system for comparison purposes. That said, any framework which does not express such precise details will, inevitably, suppress some aspects of system design or operation.

Our examination of the LoA<sup>3</sup> model (and, to a lesser degree, the 2D Interaction Description model) showed that, even though the term “supervisory control” arguably defines a relationship between supervisory and subordinate, any framework which concerns itself exclusively with this relationship and does not concurrently capture aspects of the operator, system and environment or task domain of usage is likely to be seen as insufficient. Instead, frameworks which seek to provide a basis for comparing and representing a set of alternate systems or approaches should also capture aspects of the equipment, personnel and context of usage – especially when those aspects vary in interesting ways from system to system.

Most of the models examined in the working group, and reported in this document, focused on the tasks or functions to be performed by the human + automation system. While there is an ongoing debate in the Human Factors community over the relative strengths and weaknesses of prescriptive task analysis vs. ecological function or goal analysis, the models proposed here are largely agnostic to the distinction. They are, however, focused on allocation of functions between human and automation in some fashion – whether by goal or state or function of scripted task. We believe this is due to the nature of supervisory control relationships – which were, after all, the focus of study. Supervisors necessarily retain some functions as their exclusive purview, share or retain others dynamically and in various combinations, and rely exclusively on their subordinates for performing still others.

At the end of this exercise, we believe that the 7D model held the most promise for satisfying the ends of this working group. This model was largely descriptive, but it captured several dimensions relevant to the alternate supervisory control systems, relationships and usages we were examining. While the specific dimensions examined might or might not be the best ones, and the scales for characterizing them might also be improved upon, this multi-dimensional description of alternate systems seemed to provide the right level and type of information for rapidly and easily conveying to ourselves and others how a set of supervisory control systems are similar and different from each other.

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## **Chapter 3 – CAN-1: MULTI-CREW CONTROL OF A SINGLE UNMANNED AIRCRAFT**

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### **3.1 DATES**

29 September – 3 October 2008.

### **3.2 LOCATIONS**

Faculty of Engineering, Memorial University of Newfoundland, St. John’s, Newfoundland, and technical demonstration on Bell Island, Newfoundland, Canada.

### **3.3 SCENARIO/TASKS**

The Concept Of Operation (CONOP) was to simulate a civilian Ground-Control-Station (GCS) crew as the Unmanned Aircraft System (UAS) service provider and a military crew at a Forward Control Station (FCS) as the client for the data. The civilian crew would be responsible for operation of an Unmanned Aircraft (UA) in: take-off, transition, return-to-base and landing, and hand-off the control of sensor payload and limited UA maneuver to the military crew once the UA reached the target area. The sensor data would be accessible in real time to the military FCS crew.

### **3.4 TECHNOLOGIES EXPLORED**

In the context of multi-agent supervisory control of Unmanned Vehicle Systems (UVS), the technology matrix consists of the following cases:

- 1) A single crew controlling a single UVS;
- 2) A single crew controlling multiple UVS (force multiplication);
- 3) Multiple crews controlling a single UVS (this technology demonstration); and
- 4) Multiple crews controlling multiple UVS.

Although force multiplication (Case 2) is often cited as the ultimate goal, Case 4 is a more realistic objective because a UVS is a complex system, and often involves multiple crews in its operation. The CAN-1 technology demo focuses on Case 3 as a precursor to the implementation of Case 4. The multiple-crew CONOP in Case 3 is an example of multi-agent supervisory control: the GCS provides the high-level supervisory task of bringing the UA from the launch and recovery location while the FCS is tasked with the low-level control of the sensor

## **CAN-1: MULTI-CREW CONTROL OF A SINGLE UNMANNED AIRCRAFT**

payload while the UA is on-station. This CONOP can easily be extended to Case 4 by using the GCS crew dispatching multiple UA to different FCS at different locations.

The UA often has to transit over non-segregated airspace from the launch and recovery site to the on-station sites [1],[2]. Sense And Avoid (SAA) technology [3],[4] is needed to ensure the safe integration of unmanned aircraft with other manned traffic in this transit over the non-segregated airspace. This technology demo fits within RAVEN II, a research and development program conducted by Memorial University of Newfoundland to develop SAA technology for small UA.

### **3.5 HUMAN FACTORS ISSUES EXPLORED**

The RAVEN group is interested in the human factors issues in qualifying situation awareness, responsibilities and competence of each crew over different phases of the UA mission, in particular with respect to SAA responsibilities. The External Pilot (EP) is tasked with the see-and-avoid responsibilities at all times for visual deconfliction of traffic when the UA is within visual range of the EP. SAA duties are assigned differently over the three mission phases: launch and recovery, transit and on-station, and over two different crews: the civilian GCS crew and the military FCS crew, as shown in Table 3-1. Of particular interest is the skill competence for the external pilots at the GCS and at the FCS. It is expected that the EP at the FCS would have limited ability to tele-operate the UA, and his/her duties will mostly be the command and control of the sensor payload, and to prevent the UA from falling into the possession of hostile forces.

**Table 3-1: GCS and FCS Crew Responsibilities and Competence.**

<b>Mission Phase</b>	<b>Crew Responsible for SAA Duties</b>	<b>SAA Situation Awareness</b>	<b>Skill Level of the EP</b>
Launch and Recovery	GCS	Visual + Instrument	High
Transit	GCS	Instrument Only	NA
On Station	FCS	Visual	Low

### **3.6 UNMANNED SYSTEMS USED**

The UA was an Aerosonde Mk 4.2 equipped with a Piccolo Plus autopilot from Cloudcap Technologies and an EO sensor. The UA was launched from a mobile command centre equipped with two completely redundant GCS units. The Piccolo ground control station software (version 4.0.3) and stageboxes hardware were used in the GCS and FCS units.

### **3.7 SUMMARY OF ANY NATO COMMUNICATIONS/COLLABORATIONS/ INTERACTIONS**

The results of the study have been presented at the Task Group meeting following the demo. The following table summarizes the extent of the NATO collaboration. There have been follow up collaborations between

the Canada and the US task forces on the training requirement for the EP. There are also on-going efforts in communications, coordination and collaboration between Canada, Germany and Portugal on the planning, design, execution and analysis of multiple flights tests involving small unmanned aircraft near or over the North Atlantic Ocean, involving possibly beyond-visual-range and/or night-time operations.

	<i>Planning/Design</i>	<i>Execution</i>	<i>Analysis</i>
<i>Communication</i>	X	X	X
<i>Coordination</i>	X	X	X
<i>Collaboration</i>	X	X	X

### **3.8 SUMMARY OF TD RESULTS**

#### **3.8.1 The Planned Demo**

The Canadian hosts’ plan was to demonstrate the hand-off of control of the UA from the launch-and-recovery GCS crew to a FCS crew. Once the UA reached its altitude and a trimmed flight condition, the UA would be put under autopilot mode commanded by the UVS operators inside the mobile command centre. The UA would fly a fixed pattern overhead flight to simulate the transit from the launch site to the target area. After a certain time, the UA was assumed to have reached its target area. Control would then be passed off to a portable ground control station simulating a FCS crew located near the target area. The FCS crew would monitor the Electro-Optical (EO) imagery and could, optionally reprogram the flight path of the UVS for additional intelligence gathering over target area. After a certain time-on-station period, control would be passed back to the GCS to simulate the return to the launch area. The UAV would be recovered (landed) by the GCS crew.

#### **3.8.2 The Demo Day**

On the afternoon of Wednesday October 1, 2008, members of the NATO HFM-078/170 team shown in Figure 3-1 witnessed a live flight demonstration of the Aerosonde Mk 4.2 UA (named “Takunnajik” which means “Seeker” in the Innu language from the Canadian North). This required a last-minute determination to proceed based upon weather, a transit to the ferry terminal, ferry ride over to Bell Island, and transit to the remote airstrip, and all again in reverse.



Figure 3-1: NATO Team and Aerosonde UA after Landing.

### 3.8.3 Hand-Off Procedure

The normal procedure for a hand-off from GCS to FCS is to have the GCS operator give the FCS a signal for the hand-off while the UA is still connected to the GCS via a command and control communication Channel (A). The FCS is set up on a new communication Channel (B) on hot standby. The GCS operator commands via Channel A to the UA to switch to Channel B for communicating with the FCS. If the UA does not pick up Channel B from the FCS after a certain timeout period, e.g., 5 seconds, the UA will revert back to Channel A at the GCS. Note that the hand-off is bump-less because all the waypoints are stored in the autopilot on the UA and the UA will continue its mission until receiving further commands from the FCS after the hand-off. Also note that the UA can potentially be hijacked by a hostile FCS if the hostile FCS emits a more powerful signal on Channel A than the GCS because of the closer proximity of the FCS to the UA. This vulnerability has to be mitigated via a secure datalink.

### 3.8.4 Actual Events

On the day of the demo, there was only one External Pilot (EP) available on site, and it was deemed to be unsafe if control was handed off to the FCS without another EP as a safety pilot. It was decided to use the second redundant GCS as shown in Figure 3-2 to act as a FCS. The console on the right was the GCS communicating to the UA on Channel A<sup>1</sup> and the console on the left simulated the FCS, communicating to the UA on Channel B. Both consoles were located within the mobile command vehicle.

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<sup>1</sup> A 900 MHz radio link was used, and channel designations A and B represents different numbered channels with the 900 MHz band.



**Figure 3-2: Layout of GCS and FCS in the Mobile Command Station.**

During the set-up, there was Radio Frequency Interference (RFI) between the two stageboxes providing the communication links between the two GCS's and the single UA. It was decided to put the stagebox on the left, simulating the FCS, on cold standby (turned off). After the UA was airborne and flying autonomously under autopilot on stored waypoints in the UA, a hand-off was attempted. However, a temporary link-loss from both GCS's occurred, and control was reverted back to the primary GCS automatically once the five-second timeout expired. A second hand-off was successful once more precise timing was used involving turning on the FCS stagebox during the hand-off. It should be stressed that this was not a normal or correct operating procedure for the Piccolo autopilot, but was necessary to avoid the RFI issue caused by the incorrect installation of two Piccolo GCS stageboxes in close proximity to each other. Later, a hand-off from the FCS to the GCS was accomplished successfully without needing to turn on/off any of the stageboxes. Following this demo, the UA was landed (Figure 3-1) and the mission was completed.

### **3.9 LESSONS LEARNED**

The first lesson pertained to the skill level of the External Pilot (EP) at the launch site near the GCS and on station near the FCS. The GCS software used was not STANAG 4865 compliant, namely that both the crew at the GCS and at FCG have the full control of the autonomy of the UA, and it was unsafe to leave under full

FCS control without an experience EP acting as the safety pilot. Under STANAG 4865, the FCS might only have control of the sensors at Level 1, and the control of the air vehicle would have remained with the GCS, with an experienced external safety pilot as in the case of the visual-range mission as in the Canadian demo. From Table 3-1, the EP competency was high for the GCS crew, especially the requirement for the EP to be able to do manual landing and take-off if the UA did not have Automatic Take-Off and Landing (ATOL) capabilities. On the other hand, the EP competency for the FCS crew should be low since information gathering is the primary task and not UA flying. There is however the issue of flight termination when the UA was on station under the FCS control. The UA could be damaged or hijacked by hostile forces, and it was important the UA mission can be altered or terminated by the FCS crew to prevent the UA from falling into hostile hands.

The second lesson was spectrum management. The problem in the hand-off was peculiar to the set-up in this demo: The FCS was located next to the GCS causing RFI issues. But, the general issue of spectrum management was important. The RFI issues could have been resolved if the FCS and GCS were on different frequency bands: 900 MHz and 2.4 GHz as in the Canadian manufactured Micropilot system. Another issue was the danger of the UA being hijacked by a hostile FCS. This would be an important topic for further research.

The last lesson was on the proper use of a check list. The last-minute demo was compromised by not following the manufacturer's check list. It was known that two Piccolo stageboxes should not be located in close proximity to each other (under 2 meters). This contributed to the RFI issue. If the checklist had been followed and the mission rehearsed before the demo, the unsuccessful first hand-off could have been avoided.

### **3.10 STUDY CONSTRAINTS/LIMITATIONS**

#### **3.10.1 Non-Segregated Airspace**

The flight was conducted in Class G non-segregated airspace in close proximity to the St. John's International airport. Due to current UVS regulatory restrictions, the entire mission was done at visual line of sight distance from the manual external pilot.

#### **3.10.2 Limited EP Availability**

The availability of a single EP was a constraint that limited the full implementation of an FCS with another EP at a different location than the GCS.

### **3.11 CONCLUSIONS**

This demonstration marked the first live-demonstration of unmanned vehicle supervisory control within the NATO HFM-078/170 Task Group experiences. It also included hand-off demonstrations between two UA supervisory control crews, as well as between an external pilot (flying manual control) and a supervisory control station. The flight demo was well received by all and sparked many interesting crew requirement discussions, including how to improve upon the external pilot's training/tasks. Since the 2008 demo, Dr. O'Young's team has been routinely fielding multi-UA supervisory control flights for sense and avoid research.

### **3.12 FUTURE RESEARCH NEEDS AND PLANS IN THIS AREA**

Multi-agent supervisory control of multiple UVS can be formally studied in the context of a multi-agent hybrid system. The supervisory tasks at the GCS can be modelled as discrete-event [5] tasks, such as “change of flight plans” and “return to base”. The lower level task at the FCS can be considered as a continuous dynamical task, such as the manual steering of a camera pointing to a target. The interaction between the discrete tasks at the GCS level and the continuous tasks at the FCS level can be formalized as a hybrid system. Hybrid systems [6] models interactions between discrete, e.g., decision making, and continuous, e.g., UA dynamics, processes within a unified theoretical framework. The application of hybrid system theory to UA applications have been reported in [7],[8], and it is anticipated that a formal analysis of the target level of safety of an SAA system can be achievable using hybrid system as an underpinning theoretical foundation. Future collaborations between Canada, Germany and Portugal could provide valuable field data for the verification of this theoretical framework.

### **3.13 ACKNOWLEDGEMENTS**

The Canada hosts for the CAN-1 Technology demo were Dr. Ming Hou of Defence R&D Canada, Toronto, Dr. Bumsoo Kim of Defence R&D Canada, Ottawa and Dr. Siu O’Young of Memorial University of Newfoundland, Canada. The UA flight demo was performed in collaboration with Provincial Aerospace Limited of St. John’s, Newfoundland, an industrial partner of RAVEN II at the Memorial University of Newfoundland. The Canadian hosts would like to thank Ms Leah McGrogan for her professional organizational and logistics support for this NATO meeting. Without Leah, we would not have been able to pull off this very successful event.

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## **CAN-1: MULTI-CREW CONTROL OF A SINGLE UNMANNED AIRCRAFT**

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## **Chapter 4 – CAN-2: BEHAVIOUR-BASED COLLISION AVOIDANCE AND FORMATION CONTROL OF MULTIPLE UNMANNED VEHICLES**

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### **4.1 DATES**

26-30 July 2010.

### **4.2 LOCATION**

DRDC Ottawa.

### **4.3 SCENARIO/TASKS**

Multiple UGVs (Unmanned Ground Vehicles: They also are considered as simulated UAVs) to reach to a destination without colliding each other while avoiding obstacles).

### **4.4 TECHNOLOGIES EXPLORED**

In this study, AIC (Artificial Impedance Control) is applied for the generation of trajectory of UGVs instead of pre-planning the trajectory. AIC is a Cartesian space control and is one of the control techniques which can generate trajectories for both obstacle free and obstacle avoidance cases in real time. One of the advantages of artificial impedance control for UGVs motion control is the fact that it enables UGVs to perform obstacle avoidance tasks without knowing the full geometry of the obstacles and of the environment. [1]

In the present study, we started testing AIC algorithm for single vehicle trajectory generation and obstacle avoidance performance using simulation and experimentation.

Then, it was expanded to two vehicles reaching to the designated targets while avoiding collision with each other and avoiding obstacles in their ways to targets.

Thirdly, a five vehicle formation control and single target oriented behaviour-based control were tested in simulation.

## 4.5 HUMAN FACTORS ISSUES EXPLORED

### 4.5.1 Reference Frame

Figure 4-1 indicates the global reference frame (T,Q,S) that will be used. Since the X80 robot only supports planar motion, the S coordinate will often be ignored in this work. The global frame is fixed with heading defined as a counter-clockwise rotation about the S axis. The vehicle will use a body-frame coordinate scheme (Figure 4-2) where the X-axis is always pointing forward from the vehicle, and the Y-axis is pointing to the left.

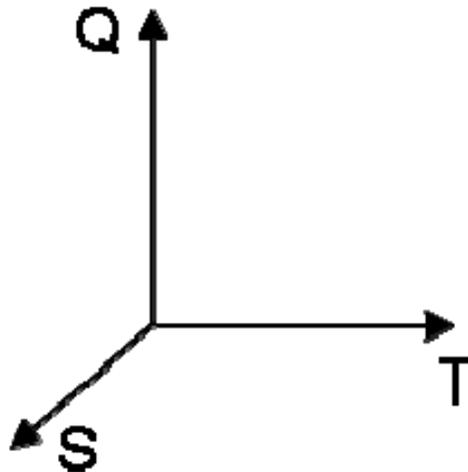


Figure 4-1: Global Coordinate System.

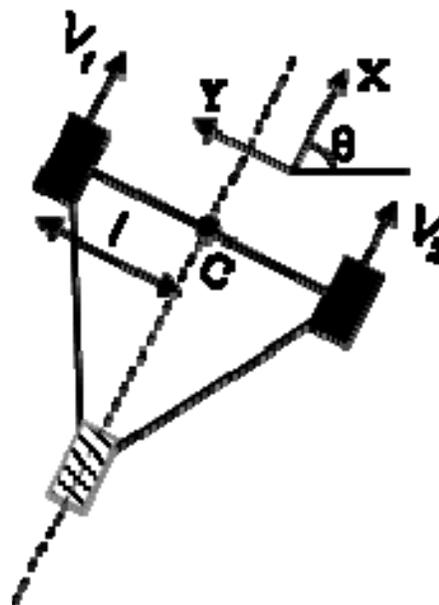


Figure 4-2: X80 Local Coordinate System.

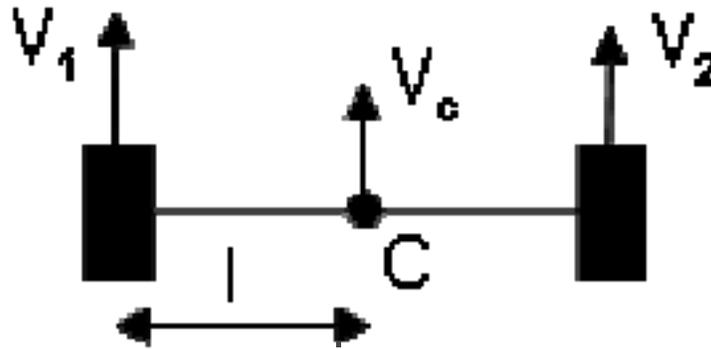
Transformations from body coordinates to global coordinates can be done as follows:

$$\begin{bmatrix} t \\ q \\ \theta \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ \theta \end{bmatrix} \quad (1)$$

### 4.5.2 Kinematic Model

The goal of the model will be to define the motion for all points on the platform, for a given set of known variables. In this case, the speed of the wheels ( $V_1$  and  $V_2$ ) and the length  $l$  from the wheels to the center of rotation  $c$ , are known. With this, we will describe the motion of the center of rotation, and can easily define the motion for all other points from there.

Figure 4-3 shows the axle, and center of rotation of the vehicle.



**Figure 4-3: X80 Axle and Center of Rotation.**

Since point C is directly in the middle of both wheels, its forward velocity will be defined by half of the velocity from each wheel. Thus:

$$V_{C_x} = \frac{1}{2}V_1 + \frac{1}{2}V_2 \quad (2)$$

Assuming there is no side-slip in the wheels, we can also assume that:

$$V_{C_y} = 0 \quad (3)$$

For the vehicle's angular rotation, we can see that wheel 1 is going to affect the rotation negatively, while the 2<sup>nd</sup> wheel will have a positive affect. Fixing one of the wheels while driving the other will result in an angular rotation as follows:

$$\omega = \frac{V}{2l} \quad (4)$$

Summing the effects from both wheels will give the platform an angular rotation, about c, of:

$$\dot{\theta}_c = \frac{V_2 - V_1}{2l} \tag{5}$$

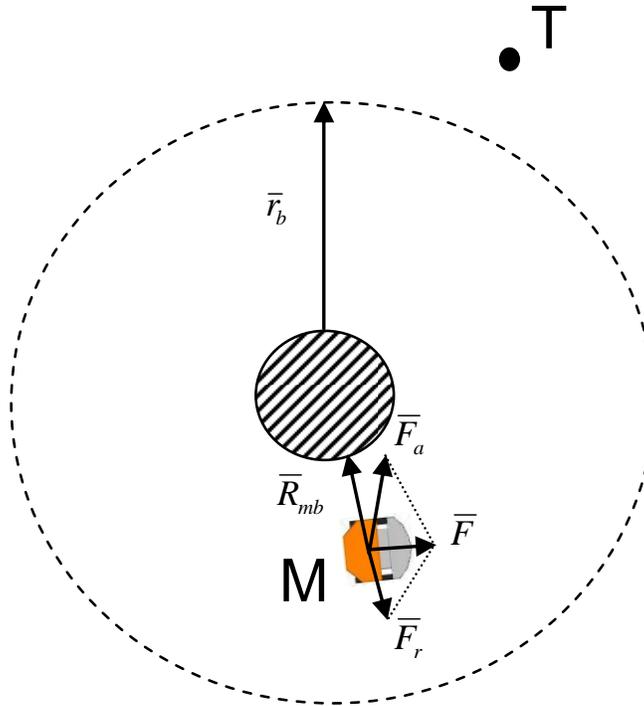
Combining equations 1 – 5, we get the following relationship for the motion at c:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1/2 & 1/2 \\ 0 & 0 \\ -1/2l & 1/2l \end{bmatrix} \cdot \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \tag{6}$$

### 4.5.3 Impedance Controller

Without the inherent vehicle dynamics, the impedance controller developed here is actually just a PD controller. However, some attempts have been made to simulate the dynamics of the vehicle and as such, we will continue to use the term ‘impedance’.

Figure 4-4 below depicts the attractive and repulsive forces presented on the vehicle during motion. We will denote the vehicle as  $M$  and the goal location as  $T$ . Let  $\bar{R}_{mb}$  be the distance from the robot to the closest obstacle,  $\bar{r}_b$  repulsive force field radius,  $\bar{F}_a$  the attractive force, and  $\bar{F}_r$  the obstacle’s repulsive force.



**Figure 4-4: Impedance Control Force Diagram.**

The repulsive and attractive forces are calculated as:

$$\bar{F}_r = K_r \cdot \frac{\bar{r}_b}{R_{mb}} \cdot (\bar{R}_{mb} - \bar{r}_b)^2 - B_r \cdot V_{cur} \quad (7)$$

$$\bar{F}_a = \begin{cases} K_a \cdot (\Delta d) - B_a \cdot V_{cur} & \forall \Delta d \leq S \\ K_a \cdot S & \forall \Delta d > S \end{cases} \quad (8)$$

where  $K$  and  $B$  are the controller constants,  $\Delta d$  is the distance to the goal, and  $S$  is a constant distance after which the force is constant.

Using these forces, we can then calculate the vehicle's desired heading by summing the forces:

$$\theta_{des} = \tan^{-1} \left( \frac{\bar{F}_a}{\bar{F}_r} \right) \quad (9)$$

To steer the vehicle to the desired heading, a proportional controller was used to determine the heading rate:

$$\dot{\theta} = K_\theta \cdot (\theta_d - \theta_c) \quad (10)$$

where  $\theta_{cur}$  is the current vehicle heading. Using this value, along with the desired trajectory speed  $V_{set}$ , equations 2 and 5 can be used to calculate the individual wheel speeds to be sent to the platform.

This controller will cause the robot to move with constant velocity to point  $T$ , while avoiding any obstacle along its path.

#### 4.5.4 Control Block Diagram

Autonomous navigation was implemented for a single robot using an AIC. An attractive virtual force pulls the robot to its goal, while a repulsive virtual force pushes the robot away from obstacles. The magnitude and direction of the vector sum of these attractive and repulsive forces is used to calculate an appropriate velocity and turning rate for the robot, so that no prior path planning is required. The block diagram showing the general flow of the impedance control program is shown in Figure 4-5 and Figure 4-6.

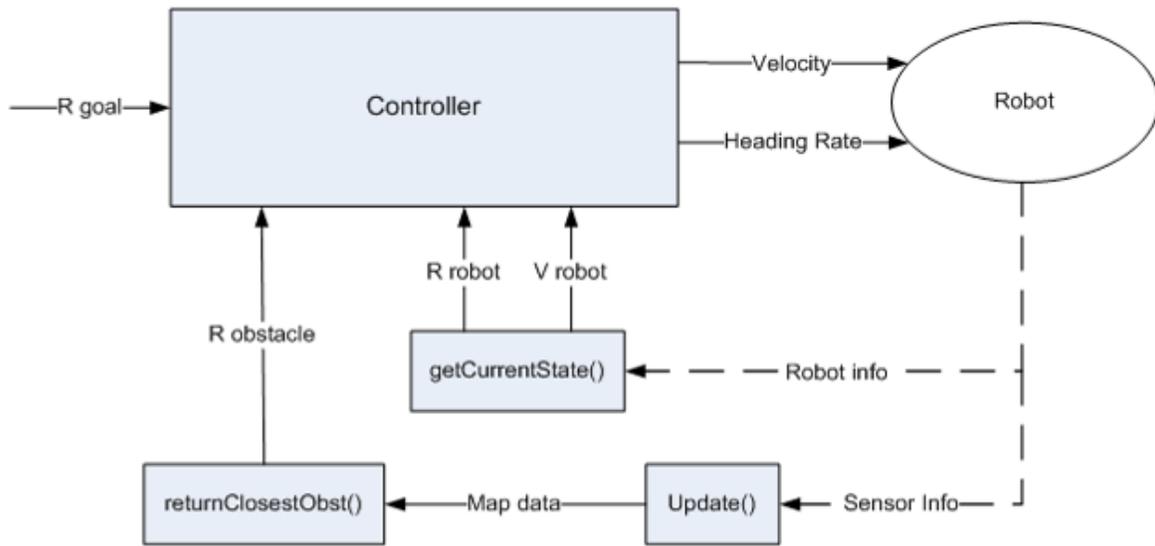


Figure 4-5: Block Diagram of the Impedance Control Program.

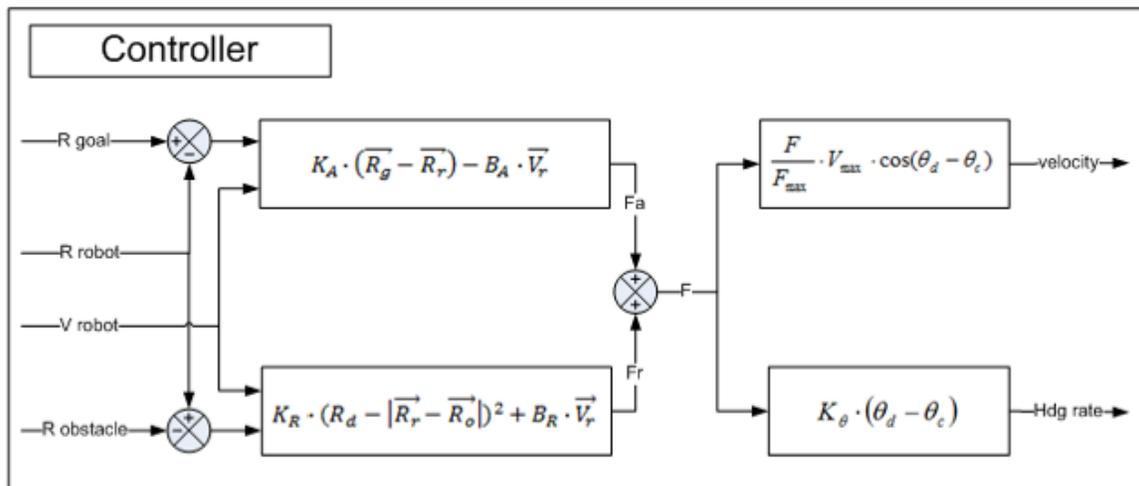


Figure 4-6: A More Detailed Block Diagram of the Controller.

## 4.6 UNMANNED SYSTEMS USED

### 4.6.1 Dr. Robot X80Pro

Modified X80Pro [2] is a WiFi enabled robot, and is designed for use as an autonomous navigation and control research platform. It comes equipped with multiple sensors, and low level motor controllers, enabling the user to focus solely on higher level algorithms. An SDK is also available for the windows operating system, simplifying access to the motor drivers, sensors, and communication system. However, for use on

different operating systems, the raw device protocols are given for direct integration. For Windows use, a detailed description of the SDK and how to get up and running with the X80Pro platform can be found in [2].

#### **4.6.2 Player/Stage**

Player [3] is a network server for robotic control. It provides access to a platform’s sensors and actuators through well-defined interfaces over a TCP connection. As such, it is easy to set up any type of network topology provides that the robot and associated computers are connected over a TCP enabled network.

Stage [4] simulates a population of mobile robots and sensors. Supported sensors cover most areas that are used within the robotics community. Player can access the actuators and sensors in the Stage simulation environment in the same way that it would the actual hardware. As such, it is easy to simulate new algorithms and then transition to the hardware by simply changing the TCP address. Furthermore, it is also possible to mix both simulation and hardware environments. An experiment could be set up where the sensors are read for the simulated world but the actuators are commanded on the actual hardware, or vice-versa. The options are wide ranging.

#### **4.7 SUMMARY OF ANY NATO COMMUNICATIONS/COLLABORATIONS/ INTERACTIONS**

Canada (Bumsoo Kim) and France (Gilles Coppin) share interests in ideas and technologies with regard to the swarming concepts of multiple autonomous vehicles operation. Collaborating in this area of research is planned by establishing joint projects and by seeking opportunities to share within NATO Nations in the Task Group.

	<i>Planning/Design</i>	<i>Execution</i>	<i>Analysis</i>
<i>Communication</i>	<i>X</i>	<i>X</i>	<i>X</i>
<i>Coordination</i>			
<i>Collaboration</i>	<i>X</i>		

#### **4.8 SUMMARY OF TD RESULTS**

Figure 4-7 shows the results of a simulated obstacle avoidance situation, comparing the case when the robot is given a constant velocity and the case when the robot is allowed to vary its speed between a specified minimum and maximum. Note that the areas where the red data points are more densely concentrated indicate where the robot slowed down.

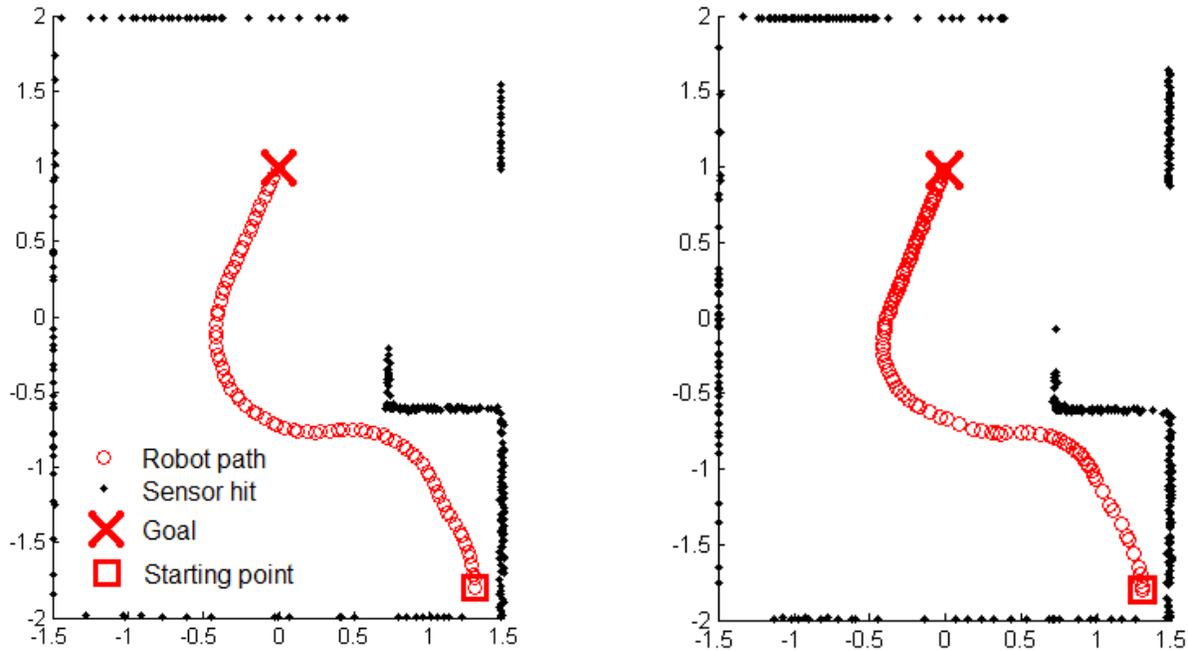
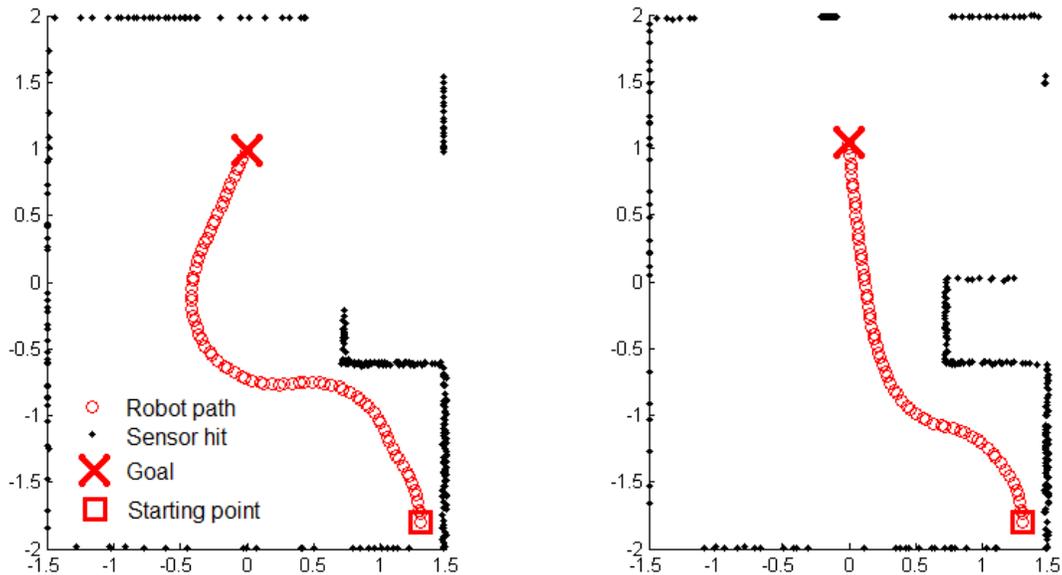


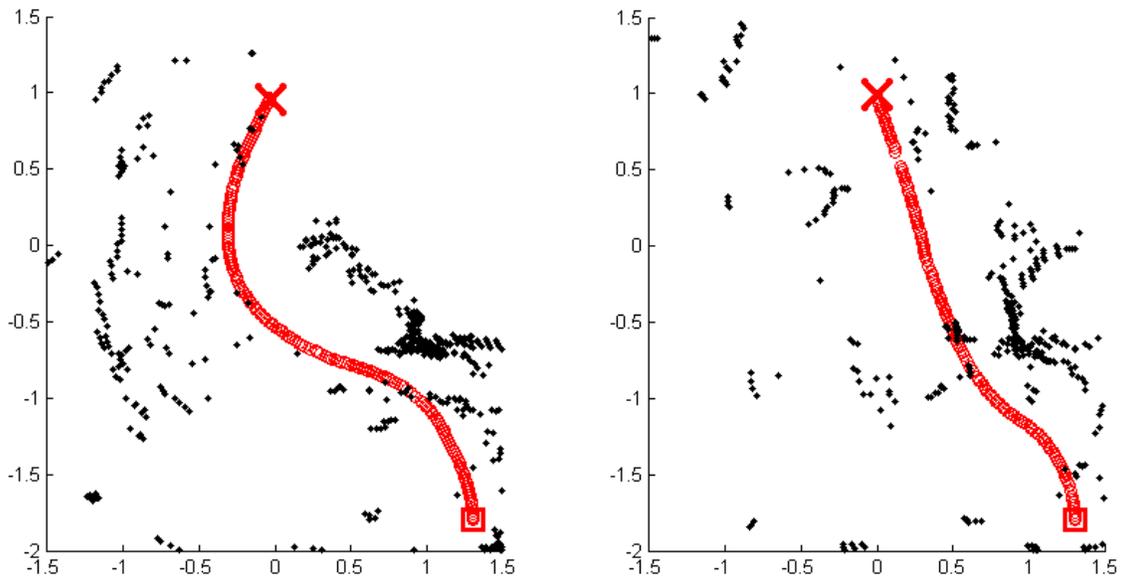
Figure 4-7: Stage Simulation Results (Left: Constant Velocity (PD Control); Right: Variable Velocity (AIC)).

For simplicity, only one repulsive virtual force is applied to the robot at a time. In the initial implementation, this force was generated from the obstacle nearest the robot. The program used the map builder module to determine the coordinates of the obstacle closest to the coordinates of the robot, and the force was then calculated based on the distance between them. However, there are certain situations in which the repulsive force is ignored, namely when the obstacle is on the other side of the goal from the robot, or when the obstacle is behind the robot. In the latter situation, a problem would sometimes arise with this implementation. That is, even if there was an obstacle within sensor range in front of the robot, no repulsive force would be applied if a closer obstacle happens to be detected behind the robot. In such cases the robot sometimes had a delayed reaction to the obstacles in front of it; it would continue on a straight path until the distance to the obstacle in front was less than the distance to the obstacle left behind.

To fix this problem, the map builder function to return the closest obstacle was modified to also take into account the heading of the robot, so that it returns the closest obstacle *in front* of the robot (with a 180° perspective). After this change was implemented, the robot became more responsive to the objects in front of it, and it allowed for a smoother motion. A comparison of the results from before and after this change is shown in Figure 4-8 and Figure 4-9 below.



**Figure 4-8: Simulation Results (Left: 360° Obstacle Return; Right: 180° Obstacle Return).**



**Figure 4-9: Experimental Results (Left: 360° Obstacle Return; Right: 180° Obstacle Return).**

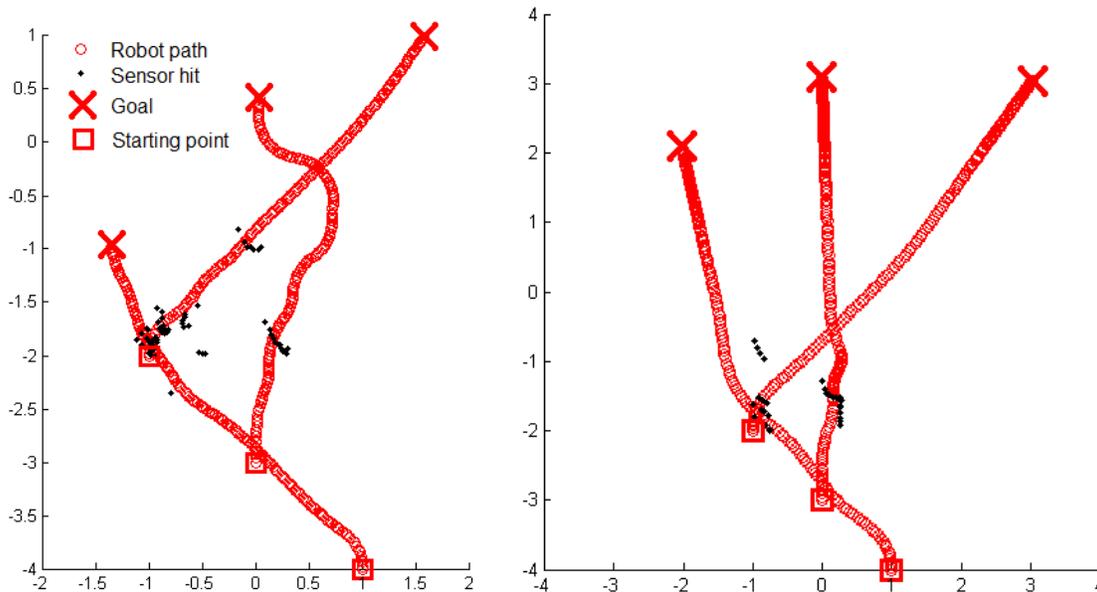
### 4.8.1 Singularities

There is a special case in which another problem arises with the impedance control program. It happens when the attractive and repulsive forces are perfectly lined up (for instance when the goal is on the opposite side of an obstacle from the robot). In the absence of a lateral repulsive force to tell the robot to try to go around the

obstacle, it will travel in a straight path until it gets stuck or crashes into the obstacle. This singularity problem has not yet been overcome.

### 4.8.2 Multiple Robots

Once the AIC for a single robot was developed and successfully demonstrated in both simulation and experiment, the next step was to extend that functionality to multiple robots. The first test that was done was a Stage simulation that was populated by three independent robots. Each robot used the AIC to navigate and each was given a separate goal point. There was no communication between robots; they could only detect each other as obstacles using their equipped sonar and infrared sensors. Since the robots were essentially moving obstacles, it was not only important for the robots to successfully detect each other, but also important for the robots to be able to detect when the others had moved out of the way. Without this, the map builder would continuously populate the occupancy grid with a streak of obstacles as the robots moved, and it would make navigating to the goals impossible. Figure 4-10 shows the results of two such simulations – one with constant velocity, and one with variable velocity.



**Figure 4-10: Stage Simulation Results (Left: Constant Velocity; Right: Variable Velocity).**

It is more useful, however, for robots to be able to communicate and work together to achieve a common goal. Two different approaches to multiple robot control were tried: a neighbour-follower approach, and a behaviour-based approach.

### 4.8.3 Neighbour-Follower Approach (Formation Control)

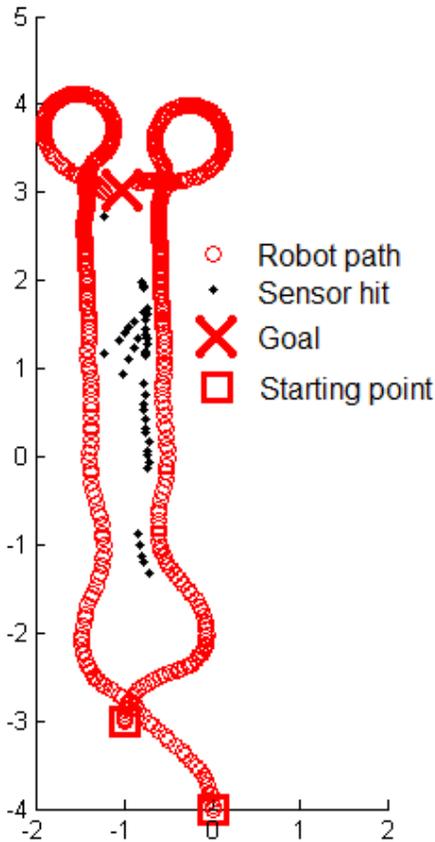
The main goal of the neighbour-follower approach is for the robots to achieve a specified formation on their way an end point. Initially each robot is assigned a 'neighbour' robot, and it is told to maintain a certain relative position with respect to its neighbour. This is done using another virtual force, called the formation force, which is added to the vector sum of the attractive force pulling the robot to the goal and the repulsive

force pushing it away from obstacles. In order to calculate this formation force, in the absence of more advanced sensor equipment, it is necessary for the robots to communicate their positions and velocities to their followers. The following equation shows how the formation force is calculated for each robot.

$$F_f = K_f \cdot (\Delta r_d - \Delta r_c) - B_f \cdot (\bar{V}_{cur} - \bar{V}_n) \quad (11)$$

where  $\Delta r_d$  is the desired position of the robot relative to its neighbour,  $\Delta r_c$  is the actual current position of the robot relative to its neighbour,  $\bar{V}_{cur}$  is the current velocity of the robot,  $\bar{V}_n$  is the current velocity of its neighbour, and  $K_f$  and  $B_f$  are controller constants.

This implementation was initially tested with two robots in a Stage simulation. The robots were instructed to form a horizontal line (1 m apart) and move to a goal several metres away, with no obstacles obstructing their path. The simulation is shown in Figure 4-11. The results show that the robots do indeed achieve the formation relatively quickly, but once they approach the end point, they get confused. The problem was that the robots were both given the exact same goal point, so while they were ‘fighting’ for it, they were unable to maintain the formation. This problem was solved by giving each robot a separate goal at a relative distance based on its relative position in the formation. Different gains  $K_f$  and  $B_f$  were tested to try to reduce the oscillations of the robots when they were getting in formation.



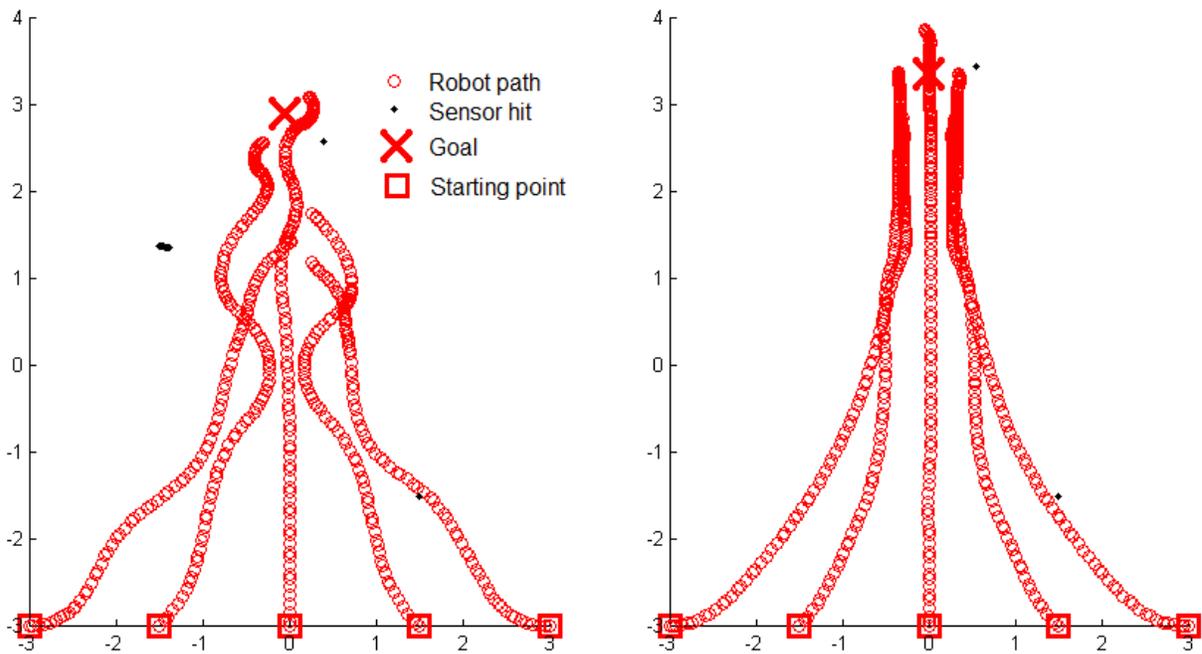
**Figure 4-11: Simulation Results for Two Robots Attempting a Horizontal Formation.**

**4.8.4 Behaviour-Based Approach (Flocking Control)**

A behavior-based approach to multi-robot control was also investigated. In this method, no specific formation is explicitly assigned to the robots. Instead, each robot tries to maintain a certain distance (although no specific orientation) with respect to the other robots in its vicinity. For example, if the desired distance between robots is 0.7 m, then robots under this distance from each other will experience a repulsive force, while robots above this distance will be attracted, up to a maximum distance of 1 m. Robots farther than 1 m apart will ignore each other.

When the X80 Pro robots only made use of their sonar and infrared sensors, communication of positions was required in order to distinguish robots from obstacles. In this case, however, instead of only needing to know the position of its one neighbour, each robot required the positions of every other robot. It then had to calculate its distance to every other robot, as well as a force for every robot in range. As more robots were added to the simulation, the computer would get increasingly bogged down, and as a result the sampling frequency of each robot diminished.

In order to determine the extent to which the sampling rate had an effect on the performance of the robots, a simulation was set up in stage involving five robots. The first run was done at normal simulation speed (real time), and it was determined that the frequency of each robot was approximately 1 Hz. Another run was done, this time at a slower simulation speed (0.3 times real time), which allowed more time for the computations to be completed, effectively increasing the frequency of the robots to 9 Hz. The results in Figure 4-12 clearly show that the sampling frequency plays an important role in the stability of the robots.



**Figure 4-12: Simulation of Behaviour-Based Control (Left: Frequency 1 Hz; Right: Frequency 9 Hz).**

## **4.9 LESSONS LEARNED**

Communication link is very important to the control of multiple unmanned vehicles. Distributed computing power is essential for the system stability. AIC proved to be an effective method to generate trajectory, avoid obstacle, and avoid collision with other Unmanned Vehicles (UVs).

The AIC enables UVs to avoid obstacles without knowing the full geometric description which usually requires a complex vision system. The only information needed is the closest point of surface of an obstacle from the vehicle at each time provided by simple range sensors.

## **4.10 STUDY CONSTRAINTS/LIMITATIONS**

Continuation of the research after the completion of present project is in question. Pending funding opportunities proposals are submitted for further investigation. The technology is very high.

## **4.11 CONCLUSIONS**

Advancements of the state of the art in supervisory control of multiple autonomous vehicles can be pursued by studying human interface aspects and the basic self-organizing and protecting autonomous control. We studied and demonstrated the self-organization and protection capabilities of multiple autonomous ground vehicles simulating air vehicles using computer simulations and verifying the results with experimental platforms. The Artificial Impedance Control for local autonomy including collision avoidance and trajectory generation shows excellent results. It is also expanded to study formation control and flocking control. The computer simulation results are really promising.

## **4.12 FUTURE RESEARCH NEEDS AND PLANS IN THIS AREA**

The operator friendly and robust ground control station interface should be researched and developed for the operational capability of the developed technology. And autonomous mission management and more robust flocking control algorithms development should be pursued.

## **4.13 ACKNOWLEDGEMENTS**

Mr. Luc Brunet and Mr. Robert Yandon, Contractors for the project.

## **4.14 REFERENCES**

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## **Chapter 5 – CAN-3: SUPERVISORY CONTROL: OMNISense**

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## **5.1 DATES**

2009 – 2012.

## **5.2 LOCATION**

Toronto, Ontario, Canada.

## **5.3 SCENARIO/TASKS**

Supervisory control.

## **5.4 TECHNOLOGIES EXPLORED**

Intelligent Adaptive Agents (IAI) to manage a multi-modal display in the Ground Control Station (GCS) interface for supervisory control of an Unmanned Aerial Vehicle (UAV).

## **5.5 HUMAN FACTORS ISSUES EXPLORED**

### **5.5.1 Background**

Our Technology Demonstration (Tech Demo) is called OmniSense. It is currently being designed and developed to demonstrate the efficacy of a multi-modal display (i.e., the presentation of visual, auditory, and tactile information) [1] for enhancing supervisory control of an automated UAV. As a prelude to OmniSense's theoretical underpinnings, we will initially discuss our research on Intelligent Adaptive Interface (IAI) which will set the stage for our discussion of OmniSense.

Hou and his colleagues [2],[3],[4],[5] designed and developed an IAI conceptual framework. An IAI is an operator interface that dynamically changes the display and/or control characteristics of human-machine systems to adaptively react to external events in real time. A typical IAI is driven by intelligent software agents that help satisfy the decision-making and action requirements of operators under different levels of workload and task complexity by presenting the right information or action sequence proposals or by performing actions, in the right format and at the right time [2],[5],[6].

### **CAN-3: SUPERVISORY CONTROL: OMNISense**

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The IAI concept was investigated within a multi-UAV control context. The selected scenario involved UAV operations in support of counter-terrorist activities. The IAI was developed as part of the UAV tactical control stations for a modernized Canadian Maritime Patrol Aircraft CP-140. This work was divided into three phases.

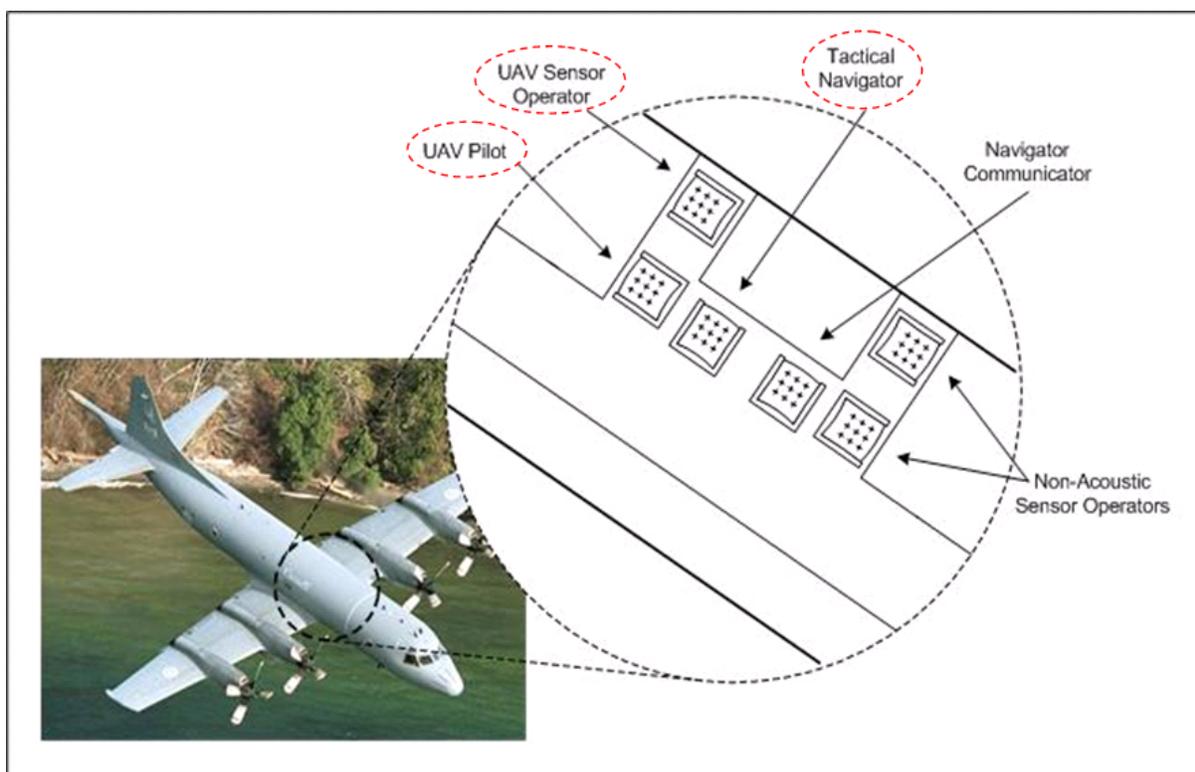
In the first phase, the IAI concept was developed [7]. Figure 5-1 shows the IAI conceptual framework, which became the guidance for the design of the UAV GCS used for this project. A generic IAI framework has four components that are listed below:

- **Situation Assessment and Support System:** This component provides information about the objective state of the aircraft/vehicle/system within the context of a specific mission, and uses a knowledge-based system to evaluate the situation; this information is then provided to the Adaptation Engine component of the IAI system.
- **Operator State Assessment:** This component provides information about the objective and subjective state of the operator within the context of a specific mission relating to real-time analysis of his or her psychological, physiological and/or behavioural state (e.g., continuous monitoring of workload, inferences about current attentional focus, ongoing cognition, visual and verbal processing load), and intentions using extensive a priori operator knowledge (e.g., models of human cognition, control abilities, and communication).
- **Adaptation Engine:** This component utilizes the higher-order outputs from the Operator State Assessment and Situation Assessment systems, as well as other relevant aircraft/vehicle/system data sources, to maximize the match between aircraft/vehicle/system state, operator state, and the tactical assessments provided by the Situation Assessment system.
- **Operator Machine Interface (OMI):** This component provides the means by which the operator interacts with the aircraft/vehicle/system to satisfy mission tasks and goals. This is also the means by which, if applicable, the operator interacts with the intelligent adaptive system (e.g., a tasking interface manager).



## CAN-3: SUPERVISORY CONTROL: OMNISense

The second phase focused on the design and implementation of IAI prototype interfaces that incorporated six system function groups: inter-crew communications, route planning, route following, screen management, data-link monitoring, and UAV sensor selection. A synthetic environment was created that followed the North Atlantic Treaty Organization (NATO) Standardization Agreement (STANAG) 4586 interface software protocol. The experimental environment had three control stations replicating CF CP-140 tactical compartment workstations, with a set of displays and controls for each of the UAV crew members: UAV pilot, sensor operator, and tactical navigator (Figure 5-2). The experimental environment also had an integrated video and audio data collection suite to facilitate empirical assessment of IAI concepts.



**Figure 5-2: IAI Experimental Environment.**

Human-in-the-loop experiments were conducted in the third phase to examine operator workload and interface adaptability with mock-up UAV control stations. Eight crews (24 operational CP-140 members) participated in the experiment. Each crew completed a two-day experiment that assessed operator interfaces with and without IAI aiding. The results showed reduced completion time for critical task sequences in the IAI mode. Also, there was a significant reduction in workload and an improvement in Situation Awareness (SA) [3],[4],[5].

The OMI component of the IAI developed by Hou and his colleagues [2],[3],[4],[5] presents information only in the visual modality. In UAV operations, an abundance of information is presented in the visual modality, resulting in cognitive overload and low situation awareness during periods of high task complexity and leading to performance degradation. Multiple-resource theory suggests that offloading information from overloaded sensory modalities to other modalities can reduce workload [11]. The effective presentation of multi-modal information in the non-dominant modalities of hearing and touch can likely enhance the perception of

information in the dominant sensory modality of vision via redundancy and complementary information presentation [1]. For example, when the same information is mapped to multiple modalities, redundancy gains such as faster response times to an incident are observed [12]. Also, multi-modal displays can increase the bandwidth of information transfer [1]. Studies that examine methods to offload the visual modality in UAV applications have been investigated. Enhanced UAV monitoring performance was observed via a multi-modal display [13],[14],[15],[16]. For example, Calhoun et al. [15] found that a unique redundant alert for critical warnings, whether aural or tactile, helped participants differentiate warning types and improved reaction time to critical events, while participants performed multiple tasks in a simulated UAV control station.

Designers need to capitalize on the benefits of multimodal displays that would lead to effective operator decision making. This is a challenging task [17]. Unlike visual displays, the mapping of information to non-visual displays is not well understood. To date, only a few studies have explored mapping techniques for representing information in auditory displays, e.g., [18]. Tactile displays are becoming increasingly common and much has been learned regarding the use of tactile cuing in display design [19]. However, most tactile displays appear to be designed in an ad hoc fashion [20], and we are unaware of any literature that has tried to describe how to systematically map information to tactile displays. To address this problem, we are currently carrying out initial work that would lead to the development of techniques to map auditory and tactile information systematically in the OMI component of the IAI framework. This framework will be used for providing information on system faults and environmental hazards in the supervisory control of a UAV. In our present work, system faults can include a low or high engine Revolutions Per Minute (RPM) warning. Environmental hazards can include wind shear or turbulence. System faults and environmental hazards will be collectively referred to as critical events. The IAI framework is first presented before describing the tech demo, OmniSense, which is a simulated UAV GCS multi-modal display.

### **5.5.2 OmniSense**

OmniSense focuses on the OMI component of the IAI framework and introduces the concept of a multi-modal display to the OMI. In the multi-modal interface of OmniSense, an auditory and a tactile display will be used to present specific display variables to help the operator monitor the health of the UAV. Specifically, the auditory display will present information regarding engine RPM, and the tactile display will present information regarding attitude upset. We are currently finalizing the design of the auditory and tactile display. The use of a multi-modal display is expected to improve SA, resulting in increased detection and faster response times to critical events during the cruise and landing phases of a UAV operation.

The current project contrasts OmniSense with a visual-only GCS interface. The experimental task requires participants to fly the UAV as the primary task, while also performing a secondary number monitoring task adapted from Sethumadhavan [21]. The secondary task was included to be representative of a multi-task environment where the participant needs to exhibit good performance in multiple, concurrent tasks. Operator supervisory control will be assessed as a function of display type, the number of critical events, and piloting experience. The project will attempt to answer the following research questions:

- a) Can a multi-modal display improve detection and response time to critical events?
- b) Can a multi-modal display improve SA?
- c) Can a multi-modal display improve the bandwidth of information transfer?

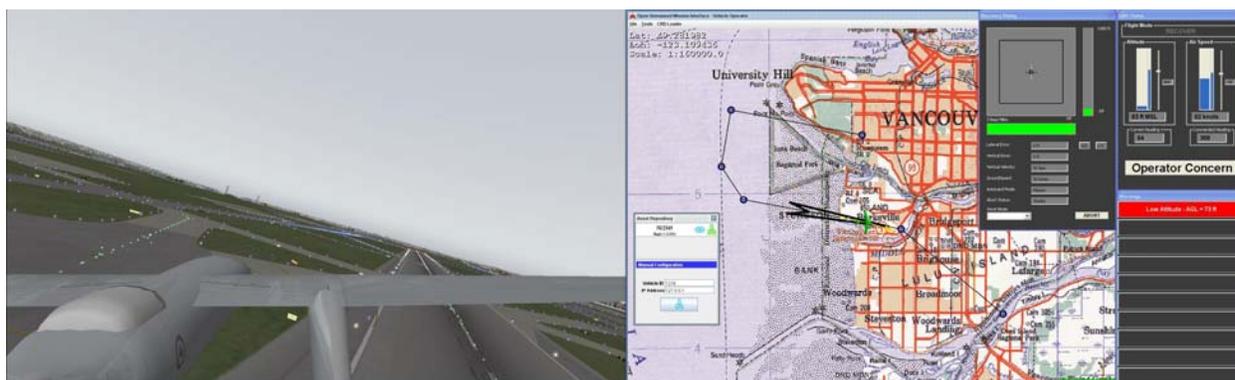
This project will provide guidance on how the output of multi-modal information can be integrated into the OMI in the IAI framework. The results of this work will help form the preliminary conceptual framework to design intelligent software agents that will systematically map information to auditory and tactile displays

which will serve as additional components in the OMI. Future work will investigate the input of multi-modal information and examine how this can provide additional information to the Operator State Assessment. This will improve the accuracy of the Operator State Assessment that will be reported to the Adaptation Engine in the IAI framework (see Figure 5-1), which in turn can optimize the presentation of multi-modal information in the OMI.

**5.5.3 Stimuli**

The UAV simulation is developed in X-Plane 9.0. The simulation begins with the UAV set to launch from Vancouver International Airport, Canada. The conditions of flight are a sunny summer day at noon in July. The city of Vancouver is developed using X-Plane’s software for simulating a city. X-plane has a seven level scale to determine the number of objects in the city. In our simulation, we used the fifth highest level on the scale for the city of Vancouver. However, no roadway vehicles, or any air traffic was simulated. The simulated environment for the onboard camera images was generated using a low-fidelity model and X-plane. Although high fidelity images were not required for this experiment, they can be generated using Meta-VR (Brookline, MA). The simulator has been adapted to interface with Meta-VR if required.

The GCS simulator has two screens, one screen dedicated to a map display and the Graphical User Interface (GUI) used to monitor the UAV and a second screen dedicated to the sensor view (e.g. the onboard camera) from the aircraft. The map display is used for navigating the UAV and providing a map-based view of its location, as shown in Figure 5-3 (right screen). This consists of a map displaying the city of Vancouver. An icon representing the UAV appears on the map and moves according to the UAV’s flight position. Tasking the UAV is initiated by having the operator right click the UAV icon to select commands from the drop down menu (e.g. launch and land). Waypoints are created directly on the map to navigate the UAV to fly specific patterns. To set a waypoint, the operator moves the cursor to a position on the map and right clicks the mouse. A menu allows first waypoint and task the UAV to fly to the assigned series of waypoints.



**Figure 5-3: OmniSense Sensor Display and Map Display.**

The GUI used to monitor the UAV is positioned to the right side of the map display screen. This GUI consists of three windows:

- a) A UAV status window;
- b) A warning panel; and
- c) An autoland panel.

The interface is presented on the far right side of the window in Figure 5-3.

The UAV status window provides information regarding the flight status, altitude, heading, air speed, and engine RPM. The altitude and air speed are fixed such that the UAV cruises at approximately 1000 feet/mean sea level (ft/MSL) at 100 knots. This window also has the *operator concern* button that will be used to indicate that the participant has detected a critical event.

The warning panel displays warnings and messages in green, yellow or red depending on the severity of the warning or message. When multiple warnings are present, more urgent messages appear at the top of the warning panel, but otherwise, they appear in chronological order from top to bottom.

The autoland panel is visible only when the UAV switches to landing mode (i.e., autoland mode). At the top of this panel is a glideslope/localizer indicator. This indicator uses a central crosshair to specify the target glideslope and localizer point. An icon representing the UAV centres over the crosshair during a trouble-free landing, indicating that the UAV is on the glideslope and localizer path. But if upon landing, the UAV deviates from the glideslope or localizer path, the UAV icon will begin to deviate from the crosshair, providing the operator with information on the accuracy of the UAV's approach. Immediately to the right of the glideslope/localizer indicator is an altitude indicator and below it, is a lateral distance indicator. The lateral distance indicator presents the lateral distance of the UAV relative to the Touchdown Point (TDP). Both the altitude indicator and the lateral distance indicator have the *decision point* marked in red. The decision point is the point in space in which an abort landing can no longer be performed. Below these indicators are several numeric-based indicators for lateral and vertical errors, vertical descent, ground speed, the autoland mode and the abort status. The *abort* button appears at the bottom of this panel. If the *abort* button is pressed before the decision point during a landing, the autoland will be disengaged and the UAV will fly to a wave off point. If the UAV has passed the decision point, the abort command will be ignored if the *abort* button is pressed.

A second screen is dedicated to a sensor display that provides a viewpoint from the rear right stabilizer from the CF CU-170 Heron UAV. With the sensor in this position, the vantage point contains a view of the front portion of the air vehicle (Figure 5-3, left screen).

The screens in Figure 5-3 will be divided into 5 main Areas Of Interest (AOIs) for the purpose of collecting eye movement data from the participant:

- a) The sensor display;
- b) The map of Vancouver;
- c) The UAV status panel;
- d) The warning panel; and
- e) The autoland panel.

The participant's eye gaze on each AOI will be analyzed for both the baseline condition (without multi-modal display) and experimental condition (with multi-modal display).

#### **5.5.4 Experimental Design**

The study is a 2 x 2 x 2 mixed design. The OmniSense display is a between-subject factor (visual-only GCS display vs. multi-modal GCS display). Flight experience (naïve vs. expert) is a second between-subject factor. The naïve group will have no pilot experience, whereas the expert group will have recently acquired at least

ten flying hours. The within-subject factor is the number of critical events (no critical events vs. multiple critical events).

The dependent variables for the UAV monitoring task are the number of critical events detected, response time to press the *operator concern* button, response time to press the *abort* button, the participant's confidence level in his/her monitoring performance to a critical event, perceived mental workload as measured via the NASA Task Load Index (NASA-TLX) [22], the participant's SA measured using a method derived from Burns et al. [23]. Participant eye movements will be monitored as a measure of visual attention. The accuracy and the response times for the secondary number monitoring task will also be evaluated to assess the participant's available bandwidth of information transfer when he/she is performing the UAV monitoring task.

### **5.5.5 Apparatus**

The OmniSense GCS simulator is based on X-Plane 9.0 developed by Laminar Research (Portland, OR). X-plane is a flight simulation environment that also includes a plug-in architecture, which allows users to create and modify their own modules. We developed X-plane to include the Heron, which is a Medium-Altitude, Long-Endurance (MALE) UAV manufactured by Israel Aerospace Industries (Ben-Gurion Airport, Israel). This particular UAV was chosen because it is currently flown by the CF in theatre in Afghanistan.

The Open Unmanned Mission Interface (Open UMI v. 3.1) developed by Defense Technologies Inc. (Tampa, FL) is used to communicate between the GCS and the X-plane simulator. Open UMI is a common operator control interface for unmanned systems that uses current NATO STANAG 4586 and Joint Architecture for Unmanned System (JAUS) standards. STANAG 4586 requires a Vehicle Specific Module (VSM) to interface between the vehicle protocol and STANAG messages to support the GUI for the GCS. The VSM and the GUI for the GCS were designed by InnUVative Systems, Inc. (Ottawa, ON). The OmniSense GUI resembles the GUI used for the United States (US) Army Shadow UAV [24]. The participant's eye movements on the GCS display (Figure 5-3) will be monitored using two Design Interactive flexiGaze eye trackers (Orlando, FL).

Customized software was developed to run on a separate computer for the experimenter to introduce system faults (e.g., low engine RPM warning, and high engine RPM warning) and environmental hazards (e.g., turbulence, and wind shear) into the UAV flight. This software allows the experimenter to pre-program a series of faults and hazards or to introduce them in real time while the participant is controlling the UAV. The experimenter display is presented in Figure 5-4.

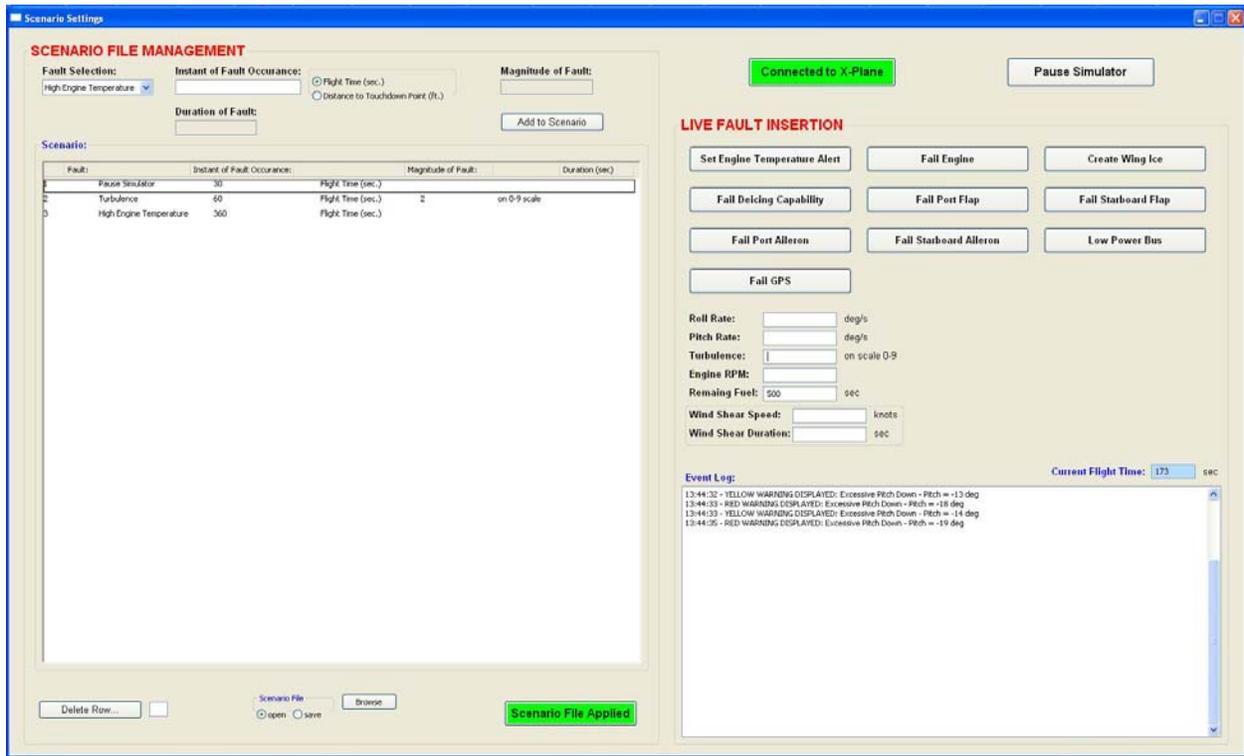


Figure 5-4: OmniSense Experimenter Display.

### 5.5.6 UAV Monitoring Task

The UAV monitoring task is the primary task in the current study. The participant will launch the UAV, command the UAV to predetermined waypoints, and land the UAV. The participant will also monitor for potential critical events. If a critical event occurs, the participant is instructed to respond by pressing the appropriate buttons (*Operator Concern* and/or *Abort*) depending on the phase of flight.

Each flight scenario is divided into 3 phases:

- a) Take-off;
- b) Cruise; and
- c) Landing.

Figure 5-5 shows each phase and the key points during each section of the flight. Table 5-1 describes the events during the flight and the possible critical events that may occur.

# CAN-3: SUPERVISORY CONTROL: OMNISense

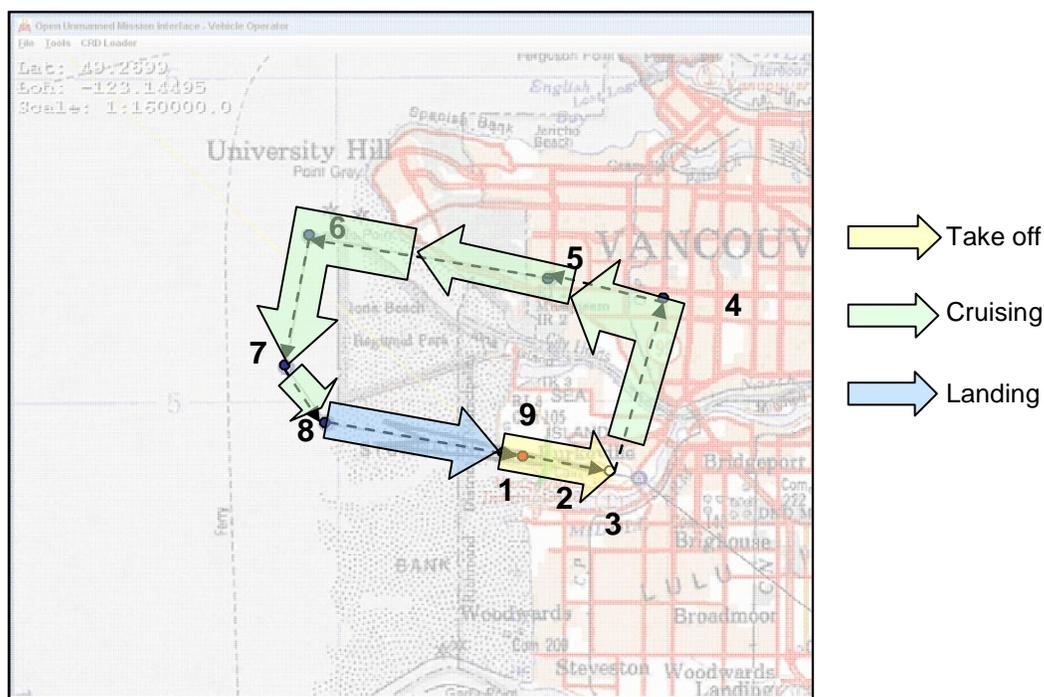


Figure 5-5: Events Associated with Each Phase of Flight (see Table 5-1 for event description).

Table 5-1: Description of Each Event Associated with Each Phase of Flight.

Phase of Flight	Flight Position	Event
Take-Off	1	Launch Participant launches UAV
	2	400 ft Secondary task begins
	3	700 ft Participant tasks UAV to waypoints
Cruise	4	Possible critical event (e.g., high engine RPM or wind shear)
		Possible simulation pause (initiate SA queries)
	Participant tasks UAV to recover	
	5	Possible critical event (e.g., high engine RPM or wind shear)
		Possible simulation pause (initiate SA queries)
	6	Possible critical event (e.g., high engine RPM or wind shear)
		Possible simulation pause (initiate SA queries)
7	Possible critical event (e.g., high engine RPM or wind shear)	
	Possible simulation pause (initiate SA queries)	
Landing Approach	8	Possible critical event (e.g., wind shear)
		Possible simulation pause (initiate SA queries)
Landing Touch Down / Landing Abort	9	Touch Down / Abort UAV lands on runway (secondary task ends) or landing is aborted

In the take-off phase, the participant launches the UAV from the runway. The participant accomplishes this task by right clicking on the UAV icon and selecting the launch command from a drop-down menu. This will launch the UAV and the participant will be able to monitor its take-off from the displays. When the UAV reaches 400 ft, the number monitoring task (described below) adapted from Sethumadhavan [21] begins. When the UAV reaches 700 ft., the participant will task the UAV to the 1st waypoint. Once this command is selected, the UAV will alter its course and fly to the 1st waypoint, entering the cruise portion of the flight.

While cruising, the UAV holds at approximately 1000 ft and flies through 4 waypoints. After crossing the 1st waypoint, the participant will be tasked to land the UAV. Once the land command has been selected, the autoland interface will appear on the GCS interface and the UAV will lower its landing gear in preparation to land.

When the UAV reaches the 5th waypoint, it begins the landing portion of the flight. The UAV will engage its flaps and begin to descend. At this point, the participant must watch the autoland panel and monitor the landing of the UAV. When the UAV lands, it will touch down at the final point, which is a runway at the same airport where the UAV took off. Once the UAV descends below 100 ft / MSL, the secondary task ends.

Critical events may occur during the cruise and/or the landing phase. During the cruise phase, the participant may encounter either system faults or environmental hazards. During the landing phase, the participant may encounter an environmental hazard. The critical events will be evenly distributed across all sessions according to Table 5-2 such that each participant will experience all combinations of system faults and environmental hazards. The time of occurrence of each critical event will be randomly determined.

**Table 5-2: Combinations of System Faults and Environmental Hazards That Can Occur in a Scenario.**

<b>Phase of Flight</b>	
<b>Cruise</b>	<b>Landing</b>
No System Faults / No Environmental Hazards	No Environmental Hazards
System Fault or Environmental Hazard	No Environmental Hazards
No System Faults / No Environmental Hazards	Environmental Hazard
System Fault or Environmental Hazard	Environmental Hazard

The participant will be told that the primary task is to monitor and react to critical events, while carrying out the secondary task. If the UAV experiences a critical event during the cruise phase, the participant will press the *operator concern* button immediately after detecting the critical event. If the UAV experiences a critical event during the landing phase, the participant will press the *operator concern* button immediately after detecting the critical event, and will press the *abort* button if the participant believes that he/she cannot land the UAV safely. If the *abort* button is pressed during a landing, the UAV will abort the landing and fly to the wave-off point that is located at the end of the runway.

### **5.5.7 Number Monitoring Task**

The participant will perform a secondary task in addition to monitoring the UAV for critical events. The secondary task consists of monitoring numbers adapted from Sethumadhavan [21]. A series of numbers between 100 and 199 will appear on the computer monitor at 2-second intervals. The participant will be told that a number that is less than 130 or greater than 170 represents a warning. The participant is to press the space bar on the computer keyboard immediately after detecting a warning.

### **5.5.8 Procedure**

Participants will be tested individually. The study will be conducted over the course of three days that will not span more than a week. The participant will first receive training prior to the experimental sessions. The training includes a 20 minute multi-media tutorial on some basic principles of flight and procedures for operating a UAV. Following the video, the participant will summarize the flight procedures to demonstrate that he/she understood the concepts in the video. Subsequently, the participant will be seated in front of the three computer monitors for the duration of the study. The experimenter will then calibrate the two eye trackers. The participant will be familiarized with the UAV monitoring task and the number monitoring task. Subsequently, the participant will fly a practice scenario on the GCS simulator.

Following familiarization, the participant will proceed to the experiment. The experiment contains 12 scenarios distributed across three sessions. Session 1 contains the previously mentioned training procedure and two scenarios; Sessions 2 and Session 3 each contain five scenarios. The order of scenarios will be randomized for each participant to control for order effects. The duration of each session is two hours; sessions will be held on separate days.

Each scenario will have 3 phases: take-off, cruise, and landing. During each scenario, two SA queries will be triggered at randomly predetermined times, one during the cruise phase and one during the landing phase. When triggered, the simulation will pause and the participant will answer three questions chosen from the set of SA queries. The participant will also rate the confidence of his/her current monitoring performance on a full range confidence scale. The scale ranges from 0 – 100%, where 0% indicates that the participant undoubtedly has no confidence in his/her monitoring performance to a critical event and 100% indicates that the participant is absolutely confident in his/her monitoring performance to a critical event [25]. Once the participant has answered these questions, he/she will click on the *resume* button on the screen and the simulation will continue from the point where it paused. At the completion of the scenario, the participant will again rate the confidence of his/her monitoring performance relative to the entire scenario on a full range confidence scale. The duration of each scenario is approximately 13 minutes, which includes time for answering the SA queries, and the participant rating his/her confidence in monitoring performance to a critical event. Subsequently, the participant will be provided with a short rest break. At the completion of the last scenario in the session, the participants' perceived mental workload will be assessed using a computerized version of the NASA-TLX [22].

### **5.5.9 Summary**

In this Tech Demo we explore effects of multi-modal display on supervisory control, SA of the mission environment, and perceived mental workload. The effects of a visual secondary task on operator performance will also be evaluated.

## 5.6 UNMANNED SYSTEMS USED

Multi-modal display for simulated UAV GCS.

## 5.7 SUMMARY OF ANY NATO COMMUNICATIONS/COLLABORATIONS/ INTERACTIONS

As indicated in Table 5-3 the OmniSense tech demo provides information pertaining to the supervisory control technology design, and development. The information was conveyed primarily at NATO HFM-170 meetings. The meetings provided an opportunity to share information on the nature of supervisory control tasks, operator interface technologies, and integration concepts that could help enhance supervisory control performance.

**Table 5-3: OmniSense Technology Demonstration – Level of Interaction with NATO HFM-170.**

	<i>Planning/Design</i>	<i>Execution</i>	<i>Analysis</i>
<i>Communication</i>	X	X	X
<i>Coordination</i>			
<i>Collaboration</i>			

## 5.8 SUMMARY OF TD RESULTS

Empirical data collection has not commenced. The following are preliminary potential dependent variables and associated hypotheses:

- 1) Critical event detection: participants will detect more critical events and detect those critical events more quickly in the multi-modal condition;
- 2) Response time to abort: the response time to press the abort button will significantly decrease in the multi-modal display condition;
- 3) Confidence in monitoring performance: the confidence in monitoring performance to a critical event will significantly increase in the multi-modal display condition;
- 4) Dwell times on UAV monitoring task: the dwell times (i.e., the sum of consecutive eye fixation durations in a particular AOI) on the UAV monitoring task will significantly decrease in the multi-modal display condition;
- 5) Secondary task accuracy: accuracy in the secondary task will significantly improve in the multi-modal display condition;
- 6) Situation awareness: the participant’s SA will significantly improve in the multi-modal display condition;
- 7) Perceived mental workload: the participant’s perceived mental workload, as measured by the NASA-TLX [22], will significantly decrease in the multi-modal display condition; and

- 8) Flight experience: the naïve participants will show poorer performance than the expert participants in the baseline condition, but will not significantly differ in performance from the expert group in the multi-modal condition. The multi-modal information is hypothesized to improve naïve performance to a greater extent than expert performance.

## **5.9 LESSONS LEARNED**

The current study is in progress. The design and development of the OMI component of the IAI framework for OmniSense is nearly complete. The empirical data collection for the visual-only GCS interface will begin in November 2011.

## **5.10 STUDY CONSTRAINTS/LIMITATIONS**

The experiments will be conducted in a virtual environment, not with an actual UAV.

## **5.11 CONCLUSIONS**

The design and development of the OMI component of the IAI framework for OmniSense is nearly complete. The empirical data collection for the visual-only GCS interface will begin in November 2011. Based on earlier work showing that multi-modal displays enhanced UAV monitoring performance [13],[14],[15],[16], we anticipate that OmniSense will enhance supervisory control by providing the human operators with the ability to perform real-time monitoring of critical variables that would otherwise be undetected if eye gaze was directed elsewhere. The benefit of OmniSense is anticipated to be particularly evident in an increase in the detection of critical events, a reduction of response times to critical events, and increased SA. This suggests that the OmniSense solution will be more effective than a visually-only GCS interface.

## **5.12 FUTURE RESEARCH NEEDS AND PLANS IN THIS AREA**

The incorporation of a multi-modal display like OmniSense into the OMI component of the IAI framework provides an example using the intelligent software agents to interact with multi-modal displays for optimizing operator-agent interactions. Furthermore, multi-modal inputs in the form of eye movements and speech assessment (e.g., loudness, vocal emotion) and facial expressions could further enhance Operator State Assessment. Future work would support the design and development of other software agents to manage multi-modal interactions and integrate them to other agents designed to assess other operator states (e.g., electroencephalography, and electrocardiography) and environmental states (e.g., weather, system status, and communication links) to enhance supervisory control of multiple UAVs.

The implication of this study is that multi-modal displays linked with IAIs have the potential to improve overall human-machine system performance if they are designed properly. However, if designed improperly, IAIs have the potential to degrade system performance by:

- a) Reducing operator trust in the automation;
- b) Presenting irrelevant information;
- c) Presenting information that distracts the user; or in the worst-case scenario; and
- d) Suppressing information that is currently required.

Additionally, other implications of this research raise the issue of the dilemma for automation and adaptation using IAI technologies for supervisory control of a UAV.

### 5.13 ACKNOWLEDGEMENTS

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## **Chapter 6 – FRA-1: UAV SWARM CONTROL – SMAART PROJECT “INTERACTING WITH MULTI-AGENT SYSTEMS / UAV SWARMS”**

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### **6.1 DATES**

SMAART (2006 – 2008) and SUSIE (2009 – 2011).

### **6.2 LOCATION**

Brest – Nancy – Paris (France).

### **6.3 SCENARIO/TASKS**

The setting chosen for SMAART is the surveillance of a strategic air-base, i.e., a military air-base which can deploy combat aircrafts with nuclear payloads, and is often used for sensitive operations (Figure 6-1). Of course, such a base has important needs in the field of security. In SMAART, we propose to introduce rotary-wing UAVs (among other things) in order to perform surveillance tasks and to track and identify intruders. The UAVs (about a dozen) and their collective decision algorithms constitute the autonomous system that the operator interacts with.



Figure 6-1: Map of the Air Base Used for Multi-UAV Surveillance and Intrusion Tracking.

The rotary-wing UAVs envisioned in SMAART weigh about 8 kg, can travel at a maximum speed of 80 km/h, have an autonomy of one hour and are able to detect intruders via optical sensors (daylight, light intensification, infrared). They are able to navigate autonomously about the air base at a low altitude, avoiding buildings and forbidden zones, to communicate between themselves and with the Ground Control Station (GCS) and their sensors allow them to detect and eventually identify intruders (Figure 6-2).

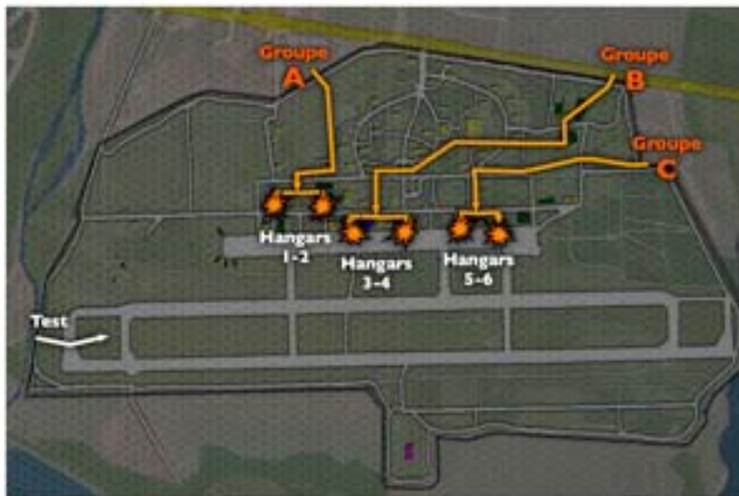


Figure 6-2: Intrusion Scenario Played on Simulation.

## 6.4 TECHNOLOGIES EXPLORED

The following paragraphs describe the principles of the self-organizing multi-agent system used in our demonstrator. The aspects specifically related to the man-machine interaction and human factors will be developed in the next section.

### 6.4.1 Modes and States

As with the behavior-based approaches, the UAVs have a finite set of base behaviors that they can adopt during their mission. In SMAART, we refined behaviors into the two notions of mode and state. At any given moment, an UAV is in a given state that has been determined by its mode. There is often a simple one to one mapping between mode and state; for example, an UAV in modePatrol is always in statePatrol. But this is not always the case, hereafter, we list the different modes and their associated states between parentheses when there is more than one: modePatrol, modePursuit, modeAuto (statePatrol, statePursuit), modeRally, modeHover, modeStop.

### 6.4.2 Patrol Pheromone

A stymergic, virtual pheromone-based algorithm was developed to allow the UAVs (the agents of the MAS) to coordinate their trajectories in order to patrol the air- base efficiently (visit every point as often as possible). Stymergy is a method of communication in emergent systems where the individual parts of the system interact with one another by modifying their local environment. This natural occurrence has been observed in ant colonies. Ants communicate with each other by laying down pheromones along their trails, so where ants go within and around their nest forms a stymergic system.

Similarly, the UAVs share a virtual grid-like environment superimposed to the actual air base. Each cell in that grid stores a numerical values (quantity of patrol pheromone) that is directly linked to patrol times: the higher the value, the more recently an UAV patrolled this cell. When a UAV enters a virtual cell, it adds a fixed amount to the value of the cell. As time goes by, this pheromone evaporates (following a cell-based evaporation value), so the longer a cell stays unvisited, the lower its pheromone value becomes.

When an UAVs under statePatrol has to choose its movement (next cell), it chooses the nearby cell with the lowest pheromone value, i.e., the one that was patrolled the longest time ago. This principle ensures that the agents will spread across the air-base, as they produce pheromones that repel each other.

### 6.4.3 Alarm Pheromone

In order to pursue intruders once they are detected by the system (by the UAVs or by other means e.g., perimeter sensors) a pheromone-based algorithm has been developed similar to the one used for patrolling. The latter is based on the production/avoidance of an evaporating patrol pheromone, while the following pursuit algorithm is based on the consumption by the UAVs in state statePursuit of an alarm pheromone that is produced each time an intruder is detected and which diffuses in the environment (another grid).

Each time a contact is detected a fixed amount of alarm pheromone is dropped in the corresponding cell. As time goes by, the pheromone from each cell diffuses in the neighboring cells. For a single contact, this can be viewed as the representation of the evolution of the intruders' probability of presence.

### 6.4.4 Alarms and Contacts

SMAART's rotary-wing UAVs system is not the only security system on the air-base, there are perimeters sensors on the fence, various alarm systems in the buildings, patrols, etc. In the SMAART project, we also study the joint use of fixed-wing UAVs and also of a sensor network, but this is outside the scope of this paper. It suffices to say that an intruder or a group of intruders can potentially trigger a lot of detection systems. For example, a commando of three people that breach the perimeter of the base could be detected at

the same moment by the fence’s sensors, one or two rotary-wing UAVs and a higher altitude fixed-wing UAV. This scenario could produce up to  $3 \times (1+2+1) = 12$  different alarms for the same event, i.e., a three-people commando breaching the fence.

In order to prevent information overload for the system as well as for the operator, alarms that happen close to each other temporally and spatially are aggregated together in a contact. This simple mechanism depends on a time interval  $T$  (a few seconds) and a radius  $R$  (about ten to twenty meters). A new contact is generated if an alarm is raised that is not close enough (closer than  $R$ ) to an “open” contact, i.e., a contact based on an alarm no older than  $T$ . Thus, the drops of alarm pheromone are generated upon detection of the contacts, not the alarms, this prevents the formation of excessive spikes of pheromone in case of multiple detection. In a similar way, the operator is not presented the alarms themselves, but rather the contacts which are a composite objects that he/she can analyze at will.

The main results of these algorithmic approaches are displayed on the following diagrams (Figure 6-3). On the left side, one finds an example of the initialization phase, where small circles represent the respective UAV, and purple layer the level of pheromone (the more purple, the more recent the area was visited). On the right side, the image represents a stabilized surveillance procedure. One can see that the coverage of the area is quite efficient.



**Figure 6-3: Main Results of These Algorithmic Approaches.**

## **6.5 HUMAN FACTORS ISSUES EXPLORED**

### **6.5.1 Framework Description**

On the one hand, there exists a very large amount of literature in the field of multi-agent systems (MAS, a sub-field of Artificial Intelligence) devoted to enable a group of artificial agents to accomplish one or several tasks in cooperation. On the other hand, most of the research on interaction between human and semi-autonomous systems focuses on “single instance” systems like intelligent cockpits, industrial process control system, etc. But there is few work conducted on the human control of a multi-agent system. The domain of

multiple UAVs control is close to MAS control, see for example the work of Cummings et al. (tactical missiles [1] or UCAVs [2]) or the research around the MIIRO test bed (Multi-Modal Immersive Intelligent Interface for Remote Operation) [3]. But these approaches do not consider giving decisional autonomy to the agents (here, the UAVs), the decision is centralized and concerns target assignments, individual path planning and so on.

Controlling or supervising an actual multi-agent system involves dealing with a number of entities that are required to take some level of decision autonomously and locally, i.e., using information that may not be available to the human controller. In the following sub-section, we review some approaches for Human – multi-agent system control.

**Behaviors** – The most straightforward way for enabling an operator to control a number of agents is to endow the agents with a fixed set of basic behaviors that the agent is able to perform autonomously (rally a point, patrol, follow a target, etc.) The task of the operator is to choose an appropriate behavior for each agent and to monitor their progress in their task, affecting behaviors accordingly.

This control-by-behavior paradigm is prevalent in MAS control for simple (often reactive) agents whose actions can be easily monitored – often visually. For example, the RoboFlag domain [4] (a game of capture-the-flag played by two opposing agent teams under Human supervision) is particularly suited to this approach [5],[6]. Control-by-behavior can be effective if a small number of behaviors cover the need of the system, but this approach loses its interest if one needs more agents, more complex or more numerous behaviors as the management of individual agents becomes impossible for the operator [7].

**Policy** – In the context of MAS control, the control-by-policy approach would have the advantage of sparing the operator from the individual management of agents. Rather than to assign individual goals or behaviors to agents, the operator issues global constraints or advices, and the agents determine their course of action accordingly. This approach involves:

- A representation and expression system, usually close to propositional logic;
- An interface, usually text or speech-based (due to the link between logic and – constrained – natural language). Control-by-policy is well suited to mixed-initiative systems [8]; and
- A software architecture able to interpret policies and evaluate them against current or hypothetical situation (hence barring reactive agents in favor of deliberative ones).

This approach was used for interaction with planning systems like SOCAP (Systems for Operations Crisis Action Planning) [9],[10] that allows enunciating constraints like “Secure Air Superiority in Sector A before Air Superiority in Sector B”, “Defend the North-East Sector” or “Don’t employ more than 5 sorties in Region H”. Other applications include communication network management on the battlefield [11] or commercial airlines operations [12].

**Playbook** – The term playbook refers to pre-defined tactics used by football teams’ coaches. Rather than to re-define from scratch and communicate to every team member how to behave for the next play phase, the coach refers to a set of tactics known by each team member and only has to instantiate them in the current context (assign a specific role, a variant, etc.) This allows effective teamwork with few communications, as each team member knows each other’s role.

This is used as a very effective metaphor for the control of multi-agent systems. The playbook becomes a library of plans of action that are available for the operator to instantiate at various levels of detail, hence

allowing various levels of autonomy for the agents. For example, in a surveillance context the operator could request a reconnoitre of an area and leave the system decide which agent to send and which pattern to choose, but he/she could also choose the number of agents (even the agents themselves) or the pattern, or any combination of parameters and leave the system decide the rest.

The playbook approach was studied in the context of tactical ground robots [13],[14], real-time interaction with heterogeneous military UAVs [15]. It was also used within RoboFlag simulations to study variations of operator’s performance [16],[17].

**Proxy Agents** – The purpose of a proxy agent is to allow Humans to interact with a multi-agent system. Such an artificial – software – agent is part in a multi-agent system in which it functions as either a Human’s or an artificial agent’s representative, i.e., communicating, negotiating at his/her behalf. A proxy agent can be seen as a common interface for Humans and artificial agents.

This approach considers the operator-system relationship in a “call center” perspective [18], operators being called by the system when it detects a coordination problem that it cannot solve. This approach has the advantage of blending together Humans and artificial agents with a common “interface”, but this inevitably has some pitfalls like the lack of situation awareness of operators who are called in when the system decides so, and the agent team’s rigid interaction strategies.

SMAART is an exploratory research project funded by the French Defence Research Agency (Délégation Générale de l’Armement) that aims at producing – in simulation – the prototype of a multiple UAVs system, including its control station. This project motivates research in the field of Artificial Intelligence/MAS, but also in Human-Information System Interaction, in this case Human-MAS Interaction. The setting chosen for SMAART is the surveillance of a strategic airbase, i.e., a military air-base which can deploy combat aircrafts with nuclear payloads, and is often used for sensitive operations. Of course, such a base has important needs in the field of security. In SMAART, we propose to introduce rotary-wing UAVs (among other things) in order to perform surveillance tasks and to track and identify intruders. The UAVs (about a dozen) and their collective decision algorithms constitute the autonomous system that the operator interacts with.

### **6.5.2 Framework Applied to HFM-170**

The purpose of our demonstrator is three-fold. In a first step, we want to demonstrate that swarm intelligence is adapted to simple missions on a dedicated area, such as surveillance and intrusion tracking. Secondly, we aim at analyzing the gap existing between swarm algorithms performance and limitations and the perception operators may have from these elements. Third, the demonstrator (through its extension) proposes some new interaction modes that can minimize operational semantic gaps and limitations and be more intuitive for the users.

### **6.5.3 Human Factors Issues**

One can see that the rotary-wing UAVs in SMAART can theoretically accomplish their task in a completely autonomous manner. That is, all the UAVs could be set to modeAuto, therefore patrolling the air-base in search of intruders and switching to pursuit when they detect a trace of alarm pheromone which would guide them toward the intruders. The operator’s only action would be to adjust the priority of some zones via the pheromone evaporation values: he/she would be little more than a spectator. But the dangers of full-blown automation without a human in the loop are well known, as well as the unique abilities of a human operator (pattern

recognition, intuition, etc.). Nonetheless, when a Human is indeed in the control loop with a partially autonomous system, more often than not, his/her role is to supervise or make up for the system’s shortcomings, which leads to various negative consequences (on mental workload, situation awareness, complacency, or skill degradation, see [19]). On the contrary we chose to adopt a human- centered approach for the control of the UAV system in SMAART. The operator is at the center of the system and has at his/her disposal a whole range of interaction levels with the system. Depending of his/her workload, moment, particular UAV, number and localization of alarms, etc., the operator will select the ones that he/she deems appropriate (Figure 6-4).



Figure 6-4: Dual Screen Man-Machine Interface of SMAART Simulator.

He/she can for example choose to let the system operate autonomously, assuming a supervisory role, and then to begin to manage very closely a few UAVs when an intrusion is first detected to track it (leaving the other in autonomous patrol). Any combination is possible.

Intruders are not so common on a strategic air-base, therefore the main task of the operator in SMAART is to supervise the patrolling of the grounds by the UAVs. The UAVs should visit every accessible location in the base regularly in order to maximize the chance to detect an intruder. In order to achieve this, the UAVs are able to use an algorithm based on a virtual patrol pheromone that tends to spread them evenly across the base. They are repulsed by points that have been recently visited by an UAV and therefore seek less visited locations.

Despite the efficiency of this algorithm, a Human operator is in charge of supervising the UAVs. His/her role is to make up for the system’s eventual shortcomings, but also to adjust the UAVs’ behavior in order to take into account extraneous constraints or various pieces of information that cannot be easily translated into the system’s representations. The interventions of the operator could include for example: sending an UAV at an overlooked location<sup>2</sup>, or that the UAVs concentrate temporarily on a higher priority zone, making sure that the UAVs avoid a certain area, etc.

A same hybrid mode is allowed for the tracking of intrusion, where UAV can autonomously track alarm pheromone spread by the intruders or follow waypoint orders given by the operator (Figure 6-5).



Figure 6-5: Time-Line of Scenarios.

Tests were handled upon a population of 8 military subjects (French Navy School students), 6 men / 2 women, from 20 to 23 years old. Quantitative and qualitative data were collected upon their performance, modes of interaction and subjective evaluation of system’s and own performance at tasks.

The main results on the previous diagram (Figure 6-6) show that though the operators usually believe the system to be far less efficient than their own strategies, the average performance they achieve is at most in the average performance bounds, and even slightly underperforming. These results can be interpreted as a clear misunderstanding – and mistrust – of the system assistance, leading to “interfering” and “spoiling” intervention of the operators. This raises the issue of man-machine interface intelligibility, in terms of commands as well as when reflecting the state of the system.



Figure 6-6: Main Results for Patrolling Phase – a) Average Idleness for Locations; b) Operators Actions Review.

On the contrary, performance results on tracking and interception of intruders show that operators are more efficient (20% gain) than autonomous tracking, especially because intruders’ “intentions” are more easily decoded by human-based situation assessment than simply following a grid-based digital map.

In order to fill the gap between operators understanding, new research directions have been defined that are related to:

- New means of interaction with operational and tactical maps / UAVs / pheromone maps: see <http://recherche.telecom-bretagne.eu/susie/video/>.
- The definition of elementary actions that could be used for mapping pheromone algorithm dedicated adaptations to operational requirements that are closer to operators’ understanding and protocols. Table 6-1 gives a first list of such elements (most relevant of them in bold case).

**Table 6-1: A First List of Elementary Actions That Could be Used for Mapping Pheromone Algorithm Dedicated Adaptations That Are Closer to Operators’ Understanding and Protocols (Most Relevant of Them in Bold Case).**

	Moving Target	Point	Line	Contour	Area
Monitor		<b>Insure a permanent surveillance of punctual target (restricted version of area monitoring).</b>	<b>Detect fixed or moving target present on a line. Can be extended to the monitoring of a graph.</b>	<b>Detect fixed or moving objects close to a given contour. Special attention may be put on objects crossing the contour.</b>	<b>Detect fixed or moving objects within a given area.</b>
Avoid	Collision or threat avoidance. Implies the perception of the moving target and a minimal ability to predict its trajectory.	See avoid area.	Avoid flying over a line that is known to exist in the area (e.g., road or highway).		<b>Avoid (or get the UAVs out of) a given area.</b>
Find	<b>Find one or several moving targets within a given space (hypothesis: objects are present in the area). Finding a moving target needs to “catch” it within the sensor range and to detect it successfully.</b>	<b>Determine the position of one or several punctual targets known to be present on zone.</b>	Find at least one point on a line that is known to exist in the environment. Possibility of taking in account complementary information that facilitate the task (road direction constraints, etc.).	Close to “find a line” with complementary notion of “inside” and “outside”.	Same as “find a contour”.
Follow	<b>Keep one (or several) moving target’s) under detection/ tracking range. Can imply to remain simultaneously out of range for security of UAV.</b>				
Intercept	Act so as to cross the trajectory of the moving target soon as possible. Needs to rely on information on moving target’s trajectory.				
Patrol			Calibrate own trajectory on a line (e.g., selected road).	Same as “patrol a line”.	Guarantee a “regular” presence within an area.

## 6.6 UNMANNED SYSTEMS USED

As described here above, the Unmanned System used was not real but only simulated.

## 6.7 SUMMARY OF ANY NATO COMMUNICATIONS/COLLABORATIONS/ INTERACTIONS

SMAART software framework is proposed to be shared amongst NATO HFM-170 partners. The software packages and a basic user manual have been communicated to the group members. Considering simple adaptation of UAV behaviors, the framework could help in simulating respective field of study.

	<i>Planning/Design</i>	<i>Execution</i>	<i>Analysis</i>
<i>Communication</i>	X	X	X
<i>Coordination</i>	?	?	?
<i>Collaboration</i>	X	X	X

## 6.8 SUMMARY OF TD RESULTS

Main TD results:

- Proof of feasibility of surveillance missions (area monitoring and intruders tracking) using swarm intelligence controlled by human operators;
- Swarms algorithms robustness and efficiency checked; and
- Preliminary design of related man-machine interfaces.

## 6.9 LESSONS LEARNED

The most important lesson learned is related to the gap of understanding and to the trust of operators in swarms' algorithm. Human factors studies have shown that there is a strong need of adapting commands and system's feedback representations in order to fill this gap and to facilitate operators work while maintaining system capabilities (mostly robustness).

## 6.10 STUDY CONSTRAINTS/LIMITATIONS

The study was – and still is – done on simulations and not on real UAVs. Results have to be confirmed statistically from an extended test panel.

## 6.11 CONCLUSIONS

Swarm intelligence seem to be a promising approach for multiple UVs control in terms of algorithmic performance and robustness, so far Human Factors and especially man-machine communication and interaction are properly adapted.

## 6.12 FUTURE RESEARCH NEEDS AND PLANS IN THIS AREA

Future research will focus upon:

- Swarm algorithm adaptation in order to enlarge supported functions to a broader spectrum of operational missions.
- Semiotic engineering of man-machine interface in order to adapt displays and commands.
- New modalities of man-machine interface in order to support the meaningfulness of interaction (see perspectives in [20],[21],[22]).

### 6.13 ACKNOWLEDGEMENTS

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## **Chapter 7 – FRA-2: PEA “HUMAN FACTORS AND AUTHORITY SHARING” (FHPA)**

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## **7.1 DATES**

PEA FHPA: 2007 – 2011.

## **7.2 LOCATION**

Paris, France.

Demonstration done at LTO – Laboratoire Technico-Opérationnel DGA (Arcueil / France).

## **7.3 SCENARIO/TASKS**

The second French Tech Demo is related to an upstream program named “Human Factors and Human/Automate Authority Sharing in Unmanned Aerial Systems”. The main objective of this program is to define new means of cooperation and interaction between Humans and Automates, based on the concept of “Authority Sharing”. In practical terms, it is intended to optimize the workload of existing UAV systems by allocating dynamically the operators’ functions, allowing thus the integration of multiple UAVs and payloads without necessarily augmenting the number of operators.

The program is organized in 4 phases during 36 months:

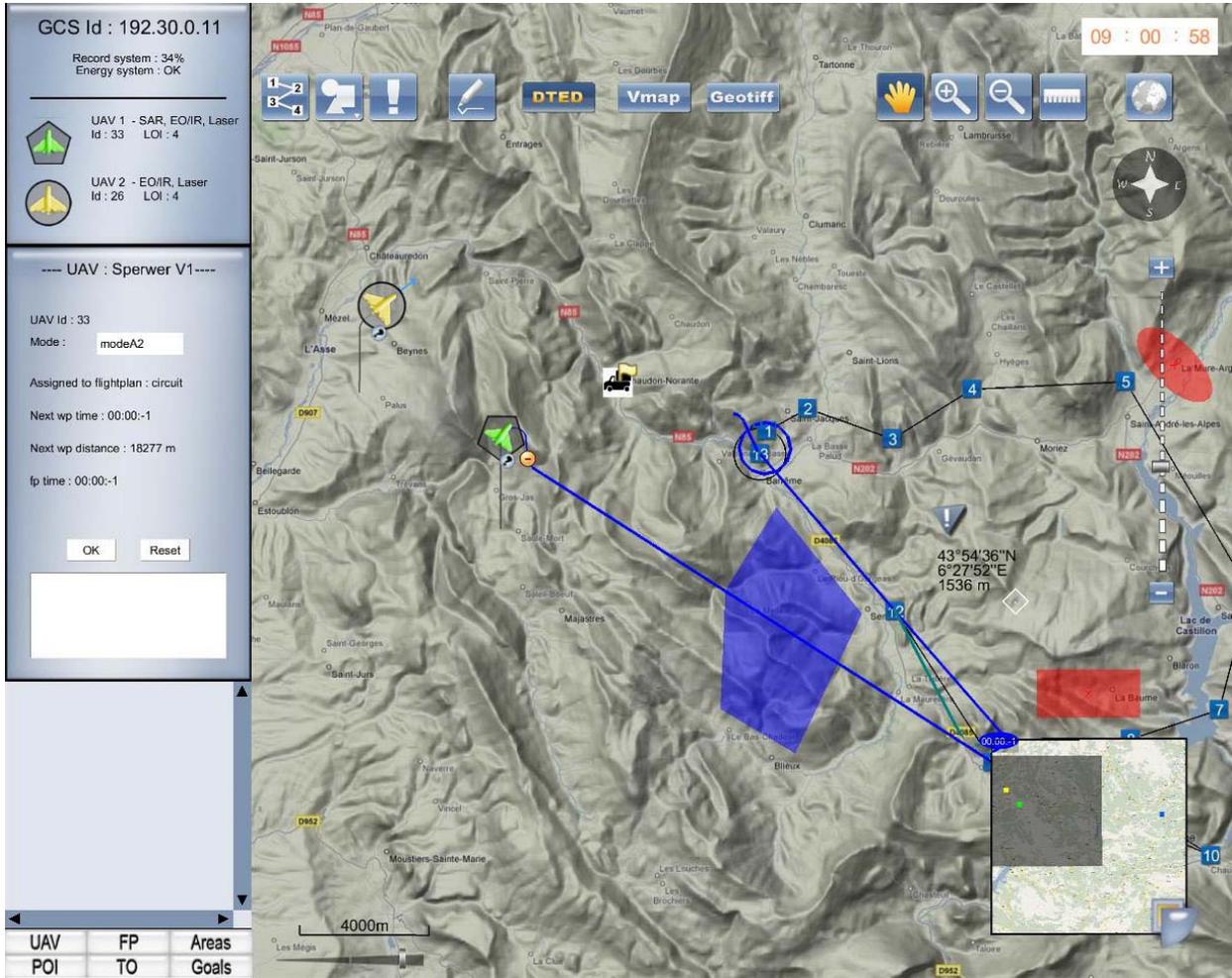
- Phase 1: “RETEX” (RETour d’EXpérience) – experience feedback from the French Army;
- Phase 2: Search for innovative solutions on HF and Authority Sharing;
- Phase 3: Implementation of the innovative solutions; and
- Phase 4: Experiments / HF evaluation.

The scenario envisioned for this project sets two Ground Control Stations (GCS) collaborating together toward the identification of a common enemy:

- The first GCS controls two tactical UAVs (fixed-wing UAVs), with one payload each, flying at two different locations on the map (in the same geographical area).

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- The other GCS controls one MALE UAV (fixed-wing), with one payload, flying in the same geographical area as the others.



**Figure 7-1: Tactical AVO's Cartography Screen.**

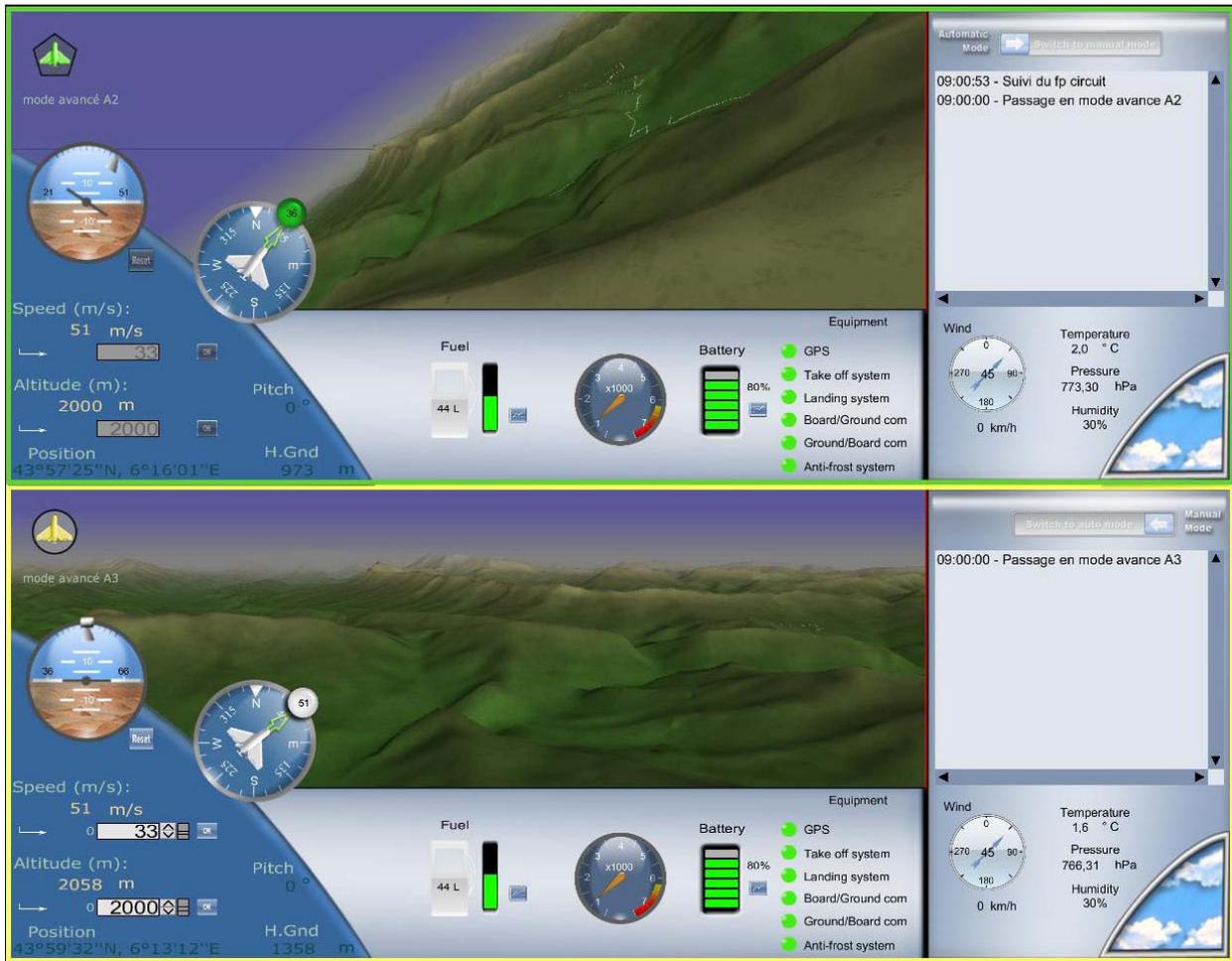


Figure 7-2: Tactical AVO's Manual Control Screen.



Figure 7-3: Tactical PO’s Camera Views Screen.

Each station welcomes a 2-member team: an Aerial Vehicle Operator (AVO) and a Payload Operator (PO). At the beginning of the scenario, each team is unaware of the other team’s presence in the area.

The tactical GCS’s mission is two-fold: UAV1’s goal is to open a road for a convoy by detecting and identifying all the potential targets along that road while UAV2 is watching the convoy and its surroundings. The MALE GCS’s mission is to watch the activity along a border.

At a certain point of the scenario, the MALE UAV is rerouted to a meeting area but an air traffic lane appears and prevents it from reaching the meeting point on time. One of the tactical UAVs is then rerouted to the meeting area and shares its payload (EO camera) with the MALE GCS. The video feedback provided allows the MALE station to perform its mission and, as the air traffic lane closes, the MALE UAV can be directly directed to the meeting point.

#### 7.4 TECHNOLOGIES EXPLORED

Within the scenario presented before, two different concepts are assessed: an “authority sharing” concept, between the AVO and the automate controlling each UAV (throughout the mission), and a human-human collaboration concept between the two payload operators (while sharing the video feed).

### 7.4.1 Authority Sharing

After the definition of the three different operative modes (automatic, intermediary and manual), each corresponding to different levels of function allocation, a set of HMI was designed to support each operative mode with a focus on the *trajectory management* macro-task.

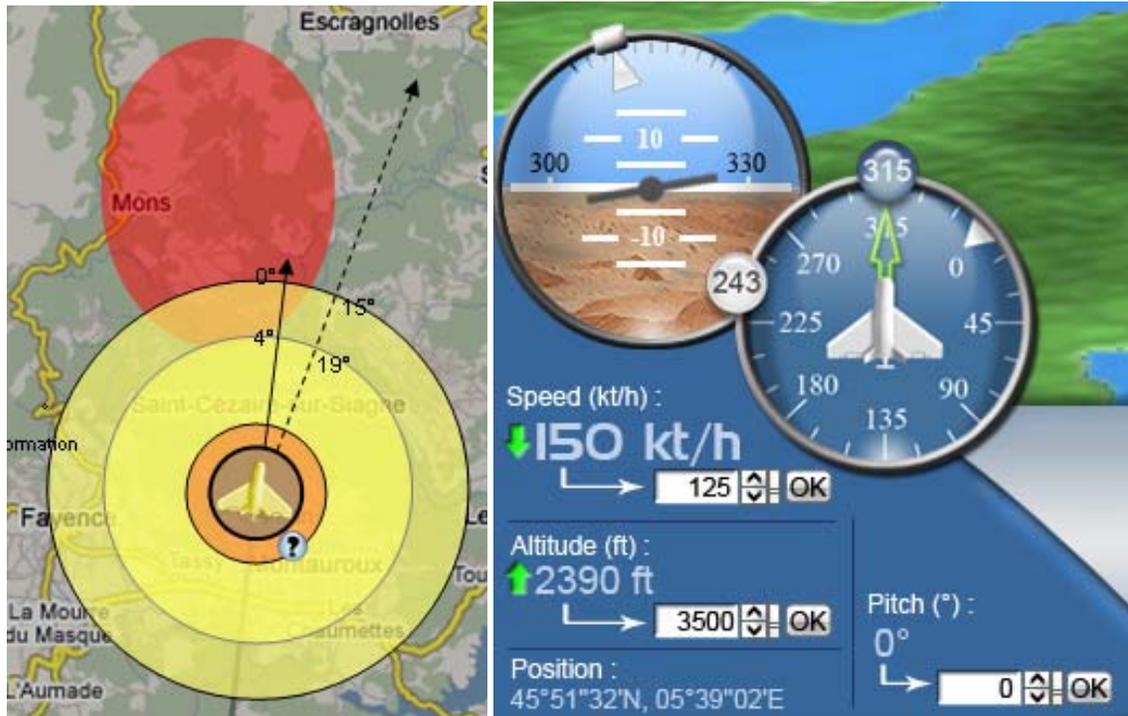


Figure 7-4: Examples of UI Designed to Support the Different Operative Modes: (a) Draggable Vector Tool and (b) Manual Controls.

### 7.4.2 Human-Human Collaboration

The human-human collaboration part of this project focuses on the payload sharing between the two ground control stations. During the mission, the tactical payload operator “lends” the payload of one UAV to the MALE payload operator. Two levels of sharing are defined: one where the full control of the tactical payload is transferred to the MALE operator, and the second where only the video feedback is sent to the MALE operator while the control remains under the tactical operator’s responsibility.

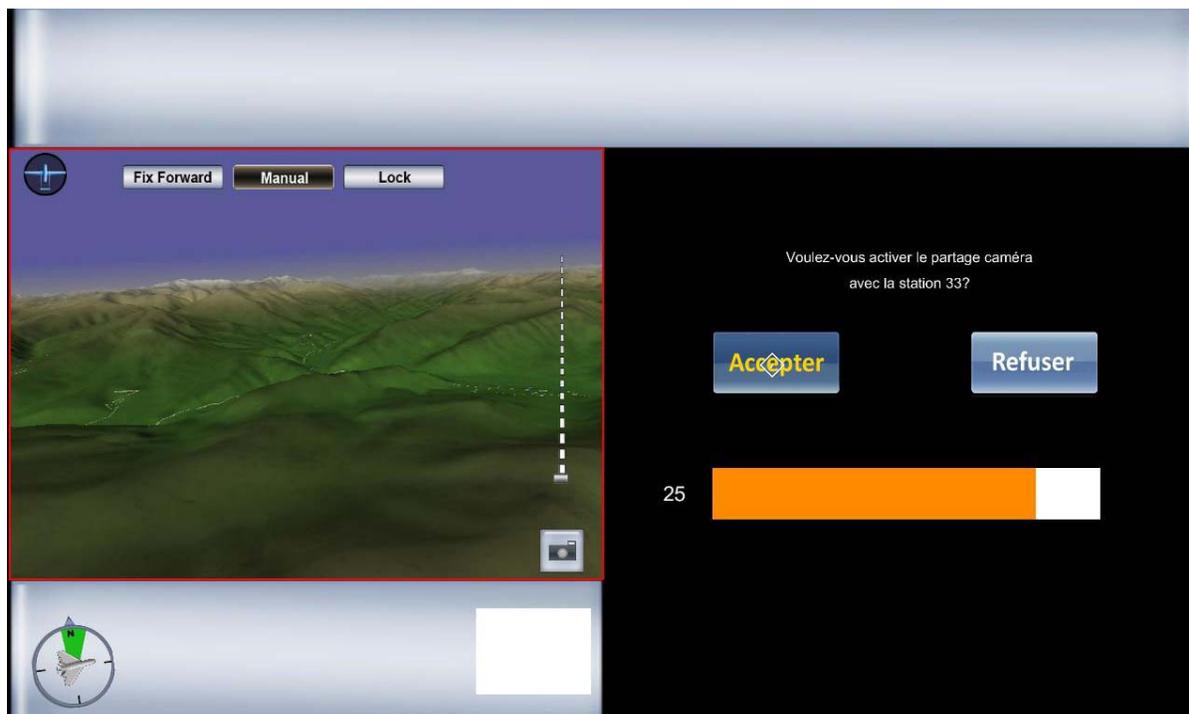


Figure 7-5: View of the MALE PO Screen When Receiving a Shared Camera.

The HMI designed to support these 2 concepts have been tested on a simulation environment during two experimentation campaigns with UAV military personnel from the French Army and the French Air Force.

## 7.5 HUMAN FACTORS ISSUES EXPLORED

### 7.5.1 Reference Frame

One of the project’s phases purpose was to design an “authority sharing” engine which function is to dynamically allocate the functions to either the automata or the operator, depending on the operational context. This “operational context” is mainly defined by different criteria:

- Number of UAVs;
- UAVs’ objectives and status;
- Types of missions / tactical environment; and
- Meteorology (specially gusts of wind).

Refining the classical approach of autonomy levels [4],[6], we defined a methodology based on Proud’s Level Of Autonomy (LOA) matrix [5] and Boyd’s OODA loop [1] in order to derive a general framework where different levels of function allocation can be coupled with the 4 phases of Boyd’s loop (Observe, Orient, Decide, Act). Three different operative modes (automatic, intermediary and manual) were implemented in the system, each corresponding to different levels of function allocation [2],[7], thus covering the spectrum of autonomy configurations [3].

### 7.5.2 Human Factors

During our experimentation campaigns, we assessed the impact of our new designs and the underlying concepts on operators’ performance and workload.

Operators played the scenarios several times with the “authority sharing” engine activated or not. This allowed us to observe and evaluate the effects of letting the computer decide to whom (between the AVO and the automation) each task is allocated throughout the scenario.

The same factors (performance and workload) were assessed with the payload operators during the camera sharing phase: we studied how well the MALE operators performed their enemy-seeking task in two configurations: when fully controlling the tactical UAV’s camera or only viewing the video feedback (and thus giving instructions to the tactical PO).

### 7.6 UNMANNED SYSTEMS USED

As described above, the Unmanned Systems used were not real but only existing in a simulation environment. It can be noted though that the GCS environment was reproduced: each team (1 aerial vehicle operator and 1 payload operator) was alone in a shelter-like room. The Mission Planner was remotely giving audio instructions to the teams.

### 7.7 SUMMARY OF ANY NATO COMMUNICATIONS/COLLABORATIONS/ INTERACTIONS

When the NATO HFM-170 Meeting took place in Paris (September 2009), only a small part of the program has been communicated to its members. Indeed, the Phase 4 (experiments / HF evaluation) of the program hadn’t started yet.

	<i>Planning/Design</i>	<i>Execution</i>	<i>Analysis</i>
<i>Communication</i>			X
<i>Coordination</i>			
<i>Collaboration</i>			

### 7.8 SUMMARY OF TD RESULTS

1) A methodology based on Proud’s Level Of Autonomy (LOA) matrix and Boyd’s OODA loop has been used and tested, in order to derive a general framework where different levels of function allocation can be coupled with the 4 phases of Boyd’s loop (Observe, Orient, Decide, Act). Three operative modes corresponding to different levels of function allocation were then defined, implemented, tested and validated.

2) The Authority Sharing Tool does not vary significantly the overall performance whether it is activated or not, but the test panel size didn’t allow us to statistically confirm this data. However, to illustrate this result, the table below shows the performance measured during a communication breakdown (workload increased).

	Overall Performance		Workload Level	
	Average	Standard Deviation	Average	Standard Deviation
AS tool active	65,50	8,52	3,00	1,15
AS tool inactive	77,28	13,94	2,50	1,29

3) AVOs may control two UAVs at the same time when (a) the workload level is acceptable and (b) they are assisted by an “authority sharing” tool, but only if (i) the operators trust the tool’s choices and (ii) the choices help ensuring UAV’s safety.

4) POs are not able to perform two missions with two different payloads, although operators may increase their situation awareness level if these two payloads are used for one mission and target the same area. Regarding the transfer modes, POs always preferred to keep control over the payload while performing the target-seeking task.

**7.9 LESSONS LEARNED**

The most important lesson learned is related to the relationship that humans have with automata (the “authority sharing” engine) capable of allocating in real time their tasks, sometimes distributing them the machine. Indeed, its acceptance degree is directly related to the situation awareness held by the operators and their trust in the automation.

**7.10 STUDY CONSTRAINTS/LIMITATIONS**

The study was carried out on a simulation environment and not with real UAVs. However, the experimentation campaigns involved several UAV-related military personnel. Results have to be confirmed statistically from an extended test panel.

**7.11 CONCLUSIONS**

The operators appreciated the HMIs designed during the program, in particular the “draggable vector tool” (it allows the operator to easily reroute the UAV in a drag-and-drop motion). Regarding the “authority sharing” engine, the overall performance does not change with or without the activation of the engine, but the test panel was too small to statistically confirm this data.

**7.12 FUTURE RESEARCH NEEDS AND PLANS IN THIS AREA**

Future research in the area should emphasize the following points:

- Managing the transitions between operating modes and related man-machine configurations so that the operators would not be handling too important gaps in subsequent configurations of the system; and
- Extend the human factors analysis, both in quantitative and qualitative way, through respectively an extended panel that will guarantee a better statistical reliability, and a focus on the instrumentation of

operators’ states (stress, fatigue, focus of attention) so that the understanding and tuning of the different operating modes could be more adequate.

### **7.13 ACKNOWLEDGEMENTS**

PEA FH/PA was supported by French MOD (DGA/UM-NBC 2006.94.0907).

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## **Chapter 8 – GER-1: COGNITIVE AND COOPERATIVE ASSISTANT SYSTEM FOR AERIAL MANNED-UNMANNED TEAMING MISSIONS**

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### **8.1 DATES**

20-24 September 2010.

### **8.2 LOCATION**

University of the German Armed Forces, Neubiberg, Germany.

### **8.3 SCENARIO/TASKS**

In future military helicopter missions a critical function is to get real-time surveillance and reconnaissance from several locations or targets at the same time without exposing humans to possible threats. Therefore, the deployment of multiple UAVs as remote sensor platforms in a Manned-Unmanned Teaming (MUM-T) scenario is investigated. The guidance of these will be realised by the commander aboard the mission leading helicopter, so the UAVs may be deployed flexibly and directly from where the surveillance and reconnaissance results are needed. This incorporates an operator to vehicle ratio smaller than one. Since the commander already works on many other tasks like mission management, system management, communication or supporting the pilot, the addition of the UAV guidance and mission management tasks will be very demanding for him/her, especially in situations when the environment requires the mission to be re-planned. On the other hand, when missions last a long time without need for action, the operator can become inattentive. These conditions may result in reduced performance or even accidents. Studies of accidents with ground-based UAV guidance attest that causes are not only technical malfunctions but also human error [1]. Furthermore, UAV guidance experiments at the Institute of Flight Systems show that operators produce errors which reduce mission performance [2]. These errors result from typical reasons like unbalanced workload conditions, interface handling problems, reduced situation awareness, degraded operator attention, vigilance decrements or complacency.

Therefore, the main objective is to reduce the workload of the helicopter commander to ensure mission success. The approach includes shifting UAV guidance from the typical waypoint-based level to a more abstract task-based level to reduce the workload of the operator and avoid overtaxing due to the multitude of various detailed system management and scheduling tasks [3],[4]. This is realised by an artificial cognition-based agent aboard each UAV, which understands the operator-given tasks and generates tactical sense making behaviours. Therefore, the commander provides single or a series of high-level tasks to each UAV via a graphical user interface based on a moving-map display. Ref. [5] describes this concept and the

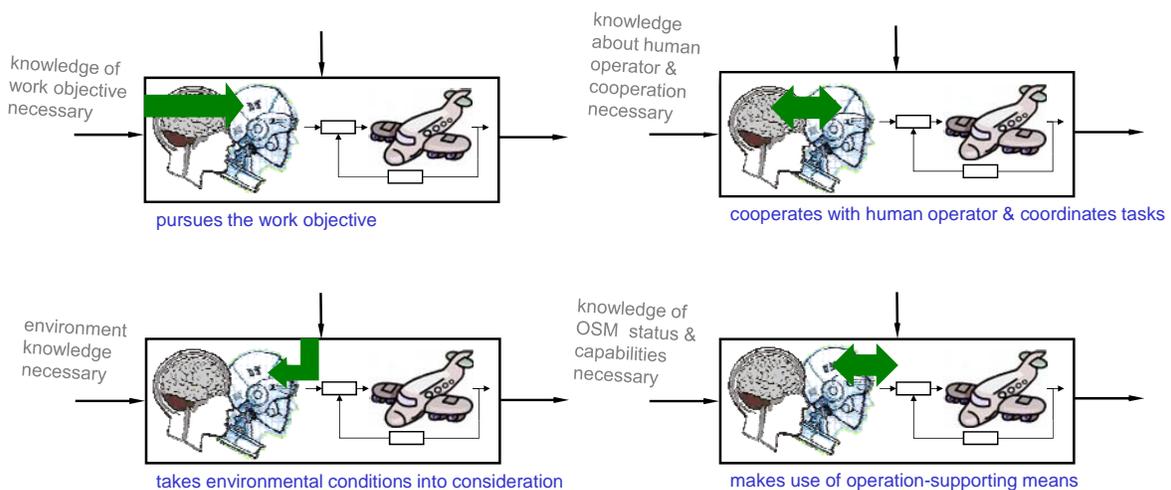
experimental findings in some more detail. Furthermore, an adapted crew coordination concept is defined, which shifts some system management and communication tasks to the pilot flying. An assistant system for the pilot flying helps him/her to adopt the new tasks and also takes over the support of the pilot flying, which further reduces the workload of the commander. Finally, an assistant system for the commander shall be developed, which helps him/her in unbalanced workload conditions, improves situation awareness and attention [2],[6],[7] and eventually improves mission performance. The concept and evaluation of the commander assistant system will be presented in this article.

## 8.4 TECHNOLOGIES EXPLORED

Research on pilot assistant systems has been conducted at the Institute of Flight Systems since the early 1990s. Several prototypes (cf. CASSY, e.g., [8]; CAMA, e.g., [9]) have also been successfully tested in real flight. From this experience, Onken and Schulte describe the general approach to assistant systems in a broader context [10], which may in turn be applied to the multi-UAV guidance domain.

### 8.4.1 Work Process Analysis-Based Requirements for Assistant Systems

The general approach by Onken and Schulte describes assistant systems from a more abstract, work process oriented point of view. Figure 8-1 shows the structure of the physical entities performing a work process in a work system.



**Figure 8-1: The Assistant System as Part of the Work System.**

The work system is defined by the work objective (arrow from the left), which should be accomplished by the work process, thereby, providing a result (arrow to the right). The work system itself consists of the Operating Force (OF, left in figure), which always incorporates a human. In Figure 8-1 the OF is extended by the assistant system (robot head). To fulfil the work objective the OF applies Operation Supporting Means (OSM, right in figure), e.g., automation or in our case UAVs and a manned helicopter. Constraining factors to the work process are the environmental conditions (arrow from top). On this level the interaction between the OF and the OSMs can be described with the supervisory control paradigm [11]. Onken and Schulte [10] characterise some properties of the assistant system resulting from its integration into the work system,

e.g., the assistant system shall also pursue the work objective. These properties were refined to form a set of four properties as depicted below each work system in Figure 8-1. To fulfil them, the assistant system needs to have knowledge in four different areas (bold arrows), i.e., the *work objective*, the *environment*, the cooperation with the *human operator* and the *OSM*. Knowledge about the *OSM* can be further divided into knowledge about the *current state* and about *how to apply* them. Also, operator knowledge is split up into knowledge about the current *operator state* and about *interaction with the human operator*.

### 8.5 HUMAN FACTORS EXPLORED

Onken and Schulte [10] also characterise the mentioned cooperation between human operator and assistant system by the postulating basic behaviour requirements for assistant systems:

“Requirement 1:

The assistant system has to be able to present the full picture of the work situation from its own perspective and has to do its best by own initiatives to ensure that the attention of the assisted human operator(s) is placed with priority on the objectively most urgent task or sub-task.

Requirement 2:

If according to requirement 1 the assistant system can securely identify as part of the situation interpretation that the human operator(s) cannot carry out the objectively most urgent task because of overtaxing, then the assistant system has to do its best by own initiatives to automatically transfer this situation into another one which can be handled normally by the assisted human operator(s).

Requirement 3:

If there are cognitive tasks, the human operator(s) is(are) principally not capable to accomplish, or which are of too high risk or likely a cause of too high costs, these tasks are to be allocated to the assistant system or operation supporting means, possibly a supporting cognitive unit.”

Based on these requirements a more detailed concept for the assistant system’s intervention and cooperation with the operator will be derived in the next section. Afterwards, the corresponding types of intervention for the triggers will be defined, which are also derived by use of the requirements stated above.

#### 8.5.1 Intervention Triggers

Referring to the introduction, an assistant system intervention should be triggered to prevent human overload and eventually human error, which may lead to reduced performance or accidents. Therefore, the identification of error causes is the trigger for an assistant system intervention. Several models for human error causes and prevention have already been stated, e.g., by Reason [12],[13] or Hollnagel [14],[15]. The basic requirements stated above also describe error causes and means to prevent these from a point of view which is very close to a system design. Therefore, the basic requirements were used to derive the following three intervention triggers:

1) *Attention Deficit*

If according to the first requirement an assistant system should ensure attention to the most urgent task it has to intervene, if the operator does not pay attention to the most urgent task. This intervention is primarily meant to support the operator’s situation awareness [16].

2) *Overtaxing*

According to the second requirement an assistant system should intervene, if the operator is overtaxed in carrying out the most urgent task to balance the workload. From our point of view, overtaxing can

occur in every step of the human information process, which roughly consists of information acquisition and analysis, decision selection and action implementation (cf. Parasuraman, Sheridan and Wickens [17]). Since overtaxing as part of the information acquisition and analysis is already covered by the first intervention trigger, only overtaxing in the decision selection and action implementation process is used as an intervention trigger.

3) *Likely Inacceptable Costs*

Finally, according to the third requirement, an assistant system should become active, if the execution of a task by the operator would produce unacceptable costs. If he/she is not capable of accomplishing the task, this also means unacceptable task costs. This trigger is especially hard to detect because the system on the one hand has to decide upon the capabilities of the operator and on the other hand has to make a prediction about the future evolution of the situation.

### 8.5.2 Intervention Types

After identifying the triggers when an assistant system should intervene, knowledge about how it should act is necessary. Intervention types basically represent different levels of automation and interaction. Here, several studies and theories have been published. Rouse and Rouse distinguish three levels of automation, i.e., “manual”, “management-by-consent” and “management-by-exception” [17]. Another theory is Sheridan’s ten levels of automation in decision and action support [18]. Endsley [19] first defined five levels of automation ranging from manual control to full automation and later refined them to ten levels of automation [20]. Onken and Schulte [10] also distinguish three different styles of cooperative assistance, i.e.,:

- **Alerting** – The assistant detects inadequate human behaviour and draws the attention of the human towards the corresponding task, if the human does not have situation awareness about this fact. It may give advice.
- **Associative** – The assistant continuously presents proposals but does not actively draw the attention of the operator. The operator can task the assistant to automatically carry out the corresponding task.
- **Substituting** – The assistant can either temporarily or permanently take over commitments of the human. Temporarily substituting assistance may be authorised by the human or intervene without waiting to be authorised. Permanently substituting assistance can be authorised in the beginning or built in by design.

Considering an attention deficit as an intervention trigger, assistance in situation awareness is needed. Here, alerting assistance was selected as an intervention type to interact with the operator. By guiding the attention, situation awareness about the most urgent task is transmitted to the operator. Inadequate behaviour not only incorporates the detection of necessary action in a certain task but also the conclusion that the action is urgent and more important than other tasks. Additionally to alerting assistance the system shall not only draw the attention towards the task but also improve situation awareness by telling the operator about the reason for the need for action. Advices in terms of decision aids should not be given directly but on request. When overtaxing is the reason for an intervention, the workload of the operator needs to be reduced by simplifying the task. Here, the intervention type associative assistance has been selected. The presentation of proposals shall reduce overload in decision selection, but in contrast to associative assistance these should not be given continuously but only in case of overtaxing. The automated execution of the task on request is also suitable for reducing overload in action implementation. Additionally to associative assistance, the assistant system should configure the user-interface for execution of the task to reduce overtaxing in action implementation through interface handling problems. Inacceptable task costs can only be avoided if the assistant carries out the task itself or passes it to an OSM. This intervention type is close to temporarily substituting assistance, which

intervenes without waiting to be authorised. Here, cooperation is still necessary in terms of letting the operator know, what the assistant system did. If this is not the case, situation awareness problems on the part of the operator could occur. Summing up, three different intervention types were defined corresponding to the three intervention triggers: *attention guidance*, *task simplification* and *task reallocation*.

### 8.5.3 Prioritisation

The defined triggers and corresponding types of intervention now form three different assistant functions derived from the three basic requirements. Since there can be several assistance needs at a time, the additional workload posed on the human operator by several interventions at once may overtax him/her. Therefore, the operator is supposed to handle only one intervention concurrently, which means that the different functions must be prioritized.

First a prioritisation is defined in case the same function is triggered multiple times at once. If the operator's attention should be guided towards several urgent tasks, not only the urgency but also the importance of tasks is considered by the assistant. Within the same task (e.g., the operator has to define the next mission task for UAV1 and UAV2 concurrently) the urgency is taken as a basis for deciding upon the higher priority. In contrast to this, between tasks of different types the task the output of which can have/has an effect on the other task's input is prioritized higher. Tasks with a lower priority will be processed afterwards. If the operator is working on several (not urgent) tasks in parallel and is overtaxed, only the task which the operator is really currently working on shall be assisted. Task reallocation however can always be executed directly, since the operator is not actively involved. Yet, the information dialog about the intervention needs to be queued, if the assistant already conducts other dialogs with the operator.

The following prioritisation was defined between the different assistant functions:

- 1) Task reallocation;
- 2) Attention guidance; and
- 3) Task simplification.

Since task reallocation can and also needs to be executed directly because of the criticality for the mission and for safety, this function has the highest priority. Finally, the second requirement states that the assistant system shall only trigger a task simplification, if the operator already works on the most urgent task. Therefore, attention guidance to the most urgent task has a higher priority than task simplification.

### 8.5.4 Operator Interactions

Only the assistant system takes the initiative for an intervention and starts dialogs with the operator. However, the operator has different possibilities to react upon the interventions by interacting either with the operation supporting means or the assistant system. In case of an attention guidance the operator has the following three reaction possibilities:

- 1) The operator accepts the advice and *switches to the respective task*. The assistant system recognizes the respective task as the current operator task and the dialog disappears. In the end the task should be accomplished. Otherwise the advice reappears.
- 2) The operator *requests support* in the task from the assistant. The assistant system switches to the task simplification intervention type and offers decision and action support.

- 3) The operator does not accept the advice and *ignores the dialog*. Here, he/she needs to tell the assistant to ignore the need for action, which is also remembered by the assistant.

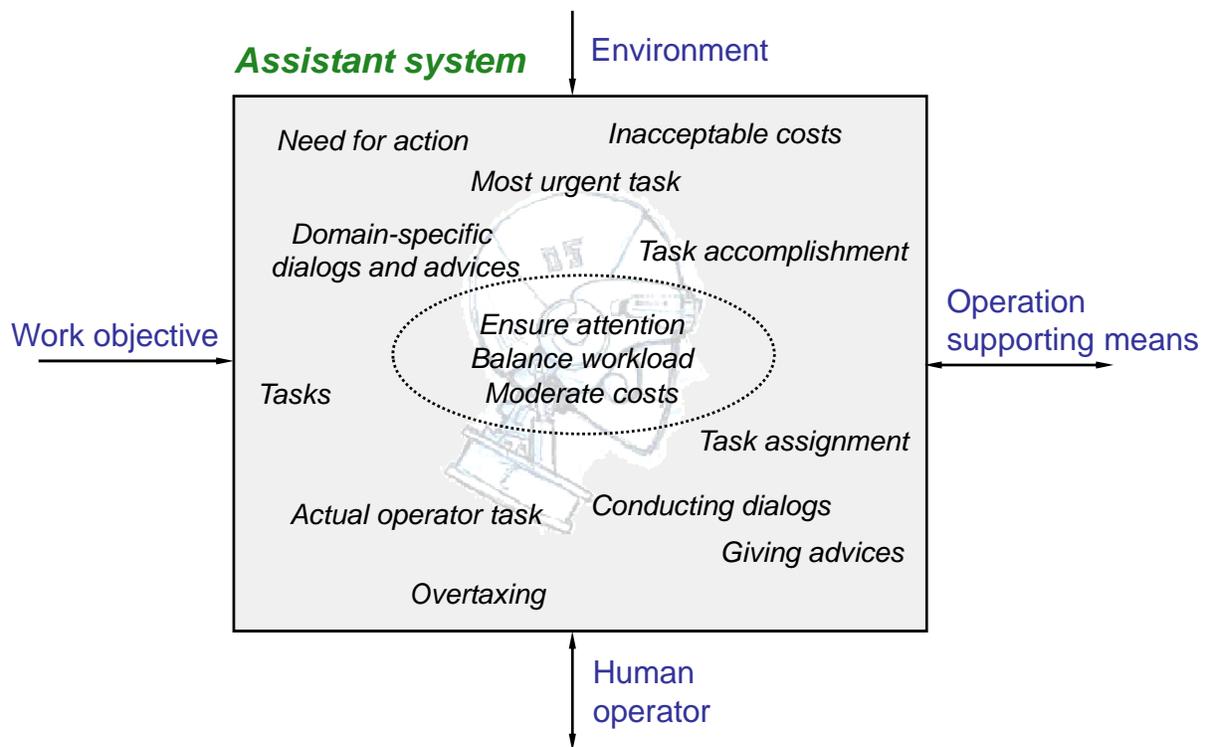
In case of a task simplification intervention the operator has similar options:

- 1) The operator *accomplishes the task* and the dialog disappears. Here, it is not relevant whether the proposed solution or a different one is executed. Only the result that the task is accomplished is important.
- 2) The operator *requests automated execution* of the task from the assistant. The assistant system switches to task reallocation intervention type.
- 3) The operator does not want to work on the task anymore and *ignores the dialog*. As soon as the operator switches to a different task, the dialog disappears. Again the reaction is remembered by the assistant.

In case of a task reallocation intervention no further interaction of the operator is possible. The assistant only sends a dialog to the operator telling which actions were performed. However, the operator can interact with the assistant in advance to prohibit task reallocation for certain tasks.

### 8.5.5 Specific Assistant Knowledge

According to the defined concept Figure 8-2 shows the specific knowledge needed by an assistant system and relates it to the knowledge areas.



**Figure 8-2: Specific Knowledge of the Assistant System as Part of the Work System.**

First of all to ensure operator attention the assistant needs to know the currently *most urgent task*. For knowledge of the most urgent task it has to know which tasks have a *need for action*. After that it can determine the urgent matters and the most urgent one. For this it is also necessary to know, which *tasks* have to be generally worked on as part of the work process. This knowledge can be derived from the *work objective* and the available *OSMs*. Since the system shall only assist tasks, which are assigned to the operator and not to the automation, knowledge is required about the current *task assignment* between human and automation. After recognizing the most urgent task, the assistant needs to know, if the operator's attention is placed on this task, that means it needs to know the *actual operator task*. For balancing the workload, it is essential to detect *overtaxing* of the operator. To be able to offer appropriate help, it also needs knowledge about the actual operator task, which causes the *overtaxing*. Finally, to keep the costs on a moderate level, the assistant system should recognize if there are tasks which likely produce *inacceptable costs*, if they stay assigned to the operator. Of course this knowledge is always connected with a distinct uncertainty since on the one hand the system predicts operator behaviour and on the other hand it defines an arbitrary cost limit above which it intervenes. If the assistant system decides that an intervention is necessary, it has to know how to *conduct a dialog* with the operator and how to *give hints* on the user-interface to present the situation. Moreover it needs *domain-specific* knowledge about which *dialogs and advices* are useful for the operator. Finally, to reallocate a task the system needs to know which commands have to be sent to the *OSMs* to *accomplish tasks*.

The derived knowledge shown in Figure 8-2 is still quite unstructured. Therefore, the next section will introduce a knowledge-based implementation technology also proposed in [10], which allows a more structured modelling of the knowledge which is also closer to an implementation.

### 8.5.6 Cognitive Modelling

The assistant system for the UAV operator is implemented as an Artificial Cognitive Unit (ACU) to realize goal-driven behaviour. For this, the "Cognitive Process" (CP) by Putzer was used, which implements the knowledge-based level of the human performance model stated by Rasmussen [21]. The CP has been developed as a model of human information processing, which is suitable for generating human like rational behaviour [22] in technical systems. The behaviour is completely defined by explicitly represented knowledge, which is split up into goals the ACU shall fulfil [1], action alternatives it can choose from, schedules to implement them and environment models to build up a situational understanding. The CP was implemented with the Cognitive System Architecture (COSA), described in detail in [10].

In this section the specified knowledge for an assistant system is structured according to the cognitive process (cf. Figure 8-3). The aim is to derive specific knowledge classes for a cognitive implementation of an application independent knowledge package "Assistance".

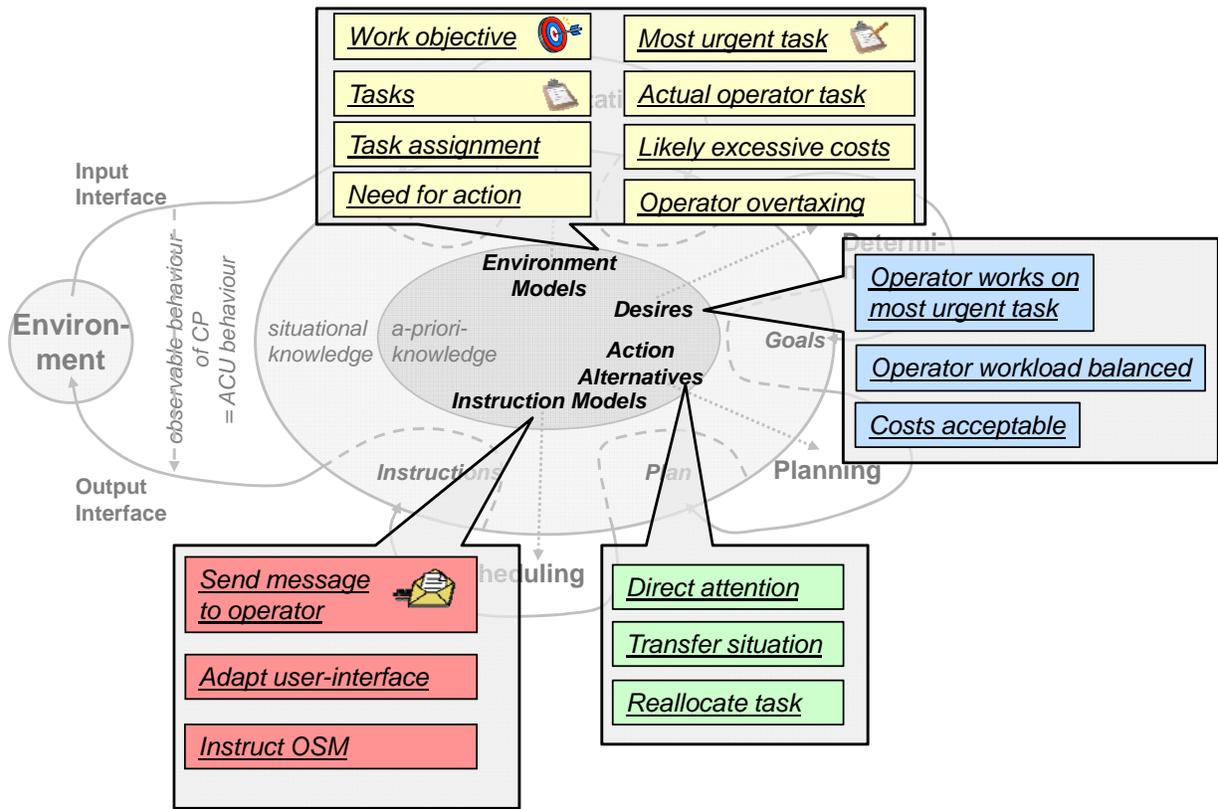


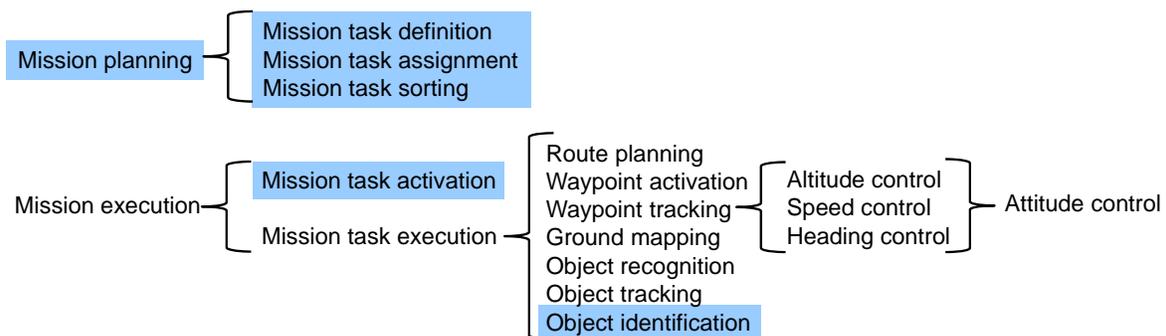
Figure 8-3: Application-Independent Knowledge Package “Assistance”.

The application of the different knowledge classes to an assistant system should start with a definition of the DESIRES to be achieved [22]. A desire is a state of the work process that shall be achieved. If the state is different, the desire becomes an active goal. In our case the intervention triggers describe states, where the state is not satisfying for the assistant. Therefore, the goal of the assistant is to achieve the opposite state, i.e., *the operator works on the most urgent task, the operator’s workload is balanced and the costs are acceptable*. The next step in deriving knowledge classes is to figure out, which abstract ACTION ALTERNATIVES could be applied to fulfil the desires. These alternatives correspond to the intervention types specified earlier. Therefore, if the operator is not working on the most urgent task, the assistant system should *direct the attention* of the operator. In case the operator workload is unbalanced, the assistant system *simplifies the task* by offering partial automation to the operator. If the task costs would become unacceptable, the assistant shall *reallocate the task*. To execute the action alternatives, INSTRUCTION MODELS are used, which describe the technical output of the system. According to the knowledge areas illustrated above, the output can be either to the operator or the OSM. Outputs to the operator may be to start a dialog by *sending a message* or *adapting the user-interface* to give additional hints or to configure the display. Outputs to the OSM would result in *sending instructions to the OSM* to execute tasks. To understand the situation, be able to check, if the above mentioned desires are met and also to send appropriate messages and instructions, an assistant system needs ENVIRONMENT MODELS. In this case they correspond to the specific knowledge stated above (e.g., work objective, tasks, task assignment, actual operator task, need for action). For a complete knowledge-based modelling also rules are necessary, which instantiate these knowledge classes and change their attributes. The desire “operator works in most urgent task” is instantiated, if there is an instance of a “most urgent task” but no instance of an “actual operator task” which links to the same task. The action alternatives are instantiated

according to the prioritisation defined above and activate the corresponding instruction models. The environment models in this package are actually abstract classes, which are inherited by domain-specific classes in a separate knowledge package “Mission”. For example in a troop transport mission there is an instantiation of a “work objective” class, which contains that the troops have to be at a certain position at the end of the mission. The “Mission” package also contains instruction models, e.g., a message for guiding the attention of the operator towards the identification of a certain object or commands to the UAVs for adding or deleting mission tasks.

### 8.5.7 MUM-T Specific Assistant Functions

The assistant functions are defined on the one hand by the different intervention types in the application-independent knowledge package and on the other hand by the application-specific tasks in the “Mission” package, which shall be supported. Therefore, a task analysis for the commander in a manned-unmanned teaming domain was performed. Tasks in the area of communication and system management were not considered because in the crew coordination concept these tasks were intentionally shifted to the pilot flying by experimental design. Results are shown in Figure 8-4.



**Figure 8-4: Task Analysis for the Helicopter Commander in a Manned-Unmanned Teaming Domain.**

On top level tasks can be divided into mission planning and mission execution. Mission planning consists of defining mission tasks (e.g. departure, transit, route/area reconnaissance or surveillance), assigning them to either a manned helicopter or a UAV and sorting them into the agent’s agenda. To execute mission tasks, they have to be activated first. Most of the time activation is done in the order given by the agenda. Mission task execution for the manned helicopters mainly consists of flight management tasks like route planning, waypoint activation and waypoint tracking. Since the UAVs have cameras as a payload, ground mapping, object recognition, tracking and identification also needs to be done for reconnaissance tasks. Since the helicopter is controlled by the pilot and the UAVs are guided on a task-based level [3], only the highlighted tasks have to be performed by the commander/UAV-operator. These tasks are also supported by the assistant system. According to the intervention types (attention guidance, task simplification, and task reallocation) each task can be assisted in three different ways. The only exception is the object identification task, where a task reallocation in terms of an automated identification seems hardly feasible with the current state of the art.

## 8.6 UNMANNED SYSTEM USED

The UAVs used in the simulation are generic vehicles with a flight performance close to the manned platform, so they are able to fly in a common mission in loose formation.

**8.7 SUMMARY OF ANY NATO COMMUNICATIONS/COLLABORATIONS/  
INTERACTIONS**

The MUM-T focus is on specific requirements of the German Armed Forces. Still, it is of great interest to discuss the system concept, experimental design and results with NATO partners.

	<i>Planning/Design</i>	<i>Execution</i>	<i>Analysis</i>
<i>Communication</i>	X	X	X
<i>Coordination</i>			
<i>Collaboration</i>	X		

**8.8 SUMMARY OF TD RESULTS**

In May 2011, during an experimental campaign for the MUM-T research at the UBM the benefit and cooperation aspects of the described assistant system were evaluated. One of the experimental missions used in this campaign was also shown as a tech demo for the NATO-HFM group in September 2010.

**8.8.1 Experimental Setup**

The primary objective for the test persons was to successfully complete a helicopter troop transport mission into hostile territory. To achieve this, they had additional three UAVs, which were guided on a task-based level. The UAVs implemented capabilities like route/area reconnaissance and surveillance in order to secure the routes/landing sites/objective for the helicopter and the troops. Each mission started at a main operation base in friendly territory. Here, the commander was mainly busy entering a mission plan for the helicopter and the UAVs. After activating the take-off and passing the corridor into insecure territory the UAVs started with the reconnaissance and the commander had to observe the progress and identify objects preselected by the UAVs. During the mission also three events for a major mission re-planning occurred: identification of hostile troops at the primary drop zone, detection of a SAM-site at the primary egress corridor and a follow-up troop transport mission after completion of the first troop transport. The experimental run was finally stopped after 30 to 45 minutes when the helicopter returned to friendly territory.

Each test person had to complete one mission with and one mission without support by the assistant system. To prevent expectations about the mission development, missions differed concerning the mission area and the threat configurations.

Eight German Army helicopter pilots participated as test persons at an average age of 37 years (min 28 years, max 51 years). Their flying experience ranged from 830h up to 5100h with an average of 1815h. The test persons were grouped into fixed crews consisting of two members (alternating in the roles of commander and pilot flying). Each test person had two days of training for the commander’s workstation. The training began with an instructed phase and continued with a free training phase. Furthermore subjects had the possibility to observe other subjects in their training (passive training).

The experiments took place in the helicopter simulator of the UBM, which was refined to support a manned-unmanned-teaming mission including UAV-guidance from the commander's seat. This workstation provides two displays with various formats especially for UAV tasking and object identification as well as one control and display unit (in this case) especially for entering mission goals and constraints and activating automated helicopter mission planning. The commander was equipped with a headset for communication within the cockpit, with other external entities (e.g., tower, AWACS) and with the assistant system.

During each mission, the simulation was paused three times in order to measure the crew's workload (with NASA TLX [23]) and the situation awareness (with SAGAT [24]). The first pause was made while the helicopter was still in friendly territory, the second in hostile territory outside the operation area (only NASA-TLX) and the third inside the operation area. Video and audio recordings were taken and all relevant simulation data was logged, which included the system interactions of the commander and the pilot flying. After the experimental runs the test persons were interviewed about acceptance of the assistant functions and possible impacts on situation awareness and workload.

The measured data shall prove that the employment of the assistant system can increase mission performance, reduce workload and increase situation awareness of the commander. Also the interventions should be considered reasonable and be well accepted by the test persons.

### 8.8.2 Experimental Results

First of all, mission performance, which is dependent from both the commander, the pilot and from the corresponding assistance configuration, is presented. Afterwards, the individual situation awareness and subjective workload are examined. Finally, the objective individual behavior of the commander and subjective ratings of the assistant system functions by the test persons are presented.

**Performance** – Mission planning for the UAVs and the helicopter as well as punctual activation of UAV mission tasks had an effect on performance. If the commander did not receive the helicopter route with the UAVs in time, the helicopter either had to wait until the route was received or fly across insecure territory. To measure the performance impacts in case the helicopter waited, mission delays were assessed by generating a standard solution for each mission offline and comparing it to the measured mission durations. Then the frequency of mission delay in segments of 2.5 minutes each was counted.

Here, in the unassisted configuration, excessive mission delays, which exceeded 7.5 minutes, occurred in four cases, whilst this could be observed only once in the assisted configuration (cf. Table 8-1). Furthermore, the duration was measured in which the helicopter had a geographical position (2D) that had not been photographed by a UAV before. In the configuration without assistant system, this exposure time was three times higher ( $t(14) = 1.74, p = 0.1$ ).

**Table 8-1: Comparison of Mission Delay for the Helicopter.**

Delay	Unassisted	Assisted
$d < 2.5 \text{ min.}$	3	3
$2.5 \text{ min.} \leq d < 5.0 \text{ min.}$	1	2
$5.0 \text{ min.} \leq d < 7.5 \text{ min.}$	0	2
$7.5 \text{ min.} \leq d$	4	1
Overall	8	8

Finally, performance of the commander in the object identification task was measured. Throughout all sixteen experimental missions 113 objects were located by the UAVs’ ATR functionality and had to be identified consequently (53 without / 60 with commander assistant system). Identification correctness was equally good (only one error in each configuration) but not analyzed because it was not supported by the assistant system. Instead a closer look was taken into critical events, where the helicopter came close to the unidentified object (15 without / 10 with assistant system) and fast task completion times were important. In the assisted configuration the assistant system guided the attention of the commander towards the object identification task and additionally offered task simplification in terms of display configuration. Attention guidance reduced mean duration from ATR recognition until the commander started the object identification from 46.8 seconds unassisted to 18.2 seconds assisted, which shows weak significance ( $t(23) = 1.79, p = 0.087$ ). The automated display configuration, which was used five times reduced the mean time for object identification itself from 17.3 seconds to 7.5 seconds, but no significant effects could be verified ( $t(21) = 0.771, p = 0.45$ ). The overall time from ATR recognition to task completion of the identification was reduced from 66.1 seconds unassisted to 27.7 seconds assisted, which also shows weak significance ( $t(21) = 1.96, p = 0.063$ ).

**Situation Awareness** – Situation awareness was measured objectively using the SAGAT [24] method. During the simulation pauses, subjects had to estimate positions of own and hostile forces in an electronic map display. Civil forces were not counted, since subjects very often considered them not relevant and omitted them intentionally. The estimated positions were compared to the true positions at this time. Each object was awarded with two points if distance between specified and actual position was less than 0.75 nm, with one point if distance was less than 1.5 nm, and no points if distance was larger or the object was missing. In the unassisted configuration 108 out of 154 points were gained (70.1%), while in the assisted configuration 105 were gained (68.2%), which shows nearly no difference.

Moreover, subjects were interviewed about the current situation (threats, reconnaissance status, next communication task, current and subsequent tasks of UAVs and helicopter). Correct and nearly correct answers were awarded with two points, still acceptable answers with one point, and wrong or missing answers with no points. Again, for every test, the points were summed up and divided by the maximum number of points to receive a percentage. In the interview the subjects gained significantly better results in the assisted (95.4%) than in the unassisted configuration (90.0%) ( $t(14) = 2.49, p = 0.026$ ). It is also worth mentioning that the test results were showing very high absolute values in both configurations.

**Subjective Workload** – Subjective workload was measured using the NASA-TLX [23] subjective workload assessment tool, which divides workload into the following six categories: Mental Demand (MD), Physical Demand (PD), Temporal Demand (TD), Performance (P), Effort (E) and Frustration (F).

Workload across all phases and subjects shows a non-significant decrease in mean from 42.3% (unassisted) to 38.8% (assisted) ( $t(43) = 0.714, p = 0.48$ ). The NASA-TLX scores did not produce significant results, because the individual utilization of the scale varies more than the differences between the system configurations. However, the main difference between these two values was caused by a significant decrease in temporal demand from 13.7% (unassisted) to 8.3% (assisted) ( $t(43) = 2.28, p = 0.027$ ). Changes in other workload dimensions range only from 0.3 – 1.6 % and are not significant.

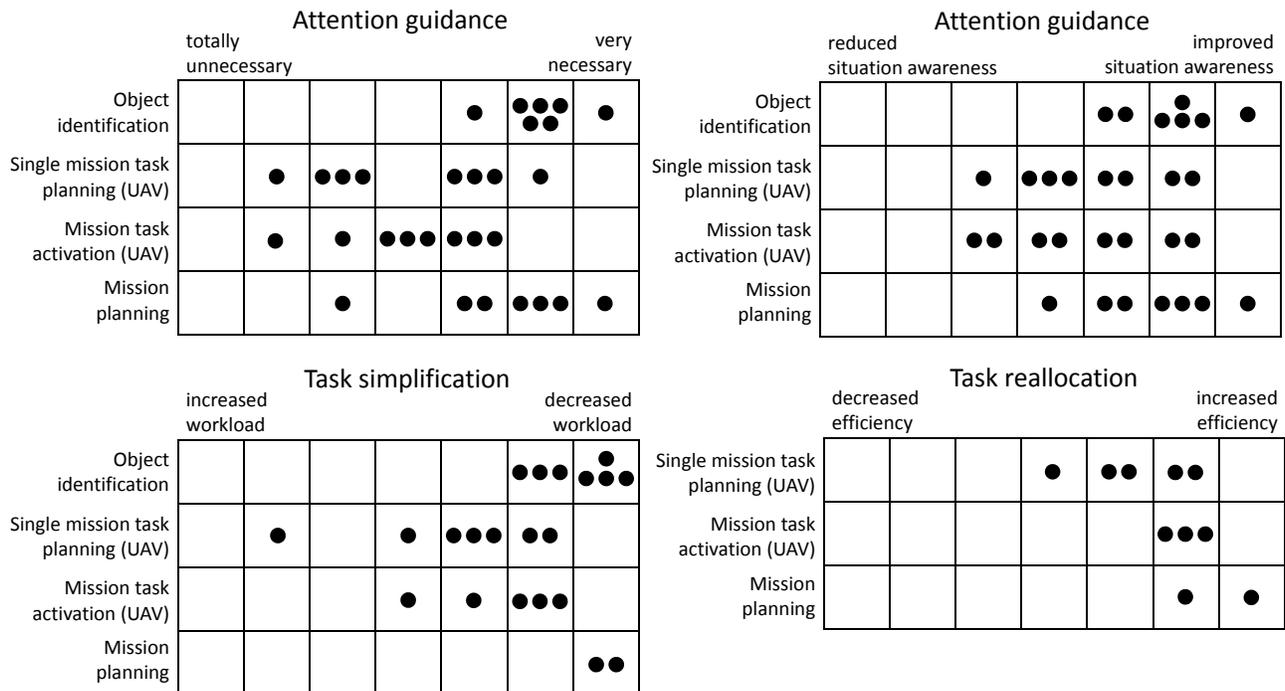
**Behavior** – The commander’s interaction with the assistant system was evaluated by video analysis of the assistant system interventions (system- or user-initiated) and the corresponding commander’s reactions. User-initiated attention guidance was not possible by design. Also, not in every task knowledge for system-initiated task simplification or task reallocation was implemented (cf. Table 8-2).

**Table 8-2: Assistant Interventions and Commander’s Reactions.**

	Object Identification		Single Mission Task Planning (UAV)		Mission Task Activation (UAV)		Mission Planning		Overall		
	System	User	S	U	S	U	S	U	S	U	Overall
<b>Attention Guidance</b>	<b>12</b>		<b>20</b>		<b>15</b>		<b>27</b>		<b>74</b>		<b>74</b>
<i>Accepted</i>	12		11		11		21		55		55
<i>Not Accepted</i>	0		9		4		6		19		19
<b>Task Simplification</b>		<b>5</b>	<b>12</b>	<b>6</b>	<b>0</b>	<b>4</b>		<b>2</b>	<b>12</b>	<b>17</b>	<b>29</b>
<i>Accepted</i>		5	8	3		4		2	8	14	22
<i>Not Accepted</i>		0	4	3		0		0	4	3	7
<b>Task Reallocation</b>				<b>8</b>	<b>5</b>	<b>4</b>		<b>2</b>	<b>5</b>	<b>14</b>	<b>19</b>
									91	31	122

Across all experimental runs 74 times the assistant system intervened with attention guidance. 55 times the commander complied with the advice by switching to the respective task. In the remaining cases subjects did not work on the respective task directly after the advice. Thus according to the test persons, in about 75% of the cases attention guidance was correct. Task simplification was evaluated by analyzing, if the subjects used the decision selection and action implementation support offered by the assistant. Since the assistant could not offer a solution for object identification, here, only the configuration of the user-interface to prevent interface-handling problems was evaluated. 22 out of 29 times (about 75%) task simplification was used by the subjects. Only single mission task planning proposals were not accepted several times, but still more than 60% (11 out of 18) of the proposals were accepted either by requesting automated task reallocation or manually inserting the mission task into the UAV’s agenda. System-initiated task reallocation was only implemented for a safety critical situation, when a UAV came close to a threat and therefore was stopped by the assistant. Here, the commander could not react, but the intervention could be regarded as correct, since no UAVs came under fire in the assisted configuration compared to five times without the assistant. Also, in the interviews all test persons stated that the intervention was necessary.

**Ratings** – In the following, the most important results of the questionnaires, which were given to the test persons during the corresponding mission debriefings, are presented (cf. Figure 8-5).



**Figure 8-5: Rating of Different Intervention Types Across the Corresponding Commander Tasks.**

Most of the test persons accepted the attention guidance for object identification and mission re-planning as necessary and stated that it improved their situation awareness. Attention guidance for activation and planning of single UAV-tasks produced more or less indifferent results. This was because test persons sometimes wanted to employ the UAVs differently from the assistant which led to the understanding that the attention guidance was too early and not necessary. According to the subjects' statements, the task simplification in terms of automated display configuration for the object identification task reduced workload. Task simplification for activation and planning of single UAV-tasks were also found to reduce operator workload slightly. For task simplification in mission re-planning, which was not used very frequently, the subjects attested a strong relief in workload. Task reallocation was also not used by all test persons, but was rated to increase efficiency.

## 8.9 LESSONS LEARNED

An interesting finding was that test persons followed different strategies in mission planning. For example some test persons wanted the UAVs to secure the operation area and wait there until the helicopter arrive, while others sent them directly back to recce the route to the main operation base. Also some test persons reced alternate routes whilst others focused on reconnaissance of the main route. This made it difficult for the assistant to propose mission plans which were in accordance with the individual test person's view. So, test person's strategies are highly individual, which might be the consequence of too little training on the particular job or too little developed procedures, since multi-UAV guidance from the cockpit is a novel task to German Army helicopter pilots.

Another surprising point was that although tasks were strictly divided upon commander and pilot flying in terms of a crew coordination concept, task assignments were shifted. The commander even acted as an

assistant for the pilot flying upon pilot errors although this should not have been necessary because the pilot was also supported by another assistant system. Since the commander assistant system did not have knowledge about these tasks it did not have the full situational picture and in one case triggered attention guidance to a currently less urgent object identification task.

## **8.10 STUDY CONSTRAINTS/LIMITATIONS**

The results are based on a simulated environment and not a real-world campaign. Therefore some aspects like e.g., data link losses were not regarded. Since there was only the possibility to simulate one manned aircraft, only intercom between pilot flying and commander and radio communication to airport towers or the mission leader was simulated. Radio communication to other aircraft was missing. This caused reduced workload for the helicopter crew / UAV-operator.

## **8.11 CONCLUSIONS**

A generic approach for the development of a knowledge-based assistant system was presented. The approach was adapted to the domain of manned-unmanned-teaming, i.e., guidance of multiple UAVs from the commander's workplace in a helicopter cockpit aided by an assistant system. The approach was evaluated by conducting experiments in the helicopter simulator of the UBM. The introduction of the assistant system improves human factors related variables like situation awareness and workload, improves performance and safety and is well accepted.

## **8.12 FUTURE RESEARCH NEEDS AND PLANS IN THIS AREA**

The next steps to further improve the assistant system performance and acceptance should be to refine the knowledge models for operator overtaxing estimation, current task recognition and cost prediction. In addition the action and decision support for tasks, which include several steps should be refined. Finally, the cooperation and variable task assignment between commander and pilot flying have to be investigated closer and be regarded within the concept.

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## **Chapter 9 – NL-1: REMOTE AUDITORY TARGET DETECTION USING AN UNMANNED VEHICLE – COMPARISON BETWEEN A TELEPRESENCE HEADTRACKING 3D AUDIO SETUP AND A JOYSTICK-CONTROLLED SYSTEM WITH A DIRECTIONAL MICROPHONE**

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### **9.1 DATES**

June 2010.

### **9.2 LOCATION**

The experiments/demonstrations were held at Fort Benning GA, USA.

### **9.3 SCENARIO/TASKS**

For soldiers, visual information is crucial in building up situation awareness. Not surprisingly, when robots are used for reconnaissance of a remote area, visual sensors are most important. Most robots are therefore equipped with visual sensors, but not with any other kind of sensor! This is surprising, because an approaching car (yet invisible because still around the corner), someone moving in an adjacent room, a slamming door, or the loading of a gun, are important events during reconnaissance which cues are primarily auditory. When such sounds occur, human beings almost instinctively direct their heads (eyes) to the sound source for visual inspection before deciding to hide, or to make contact, to get out very fast, to attack, etc. Even more so, human beings immediately know where to hide or where the safe exit is because of their excellent spatial situation awareness that results from the human-intrinsic integrated perception of visual, auditory, and proprioceptive information. We hypothesize that if such intrinsic integrated multi-modal perception would be facilitated in remote perception using robots (by having headtracking control for robot's sensor system that includes stereo vision and spatial 3D audio, a setup we refer to as Telepresence [1]), spatial situation awareness would boost performance in a robot reconnaissance mission. This hypothesis was investigated in the experiment reported here, which was conducted as part of a research collaboration between the US Army Research Lab, ft Benning, and TNO.

## 9.4 TECHNOLOGIES EXPLORED

### 9.4.1 Reconnaissance Environment

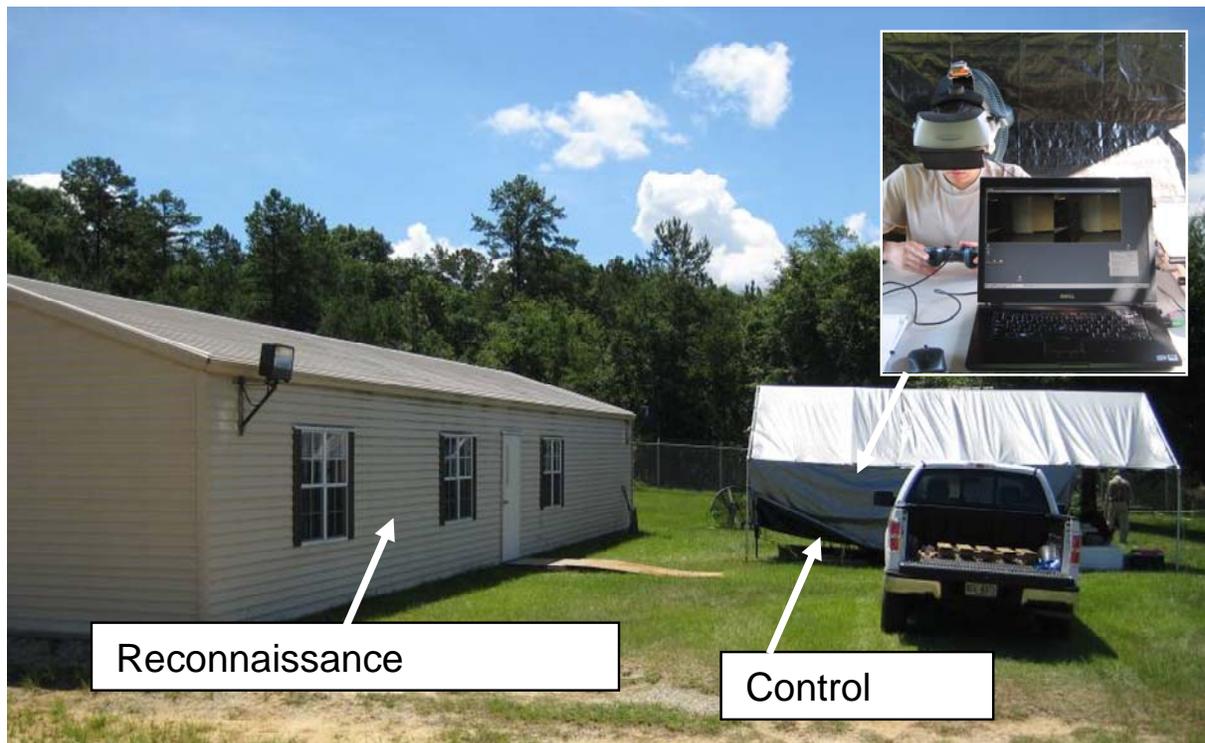
The reconnaissance environment consisted of a large room (about 60 m<sup>2</sup>) subdivided in several sections, and a smaller adjacent room (about 8 m<sup>2</sup>). Eleven possible target objects varying in size were positioned at different height levels in the reconnaissance environment:

- A) Soda can bomb on a table;
- B) Hand grenade on the ground;
- C) Soda can bomb on the ground;
- D) Hand grenade near the ceiling;
- E) Semtex on the ground;
- F) Bomb shell on a table;
- G) Pipe bomb on the ground;
- H) Semtex with timer on a chair;
- I) Mine on a water container;
- J) Land mine on a high cupboard shelf; and
- K) Land mine on a high cupboard shelf.

Objects B, D, E, G, H, J were used as targets; the others were used as decoy targets or practice targets.

### 9.4.2 Control Station

The control station was located in a tent next to the building of the reconnaissance environment (see Figure 9-1). The control station consisted of a user interface with a NVIS nVISOR Head-Mounted Display (either stereo or mono, depending on the experimental condition), an Xsens MTi motion sensor as a headtracker, stereo headphones, and a Logitech Dual Action game controller. Three human-robot interface setups of the control station were used in this experiment, as explained in the section below on Experimental Setup.



**Figure 9-1: Reconnaissance Area and Control Station.**

### 9.4.3 Unmanned System

The Unmanned Ground Vehicle (UGV) used was TNO's robot called 'Generaal'. This UGV is a fully manually controlled UGV, with a fast and powerful pan-tilt-roll sensor system that can accurately mimic human head movements enabling remote perception of the UGV environment.

## 9.5 HUMAN FACTORS ISSUES EXPLORED

Our main human factors research questions for the current experiment were:

- Does headtracking control lead to improved performance as compared to joystick control? (comparison between Mono Headtracking and Mono Joystick human-robot interfaces, see description below);
- Does a 3D audio system lead to improved performance as compared with a directional microphone? (comparison between Mono-Headtracking and Telepresence human-robot interfaces); and
- What would be the maximum performance benefit of telepresence functionality (with headtracking and stereo sensor information) as compared with the currently mostly used control systems with joystick control and mono sensor information? provided it exists? (comparison between Telepresence and Mono-Joystick human-robot interfaces).

For answering these questions we considered the quality of performance in locating and identifying objects in an indoor audio detection task, in three experimental conditions for the user interfaces:

- Mono-Joystick: Mono audio and video on Head Mounted Display, with joystick control for robot movements and heading of sensor system. Participants were asked (and reminded when needed) not to move their heads.
- Mono-Headtracking: Mono audio and video on Head Mounted Display, with joystick control for robot movements and headtracking for directing the sensor system.
- Telepresence: Stereo audio and video on Head Mounted Display, with joystick control for robot movements and headtracking for directing the sensor system. We refer to this configuration as Telepresence.

Each participant performed the sound detection task 18 times. Each of the six targets was used for each of three conditions. After each trial, the participant switched to one of the other two experimental conditions.

## **9.6 UNMANNED SYSTEMS USED**

The Unmanned Ground Vehicle (UGV) used was TNO's robot called 'Generaal'. This UGV has been used in prior studies in our lab [2]. It is a fully manually controlled UGV, with a fast and powerful pan-tilt-roll system that can accurately mimic human head movements. On top are two cameras for providing stereo vision at the control station, and two microphone arrays that can be positioned at either side for spatial 3D audio, or next to each other in front thereby functioning as a directional microphone. The horizontally positioned red-tipped pointer in front of the vehicle was the reference point for the participants in approaching the target as closely as possible.

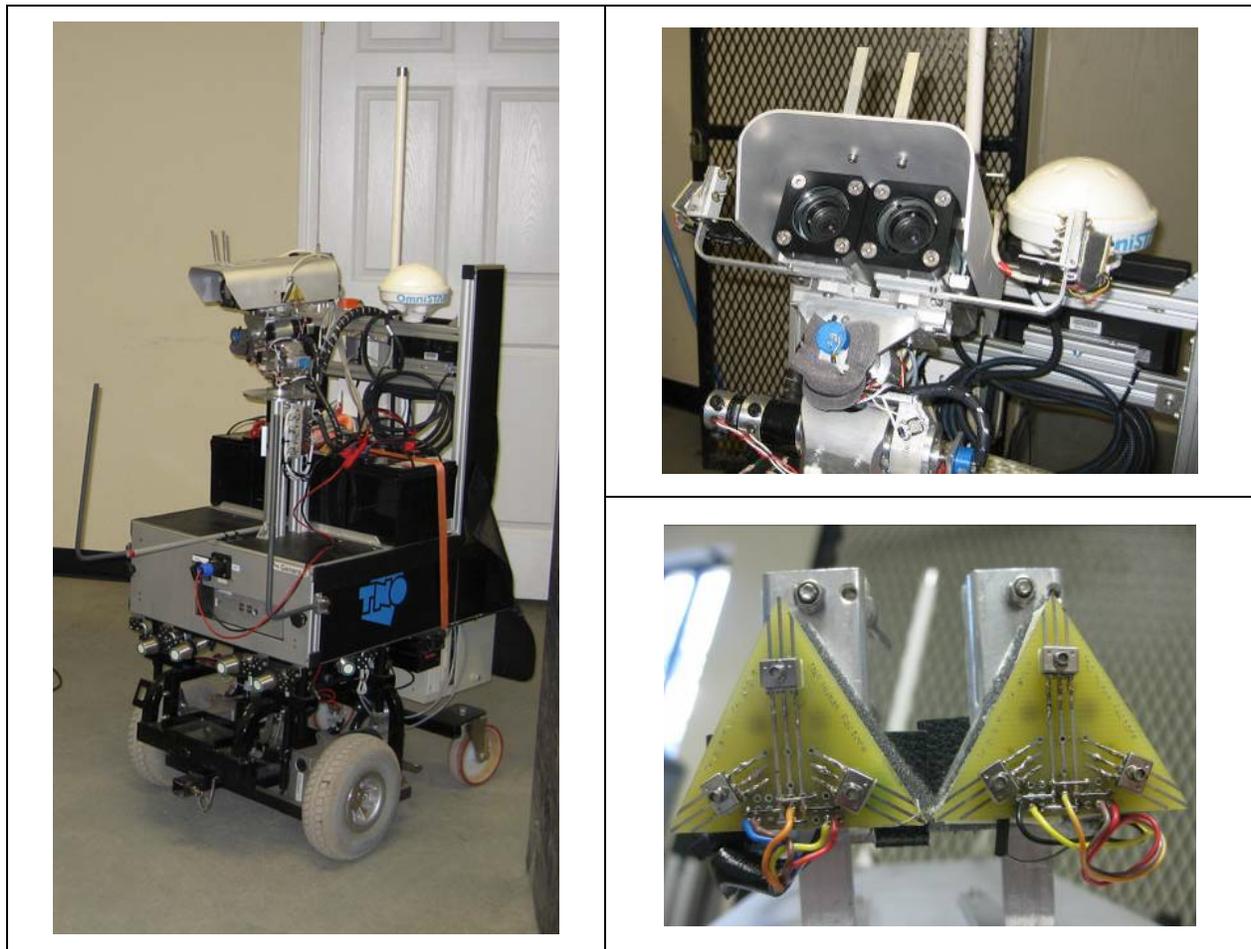


Figure 9-2: TNO's Unmanned Vehicle 'Generaal'. Left panel shows the vehicle with sensor unit on a pan-tilt-roll motion platform with 3D audio and stereo visual sensors. The sensor unit is presented enlarged in the upper right panel, with the microphone array placed in their 3D audio position, at either side of the stereo cameras. The lower right panel shows how the two microphone arrays were placed in the centre position right above the stereo cameras, for receiving directional mono sound.

## 9.7 SUMMARY OF ANY NATO COMMUNICATIONS/COLLABORATIONS/ INTERACTIONS

	<i>Planning/Design</i>	<i>Execution</i>	<i>Analysis</i>
<i>Communication</i>	<i>TNO and US Army</i>	<i>TNO and US Army</i>	<i>TNO and US Army</i>
<i>Coordination</i>	<i>TNO and US Army</i>	<i>TNO and US Army</i>	<i>TNO and US Army</i>
<i>Collaboration</i>	<i>TNO and US Army</i>	<i>TNO and US Army</i>	<i>TNO and US Army</i>

## **9.8 SUMMARY OF TECHNICAL DEMONSTRATION RESULTS**

Non-parametric Wilcoxon Matched Pairs tests show that the percentage correct target ID in the Telepresence condition is significantly higher (87.5%) than in both Mono-Joystick (61.5%;  $p < .05$ ) and Mono-Headtracking (64.6%;  $p < .005$ ); Mono-Headtracking and MJ do not differ ( $p = .51$ ).

The repeated measures ANOVA on time to target identification indicates a main effect for Human-Robot Interface ( $F(2,30) = 17.48$ ,  $p < .001$ ); all Tukey HSD post hoc tests were significant (all  $p < .05$ ). Time to target identification is shortest for Telepresence (65.0 seconds), followed by Mono-Headtracking (88.8 seconds), and longest for Mono-Joystick (113.5 seconds).

## **9.9 LESSONS LEARNED**

Including head motion tracking for controlling a directional microphone significantly improves a human operator's detection and localization of audio targets in a reconnaissance mission. This performance is boosted even more when human natural listening behavior is further mimicked when 3D audio is presented using advanced microphone arrays instead of mono audio generated by a directional microphone.

We have learned that field tests are valuable if not crucial in estimating the possible operational benefits of technology that already has been tested and improved in the laboratory conditions.

## **9.10 STUDY CONSTRAINTS/LIMITATIONS**

The findings of this study are limited to indoor reconnaissance in which no other sounds are present except for the audio target.

## **9.11 CONCLUSIONS**

In Section 9.5 we identified three research questions that can be answered:

- Does headtracking control lead to improved performance as compared to joystick control? The results show no difference between the Mono-Headtracking condition and the Mono-Joystick condition in correctness of target identification. However, with joystick control, more time is needed for target identification: about 26% more time is needed when using a joystick for sensor control (here Mono-Joystick with 111.2 seconds on average) as compared to headtracking (here Mono-Headtracking with 88.2 seconds).
- Does a 3D audio system lead to improved performance as compared with a directional microphone? When comparing the Telepresence condition (having 3D audio) with the Mono-Headtracking condition (having a directional microphone), we see that with Telepresence the percentage of correctly identified targets is about 23% higher. In addition, target identification takes about 35% more time without having the 3D audio functionality available (here 88.2 and 65.0 seconds for Mono-Headtracking and Telepresence respectively).
- What would be the maximum performance benefit of telepresence functionality as compared with the currently mostly used control systems with joystick control and mono sensor information, provided it exists? Based on the results in this study, the use of a Telepresence human-robot interface results in identification/localization times for audio that are about 42% shorter than with current commonly

used interfaces (65.0 sec and 111.2 sec for Telepresence and Mono-Joystick respectively). In addition, the target identification performance increases by about 26% when using the Telepresence human-robot interface.

These promising results encourage more elaborate testing in operational settings, following our initial field trials with telepresence UGV control reported in [3].

## **9.12 FUTURE RESEARCH NEEDS AND PLANS IN THIS AREA**

In continuing the collaboration between TNO and ARL, we are considering two options that could be performed in parallel. First, we believe that telepresence could be even more beneficial if other multi-modal user interface are included as well, in particular vibrotactile interfaces (e.g., for indicating direction of movement, the next waypoint, collision warnings for obstacles). Second, we plan to investigate the extent to which performance in a reconnaissance mission could further increase by combining telepresence operator involvement with robot autonomy in a well-designed adaptive automation concept.

## **9.13 ACKNOWLEDGEMENTS**

The authors would like to acknowledge NL army programme V923 and the US ARL for sponsoring organization for this study.

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## **Chapter 10 – PT-1: SUPERVISORY CONTROL: OPTIMAL DISTRIBUTION OF WORKLOAD AMONG OPERATORS FOR MIXED INITIATIVE CONTROL OF MULTIPLE UAVS**

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### **10.1 DATES**

24 January 2011 – 4 February 2011.

### **10.2 LOCATION**

OTA, Lisbon, Portugal.

### **10.3 SCENARIO/TASKS**

At the Underwater Systems and Technology Laboratory (LSTS) [1] we have been designing, building and operating a number of heterogeneous unmanned vehicles. These include Remotely Operated Vehicles (ROV) [2], Autonomous Underwater Vehicles (AUV) [3],[5],[6], and Autonomous Surface Vehicles (ASV) [4]. We have been also developing UAVs [7] as a result of our collaboration with the Portuguese Air Force Academy.

Recent technological advances led to the creation of very capable unmanned systems constructed using low cost hardware. This allows the application of these technologies to scenarios where multiple unmanned systems can be employed simultaneously like patrolling, adaptive sensing, search and rescue, etc. However, human operators have turned into an increasingly scarcer and more expensive resource whose exploitation shall be optimized.

In this chapter, we describe a conceptual framework for optimal inclusion of the operator in the control loop and the application of these concepts into a Command and Control (C2) operator interface. Our objective is to distribute and reduce the workload of a decentralized team of operators controlling multiple UAVs. To achieve this goal we intend to advise operator's actions and reconfigure C2's layout using an automated methodology. The operator can have different levels of situation awareness, at different stages of the mission. The system will help operators to dynamically configure an optimal view of the mission state from a set of predefined console layout profiles.

We interpreted and adapted the original (Level Of Autonomy) LOA matrix (Table 10-1) into our framework for optimal inclusion of the operator in the control loop. The LOA-Level of Autonomy Table [10] is based on



Sheridan’s 10-level of autonomy scale [11] and simplified to present only eight levels of autonomy. The two dimensions of the matrix (Table 10-1) are the eight levels (matrix rows) crossed with four functional categories (matrix columns). The second dimension presented in this matrix is the division of each task into four functional steps. These tasks present human decision-making processes as a set of OODA cycles (Observe, Orient, Decide, and Act).

**Table 10-1: Partial LOA Matrix as Originally Published in [10].**

Level	Observe	Orient	Decide	Action
8	The computer gathers, filters, and prioritizes data without displaying any information to the human.	The computer predicts, interprets, and integrates data into a result which is not displayed to the human.	The computer performs ranking tasks. The computer performs final ranking, but does not display results to the human.	Computer executes automatically and does not allow any human interaction.
7	The computer gathers, filters, and prioritizes data without displaying any information to the human. Though, a “program functioning” flag is displayed.	The computer analyses, predicts, interprets, and integrates data into a result which is only displayed to the human if result fits programmed context.	The computer performs ranking tasks. The computer performs final ranking and displays a reduced set of ranked options. Without displaying “why”.	Computer executes automatically and only informs the human if required by context. It allows for override ability after execution. Human is for shadow contingencies.
...				
1	Human is the only source for gathering and monitoring (defined as filtering and prioritizing) all data.	Human is responsible for analyzing all data, making predictions and interpretation of the data.	The automate does not assist in or perform ranking tasks. Human must do it all.	Human alone can execute decision.

Table 10-2 is used to categorize the operator skills using the LOAs he is certified to respond to, the CP (Console Profile) the operator is familiarized and the number of vehicles he can handle safely at a certain LOA.

**Table 10-2: Fields Used to Infer About the Operators Skills in the Framework.**

Certified Type of LOA	Certified Consoles Profiles	Number of Vehicles
Type of manoeuvre the operator is certified.	Set of operation Consoles the operator is familiarized. By preference order. (for one LOA)	Operator fan-out of vehicles (for one LOA)

To exemplify the framework’s execution we will evaluate a mission scenario where the operators have to find a target and follow it. There will be two operators and five UAVs in this scenario.

Currently existing UAVs offer little adaptability in terms of automation: operators can command the UAV to fly autonomously, following a pre-defined flight path, or they can control it manually. For this example we will use 2 LOAs for the operators, and another one of full autonomy used in handover and in emergency situations. The operators LOAs to be used are further sub-divided into a high level control LOA and low level control LOA in this scenario.

All three LOAs used are described as follows:

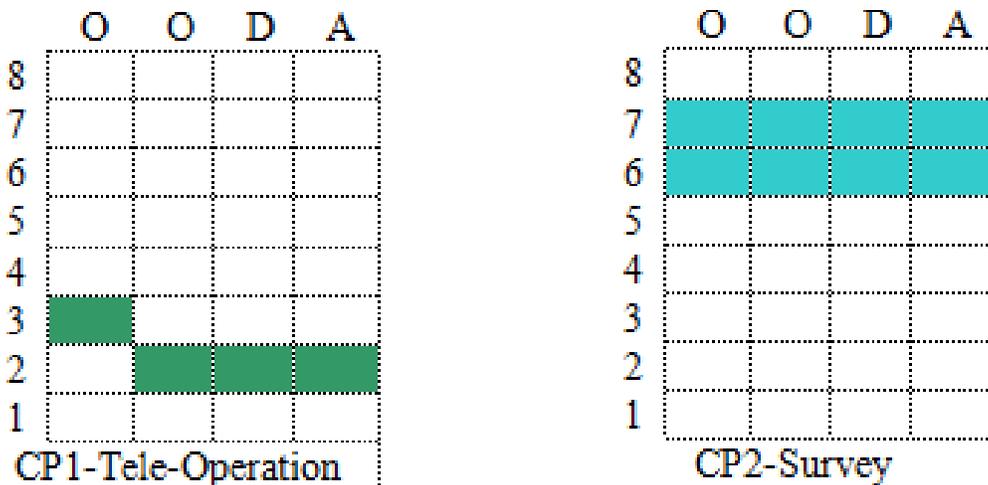
- **Operational Mode 1** – Tele-Operation or Direct Control – LOA = (3,2,2,2);
- **Operational Mode 2** – Survey – LOA = (6,6,7,6); and
- **Operational Mode 3** – Full Autonomy – LOA = (8,8,8,8).

The matrix represented in Table 10-1 can be related with the creation of different types of console profiles. Different console profiles can be associated to different combinations of the four functional categories (OODA) – operational modes. For the presented framework we have a direct relation of LOA and CP. The formal representation for CP-LOA tuple is:

$$CP-LOA = (\{Obs_1...Obs_n\}, \{Ori_1...Ori_n\}, \{Dec_1...Dec_n\}, \{Act_1...Act_n\})$$

The elements on the tuple are represented as sets so we can group the OODA functional categories. This way it is possible to have one CP capable of handling different Operational Modes.

We will use two CPs (CP1 = ({3},{2},{2},{2}) and CP2 = ({6-7},{6-7},{6-7},{6-7})) to handle this mission example as follow:



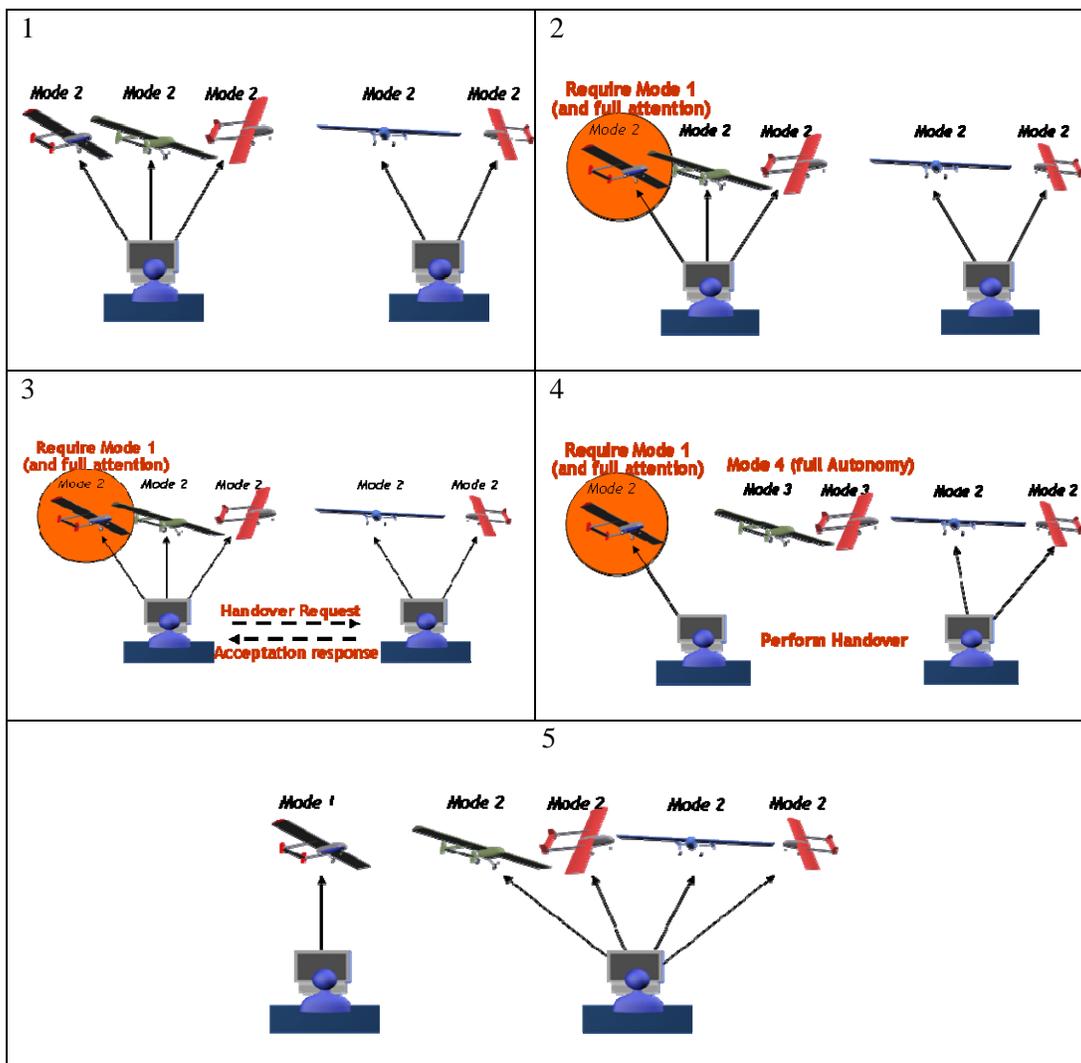
**Figure 10-1: Two Console Profiles Used in Mission (For Low and High Level Control).**

For this mission example we will have two operators with the following Skills Tables.

**Table 10-3: Skills Table – Operator 1 Can Handle 3 UAVs in High Level Control and 1 UAV in Low Level Control; Operator 2 Can Handle 4 UAVs in High Level Control.**

	Certified Type of LOA	Certified CPs (Consoles Profiles)	Number of Vehicles
Operator 1	(3,2,2,2)	{CP1}	1
	(6,6,7,6)	{CP2}	3
Operator 2	(6,6,7,6)	{CP2}	4

Figure 10-2 illustrates the 5 most important steps taken when one of the operators finds the target. The state of the system before any of the operators finds the target is the beginning step (step 1) of Figure 10-2. Initially, all the UAVs are in survey mode – mode 2 of our LOA definition. Both of the operators are using CP2 to control the UAVs: define survey areas and look at part of the payload data (video).



**Figure 10-2: Logic of Operation for Workload Distribution Mission Example.**

In step 2 of Figure 10-2, Operator 1 finds the target. The target must be followed using direct control. To solve the excessive workload of Operator 1 (Operator 1 can handle only 1 UAV in Operational Mode 1 – Tele-operation – and Operator 2 is not certified for Operational Mode 1, consult Table 10-3), the system (mission supervisor) will try to assign this UAV in mode 1 – Tele-Operation – to some operator. The only operator capable of handling mode 1 is operator 1, as defined in Table 10-3. Since the operator 1 is capable of handling only one UAV in this Mode, the mission supervisor will advise Operator 1 to hand-over the other 2 UAVs from Operator 1 to Operator 2. Here starts step 3 with the handover process: Operator 1 releases the two controlled UAVs by setting them at mode 3 (Full Autonomy).

Finally, in step 5, Operator 2, that has accepted the hand-hover, takes over these UAVs which are on Mode 2 and the Operator 1 can now handle Mode 1 (Tele-Operation) and follow the target. In this step the Mission Supervisor advises Operator 1 to use CP1-Tele-operation to respond mode 1 LOA, which requires full attention to the vehicle, according to his skills in Table 10-3.

## **10.4 TECHNOLOGIES EXPLORED**

The concepts of operation for multi-UAV teams differ from single UAVs in the sense that in the former there exist common objectives like maintaining a common knowledge database [8] and redundant execution of crucial actions [9].

In our C2 framework, UAVs can be tasked either individually by an operator or they can be tasked by a software agent that acts as an operator (Team Supervisor). The team supervisor divides work among the vehicles according to a multi-UAV mission specification and simple task-allocation algorithms. If the control over the UAV is not overridden, they carry out planned behavior until they are faced with failures, or there are any other unpredicted situations in which they contact the ground station and require human intervention.

To provide system-level control of multiple vehicles, we use a software agent that holds a multi-UAV mission specification. This mission specification is currently a list of individual plans that need to be executed by UAVs. Tasks are divided among UAVs in a way that workload is shared among capable vehicles. Some tasks however also require the intervention of human operators for correct execution, so the availability of operators must be taken into account by the team supervisor while tasking the network.

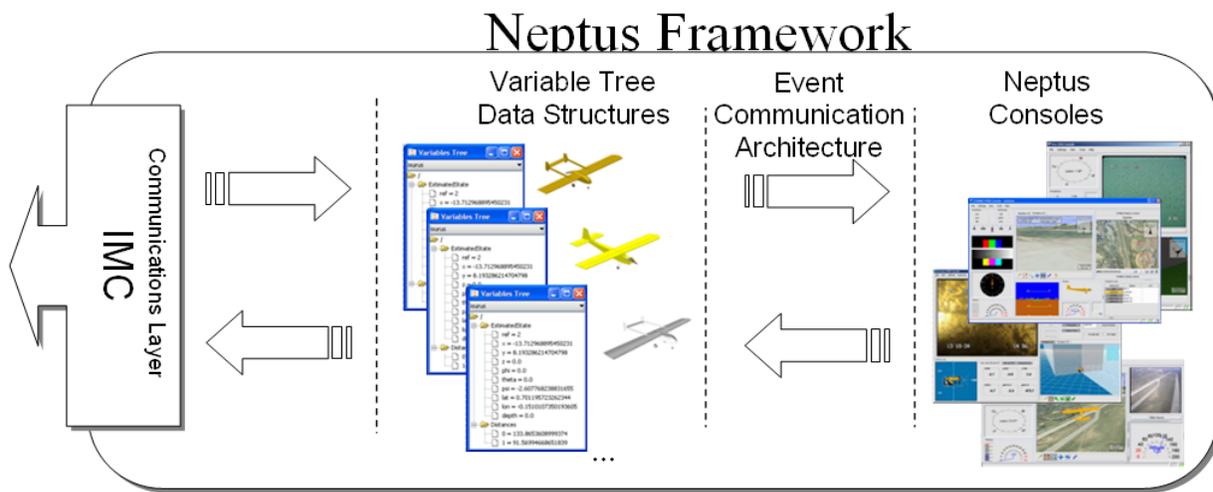
As stated before, this framework was employed in an existing C2 software framework: Neptus. Neptus has an underlining architecture that provides the means for creating the various consoles used in different CPs. This section introduces Neptus and gives an example of such consoles.

Neptus is a distributed C2 framework for operations with networked vehicles, systems, and human operators. Neptus supports all the phases of a mission's life cycle: planning, simulation, execution, and post-mission analysis. Neptus supports concurrent operations. Vehicles, operators, and operator consoles come and go. Operators are able to plan and supervise missions concurrently [12].

In Neptus, the Console Builder application facilitates the addition of new vehicles with new sensor suites to Neptus. In this application the operator can build, configure, and save vehicle consoles. There are two important aspects for console configuration: visual components and event communications. The internal Neptus event communication system is based on a tree structure (following the blackboard design pattern [13]), where nodes indicate the subject of data values in leafs. Neptus visual components can become listeners of a single variable (tree leaf) or of a defined variable domain (tree branch). Whenever a message arrives, using the IMC [14] communication protocol, that data is stored in a specific tree branch and listeners for any

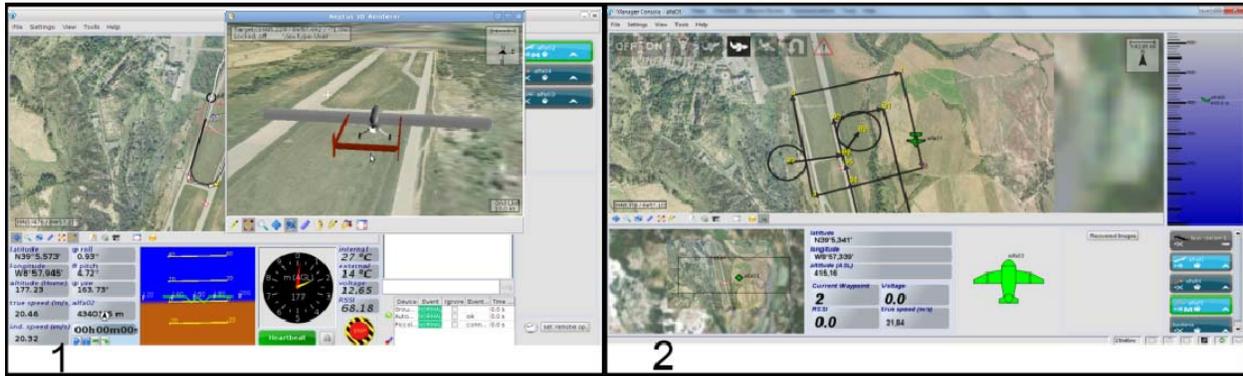
branch that encloses the affected branch/leaf are informed of the incoming network data. In a similar way, output data is sent to the network by Neptus console components through the variable tree. The variable tree system is also used for event communication between Neptus console components.

There are two states in the Neptus generic console builder application: editing and operational. In editing mode, the palette of available components (STANAG planning panel, compass panel, renderer panel, video panel) becomes visible. Users can then add and place components freely inside console main panel. Component properties can be edited to connect the panels to different systems and variables. When all components are ready, correctly placed and connected to the system variable tree, the user can switch the state of the application to the Operational mode. In this mode, the position of the components in the console is fixed and it responds to the user interactions (Figure 10-3).



**Figure 10-3: Neptus Internal Communications System.**

Besides having the capability of dynamically creating new consoles during a specific mission, Neptus also has predefined consoles already available for the LOA switches the presented framework requires. These consoles go from standard tele-operation consoles, as seen as example 1 of Figure 10-4, to supervision consoles, as seen on the right (example 2) of Figure 10-4. These consoles have different layouts depending on the central function they have. For instance a tele-operation console will typically have more detailed data about the UAV under its control, whereas a supervision console will only have a simplified view of the current UAV to allow a broader view of the whole team. As an example of said consoles we introduce the details behind the current flight manager console used for UAV mission supervision at the LSTS.

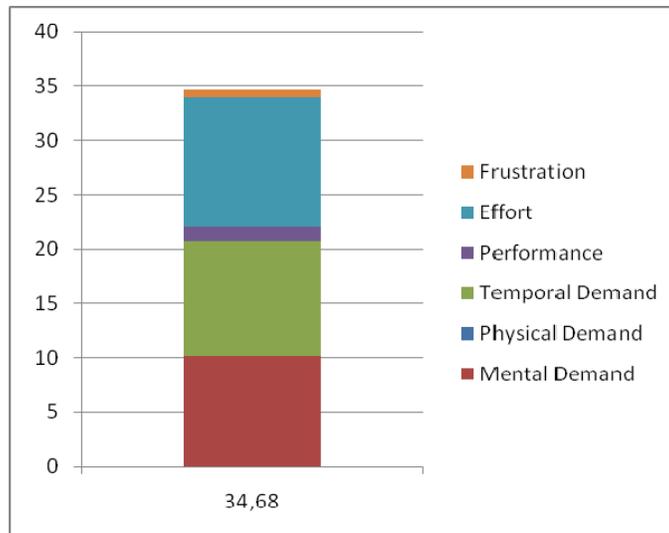


**Figure 10-4: Tele-Operation (Low Level Control – 1) and Supervisory Control (High Level Control – 2) Consoles.**

The supervisory control console, as seen in Figure 10-4, was developed based on a Real-Time Strategy (RTS) paradigm with the intent of applying the concepts, learned by this type of games, on how to efficiently control and supervise groups of units of various dimensions and with varying capabilities. This approach, while not being new, has allowed the implementation of a console which supports high LOA levels CP-LOA =  $(\{6-7\}, \{6-7\}, \{6-7\}, \{6-7\})$  while, at the same time, enables the supervision of UAV teams with a low workload rating value for the operators.

### 10.5 HUMAN FACTORS ISSUES EXPLORED

The two main human factors that we explore in this framework is situation awareness and workload index. To that extent, we perform systematic evaluations of these metrics through the use of NASA’s TLX method, for workload analysis and the SAGAT method for situation awareness testing. An example of the workload values collected in one of these tests can be viewed in Figure 10-5.



**Figure 10-5: Flight Manager Console’s Total Workload Rating, Using NASA-TLX [15], in a 3 UAV Scenario.**

## 10.6 UNMANNED SYSTEMS USED

For the various flights performed a vast array of unmanned systems were used. Some of these systems can be viewed in Figure 10-6.



**Figure 10-6: UAVs ANTEX X02 1-4 Series.**

Due to maintenance reasons, it is for us very common to change UAV models in the middle of a test run. Nevertheless we present specific details of the systems which are more regularly used on the shakedown tests.

**Table 10-4: Specific Data of the ANTEX X02 – 03 UAVs.**

	ANTEX X02 Series
<b>Max Weight</b>	10 KG
<b>Width</b>	2,4 m
<b>Max Speed</b>	150 Km/h
<b>Max Payload</b>	4 Kg
<b>Max Autonomy</b>	5 h
<b>Max Altitude</b>	2 Km

## **10.7 SUMMARY OF ANY NATO COMMUNICATIONS/COLLABORATIONS/INTERACTIONS**

	<i>Planning/Design</i>	<i>Execution</i>	<i>Analysis</i>
<i>Communication</i>	X	X	X
<i>Coordination</i>			
<i>Collaboration</i>			

## **10.8 SUMMARY OF TD RESULTS**

We presented the concepts behind a framework for managing UAV task and workload allocation between various operators in a mission scenario. This framework was applied to the development of a Command and Control (C2) application which is capable of self-adaptation, operator advisement and automatic task distribution among operators and UAVs according to mission objectives, phase and occurrences. An example scenario of this framework, as well as an example of the details around one of the consoles used by the operators, was presented and discussed.

## **10.9 LESSONS LEARNED**

This C2 application enables a clear view and presence on the remote environment by putting the operator much closer to the control loop, whether it is high level or low level control, with the consequent improved redistribution of tasks and situational awareness. NASA Task Load Index (TLX) was used as a means to determine the adequacy of the C2 interface and functionalities. The preliminary results obtained with this framework are promising and we are confident that its use will vastly improve the reliability of multi-UAV teams by augmenting their compatibility with more mission scenarios.

## **10.10 STUDY CONSTRAINTS/LIMITATIONS**

Although we have a vast base of operations and a large array of working vehicles to test this framework, the majority of the testing took place in a simulated environment. This will, on one hand, allow us to detect faults in the system without endangering our vehicles but, on the other hand, limit the conclusions that can be extrapolated from the experiments due to lack of realism.

## **10.11 CONCLUSIONS**

Throughout this chapter we referenced the growing importance of multi-UAV systems, paying special attention to the need of optimal in-the-loop inclusion of operators for the successful use of these systems. The tested framework for managing UAV task and workload allocation between various operators in a mission scenario proved to be an improvement over the previous approach. Further testing, with simulated scenarios, will provide new insights over the real capabilities of the proposed framework.

## **10.12 FUTURE RESEARCH NEEDS AND PLANS IN THIS AREA**

We intend to implement another formal layer over the presented framework to extract the viability of mission execution. It is possible to reach combinations of plan state manoeuvres that overload the response of the operator's team. Our approach will use Petri Nets for the model to tackle this issue (another similar example can be consulted in [16]). By studding the plan loaded in each UAV and applying a transformation that combines all UAV plan states, the plan state change events probabilities, and the operators team recourses into a Petri Net, we can infer about the probability of reaching a failure state. The failure state can be considered to be a state where operator resources do not correspond to the mission state demands. In the last analysis, we can know the probability of reaching one mission state before the Mission Team Supervisor has to process the resource allocation. This information can be used to optimize the resource allocation process and also to help avoiding some mission states in the mission planning phase (e.g., find and avoid states that require full autonomy LOA = (8,8,8,8) manoeuvres).

## **10.13 ACKNOWLEDGEMENTS**

The authors acknowledge the contribution of AsasF-FEUP team in the requirements identification and in the demonstration tests. Also acknowledge the Portuguese Air Force Academy (AFA) in the field tests and developments and design of ANTEXs X02 UAVs under the *PITVANT* project funded by the Portuguese Ministry of Defence. Neptus relies on other components of the LSTS tool chain for its correct execution. For this, we would like to thank Eduardo Marques, Paulo Dias, and Ricardo Martins mainly for their efforts in developing the IMC protocol. Rui Gonçalves and José Pinto were partially supported by FCT grants.

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## **Chapter 11 – SWE-1: TASK SWITCHING FOR MULTI-UGV CONTROL**

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### **11.1 DATES**

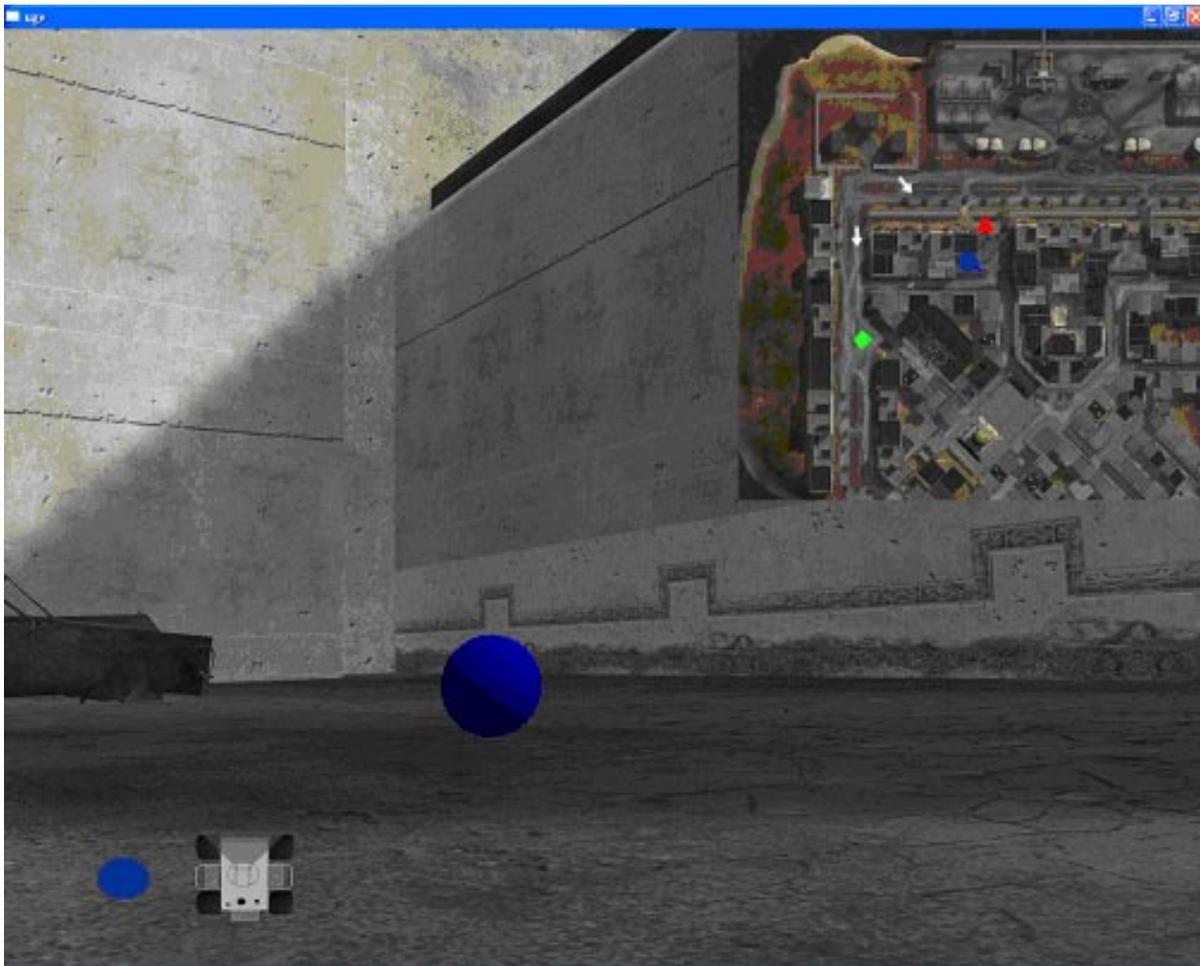
1 – 30 November 2006.

### **11.2 LOCATION**

FOI, Linköping, Sweden.

### **11.3 SCENARIO/TASKS**

The operator's task was to navigate one, two, or three partly autonomous UGVs to pre-designated inspection points in a simulated urban environment. The UGVs were mainly manually controlled and had only a limited autonomous function in that they could maintain the current heading and velocity while unattended to by the operator. Figure 11-1 shows an example of the operator's control station where the position of the UGVs and the shape and colour coded inspection points are indicated on the map in the upper right corner. The colour coded 3D-objects representing the inspection points were shown when within view of the UGV's camera. The task was to navigate each UGV to the inspection point with the corresponding colour. A new inspection point was shown when the UGV reached the indicated inspection point. The operators alternated control sequentially between the UGVs to manually change the heading and velocity and engage the autonomous function to maintain the last control action while the operator attended to the other UGVs. Performance was measured by the number of inspection points that were reached within a 10-minute period.



**Figure 11-1: Example of the Operator's Control Station. The task was to navigate the blue UGV to the blue inspection point, the red UGV to red inspection point, and the green UGV to the green inspection as indicated on the map in the upper right corner.**

## **11.4 TECHNOLOGIES EXPLORED**

Only a limited autonomous function was used that enabled the UGVs to maintain the current heading and velocity.

## **11.5 HUMAN FACTORS ISSUES EXPLORED**

One reason why it is so difficult to improve the operator to vehicle ratio and enable one or a few operators to control several robots is that the attentional requirements are so high for controlling even one robot that any additional robots overload the operator or operators and hampers the performance. The purpose of the study was to investigate these attentional requirements for a typical ground robot when performing a basic navigation task in a military setting, and to what extent a limited autonomous function was useful in facilitating control of several robots.

An exploratory performance measure called Instantaneous Performance was also used to measure performance continuously during a trial rather than only at the end of a trial by the number of inspection points that were reached [2]. The Instantaneous Performance is computed by normalizing the UGVs' current velocity and heading relative the shortest path towards the next inspection point and the maximum velocity. This results in measure where 1 means that the UGV is moving along the shortest path towards the inspection point at maximum velocity and -1 that the UGV moving in the opposite direction at maximum velocity. The benefit of Instantaneous Performance is that it allows an assessment of operators' control strategies. Please see Lif et al. [1] for more information about the study.

**11.6 UNMANNED SYSTEMS USED**

One, two, or three simulated UGVs.

**11.7 SUMMARY OF ANY NATO COMMUNICATIONS/COLLABORATIONS/ INTERACTIONS**

The results of the study have been presented at Task Group meetings, as well as at a conference session arranged by a Task Group member [1]. The following table summarizes the extent of the NATO collaboration.

	<i>Planning/Design</i>	<i>Execution</i>	<i>Analysis</i>
<i>Communication</i>			X
<i>Coordination</i>			
<i>Collaboration</i>			

**11.8 SUMMARY OF TD RESULTS**

The results show that the operators reach 30% more inspection points when using two UGVs compared to when only using one UGV. Adding a third UGV did not provide any additional improvement in performance, however. Due to mental overload when using more than one UGV, the UGVs stand still 30% of the time when using two UGVs and 50% of the time when using three UGVs. Furthermore, the duration of the stand stills last between 5 seconds and 1 minute, which is undesirable in a potentially hostile environment. The mental overload was also evident in the operators' control strategies where some operators aimed the UGVs towards walls to know where to find the UGV when they regained control, or even completely abandoning UGVs. Overall, the operators control the UGVs manually 90% of the time although they use the autonomous function more when controlling more UGVs. The correlation between Instantaneous Performance and the number of reached inspection points was .95, which shows that it is valid performance measure. The operators' control strategies were not explored further, however.

**11.9 LESSONS LEARNED**

Typical issues in control of multi-robot systems can be investigated in a laboratory environment without experienced operators.

## **11.10 STUDY CONSTRAINTS/LIMITATIONS**

The operators did not have any previous experience in controlling UGVs and were thus rather naïve. The lack of experience was evident in that some subjects had difficulty operating the UGVs in a safe way, particularly when controlling more than one UGV.

## **11.11 CONCLUSIONS**

The results show that the limited autonomous function was insufficient to significantly improve the operator to vehicle ratio. The operators are saturated even when only controlling two UGVs in a basic navigation task. More advanced partly autonomous functions or control station interfaces that reduce the attentional requirements are therefore necessary to improve the operator to vehicle ratio.

## **11.12 FUTURE RESEARCH NEEDS AND PLANS IN THIS AREA**

Although research programs, such as the DARPA Grand Challenge, show that ground robots can navigate autonomously in an uncertain environment, such technologies are typically not available for UGVs that are used for tactical reconnaissance. An alternative approach is therefore to develop better interfaces that reduce the attentional requirements and improve the operators' strategies for sequentially alternating the control between robots. One approach to develop such interfaces is to derive a prioritization order for relevant goal attainment states from either simulated or empirical data [3]. This prioritization order can then be used to indicate which UGV that is in most need of service. There are currently no plans for future research, however.

## **11.13 ACKNOWLEDGEMENTS**

The study was performed by Patrik Lif and Johan Hedström.

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## **Chapter 12 – SWE-2: SUPERVISORY CONTROL OF UGVs FOR TACTICAL RECONNAISSANCE**

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### **12.1 DATES**

1 December 2007 – 28 February 2008.

### **12.2 LOCATION**

FOI, Linköping, Sweden.

### **12.3 SCENARIO/TASKS**

The operator's task was tactical reconnaissance along the route of advance for a convoy to locate and neutralize mobile threats in a simulated urban environment. The convoy consisted of 15 vehicles that advanced along a fixed route that was about 1.7 km long. Along the convoy's route of advance were 28 mobile threats that either crossed or came near the route of advance. The operators performed the tactical reconnaissance using either six or twelve UGVs that autonomously searched for the mobile threats within designated areas, as well as detected and tracked the mobile threats. The operator controlled the UGVs by allocating them into search group and designating search areas for groups of UGVs. Detected threats were neutralized by simply clicking on the threat's icon in the control station's interface. Performance was measured by the number of hits that the mobile threats inflicted on the convoy when the vehicles were within weapon range.

Figure 12-1 shows an example of interface. The pane on the left was used for allocating UGVs into colour coded search groups and selecting groups for designation of search areas. Six search groups were available in both conditions, whether the tactical reconnaissance was performed using six or twelve UGVs. After selecting a search group, the operator drew the search area on the map to the right. The map could be scrolled and zoomed in and out any time during a trial. The position of the convoy vehicles, UGVs, and detected threats were indicated on the map. The detection of threats was also indicated by changing the icon colour of the corresponding UGV in the left pane and sounding an auditory alarm. Convoy vehicles that were recently hit by a threat were also indicated.

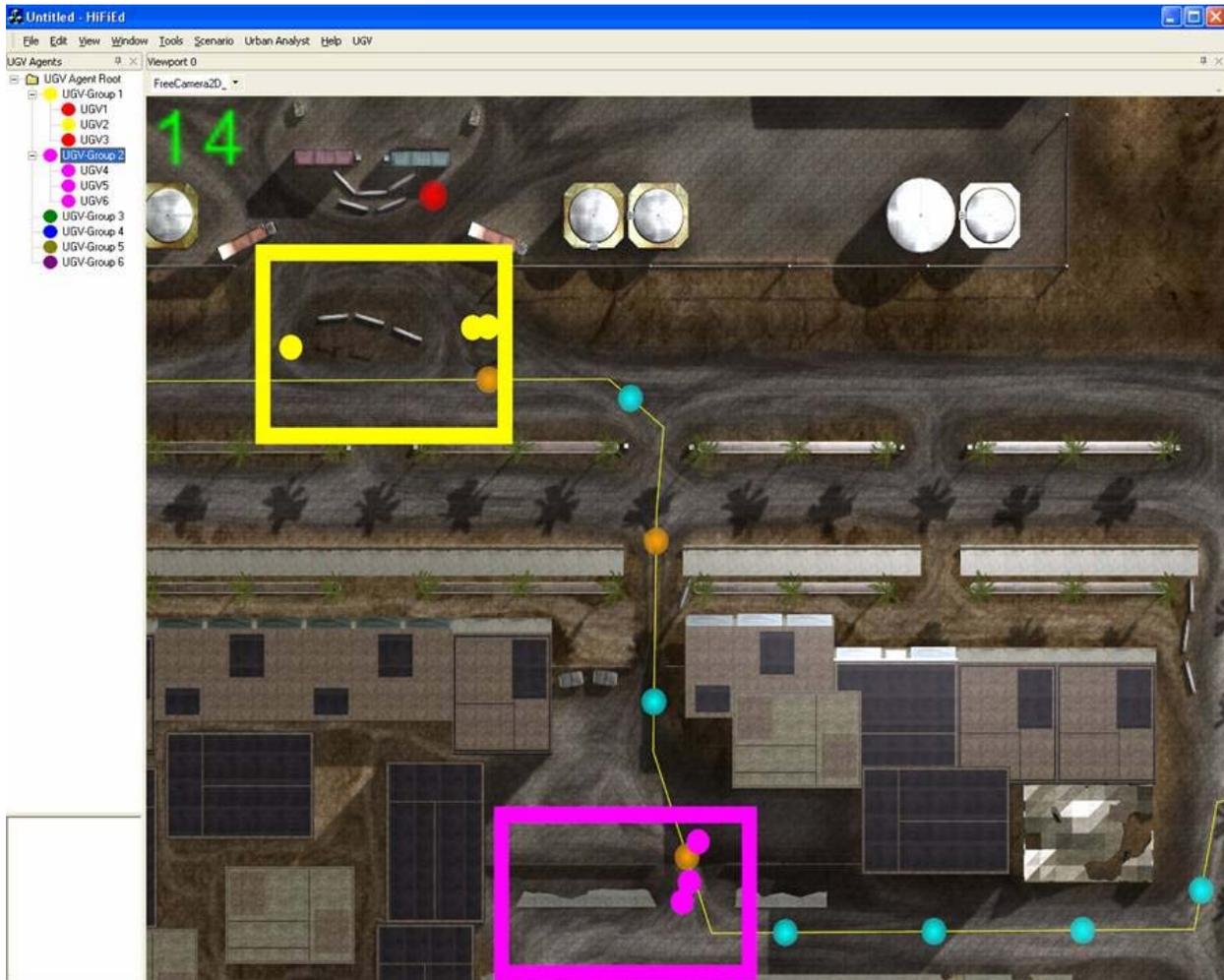


Figure 12-1: Example of the Operator Control Station. The blue circles indicate convoy vehicles. The yellow and pink circles indicate UGVs in colour coded search groups. The red circle (encircled in white for clarity) in the upper-left corner of the map in the industrial area shows a mobile threat approaching the convoy. The UGVs that detect the threat have a red icon in the left pane. Convoy vehicles that were recently hit by a mobile threat are shown with an orange colour.

## 12.4 TECHNOLOGIES EXPLORED

A partly autonomous search function for multiple UGVs was investigated that minimize the time for capture rather than guaranteeing capture [3]. The algorithm simplifies the search problem by composing the environment into convex cells where an UGV that enters the area of a cell can always detect any threats that are present within the cell. Initially, there is an equal probability that there is a threat within all the convex cells within a search area. Over time, however, these probabilities change depending on the connections between adjacent convex cells and which cells the UGVs visit. The algorithm prioritizes which adjacent convex cell to visit using a heuristic entropy function that minimizes the entropy over five consecutive cells starting from the UGV's current cell.

## **12.5 HUMAN FACTORS ISSUES EXPLORED**

There are many potential applications for robotic systems that are only feasible if one or a few operator can simultaneously control several robots. One way to enable such multi-robot systems is to use partly autonomous functions where the robots can maintain an acceptable performance level even when unattended to by the operator. However, similarly to many automated systems, partly autonomous functions are most successful in applications that only require limited interaction between the operator and the autonomous function (e.g. [4]). Applications that require much interaction are more likely to have human-robot coordination problems. An important factor for the interaction are the dependencies between the task that operator performs and the task that the partly autonomous function performs. Tasks with only weak dependencies are more likely to be more suitable for multi-robot systems than tasks with strong dependencies [5].

The purpose of the study was investigate how the operators perceived the dependencies between the designation of search areas and the partly autonomous search function in a representative urban environment. With weak task dependencies, an increased number of UGVs for tactical reconnaissance should reduce the number of hits on the convoy without any significant effect on the operator’s task. Weak task dependencies were expected since search tasks generally have weaker dependencies than other tasks, such as navigation [1]. Please see Svenmarck et al. [1] for more information about the study.

## **12.6 UNMANNED SYSTEMS USED**

Six or twelve simulated UGVs.

## **12.7 SUMMARY OF ANY NATO COMMUNICATIONS/COLLABORATIONS/ INTERACTIONS**

The results of the study have been presented at Task Group meetings, as well as at conference sessions arranged by Task Group members [1],[2]. The following table summarizes the extent of the NATO collaboration.

	<i>Planning/Design</i>	<i>Execution</i>	<i>Analysis</i>
<i>Communication</i>			X
<i>Coordination</i>			
<i>Collaboration</i>			

## **12.8 SUMMARY OF TD RESULTS**

The results show that increasing the number of UGVs from six to twelve reduce the numbers hits on the convoy by 25%, due to a 26% increase in detected threats and a 33% increase in neutralized threats. Subjectively, the operators also reported higher situation awareness as measured by 3D-SART. More importantly, these benefits were achieved without any detrimental effects on the mental workload as measured by NASA-TLX. Overall, the operators used fairly large search areas and a uniform allocation of the number of UGVs into search groups.

## **12.9 LESSONS LEARNED**

Typical issues in control of multi-robot systems can be investigated in a laboratory environment without experienced operators, although care should be taken when interpreting the results.

## **12.10 STUDY CONSTRAINTS/LIMITATIONS**

The operators were college students and thus rather naïve towards the complexity of tactical reconnaissance.

## **12.11 CONCLUSIONS**

The results show that partly autonomous functions can improve the operator to vehicle ratio in a military environment if there are weak dependencies between the task that the operator performs and the task that partly autonomous function performs. However, the task dependencies also partly depend on the operators' task experience, as well as the formal task properties. The operators' control strategy shows that they were rather naïve towards the complexities of tactical reconnaissance. More experienced operators may therefore find different task dependencies.

## **12.12 FUTURE RESEARCH NEEDS AND PLANS IN THIS AREA**

One future research need is better theories for conceptual evaluation of task dependencies to reduce the need for empirical investigations when introducing partly autonomous functions. Future studies may also investigate suitable control strategies for comparison with operator performance, as well as to support the operators' control decisions. Finally, mixed-initiative control may be investigated by varying the operators' degrees of freedom in designating search areas. There are currently no plans for future research, however.

## **12.13 ACKNOWLEDGEMENTS**

The study was performed in cooperation with Dennis Andersson, Johan Hedström, Björn Lindahl and Patrik Lif.

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## **Chapter 13 – UK-1: DYNAMIC AIRBORNE MISSION MANAGEMENT**

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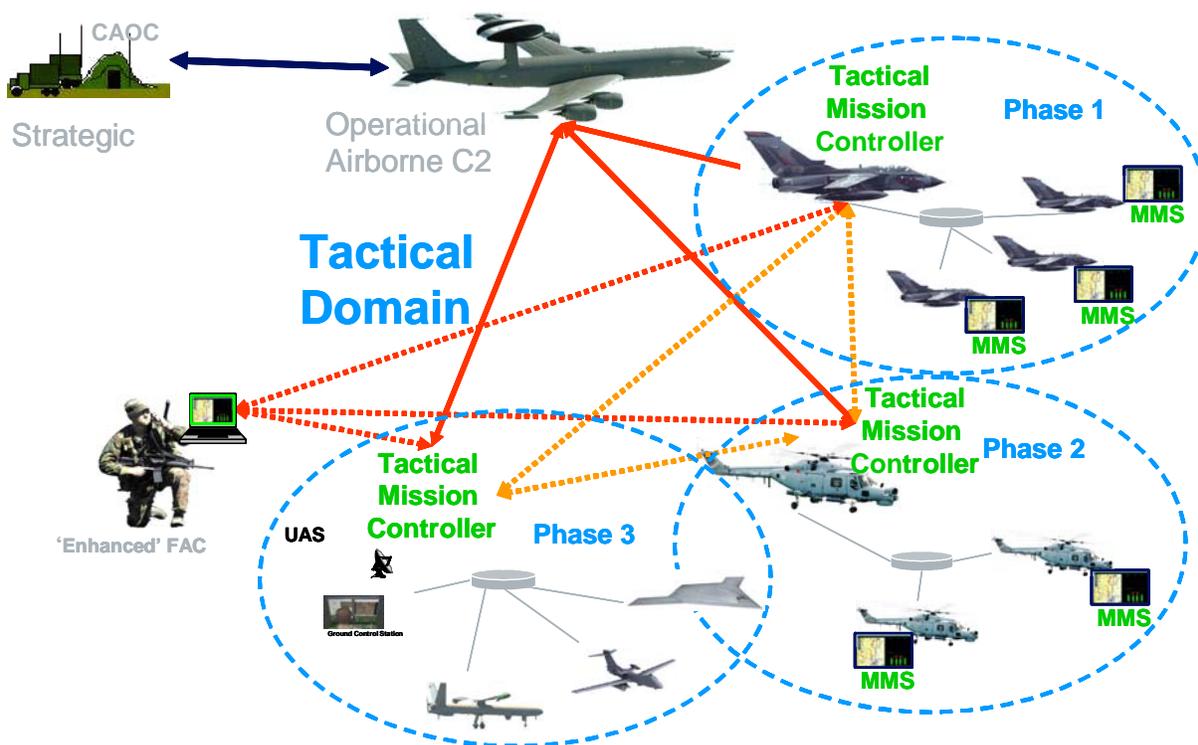
### **13.1 DATES**

This chapter concerns the series of technology demonstrations and test and evaluation trials conducted under the United Kingdom (UK) Ministry Of Defence (MOD) Dynamic Airborne Mission Management (DAMM) research programme. DAMM is a set of principles, interfaces and interactions for the delivery of effects, enabled by advanced digital networking and mission enabling technologies, providing a distributed, collaborative and adaptive mission capability for stability and dominance in a dynamic environment. The research was performed by UK Defence Industry, led by QinetiQ, with other Industry participants, including Thales, BAES, General Dynamics and Augusta/Westland. The research was performed under the DAMM Capability Concept Demonstrator (CCD) research programme, with underpinning research provided under the MOD Applied Research Programme (ARP), Research Entity (RE) 314, Mission Enabling Technologies and Demonstration (MET&D). The work was sponsored by MOD Cap TA (Capability – Theatre Airspace) and contracted through DE&S FBG-3 (Defence Equipment and Support, Future Business Group), with programme support technical advice provided by MOD Defence Science and Technology Laboratory, Air Weapons and Systems Department (DSTL AWS). International Research Collaboration (IRC) on DAMM was conducted between MOD/Dstl and United States (US) Air Force Research Laboratory (AFRL), 711<sup>th</sup> Human Performance Wing (HPW), Human Effectiveness Directorate (HEC), Warfighter Interface Division, under the auspices of the US-UK Project Arrangement (PA), Network Centric Strike Controllers (NCSC).

The UK MOD DAMM CCD programme with QinetiQ commenced on contract in December 2008, with completion of Phase 3 scheduled for July 2011. The underpinning UK MOD research programme RE314 MET&D with QinetiQ provided Mission Management System (MMS) technical work and risk reduction for DAMM CCD throughout this period, with Synthetic Environment (SE) trials and technology demonstrations.

The DAMM CCD programme was conducted over 3 years, and divided into three phases, as illustrated by the Command and Control – Mission Management (C2-MM) architecture in Figure 13-1. Each phase advanced the degree of DAMM architecture complexity and built upon the previous phase to demonstrate enhanced capability:

- Phase 1, YR1 (2008 – 2009) Demonstration of baseline DAMM architecture including a Fixed Wing (FW) Tactical Fast-Jet (TFJ) package co-ordinated by a C2 element.
- Phase 2, YR2 (2009 – 2010) Integration of Rotary Wing (RW) MMS into the Phase 1 architecture and demonstration of rapid re-planning between assets in close support of land forces.
- Phase 3, YR3 (2010 – 2011) Integration and demonstration of an autonomous Uninhabited Air System (UAS) element to the Phase 2 for co-ordinated targeting capability.



**Figure 13-1: DAMM C2-MM Architecture.**

Under RE314 MET&D and DAMM CCD, over ten technology demonstrations, SE and flight trials were completed in total; the four activities involving UAS components, reported here, were as follows:

- RE314 MET&D Joint US-UK SE Trial, September 2010 – FW TFJ and RW AH/SH Inter-Flight Co-ordination with FAC/JTAC, C2 and UAS.
- DAMM CCD UAS SE Technical Demonstration, April 2011 – UAS Co-ordination with RW SH, FW TFJ, C2 and FAC/JTAC.
- RE314 MET&D Joint US-UK SE Trial, July 2011 – Multiple UAS Co-ordination with RW SH, FW TFJ, C2 and FAC/JTAC.
- DAMM CCD RW Flight Trial, August 2011 – RW AH and RW SH Co-ordination with FW TFJ, C2, UAS and Deployed FAC/JTAC.

## 13.2 LOCATION

RE314 MET&D and DAMM CCD were UK Ministry of Defence research programmes managed by Dstl AWSO from Farnborough (2001 – 2009) and Portsmouth West (2009 – 2011) in Hampshire UK. The work was performed under contract with QinetiQ Mission Management Group, based at Farnborough, Hampshire, UK. Technology development, laboratory studies and SE trials were conducted at QinetiQ Farnborough; flight trials were conducted in various UK airspace geographic locations.

### 13.3 SCENARIO/TASKS

DAMM comprised the following tactical mission capabilities:

- Airborne re-planning/modification of a pre-planned mission in response to dynamic events;
- Airborne plan formulation for missions which cannot be planned in advance; and
- Airborne co-ordination and de-confliction of multiple packages with a mission and between multiple missions.

RE314 MET&D and DAMM CCD focused on air-to-ground missions with increasing emphasis on improved air-land integration. Each phase included increased integration levels with relevant C2 and Intelligence Surveillance Target Acquisition and Reconnaissance (ISTAR) systems.

- **Tactical Fast Jet (TFJ) Scenario** – Unplanned Time Sensitive Target (TST) and Close Air Support (CAS) mission co-ordinated with Suppression of Air Defence (SEAD) support; C2 (Combined Air Operations Centre (CAOC) / E3 AWACS) to TFJ co-ordination (Figure 13-2).

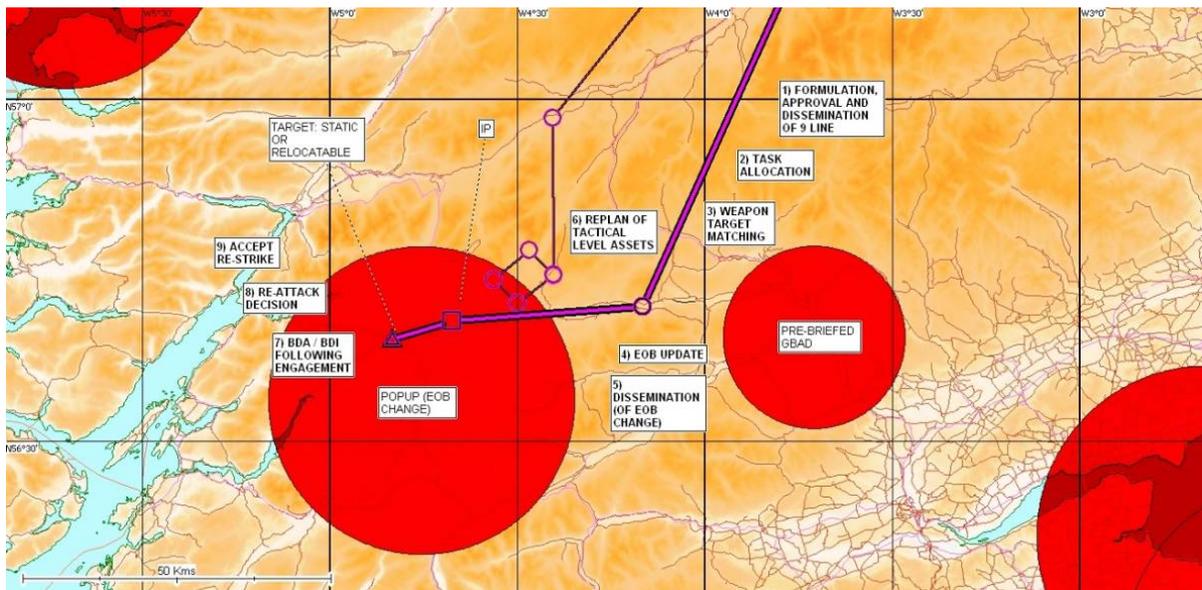


Figure 13-2: DAMM TFJ SE Trial NDZ Scenario Routes, Threat Locations and Decision Points.

- **Rotary Wing (RW) Scenario** – Stop and detainment of leadership target, co-ordinated with Joint Terminal Area Control (JTAC) / Forward Air Control (FAC) and TFJ support; C2 to helicopter MMS and TFJ co-ordination; Joint Personnel Recovery (JPR); Dynamic digital reallocation of airspace.
- **Uninhabited Air Systems (UAS) Scenario** – Providing ISTAR capability extension of the RW scenario, with reconnaissance, observation, and overwatch; TFJ CAS/TST co-ordination.

DAMM development used a validated Joint Warrior military scenario based on a NATO Joint Training Exercise (Joint Combat Aircraft / Maritime Integrated Systems Capability). This Joint Warrior scenario provided military realistic assets and a validated Air Tasking Order (ATO) and Airspace Co-ordination Order (ACO). The fictional scenario involved geo-political tension and the early phase of an escalating conflict

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between adjacent national interests with disputed border regions. Neighbouring Nation states, named Avalon, Caledonia and Dragonia, were in dispute over two territorial zones, with the Northern Disputed Zone (NDZ) set for convenience in Argyll in the north-west Scotland, and the Southern Disputed Zone (SDZ) in Wiltshire and Somerset in south west of England. Scenario missions were operations of a multi-national coalition force assembled to maintain stability with backing by United Nations Security Council Resolutions (UNSCR). Coalition forces operated against insurgents, threats and covert activities (e.g., weapons importations and movements), with intelligence on High Value Targets (HVT). Coalition operations involved insertion and extraction of forces and the maintenance of logistical support. The Coalition had air superiority within the disputed airspace. Coalition operations had defined political and geographical settings (POL-MIL), Areas Of Responsibility (AOR), and monitored enemy Order of Battle (ORBAT), including re-locatable air defence units threatening operations close to borders and within disputed territory. Missions were briefed with Package composition, Commanders Intent (e.g., increasing stability in AOR) and Rules Of Engagement (ROE), with discrete operational phases (e.g., seize initiative, dominate).

In planning the scenario mission, a balance was sought in between the requirements of operational realism and the need to exercise and practice the DAMM tools. Consideration was given to factors influencing the dissemination of command intent, operational and tactical task evaluation and task allocation, and tactical mission management. Factors assessed included objectives to accomplish, threats to success, environmental factors, ROE, and agility. This analysis was used to elicit prioritisation of key mission system stressors across aircraft roles, judged as likely to be mitigated by tool usage, and significantly impacting on dynamic mission effectiveness. The generic mission stressors identified and employed in the scenarios were as follows:

- Electronic Order of Battle (EOB) Change;
- Ability to Interoperate (Communications);
- Force Intent Change;
- Force Capability Degradation;
- Weather; and
- ROE Change.

Scenarios and tasks, with stressing decision points (e.g., Figure 13-2), employed for development and testing used appropriately realistic operational contexts, with representative C2 system architectures, current Concept of Operations (CONOPS) and Concept of Employment (CONEMP), Standard Operating Procedures (SOPs), Special Instructions (SPINS) and ROE. Qualified and experienced serving military commanders and operators were used as military advisors and test participants to ensure best use of current military procedures, tactics and planning assumptions.

### 13.4 TECHNOLOGIES EXPLORED

DAMM CCD integrated mature MMS developed under the RE314 MET&D underpinning research programme. DAMM MMS comprised Situation Awareness (SA) tools, collaboration aids and decision support techniques, across dissimilar platform types, exploiting and advancing research conducted within FJ, RW and UAS domains. These MMS were further integrated with C2, ISTAR and ground-force elements to demonstrate the benefits and effectiveness of near-term airborne Network-Enabled Capability (NEC) using current data link technology. A key component of the NEC is information management, including maximizing effective use of available radio frequency spectrum and Human Machine Interface (HMI) which supports current doctrine and operational methods.

The CCD demonstrated and evaluated architectures for enabling DAMM at the tactical level including:

- Identification of information management issues and development of strategies that make the most of the effective use of the available bandwidth; and
- Information Exchange Requirement (IER) understanding/development leading to definition of bandwidth efficient protocols and Interface Control Definitions (ICD).

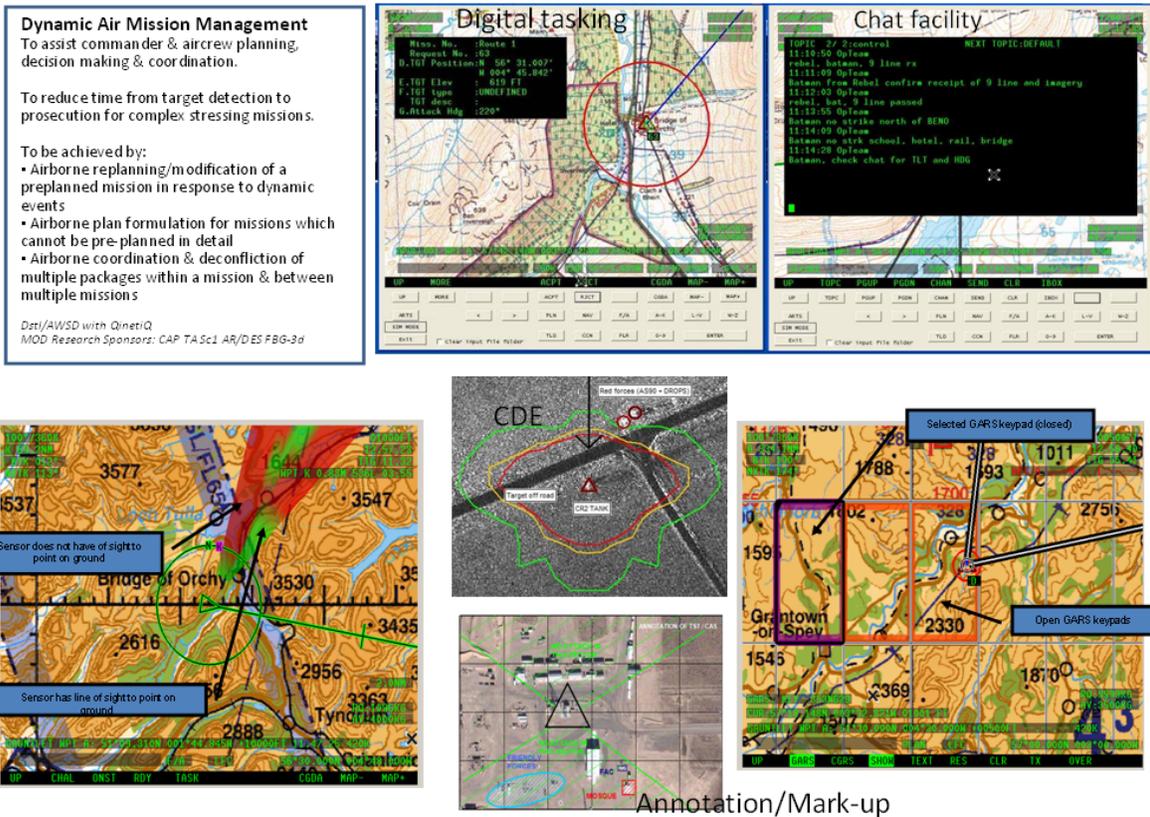
In terms of Technology Readiness Levels (TRL), the RE314 MET&D research programme raised relatively low TRL, early concept prototype development work (TRL 1 – 3) to TRL 5 by demonstration in a representative SE environment. TRL 5 was the entry level for MMS technology insertion into the DAMM CCD programme for flight trial demonstration and for raising to TRL 7.

The DAMM sub-system spans the Operational and Tactical C2-MM layers. DAMM is based on a three tier C2-MM architecture designed to provide sensible and adaptive spans of control needed for tight dynamic tactical co-ordination. The three tiers differ in the roles and functionality provided, and the kinds of decision support tools needed. The three tiers and associated tools are identified as follows:

- Tier 1 Operational C2 Level – Ground (e.g., CAOC) or airborne (e.g., AWACS E-3) C2 nodes: OpTEAM – Operational Task Evaluation and Authorisation Manager.
- Tier 2 Tactical C2 Level – Mission Commander, Package Commander: TacTEAM – Tactical Task Evaluation and Authorisation Manager; DESCAT – Digital Exchange System for Control and Targeting FAC equipment.
- Tier 3 Effector Levels – Flight formation members: TDSS – Tactical Decision Support System; OMPS – Rotorcraft TDSS On-board Mission Planning System; UAS Ground Control Station (GCS).

OpTEAM, TacTEAM and TDSS comprised different sets of DAMM MMS networked SA tools, collaboration aids and Decision Support System (DSS) techniques, as needed for supporting tactical co-ordination and decision making at the three tier levels. Examples of the DAMM tools are illustrated in Figure 13-3.

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*Images courtesy of QinetiQ Farnborough, Airborne Mission Management*

**Figure 13-3: Examples of DAMM Networked SA Tools, Collaboration Aids and Decision Support System Techniques.**

OpTEAM provided the Tier 1 Operational C2 layer (CAOC/AWACS E3) with the following tool features (Figure 13-4):

- Map display; multiple map types; zoom options; lat long read out, distance measures and unit conversion; cultural, aeronautical and tactical overlays; multiple display options (e.g., de-clutter); inter-visibility analysis; the ability to create and review mark-up.
- Datalink capability (real and simulated); ATO and ACO import and display (along with other IER data feeds); digital Global Area Reference System (GARS) airspace de-confliction and management; chat facility; current position of assets; positions of threats, targets, forces, and wingmen.
- Routing information (for multiple assets and packages); route editing capability; route de-confliction; route timing information; route rehearsal and three dimensional (3D) fly through.
- Aircraft status; predicted fuel levels and tanking plans.



**Figure 13-4: OpTEAM Supported Airborne Warning and Control SE Flying Desk.**

Under DAMM CCD, Thales Air Systems Division provided an advanced web-enabled solution for OpTEAM C2 based on their WebS<sup>2</sup>AT product with ATO/ACO visualisation, supplemented by the Recognised Air Picture (RAP) and feeds from the Joint Operation Picture (JOP).

The following tool features were provided by TacTEAM at the DAMM Tier 2 Tactical C2 layer, and by TDSS/OMPS at the DAMM Tier 3 effectors layer (TFJ, RW) (Figure 13-5):

- Moving map display; multiple map types; zoom options; cultural, aeronautical and tactical overlays; multiple display options (e.g., brighten/dim screen, or show hide wingmen routings); the ability to review mark-up; inter-visibility analysis.
- Datalink capability (real and simulated); digital tasking; Planned Position Location Indication (PPLI); positions of threats, targets, forces, and wingmen.
- Routing information (for multiple assets and packages); route editing capability; route timing information.
- Aircraft status; chat facility; tactical decision support; Collateral Damage Estimation (CDE) visualisation and assessment.



**Figure 13-5: TacTEAM Supported TFJ Weapons System Officer SE Flying Desk.**

DESCAT 2 (Digital Exchange System for Control and Targeting) was provided to support the Forward Air Controller (FAC) or Joint Terminal Attack Controller (JTAC), operating at DAMM Tier 2 Tactical C2 layer (Figure 13-6). DESCAT 2 facilitated digital communications between ground and air assets, specifically the designation and allocation of targets to assets via the 9-line brief. The system capabilities and Windows XP-based user interface provided the following tool features and functions:

- Raster map display; Digital Terrain Elevation Database (DTED) terrain database height information; multiple map types; zoom options; multiple display options (e.g., brighten/dim screen, de-clutter); lat long read out, distance measures and unit conversion; tactical overlays; receipt and display of imagery, representative of UAS ROVER capability; ability to create and review mark-up; route forwarding; Collateral Damage Estimation (CDE) visualisation and assessment.
- Improved Data Modem (IDM) data-link protocols (TACFIRE, AFAPD, VMF), real and simulated; digital 9 line tasking; receipt, display and transmission of PPLI; positions of threats, targets, Blue forces; aircraft status, e.g., altitude; indirect target mensuration with GPS and Laser Rangefinders interfaces.
- C2 control interfaces with Joint Automated Deep Operations Co-ordination System (JADOCS) and Cursor On Target (COT) XML message set; local control, receipt, display and transmission of digital Global Area Reference System (GARS) airspace de-confliction and management messages; chat facility.



**Figure 13-6: DESCAT 2 Supported FAC/JTAC.**

Under the auspices of the US-UK NCSC / Strike Warrior II PA IRC programme, USAF AFRL provided the JTAC/FAC Battlefield Air Targeting Man Aided kNowledge (BATMAN) system for DAMM SE integration and testing with DESCAT 2. The BATMAN Bareback software application provided an electronic 9 line capability, with target data input via Laser Range Finder (LRF) or manually, using Speech Software with voice feedback, and friendly data input via Global Positioning System (GPS) or manually, with digital data transmission to CAOC. The BATMAN system provided operator aiding via Falconview mapping and terrain visualisation, with decision support information for the Special Tactics (ST) operator, and UAV tools. The system included a 3D audio and DRAW mark-up research capability.

UAS GCS, based on UK Watchkeeper (WK) Tactical Unmanned Air Vehicle (TUAV), provided the following functions and capabilities at DAMM Tier 3 Effectors layer (Figure 13-7):

- Moving map display; multiple map types; zoom options; cultural, aeronautical and tactical overlays; routing information (for multiple assets and packages); route editing, timing information, and route following capability; inter-visibility analysis; mark-up; multiple display options (e.g., brighten/dim screen, co-operating platforms routes); route assessment tools, e.g., threat envelopes, airspace constraints; target mensuration.

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- Datalink capability (real and simulated); digital tasking; Planned Position Location Indication (PPLI); positions of threats, targets, forces, co-operating platforms; aircraft status.
- Real-time sensor video; sensor footprint overlay; vehicle controls, e.g., camera guide mode, auto-track mode.



**Figure 13-7: UAS GCS Based on WK TUAV.**

Current UAS operate as single platforms under Remotely Piloted Vehicle (RPV) control. With more autonomous UAS systems, it is likely that the operator will be controlling multiple UAVs, using for example a goal-oriented, service request-based approach. A multi-UAS GCS operator could be considered as operating more at the DAMM Tier 2 Tactical C2 layer.

A C2-MM capability scale was used to summarise the technologies involved and the impact of capability enhancement, as shown in Table 13-1 below. This capability maturity scale provides levels coupling network communications and collaborative decision support technologies and interfaces for C2-MM. The DAMM programme spanned Level 2 (DAMM Baseline architecture) to Level 4/5 (DAMM Objective architecture).

**Table 13-1: Levels of Capability Maturity for C2-MM.**

<b>C2-MM Capability Level</b>	<b>Communications</b>	<b>Mission Management Decision Support</b>
1	Voice Radio	No onboard integrated planning tool – Aircrew unsupported (re-planning and reactive)
2	Legacy Data Link (Limited message set)	Limited or no onboard planning aid, limited or no onboard collaboration tools, co-ordinated planning and co-ordination by voice
3	Legacy Data Link (Enhanced Message Set (EMS))	Intra-flight MM, adaptable decision support, co-ordinated machine-machine planning within package
4	Legacy Data Link (EMS)	Inter-flight MM within and across missions, adaptable decision support, fully integrated with operational C2 (year 1 DAMM)
5	Legacy Data Link (EMS) 5 <sup>th</sup> -Generation Capability	Full adaptive/adaptable MM, dynamic battle management supported by (limited by) legacy data link. Cross-domain (air and land) dynamic co-ordinated planning.
6	Advanced Data Link	As above, but high capacity ad hoc network, agility, scale, richness
7	Advanced Data Link	As above, with pro-active Decision Support System

### **13.5 HUMAN FACTORS ISSUES EXPLORED**

DAMM enables the provision of capability that is efficient and effective in a complex dynamic tactical environment. Complex high tempo operations, such as TST, CAS, SEAD and JPR, require persistence and urgency, and need rapid co-ordination and collaboration, both within and between mission packages, to deliver complex effects and ensure mission success. Critically, a DAMM collaborative capability is needed to provide operational flexibility, versatility and adaptability, enabling responsiveness to rapidly changing mission requirements and dynamic events, such as re-tasking or threat changes. A collaborative and adaptive DAMM capability requires important Mission Essential Competencies (MEC), involving interpretation of command intent, rapid situation assessment, re-planning and communication, all with decision making for decision superiority at the core. Thus, the main Human Factors (HF) research thrust under DAMM was improving Critical Mission Decision Making (CMDM) in a distributed, collaborative, adaptive environment.

The HF issues of primary interest concerned understanding the requirements for aircrew interactions and interfaces needed for improving collaborative CMDM, and the development of applicable analytical tools and techniques for DAMM requirements capture, design, development, testing and evaluation. The focus was on the Operator-Mission Interface (OMI), and on the mission system functional and cognitive requirements, rather than on HMI ergonomics. Relevant OMI issues included the following: mission plan co-ordination and critiquing;

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the centralisation, distribution and hierarchical structure of mission command flows; the communication and interpretation of command intent; prioritisation of mission critical decision information.

Specifically, the HF issues explored under DAMM were concerned with the following: developing HF methods for capturing user functional and information requirements for OMI CMDM in a distributed networked environment using SE technical demonstration testing and flight trials; modelling and measurement of the effects of highly networked MMS mission enabling technologies OMI, and associated collaboration and decision support tools, on CMDM; understanding and supporting CMDM processes at the tactical level, with cross-capability applicability, and within the broader system-of-system and C2 context; understanding the impact of C2-MM technologies on Mission/Tactical Director (TD), Mission Commander (MC) and Package Commander (PC) roles and responsibilities, and Mission Essential Competencies (MEC).

Requirements for CMDM processes involved in DAMM task MECs needed investigation, such as the following 9 CAS/TST examples:

- 1) Formulation, approval and dissemination of 9 Line;
- 2) Task allocation;
- 3) Weapon target matching;
- 4) EOB update;
- 5) Dissemination of EOB change;
- 6) Re-plan of tactical level assets;
- 7) Battle Damage Assessment (BDA) / Battle Damage Identification (BDI);
- 8) Re-attack decision; and
- 9) Accept re-strike.

Throughout the DAMM demonstration programme, trial planning and analysis prioritised the identification of scenarios and vignettes with operationally significant CMDM events and triggers. This was to provide valid and relevant use cases for testing the DAMM CMDM tools in a realistic operational context, with current SOPs, ROE, CONOPS, and C2 system architectures.

So, the HF challenge was to develop and exploit HF frameworks and protocols appropriate for highly networked, distributed, collaborative, adaptive DAMM CMDM assessment, and to support modelling and measurement of DAMM CMDM to improve utility and scientific robustness, i.e., improved validity and reliability, sensitivity and discrimination, diagnostic and prognostic power.

Development of DAMM capability, and development of the DAMM CMDM assessment approach, needed to be sensitive to the following: mission context, particularly the changing conditions on the ground; command intent and ROE; exchange of relevant SA information.

DAMM capability development needed to deliver timely Network Enabled Effects in response to dynamic events, such as the following: reducing time from task nomination-to-effect delivery; reducing the time from target detection to prosecution; co-ordinated and planned Time On Target (TOT exchange); accuracy and precision in CDE and BDA/BDI.

Development of the DAMM CMDM assessment approach needed to improve requirements capture and analysis, and improve assessing the effectiveness of collaborative decision support tools. Applicable methods

considered included: models and metrics for individual, team and organisational decision making; C2 Measures of Performance (MoP); C2 Measures of Effectiveness (MoE); system-of-systems views and system architecture representations of decision making derived from MODAF/DODAF system architect tools.

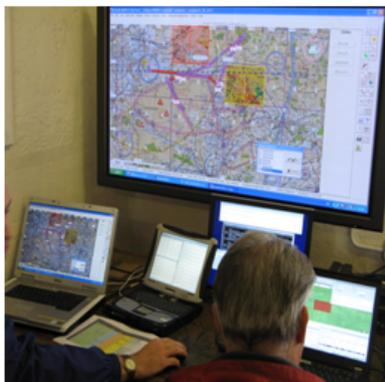
The strategy for DAMM CMDM assessment development was to extend traditional HF metrics of speed and accuracy, SA and workload, and to develop models and metrics of decision quality, teamwork and C2-MM system effectiveness, such as dynamic efficiency.

### **13.6 UNMANNED SYSTEMS USED**

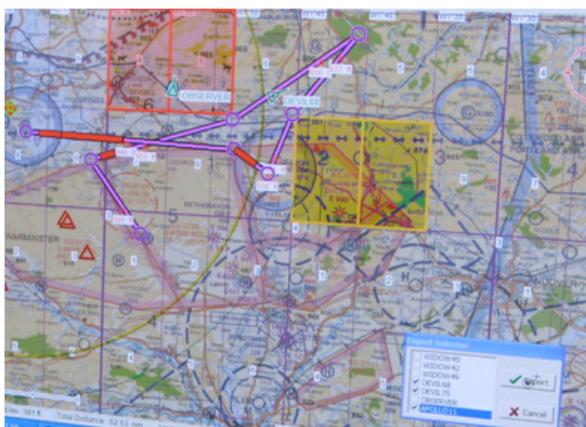
The DAMM research programme informed understanding of the requirements for current and future autonomous UAS to support DAMM capability. In particular, the work sought to understand the implications of UAS for the DAMM architecture, CONOPS and SOPs. Integration of UAS requirements into the DAMM architecture commenced in September 2010 under Phase 3 of the programme. In Phase 3, a UAS capability and GCS was integrated into SE work, and associated MMS into the DAMM architecture, based on the UK WK TUAV.

Thales is the primary UK supplier of UAS capability in-theatre. Currently, this is in the form of standard Hermes 450 air platform under the Lydian programme working closely with Sea King ASaC. This is coupled in-theatre with RAF operated, General Dynamics supplied, Predator/Reaper air platforms. Hermes 450 is soon to be replaced by the Thales WK system. Thus, WK will become a significant element of the UK's ability to provide ISTAR in-theatre. Currently, the contracted WK system includes an Improved Data Modem (IDM) data link, and ROVER video down-link. Building on this WK sensor and data link capability, the DAMM system sought to provide further digital networked co-ordination between WK and C2 assets (E3 AWACS), other tactical air platforms (RW Support Helicopter (SH) and Attack Helicopter (AH); FW TFJ strike aircraft), and FAC/JTAC air-land integration assets. WK with DAMM enabled capability has the potential to provide in-theatre real-time ISTAR, including cross-cueing of one asset from another using DAMM digital messages, enabling rapid and accurate dissemination of sensor tasking between assets, shortening reaction times, enabling more contacts to be investigated, and effects to be delivered more rapidly, with potentially life saving consequences. The work demonstrated co-ordinated mission planning and execution between manned and unmanned platforms as part of complex missions. The simulated WK TUAV with IDM data link provided ISTAR capability including the cross-cueing of one asset from another, using digital messages, and investigation of the utility of direct Full Motion Video (FMV) feeds from WK with ROVER video down-link (Figure 13-8). This final phase of the DAMM programme continued to progress TFJ to RW integration, as well as air-land integration through FAC/JTAC capability. Op-TEAM, Tac-TEAM and platform MMS incorporated additional tactics required to conduct Phase 3 missions with UAV elements.

**C2 E3/AWACS OpTEAM**



**UAV GCS**



OpTEAM shows DEVIL 68 Lynx SH helicopter operating on route between two sets of GARS boxes  
 Observer UAV PPLI is shown operating within northern pair of GARS boxes. Threat is update ready for export.  
 UAV provides virtual RVT BDI of 2 Technicals post strike, with ID of location of 3rd target vehicle for FJ re-strike

**Figure 13-8: C2 Co-ordination of RW Support Helicopter, UAV and Fast Jet.**

In parallel with WK TUAV GCS integration, under the auspices of the US-UK NCSC / Strike Warrior II PA International Research Collaboration (IRC) programme, USAF AFRL provided the Multi-UAV Supervisory Control Interface Technology (MUSCIT) Vigilant Spirit GCS and UAS system for integration and testing in the DAMM SE environment. This was used for investigation of advanced UAS capabilities and concepts in the RE314 MET&D UAS Integration SE Trial, July 2011 (Figure 13-9). MUSCIT / Vigilant Spirit is a single operator/multiple TUAV (x4) system, providing UAS ISTAR capability using a goal-oriented, service request-based approach to the provision of imagery. The MUSCIT / Vigilant Spirit GCS delivers UAS imagery on-demand through real-time sensor feeds to individual DAMM assets. Individual TUAVs providing the sensor feeds are managed by the GCS, through routing optimisation processes that are transparent to the originators of service requests. By introducing this supervisory control approach for a multiple TUAV system, compared with UK WK TUAV GCS, the integration of the USAF AFRL MUSCIT / Vigilant Spirit UAS GCS through IRC enabled the DAMM research programme to investigate the effects of UAS GCS working more at the DAMM Tier 2 Tactical C2 layer.



**Figure 13-9: USAF AFRL MUSCIT / Vigilant Spirit TUAV GCS in DAMM SE.**

The focus of the DAMM programme was on de-risking near-term UAS exploitation. In a complementary research activity, briefed and demonstrated to NATO HFM-170, MOD/Dstl sponsored a joint Industry advanced UAS research programme with QinetiQ, BAES and Thales entitled Autonomy and Mission Management (A&MM). The A&MM research programme investigated advanced UAS concepts for airspace and mission management with a focus on relatively low TRL development. The A&MM programme covered integration of tactical UAV (Thales WK TUAV) and operational UAV (BAES MANTIS OUAV) capabilities, and included the QinetiQ Task Execution Framework (TEF) for increasing UAV autonomy of heterogenous UAS ISTAR assets. The TEF approach uses goal-based tasking, “person-to-purpose” HMI, and agent oriented software-based planning solutions for optimised task allocation, co-ordination and routing. In this A&MM work, a Service-Oriented approach to the provision of UAS services is investigated, moving away from current process of tasking specific sensors/weapons on specific platforms to collect intelligence or deliver effects, and moving towards a more ‘Internet Protocol cloud-based model’. A&MM programme aspirations include the integration of autonomous software on the European Common Operating System (ECOS) architecture, and the development of a common ASAC three-layer stack architecture (Hardware, Common Operating System and Applications layers) for UAS control.

### **13.7 SUMMARY OF ANY NATO COMMUNICATIONS/COLLABORATIONS/ INTERACTIONS**

The DAMM research programme focuses on UK specific requirements. Reports on DAMM status and progress were routinely communicated to NATO through HFM-170 meetings. Involvement of NATO Nations occurred at a number of levels.

*US AFRL* – Direct US involvement under RE314 underpinning SE work has been achieved through bilateral US-UK NCSC / Strike Warrior II PA, between MOD Dstl and US AFRL 71/HPW/HEC/Warfighter Interface Division, based at Wright Patterson AFB, Dayton Ohio. This provided integration of AFRL capabilities into three RE314 MET&D US-UK Strike Warrior II SE Trials, including Multi-Modal Communications (MMC), 3D spatial audio, US JTAC Batman capability imagery mark-up enhancements, and UAS MUSCIT Vigilant Spirit GCS.

Under HFM-170, discussions on DAMM UAS planning, concerning supervisory control and HF assessment issues, have been held with AFRL 711/HPW/RHCI (Dr. Mike Patzig / Dr. Mark Draper) on the MUSCIT programme and Vigilant Spirit GCS. This was supported by the MUSCIT multi-UAV (x4) flight demonstration at Camp Atterbury, Indiana on 5 May 2010.

US-UK PA collaboration facilitated by HFM-170 discussions, led to successful integration of MUSCIT / Vigilant Spirit GCS capability into the RE314 MET&D 3<sup>rd</sup> US-UK Strike Warrior II UAS Integration SE Trial, July 2011. US-UK IRC enabled the DAMM research programme to investigate the effects of UAS GCS supervisory control working at the DAMM Tier 2 Tactical C2 layer.

A new PA on UAS, entitled “Monitoring and Controlling Multiple Assets within Complex Environments” (MC-MACE), has been developed between AFRL 711/HPW/RHCI and MOD Dstl, lead by Brian Donnelly / Dr. Mark Draper (US) and Robert Taylor / Antony Grabham (UK). The MC-MACE PA is a multi-Nation programme of co-ordination under The Technical Co-operation Programme (TTCP), Human Resources and Performance (HUM) Group, Technical Panel 7, Human Systems Integration – Air. This TTCP HUM TP7 PA will provide increased international research collaboration on UAS programmes involving DRDC Canada and DSTO Air Operations Division, Australia, in addition to US and UK. The PA will support new UK work on Autonomy and Mission Systems, focussing on manned-unmanned teaming issues, including autonomy and mission management, collaborative autonomy and cohesive collaborative control capability.

*US Army / NASA* – US Army / NASA (Jay Shively) provided advice on RW scenarios, Playbook and UAS issues for the RE314 US-UK Strike Warrior II SE Trials, at a planning meeting held in San Francisco, USA in May 2009.

*Sweden FOI* – Discussions with Sweden FOI FLSC and UK MOD/Dstl under the UK-SWE MOU, and supported by HFM-170, have led to planning of a joint UK-SWE project (Project CODE) on distributed mission simulation and synthetic training with Live Virtual Constructive (LVC) capability. A meeting between MOD Dstl (Bob Taylor / Ebb Smith / Robert Anderson) and FOI FLSC (Jonathan Borgvall / Lars Kristensson / Martin Castner) was held at FLSC on 3-4 March 2010 to develop scenario vignettes. The scenario will involve network linking of SE facilities at FLSC Stockholm with the UK MOD Air Battle Training Centre (ABTC) at RAF Waddington. The first UK-SWE Exercise SNOWSTORM is planned for June 2011. SNOWSTORM will focus on synthetic training requirements for operational DAMM capability.

*France DGA / Telecom Bretagne* – Arising from meetings under HFM-170, bi-lateral meetings between UK and France on DAMM UAS capability and HF research requirements, have been held in UK (4 December

2008, Farnborough) and France (1-2 April 2009, Brest) between Institut Telecom / Telecom Bretagne (Dr. Gilles Coppin) and France MOD/DGA (Mr. Didier Bazalgette) and UK MOD/Dstl (Robert Taylor / Antony Grabham). In parallel, a joint Anglo-French research programme on Autonomy and Mission Management has been agreed commencing 2010. The aim of this collaboration is to ultimately develop a joint SE capable of allowing dissimilar UK and French autonomous UAS to interoperate within the simulated battlespace to carry out multiple missions controlled by a limited number of operators.

*Australia DSTO AOD* – Under the auspices of TTCP (HUM TP7/TP2), DSTO Australia, Air Operations Division (POC Dr. Chris Best) had direct involvement in the RE314 MET&D 2<sup>nd</sup> US-UK Strike Warrior II SE Trial, September 2010, working with MOD Dstl and US AFRL 711/HPW.

Understanding of the implications for coalition and NATO joint operational requirements are potentially of interest for future work. The main area for NATO involvement was in the planning and design stages of the demonstration activities, with possibilities for involvement in analysis, as summarised in Table 13-2. There was potential for collaboration with NATO Nation’s related efforts at the level of aims, objectives, approach, CONOPS, metrics, architectures, and in particular the application of HF lessons learned.

**Table 13-2: NATO Collaboration for DAMM CCD.**

	<i>Planning/Design</i>	<i>Execution</i>	<i>Analysis</i>
<i>Communication</i>	<i>x</i>	<i>x</i>	<i>x</i>
<i>Co-ordination</i>	<i>x</i>		<i>x</i>
<i>Collaboration</i>	<i>x</i>		<i>x</i>

In practice, NATO Nation’s direct involvement in the execution of DAMM activities was difficult to achieve, due to the constraints, funding arrangements and complex nature of the project, and the UK specific requirements. Nevertheless, the DAMM network interfaces were considered ‘open’, and as such, NATO Nations could bring elements for integration into future demonstration activities. Collaboration through an SE trial is probably more readily achievable than through a joint flight trial.

## **13.8 SUMMARY OF DAMM UAS TECHNOLOGY DEMONSTRATION RESULTS**

### **13.8.1 RE314 MET&D Joint US-UK SE Trial, September 2010 – FW TFJ and RW AH/SH Inter-Flight Co-ordination with FAC/JTAC, C2 and UAS**

A 2<sup>nd</sup> in a series of Joint DAMM SE Trials was conducted with USAF AFRL at QinetiQ Farnborough in September 2010, under the US-UK NCSC / Strike Warrior II PA, with the aim of increasing Air-Land integration, and providing further development of collaboration performance measurement. This trial introduced a nominal synthetic UAS component for future capability development. The trial involved USAF aircrew and UK MOD serving military operators, with additional military participation provided by DSTO AOD Australia, under TTCP collaboration. The scenario was based on the previous FW/RW/C2 SE Trial, under Joint Warrior conditions, with increased FAC/JTAC involvement, and a nominal UAS reconnaissance capability. The expanded scenario comprised the following elements:

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- 1 AWACS E3-D Airborne C2 with OpTEAM;
- 2/3 FAC/JTAC with digital targeting technology (DESCAT and/or BATMAN);
- 2 FW TFJ Ground Attack aircraft with TacTEAM/TDSS – one single seat aircraft emulating Typhoon capability (FWSS), and one twin seat aircraft emulating Tornado GR4 (FW2S);
- 2 RW aircraft – one RW AH and one RW SH – both operated by two aircrew with standard avionics (Baseline), stand-alone DIGIMAP (Threshold) or networked OMPS Technology (Objective); and
- 1 Reconnaissance UAS – Platform not represented but simulated sensor feeds provided via network to different nodes depending on Baseline, Threshold or Objective.

White Force Trial Control was provided with networked OpTEAM as SA and trials management tool. Functionality and networking varied depending on Baseline, Threshold or Objective. The trial aim was to examine the effects of C2-MM architectures and MC positions on crew decision making. Based on the Joint Warrior NDZ scenario, the missions involved a series of unexpected events requiring re-planning and mission critical decisions. These provided discrete decision making points for CMDM assessment. The geographic location was centred on the Invergarry / Fort Augustus / Loch Lochy area north-east of Fort William and Ben Nevis. The scenario involved co-ordination between land component and air component commanders prosecuting CAS missions and Time TST within a coalition context where coalition partners are undertaking pre-planned missions. Due to dynamic events, cross-co-ordination between the CAS/TST missions and the pre-planned missions that were originally under a separate AOR becomes necessary. The trial sought to improve understanding of the effects on mission command flow and locus of critical mission decision making, such as the balance of centralized versus distributed decision making.

The trial followed an experimental plan designed to test and compare three alternative C2-MM architectures – Baseline, Threshold and Objective – and three positions for Mission Commander (MC) – C2, RW (AH), FW (SS and 2S) – with nine combinations of C2-MM architectures and MC positions operating over three days, with three different runs per day. The scenario was controlled by White Force and developed progressively during the trial runs in phases using three mission vignettes. Different events, threats and target behaviours were produced by WF, designed to maintain operator engagement and mitigate learning. Performance with the Baseline architecture was tested on the first trial run. The comparison architectures were tested on subsequent runs (Threshold x 3: Objective x 4), with the order balanced to control for learning.

DSTL SMEs provided assessments of performance and effectiveness based on identified CMDM critical decision points. These were obtained during post-run de-briefing sessions from participant self-ratings and SME observer scoring. Subjective ratings (7-point Low-High anchors, Likert scales) were obtained for 66 trial parameters in total. These comprised 21 participant CMDM self-ratings for identified critical decisions including REMDAER activity phase demand, 4T's change management demand, workload, SA and decision quality. For individual trial runs, participant ratings were obtained for tools usability (x19), and for generic system CONOPS and architecture assessment parameters (x12), including dynamic mission efficiency, teamwork and technical system performance. Additionally, ratings were obtained from SME observer on 14 assessment scales covering workload, decision making, dynamic efficiency and teamwork. Teamwork metrics included estimations of collaboration power and collaboration correlation, and new higher order measures of team collaboration co-efficiency, dynamic efficiency, and team adaptability proficiency. DSTO AOD conducted an independent assessment complementary process, including a CAS SME continuous assessment of CAS performance, captured on-line using a digital tablet-based protocol, and administered validated self-ratings of CAS Taskwork, Team Workload and Teamwork during post-run de-briefing.

Statistical analysis (ANOVA) of the DSTL assessment subjective ratings showed significant effects ( $p < 0.05$ ) of the Baseline (B), Threshold (T) and Objective (O) architectures as follows:

- Activity phase demand: Mitigation (B<T); Dissemination (B<OT)  $p < 0.05$  (NB Evaluation (B<T)  $p < 0.09$ ; Acknowledgement (B<T)  $p < 0.08$ ).
- 4T Change demand: Task, Threat (B<OT)  $p < 0.01$ .
- Workload: Time pressure (B<OT)  $p < 0.01$ ; Mental effort, Stress (B<T)  $p < 0.05$ .
- SA: Understanding (T<O)  $p < 0.01$ .
- DQ: Confidence (T<O), Effectiveness (BT<O), Timeliness (B<TO)  $p < 0.001$ .
- Dynamic Efficiency: Reward/Effort (T<O), Rate (B<O)  $p < 0.05$ ; Sustainability (BT<O)  $p < 0.001$ .
- Team Work: Co-ordination, Co-operation, Collaboration, Communication, Leadership, Power (BT<O)  $p < 0.001$ .
- System: Confidence (T<O)  $p < 0.01$ ; Reliability (B<O)  $p < 0.05$  (NB Usability (T<O)  $p < 0.07$ ).

In summary, there was some evidence that Baseline architecture evoked lower ratings of activity phase and change demand, and workload. Importantly, there was very strong evidence that the Objective architecture evoked significantly higher ratings of SA, DQ, Dynamic Efficiency and Team Work. The consistently high ratings for Team Work with the Objective architecture were the strongest differentiator from the Baseline and Threshold architectures. This is evidence that the enhancement of collective effort afforded by advanced DAMM technology is probably the strongest factor underpinning the improvements in adaptability proficiency and performance.

The results of the DSTL assessment contrasting the individual trial runs are summarised in Table 13-3 below. Improved adaptability proficiency, followed by improved dynamic efficiency, is hypothesised as directly underpinning improvements in performance and effectiveness on dynamic missions. Guided by this assertion, in Table 13-3, the data for the individual eight trial mission runs are presented in the position order (P 1-8) of the adaptability proficiency ratings provided by White Force SME assessors. The summation total of the adaptability proficiency ratings are reported first, followed by with the number of observations contributing to the total. Then, target performance (+ve/-ve) is shown, followed by an estimation of Decision Flow (Decision points, run time, decision tempo), Dynamic Efficiency (SME Observer and Participant ratings means), and Collaboration Co-efficiency (Power and Correlation estimates). Trial runs with the Objective (OB) architecture occupied P1/2/3/4/6. Threshold (TH) architecture runs are at P5 and P7. The Baseline (BA) architecture tested on Run 1 provided the lowest adaptability proficiency ratings and thus was positioned at P8. The pattern of adaptability proficiency results are generally supported by the metrics of decision flow, dynamic efficiency and collaboration co-efficiency. Run order, with associated learning effects, and Architecture condition, were partially confounded. Notwithstanding, the pattern of results overall is consistent with superiority for the Objective architecture. The pattern of target performance scores is complex and less clearly related to the architecture condition. Four MC positions were tested: FWSS; FW2S; RWAH; E3. MC position was partially confounded with architectures and run order. The effect of MC position on adaptability proficiency was complex. The MC role requires good communications and SA. On aggregate, based on adaptability proficiency, the FW positions appeared most favoured, and the E3 the least favoured positions (FWSS P1/6; FW2S P2; RWAH P3/7; E3 P4/5/8). The Objective architecture provided relatively good adaptability proficiency with the MC in all four positions, consistent with good communications and SA. Evidence from specific events and interventions on individual runs showed benefits of distributed and adaptive decision making, afforded most by the networked Objective architecture.

**Table 13-3: Summary of Results from the 2<sup>nd</sup> US-UK NCSC / Strike Warrior II SE Trial.**

P	Mission	Adaptability Proficiency		Targets		Decision Flow			Dynamic Efficiency		Collab Coeff	
		Total	Obs	+	-	Pts	Time	Tmp	Obvr	Part	Pwr	Corr
1	OB-FWSS-V3-R8 Bridge Stop West	48	8	4	0	36	26:00	0.43	6.00	5.43	5.71	5.05
2	OB-FW2S-V3-R7 Ugly North South	46	7	3	2	23	21:15	1.22	6.00	5.78	6.00	6.27
3	OB-RWAH-V3-R5 Late West	39	6	5	0	23	32:30	1.25	6.00	5.11	5.56	5.82
4	OB-E3-V2-R4 Bridge Stop North	27	4	4	0	18	28:00	1.33	5.80	5.37	5.62	5.85
5	TH-E3-V3-R6 Wrong Bridge	25	6	3	2	25	34:00	1.22	4.00	4.33	3.67	4.96
6	OB-FWSS-V2-R2 Pick-up JTAC	24	4	4	1	12	34:35	2.53	5.80	4.87	5.37	6.85
7	TH-RWAH-V2-R3 Support TIC	25	4	4	0	13	41:45	3.12	5.60	5.12	5.12	5.37
8	BA-E3-V1-R1 Abort Hard Stop	7	3	2	2	14	26:15	1.52	4.80	4.62	4.12	4.42

### 13.8.2 DAMM CCD UAS SE Technical Demonstration, April 2011 – UAS Co-ordination with RW SH, FW TFJ, C2 and FAC/JTAC

Under DAMM CCD Phase 3, work was undertaken with Thales to develop a UAS reconnaissance capability for integration and demonstration in DAMM trials, based on the UK WK TUAV, thereby de-risking near-term UAS exploitation of DAMM capability. Thales provided a representation of the WK GCS and a representation of the WK Full Motion Video (FMV) feed using a Remote Viewing Terminal (RVT) for demonstration at QinetiQ in a fully immersive environment. The UAS demonstration scenario was based on the Joint Warrior NDZ scenario used for the 2<sup>nd</sup> Joint US-UK SE Trial, centred on the Invergarry / Fort Augustus / Loch Lochy area of Scotland. The scenario involved a pre-planned deliberate operation, with a High Value Target (HVT) meeting at a known site, RW SH inserted capture, and a co-ordinated FW TFJ strike on arms cache. The assets and tasking were for a WK UAS over-watch on meeting site, FAC/JTAC control of FW TFJ strike, RW SH inserts ground forces to effect capture, FW TFJ time co-ordinated to attack while RW SH on ground, and C2 overall co-ordination and control. The DAMM mission enabling tools involved were OpTEAM, TacTEAM/TDSS, OMPS and WK GCS. The following event flow was successfully demonstrated in the QinetiQ SE facilities:

- Initial asset disposition as pre-plan, GARS airspace pre-allocated.
- HVT arrives, 3 vehicles scatter – WK reports to C2; HUMINT reports SIED north, HVT west, Arms transfer south.
- C2 calls abort – RW to hold; TFJ to hold; FAC/JTAC relinquishes airspace.
- C2 re-tasks WK to follow SIED – WK re-plans; WK publishes route.
- C2 re-plan – C2 assigns WK airspace; C2 re-tasks RW to pursue/stop SIED; C2 re-tasks TFJ to delay/obstruct HVT.
- Assets execute re-plan – Shared SA through GARS, route, PPLI enables distributed re-planning and co-ordination of individual taskings.

In a second phase of work, the QinetiQ HOVERS SE was used to demonstrate the UAS RVT supporting representative RW SH operations in an immersive environment, with the Joint Warrior NDZ scenario centred near Fort Augustus, north of Loch Lochy in Scotland. In the UAS RVT demonstration, the RW SH operated with serving military aircrew, was tasked with short movement of ground troops to a known Landing Site (LS) to create and man a temporary road block, searching for small-scale movement of arms caches. Insurgents were known to have 4 armed “technicals”. In the event, a moving vehicle departed the road, and arrived at the LS, co-incident with a White Force SAFIRE inject causing an RW SH direction change en route close to the LS. Two runs trial were flown, each with a pre-loaded route on an OMPS-based hand held DIGIMAP system. The first run was performed without the RVT capability. The second run was flown with the RVT capability. On the RVT run, a TUAV air vehicle, controlled from the WK GCS, was positioned to give a virtual RVT view of the LS. The participant aircrew assessments reported that Crew Resource Management issues concerning information interpretation were dependent on the individual aircraft receiving RVT, i.e., AH direct feed; RW SH to crewman or off-board UAS image analyst; live feed to SH embarked troops. It was considered that objective-based tasking (e.g., point sensor at location X) would most likely be more appropriate than attempting direct control of one or more UAS. Generally, SA was considered to be enhanced with live positional information from UAS in close proximity.

### **13.8.3 RE314 MET&D Joint US-UK SE Trial, July 2011 – Multiple UAS Co-ordination with RW SH, FW TFJ, C2 and FAC/JTAC**

A 3<sup>rd</sup> in series Joint DAMM SE Trial involving USAF AFRL was conducted under the US-UK NCSC / Strike Warrior II PA at QinetiQ Farnborough in July 2011, with a focus on multiple UAS co-ordination. USAF AFRL provided the MUSCIT / Vigilant Spirit multiple UAS system and GCS for DAMM SE integration and testing. The trial involved UK MOD serving military operators and USAF aircrew, including US and UK UAV operations specialists. The scenario comprised the following elements:

- AWACS E3 Airborne C2 with OpTEAM;
- 2 FAC/JTAC with digital targeting technology (DESCAT and/or BATMAN);
- 1 FW TFJ Ground Attack aircraft with TacTEAM/TDSS;
- 1 RW SH using an immersive simulator (HOVERS) with networked DIGIMAP; and
- 4 Reconnaissance UAS.

USAF AFRL provided 3D audio cueing capability for moving target designation by FAC/JTAC and UAS. White Force / Trial Control were provided with networked OpTEAM as SA and trials management tool.

The trial was based on Joint Warrior NDZ scenario operations centred on the Invergarry / Fort Augustus / Loch Lochy area of Scotland, with increased UAS involvement in observation and reconnaissance. The scenario involved a pre-planned deliberate operation, with a High Value Target (HVT) meeting at a known site, RW SH inserted capture, and a co-ordinated FW TFJ strike on arms cache. The assets and tasking were for a SF FAC observation and UAS over-watch on an adjacent urban area for known HVTs, in addition to the meeting site, FAC/JTAC control of FW TFJ strike, RW SH inserts of ground forces to effect capture, FW TFJ time co-ordinated to attack while RW SH on ground, and C2 overall co-ordination and control. Trial White Force inserted information, events, threats and target behavioural changes requiring real-time re-planning and co-ordination. The trial took place over a period of 5 days, following a 4 weeks of extensive technical development, integration, and system and SE testing, and progressive scenario refinement. After completion of role specific training, the trial runs were conducted in two phases, with the first phase comprising tool use-case

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vignettes and the second phase end-to-end scenario runs. All use cases and end-to-end runs involved active operator participation and decision making, post run de-briefing and performance measurement. DAMM tools were available for use on all the trial runs. The use-case runs provided additional training and focussed performance data on DAMM tool usage. Additionally, the use-case runs increased participant familiarisation with the DAMM tools applicability and benefits, in readiness for the end-to-end scenario runs. The scenario runs were developed progressively with changing and evolving complexity to maintain operator interest, engagement and to challenge DAMM competencies and tool usage. In total, 6 use-case vignettes and 4 end-to-end scenario runs were completed. The DSTL trial assessment included participant self-ratings and observer SME ratings obtained for use cases and end-to-end runs during post-run de-briefing sessions. Subjective ratings (7-point Low-High anchors, Likert scales) were obtained for 57 trial parameters in total.

Participants provided CMDM self-ratings on 17 parameters for individual identified critical decisions:

- Workload: WL Time Pressure, WL Mental Effort, WL Stress, Team Workload.
- Re-plan Task Load: Re-plan Decision (Recognise–Evaluate–Mitigate), Re-plan Action (Disseminate–Acknowledge–Execute–Report).
- Situation Awareness: SA Demand on Attentional Resources, SA Supply of Attentional Resources, SA Understanding.
- Decision Quality: DQ Confidence, DQ Survivability, DQ Effectiveness, DQ Timeliness.
- Performance: Task Performance, Tools Utility, Adaptability Proficiency, Probability of Mission Success.

Participants provided ratings on DAMM technical system performance for 25 items:

- Assessment of the relative usability of information and tools – 22 items in total divided into the 6 categories (Comms, Route, Position, SA, Task, UAS Services).
- Technical System General Performance: Confidence, Reliability, Usability.

Observer SMEs recorded observations and events with associated mission times, and provided ratings on the 15 parameters:

- Decision Quality: DQ Confidence, DQ Survivability, DQ Effectiveness, DQ Timeliness.
- Teamwork: Communication, Shared SA, Leadership, Support, Team Workload.
- Performance: Task Performance, Collaboration, Influence Power, Adaptability Proficiency, Probability of Mission Success.

Analysis of the results (ANOVA) comparing Observer and Participant ratings showed significant differences in the ratings of DQ Survivability, Effectiveness ( $p < 0.01$ ) and Timeliness ( $p < 0.05$ ), Adaptability Proficiency ( $p < 0.05$ ), and Probability of Mission Success ( $p < 0.01$ ), with significantly higher ratings provided by observers. Comparisons between ratings for decision events showed significant differences. Observer data showed significant differences between ratings of decision events within end-to-end runs for Shared SA and Team Workload ( $p < 0.05$ ), Adaptability Proficiency ( $p < 0.01$ ) and Probability of Mission Success ( $p < 0.05$ ). The Comparisons between the four end-to-end runs showed a pattern of higher ratings for the 2<sup>nd</sup> trial run. Overall, these results provide evidence in support of the use of Observer SME ratings.

Demand for UAS over-watch, reconnaissance and observation services varied continuously and reached high levels during dynamic phases and events. Deployment of the multiple UAS was stretched by the scenario.

Generally, the UAS were deployed effectively and efficiently via the MUSCIT / Vigilant Spirit GCS, with the UAV operator assessment ratings indicating good operator engagement and SA, and contributing significantly to maintaining mission SSA and command flow. Scenario emersion and workload was observed to be high for both the UAS GCS operator and JTAC/FAC. This was confirmed by AFRL-provided real-time physiological measures. Demand for UAS over-watch, reconnaissance and observation services varied continuously and reached high levels during dynamic phases and events. Deployment of the multiple UAS was stretched by the scenario. Generally, the UAS were deployed effectively and efficiently via the MUSCIT / Vigilant Spirit GCS, indicating high operator engagement and SA. UAS contributed significantly to maintaining mission SSA and command flow. Scenario emersion and workload was high for UAS GCS operator and JTAC/FAC. This was confirmed by AFRL-provided real-time physiological measures.

#### **13.8.4 DAMM CCD RW Flight Trial, August 2011 – RW AH and RW SH Co-ordination with FW TFJ, C2, UAS and Deployed FAC/JTAC**

This trial was an airborne demonstration of the Rotary Wing elements of previous RE314 SE trials with a deployed FAC/JTAC using the Joint Warrior SDZ operating out of AAC Middle Wallop and Westdown Camp. Two trial missions were flown as training sorties, followed by 4 trial sorties, flown with or without the networked architecture, conducted over a period of four days. This was followed by a fully networked visitor day demonstration. All trial runs involved DSTL provided performance measurement. The scenario involved the following components.

- 2 deployed RW Lynx aircraft with networked DIGIMAP;
- 1 deployed RW Apache AH (Day 4 only);
- 1 deployed FAC/JTAC with digital targeting technology (DESCAT);
- 1 simulated AWACS E3 Airborne C2 node with OpTEAM;
- 1 simulated FW TFJ Ground Attack aircraft with TacTEAM/TDSS; and
- 1 simulated Reconnaissance WK TUAV.

The DSTL provided trial assessment included participant self-ratings and observer SME ratings obtained during post-run de-briefing sessions. Subjective ratings (7-point Low-High anchors, Likert scales) were obtained for trial parameters using the protocols developed for the July 2011 Joint US-UK SE trial.

Participants provided CMDM self-ratings on 17 parameters for individual identified critical decisions:

- Workload: WL Time Pressure, WL Mental Effort, WL Stress, Team Workload.
- Re-plan Task Load: Re-plan Decision (Recognise–Evaluate–Mitigate), Re-plan Action (Disseminate–Acknowledge–Execute–Report).
- Situation Awareness: SA Demand on Attentional Resources, SA Supply of Attentional Resources, SA Understanding.
- Decision Quality: DQ Confidence, DQ Survivability, DQ Effectiveness, DQ Timeliness.
- Performance: Task Performance, Tools Utility, Adaptability Proficiency, Probability of Mission Success.

In addition, participants provided ratings of the relative usability on DAMM information and tools performance for 13 items in 6 categories (Comms, Route, Position, SA tools, Task).

Observer SMEs recorded observations and events with associated mission times, and provided ratings on the 15 parameters:

## **UK-1: DYNAMIC AIRBORNE MISSION MANAGEMENT**

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- Decision Quality: DQ Confidence, DQ Survivability, DQ Effectiveness, DQ Timeliness.
- Teamwork: Communication, Shared SA, Leadership, Support, Team Workload.
- Performance: Task Performance, Collaboration, Influence Power, Adaptability Proficiency, Probability of Mission Success.

In addition, SME observers provided ratings of the relative usability on DAMM information and tools performance for 13 items in 6 categories (Comms, Route, Position, SA tools, Task). Analysis of the trial results showed significant confounding of architecture conditions due to strong training/sortie order effects. Notwithstanding, for the networked sorties, there was evidence of a consistent pattern of lower workload ratings, together with significant improvements ( $p < 0.05$ ) in decision quality, team task performance, and adaptability proficiency. All the DAMM tools, apart from 1<sup>st</sup> Cut Time Distance Fuel and Route Timing Information scored very high on both Usability of Information and Tools and Utility of Functional Purpose.

In conclusion, the results of the trial provided high TRL evidence, proof and validation of the efficacy of the DAMM networked architecture and tools, of the DAMM principles, interfaces and interactions, and of the CONOPS and TPPs, integrated with a representative synthetic UAS reconnaissance capability component, through testing with real aircraft under realistic, live flight, operational mission conditions.

### **13.9 LESSONS LEARNED**

#### **13.9.1 Dynamic Airborne Mission Management**

Evidence from the UK MOD DAMM research programme of technical demonstrations and test and evaluation trials on advanced digital networking and mission enabling technologies provides robust verification and validation of DAMM principles, interfaces and interactions for delivering effects and providing stability and dominance in a dynamic environment. DAMM technologies and applications are shown consistently to deliver an efficient and effective distributed, collaborative and adaptive mission capability. In summary, the DAMM programme provides evidence of the efficacy of the following:

- Advanced digital network technologies, operating within a multi-tier C2-MM architecture with operational and tactical layers, provides the high capacity ad hoc networking with the agility, scale and richness needed to maintain mission and command flow through intra- and inter-flight communication, cross-domain (air and land) integration, and integrated operational C2.
- Mission enabling technologies, coupled with advanced digital networking, provide the tools needed for intra- and inter-flight mission management, cross-domain (air and land) dynamic co-ordinated planning, and dynamic battle management:
  - Airborne re-planning/modification of a pre-planned mission in response to dynamic events.
  - Airborne plan formulation for missions which cannot be planned in advance.
  - Airborne co-ordination and de-confliction of multiple packages with a mission and between multiple missions.

#### **13.9.2 UAS Integration**

MoD requirements for a UAS DAMM enabled capability are the need for flexibility, agility and persistence for over-watch support and targeting. To achieve these requirements, the following is needed:

- Ability to co-ordinate airspace and missions between manned and unmanned platforms.

- Ability to rapidly task UAS.
- Ability to rapidly exploit the output from UAS.
- Support improved Shared Situational Awareness (SSA) with UAS.

This involved the identification, specification, development and implementation of DAMM Information Exchange Requirements (IER) and Interface Control Documents (ICD) for UAS requirements for airspace management, route data and Plan Position Location Information (PPLI).

In order to address the requirements for airspace management, under the DAMM programme, MoD have developed an electronic version of the Global Area Reference System (GARS) for airspace management. The reason for this is that GARS is the currently accepted standard used by NATO for managing theatre airspace. Air Battle Managers currently allocate airspace to operational users using height-banded air cells communicated by voice, and recorded manually by UAS operators by marking-up charts. Electronic GARS offers user benefits for speed, accuracy and electronically assisted de-confliction. Under DAMM, electronic integration provides seamless communication across the operational and tactical tiers from airborne C2 (E3 AWACS), through effector platforms, down to ground-based co-ordinators (FAC/JTAC). For rapid tasking of UAS, and for interoperability with manned platforms, under the DAMM programme MoD have extended the use of standard data links and message protocols to UAS taskings. These include Link 16/J Series messages for Operational UAS (OUAS), and Improved Data Modem (IDM) for tactical UAS. For rapid exploitation of UAS output in effector platforms (RW, FW), under the DAMM programme MoD have proposed use of the K04.17 Variable Message Format (VMF) imagery message for passing still images around the DAMM network. This message is used, both over IDM and over Link16, in support of Joint Strike Fighter (JSF). In addition to the above, in support of shared SA with networked UAS, under the DAMM programme, MoD have extended the use of route data and Plan Position Location Information (PPLI). This is achieved through an adaptation of the K05.1 VMF/IDM, J2.2 Link16 messages for passing geo-location information. For route plan messages, MoD has adopted the J16.1 J Series message send over both Link16 and IDM.

A key thrust of the UAS DAMM integration work was the investigation of the utility of direct Full Motion Video (FMV) feeds from platforms such as WK and other ROVER compatible sensors, such as Reaper and Litening targeting pods, into cockpits such as Julius Chinook RW SH. This would allow the Julius Chinook crew to task a sensor carrying platform, direct from the mission system, such as the Onboard Mission Planning System (OMPS). Such tasking could provide co-ordinated over-watch and to receive live in-cockpit FMV during critical moments of operations, such as heli-borne insertion and extraction of troops. Such a capability would significantly improving SA and therefore survivability. Evidence obtained from DAMM of the utility of in-cockpit FMV directly supports procurement decisions for such a capability in addition to de-risking implementation by addressing HMI and other integration aspects.

Refer to the Annex A in the report for further detailed information on DAMM UAS Lessons Learned.

## **13.10 CONCLUSIONS**

The DAMM SE and flight trials provide evidence with high levels of proof for real benefits of a full suite of collaborative decision support tools across all three tiers of the networked dynamic C2-MM architecture. This work contrasting DAMM architectures and networked collaborative decision making tools has shown that as data rate, confidence and context increase/improve nodal (micro) and system (macro) C2 OODA loop activity transposes from slow serial to concurrent-NRT speeds. Consequently, kill-chain timeline, fratricide and collateral incidents should reduce, as illustrated in Figure 13-10 below.

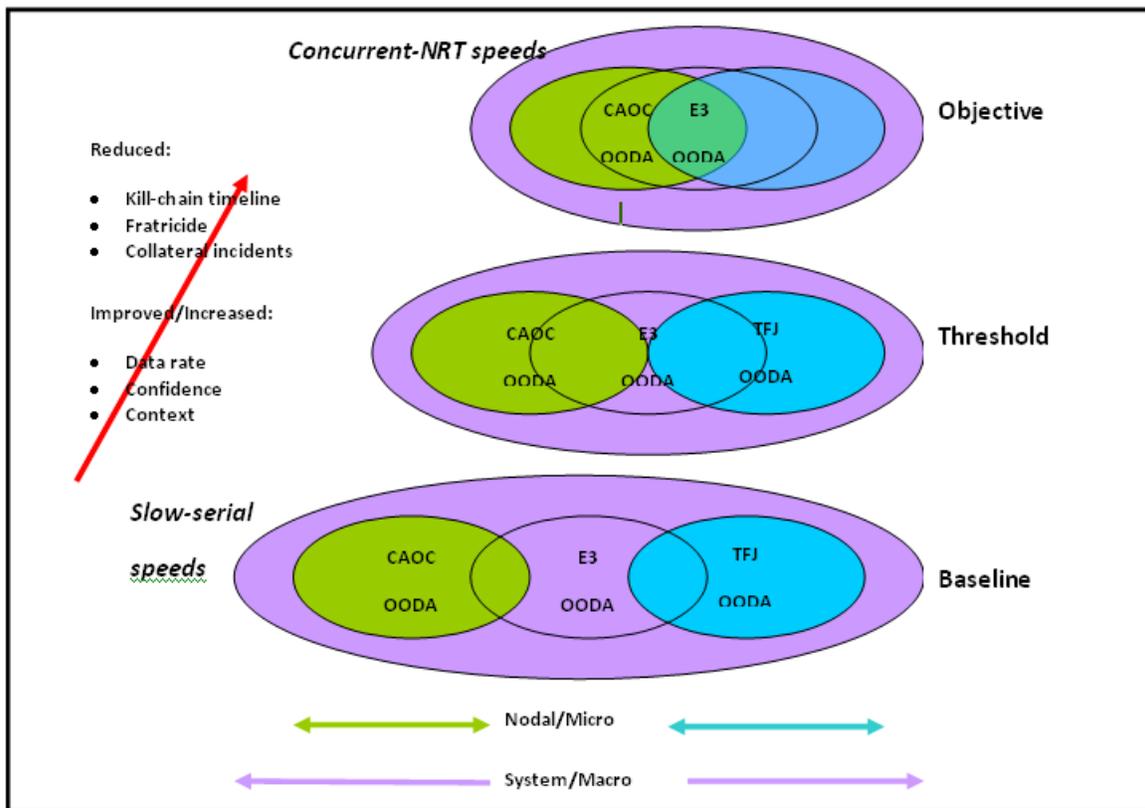


Figure 13-10: COODA Fusion.

### 13.11 FUTURE RESEARCH NEEDS AND PLANS IN THIS AREA

Further trials are needed to examine the effects of highly networked C2-MM architectures and MC positions on crew decision making with increasing capability provided by UAS. Work is needed to identify emerging CONOPS and architectures associated with highly networked and distributed mission systems involving manned aircraft and UAS. User requirements need to be identified and validated for tools to improve dynamic mission efficiency and adaptability and to enable improved tactical mission battle space integration, across capabilities. In particular, work is needed to focus on proactive decision support tools in support of improved anticipatory decision making. We need to improve understanding of the effects on mission command flow and locus of critical mission decision making, such as the balance of centralized versus distributed decision making. Changes in decision making strategies are likely towards more decentralized, distributed decision making afforded by networked collaborative decision support tools.

### 13.12 ACKNOWLEDGEMENTS

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## **Chapter 14 – US-1: MULTI-UAV SUPERVISORY CONTROL INTERFACE TECHNOLOGY (MUSCIT) DEMONSTRATION**

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### **14.1 DATE**

6 May 2010.

### **14.2 LOCATION**

Camp Atterbury, Indiana, USA.

### **14.3 SCENARIO/TASKS**

The objective of the MUSCIT program is to develop, integrate and demonstrate technology for effective single-operator control of multiple Unmanned Aerial Vehicles (UAVs) conducting dynamic tactical intelligence, surveillance, and reconnaissance and close air support missions. The program has set up a series of spirals, made up of simulation and flight tests (see Figure 14-1), to examine human and system performance for an assortment of UAV Reconnaissance, Surveillance, and Target Acquisition (RSTA) tasks and operations.

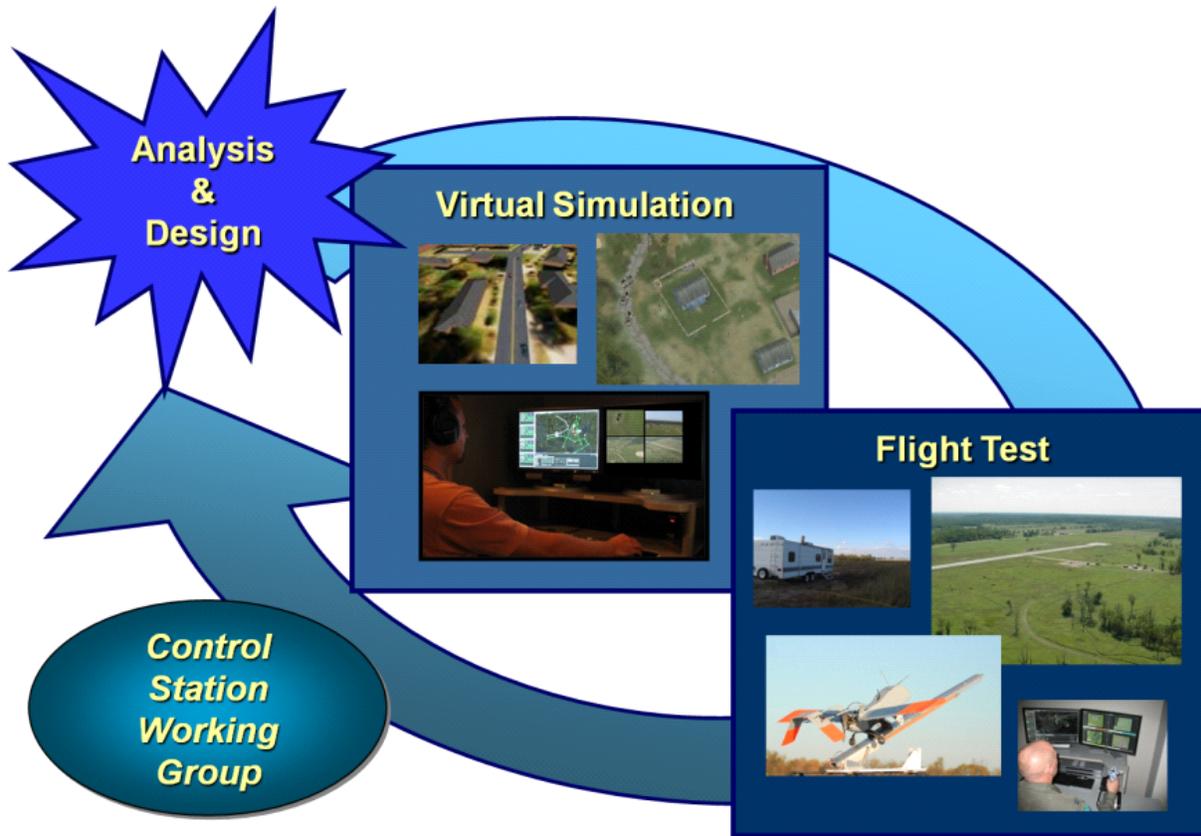


Figure 14-1: MUSCIT Program's Spiral Approach.

The NATO technology demonstration was conducted in conjunction with MUSCIT's Spiral 2 flight test and represented a sub-set of the tasks and conditions tested. The NATO technology demonstration consisted of a live flight demonstration of advanced single-operator, multi-UAV control station technology conducting point surveillance and vehicle re-routing tasks. The control station technology, referred to as the Vigilant Spirit Control Station (VSCS) (see Figure 14-2) [1], was demonstrated in a four-vehicle configuration made up of two flight test UAVs (MLB Bat 3s) and two simulated UAVs. The main task demonstrated was point surveillance where the control station operator positioned the UAVs and manipulated their gimballed sensors to detect individuals either entering or exiting specified locations and reported whether or not the individuals were armed with a mock weapon (see Figure 14-3).



**Figure 14-2: Flight Demonstration of Vigilant Spirit Control Station Performing Multi-UAV Operations.**



**Figure 14-3: Point Surveillance Actor Carrying Mock Weapon During Flight Test.**

Secondary tasks included monitoring radio calls and reporting vehicle heading, power remaining, position reports, any simulated air tracks transiting the area of operations, monitoring and reporting system cautions and warnings, and responding to vehicle relocation requests. The point surveillance portion represented a second test of point surveillance for the MUSCIT program to determine if added technology and design enhancements significantly improved target acquisition and secondary task performance from that found in the Spiral 1 test. The goal was to strive for near-equivalent performance (e.g., percentage of targets detected) and subjective ratings (e.g., situation awareness ratings) across the different number of UAV conditions.

#### **14.4 TECHNOLOGIES EXPLORED**

The control station consists of a desktop computer with two side-by-side 24" widescreen liquid crystal displays (see Figure 14-4 and Figure 14-5), a keyboard and a mouse. The user interface is comprised of vehicle and system status information, a Tactical Situation Display (TSD), vehicle and payload controls, and a sensor management area. The vehicle status area provides current and commanded state information to help the operator maintain situation awareness of the UAV(s). The TSD provides a 2-dimensional map or image with vehicle locations and other points of interest depicted on it. The operator can directly control certain UAV actions on the TSD. For example, the operator can select a UAV and change its direction of flight by manipulating graphic controls associated with the UAV symbol. The vehicle and payload controls provide additional control options. For example, the operator can place the sensor in latitude/longitude slaved mode and control the zoom level. The sensor management area allows the operator to control and view the sensor feeds, manipulate the presentation using digital video recorder and mosaic tools, and perform additional payload control.



**Figure 14-4: Left Control Station Display with System Status Display, Tactical Situation Display, and Vehicle and Payload Controls.**



**Figure 14-5: Right Control Station Display with Aircraft Video and Sensor Management Area.**

## **14.5 HUMAN FACTORS ISSUES EXPLORED**

The objective of MUSCIT Spiral 2 was to investigate the impact and demands associated with multi-UAV control within the context of a static and dynamic RSTA mission scenario and establish a performance benchmark for the control of multiple UAVs. Elements of the test included:

- 1) Evaluating the value of the operator control station design enhancements;
- 2) Investigating the performance effects and behavioral adaptation of operators as the number of UAVs being controlled and video image streams being monitored increased; and
- 3) Identifying opportunities via automation, visualizations, control mechanization, and employment concepts that would enhance the feasibility of multi-UAV control.

The previous spiral's tests generally showed that as the number of UAVs increased there was an overall decrease in the percentage of targets detected and the associated performance in identifying whether or not the individual was armed. This downward trend was also seen in the secondary task performance. In addition, higher workload and lower situation awareness ratings were noted. Technical challenges for the MUSCIT team to address included improving attention management, sensor selection and control, and information access. With the objective data and the subjective feedback from Spiral 1, the MUSCIT team modified portions of the control station and integrated additional control, display, and decision aiding technologies. Additional technologies utilized for Spiral 2 to enhance situation awareness and improve operator performance included the following:

- Speech recognition and synthetic speech reporting to allow the operator to request information of the system and have the system retrieve and report the requested information. The speech recognition and speech synthesis technology was included in an attempt to reduce the overall visual demand/load and permit the operator to focus more on the sensor videos during the RSTA operations.
- Sensor steering using the mouse/cursor to allow a point and click method to steer the sensor, along with zooming via the mouse scroll wheel. The rationale for integrating the mouse steering was to reduce control time and errors in aircraft video selection/manipulation and alleviate the need to switch between two input devices (sensor stick and mouse).

- Synthetic overlays in the form of targeting flags were developed to permit the operator to mark locations of interest and have graphics overlaid on the sensor video to depict the mark. The flags were color coded to correspond to the aircraft/video source from which the mark was made. The intent was that the synthetic flags would help enhance the operator's situation awareness in recognizing locations and points of interest. The technology could also serve as a method to share information with others about the battlespace and areas of interest.
- Glyph symbology integrated as a sensor overlay in an attempt to reduce the visual scan requirements. The graphic contained vehicle heading, vehicle altitude, sensor heading, communication data link, and fuel state information.
- Caution and warning annunciations to convey important state change information were modified from the Spiral 1 design. Visual alerts were annunciated on the sensor video, as overlays, and aural alerts using synthetic speech to help reduce the visual scan requirements for information retrieval and assessment, and help in overall attention management.

## **14.6 UNMANNED SYSTEMS USED**

The MUSCIT demonstration used the MLB Bat 3 UAV (see Figure 14-6) equipped with Cloud Cap Technology's Piccolo II autopilot and TASE stabilized gimbaled video camera (see Figure 14-7). The Bat 3 version used in the MUSCIT flight demonstration was approximately 5 feet long with an 8.5 foot wingspan. As outfitted, the Bat 3s provided the ability to perform mission, flight and sensor management tasks, which in turn helped the MUSCIT team exercise the control station controls, displays and decision aids and assess operator performance and usability via flight tests and demonstrations. For example, the vehicle could be vectored to fly a commanded heading, follow a waypoint defined route, or loiter about a given latitude and longitude. The sensor steering and management tasks could entail assigning a stare point location based on coordinates, and manually steering and zooming the gimbaled video camera with the control station mouse. VSCS was capable of receiving state data and the sensor video from each Bat 3 while simultaneously displaying multiple videos on the control station displays.



**Figure 14-6: Bat 3 UAV.**



**Figure 14-7: Bat 3 with Gimbaled Sensor Deployed.**

**14.7 SUMMARY OF ANY NATO COMMUNICATIONS/COLLABORATIONS/  
INTERACTIONS**

As indicated in the table below (see Table 14-1) the MUSCIT technology demonstration provided information pertaining to the supervisory control technology design, development and the approach for how the technology was tested and evaluated. The information was conveyed primarily at NATO HFM-170 meetings and the flight demonstration (see Figure 14-8). The events provided an opportunity to share information on the nature of the supervisory control tasks, operator interface technology and integration concepts that could help enhance supervisory task performance, and evaluation methods and metrics.

**Table 14-1: MUSCIT Technology Demonstration – Level of Interaction with NATO HFM-170.**

	<i>Planning/Design</i>	<i>Execution</i>	<i>Analysis</i>
<i>Communication</i>	<i>x</i>	<i>x</i>	<i>x</i>
<i>Coordination</i>			
<i>Collaboration</i>			



**Figure 14-8: Launch of Bat 3 at MUSCIT Technology Demonstration.**

## 14.8 SUMMARY OF RESULTS

In manipulating the number of UAVs (1, 2, and 4), the number of operators (1 and 2), and the target event rate or tempo (“low”: 60 seconds on average and “high”: 30 seconds on average), Spiral 1’s human-in-the-loop simulation data led to the following conclusions:

- UAV, Crew Size, and Tempo each had significant impact on performance;
- Reduction in crew size adversely affected performance as number of UAVs being controlled was increased;
- Increase in event rate had a significant impact on performance as the number of UAVs being controlled increased;
- Secondary task performance dropped as a function of number of UAVs; and
- Operator attitudes relative to feasibility, reasonableness and acceptability was significantly influenced by number of UAVs.

The Spiral 1 flight test, which only tested the number of UAVs and the number of operator’s conditions, revealed similar trends in performance and subjective feedback to what was seen in the simulation. The averages across the conditions were generally lower in flight test as compared to the simulation. However, it should be noted that the flight test data was limited as the number of participants was only four (Spiral 1 simulation had 12 participants) and some of the test cells were incomplete due to flight test conditions and constraints.

Both the empirical data collected and experimenter observations from Spiral 1 indicated that the visual load and attention demands were heavily concentrated on the task of sensor video inspection, looking for ground personnel and manipulating the sensors to determine whether or not the detected personnel were armed. This load increased with the number of UAVs resulting in reduced primary and secondary task performance. The empirical findings, both objective and subjective, led the team to the development and integration of additional technology and modifying the operator interface design to help reduce the visual demands (e.g., scanning and dwell time) required across the control station displays. The goal was to make pertinent task information more easily accessible by placing the data on or adjacent to the sensor management area of the control station and provide alternate ways to become aware of state changes and retrieve requested information through multi-modal methods (e.g., visual alerts and state information overlaid on the videos, auditory alerts, speech recognition and synthesis to retrieve and report data).

Preliminary analysis of Spiral 2’s simulation results, which had ten participants and only employed the “high” event rate, suggests the methods had a positive impact overall as the multi-UAV point surveillance target detection and secondary task performance data, as well the situation awareness and workload ratings, improved from Spiral 1’s simulation results. For example, the 1-operator, 4-ship condition showed an 11% increase in target detection and the secondary task performance increased by 40%. Additionally, across all the UAV levels (i.e., 1-, 2-, and 4-UAVs), Spiral 2’s China Lake Situation Awareness ratings were better and the NASA-TLX Workload weighted scores were lower than seen in Spiral 1.

It should be noted that the trial times between Spiral 1 and Spiral 2 point surveillance simulations were different with Spiral 1’s lasting approximately 10 minutes whereas Spiral 2 was approximately 8 minutes in length. The interval between target events for the primary task was the same (30 seconds on average) so there was a difference in total number of target events given the total trial times were different, while the number of secondary tasks was the same for both spirals. Another performance measure taken in the point surveillance

task was based on correctly reporting whether or not the personnel detected were armed. The Spiral 2 simulation had a different ground texture and weapon model than used in Spiral 1 which could have had some effect on the ability to identify whether or not the personnel were armed. As a result, the associated performance data (i.e., percentage of targets correctly identified) is not included as part of the comparison.

The MUSCIT Team experienced significant challenges in preparing for and conducting the Spiral 2 flight test. Weather and equipment problems hampered the ability to conduct the tests as planned. Only four of the planned six participants actually completed the tests. Furthermore, due to equipment issues, only two aircraft were available for the data collection which led the team to employ two Bat 3 aircraft and two simulated aircraft for the 4-UAV trials. Additionally, windy conditions for portions of the data collection sessions resulted in less than ideal test conditions. Consequently, the data is somewhat suspect in fulfilling the intended analyses and drawing any firm conclusions, but the data showed similar trends to the simulation but with a sharper drop-off in detection performance for the 4-vehicle condition, along with generally less positive subjective ratings.

## **14.9 LESSONS LEARNED**

As the MUSCIT program proceeded from Spiral 1 to Spiral 2 the need to re-address attention management, information access and control methods became apparent. The multi-vehicle control station prototype design evolved from earlier applied research that concentrated primarily on scenarios with tasks that were typically more sequential in nature. A priori knowledge of the targets (and their locations) and associated operator tasks permitted the mission routes and operator action points to be set up in a scheduled and orderly fashion. The information presentation and control methods supported the tasks and the allotted time could be managed to some degree by the operator through careful mission and route planning. The fact that assorted mission, flight, and sensor management information was spread across a large display area did not surface as a significant issue in previous efforts and demonstrations. The scenarios and RSTA tasks examined in MUSCIT's tests exercised the user interface in some different ways, which in turn, highlighted some areas for improvement.

Initially MUSCIT's point surveillance scenario was thought to be fairly low in terms of complexity in that the vehicle(s) loitered about the known locations and the operator would concentrate mainly on manipulating the sensor(s) and reporting on the ground activity. However, given the asynchronous nature of the target events, there was a degree of uncertainty on what to expect and when to expect it. This, along with the rate of target events, compelled the operator to visually attend to the sensor management area in an attempt to detect and identify the targets. Cross-checking for system status and tactical information in the mission and flight management areas could come at the cost of not detecting one or more targets. Therefore, the uncertainty and pace of these mission tasks highlighted the need for design enhancements to the control station prototype. As previously noted, the subsequent spiral concentrated on enhancing the design by introducing additional technology and modifying the control station, and improvements in performance were realized. The modified control station provided means to relieve some of the visual demands and ease control, however, challenges remain to enhance operator performance beyond levels achieved.

The spiral approach taken to conduct a human-in-the-loop simulation followed by a closely aligned flight test has afforded important insights into the supervisory control technology and human performance. The simulations were tightly controlled experiments used to manipulate the number of operators and UAVs and permitted a rigorous method to quantify human performance and capture subjective data. The flight tests were more constrained given the flight test environment and resources, and it was subject to more nuisance variables and variability across the conditions and between the participants, but it provided the team a greater

understanding and appreciation for how actual UAV systems perform and can be affected by assorted environmental conditions. The flight tests exposed the test conditions to elements that may have been overlooked, ignored, or over simplified in the simulations. For example, the wind and visual conditions were not varied in the simulation but in flight test the conditions could vary across the course of the data collection for a given participant, as well as between the participants, and could invoke different levels of sensor management workload. Thus, the flight test brought a better understanding of the real-world complexities associated with multi-UAV supervisory control and can be used, with the simulation findings, to derive technology requirements and lead to further advancements in the controls, displays and decision aids, and the overall supervisory control capability.

Finally, given what has been learned in the MUSCIT program to this point, perhaps “the problem” should be examined from another perspective as well. Rather than focus entirely on the operator-to-vehicle ratio and striving for equitable performance as the vehicles are increased, the program might consider including a detailed assessment of the number and type of tasks and sub-tasks that must be completed within an allotted amount of time, with a goal to effectively manage more tasks, of greater complexity, and within the mission time “budget”. In essence, try to characterize capability (e.g., mission effectiveness and crew performance) as a function of task complexity, number of simultaneous tasks, task sequence, time available, number of assets, number of operators, etc. This more bottom-up approach to developing MUSCIT’s control station technology could potentially complement the top down approach by addressing the fundamental work components which, in turn, might help guide technology development and ultimately provide answers to how many UAVs and operators are needed to effectively and consistently accomplish specified mission tasks. In addition, rather than use equitable operator performance and feedback across all the data collected as a goal when increasing the number of UAVs, perhaps the team needs to more closely examine task and sub-task priorities, dictated by the mission and the operator, and come up with a way to recognize and weight these priorities with regard to assessing the adequacy and effectiveness of the entire system. Finally, it might be useful to explore how multiple vehicles could be concentrated on a single objective or a set of serial objectives, looking at how 1-*n* vehicles can be used to more effectively accomplish RSTA tasks and missions. In other words, determine when it is more effective to use a team of UAVs on a given objective versus one UAV. Certain multi-UAV operations may be more acceptable in terms of situation awareness, workload, and performance levels when the UAVs are concentrated and coupled on one common task or objective, rather than disparate ones.

## **14.10 STUDY CONSTRAINTS/LIMITATIONS**

### **14.10.1 Flight Testing “Live” and “Virtual” UAVs**

For the flight tests, the goal was to conduct the one, two and four UAV case using the Bat 3 UAVs in all the conditions. However, all the Bat 3s planned for were not available due to assorted reasons for both Spiral 1 and 2 flight tests resulting in tests that involved a mixture of “live” and “virtual” UAVs, thus the sensor imagery depicted was actual video and simulated video in the four UAV cases. Observations suggested that the participants attended to the systems differently at times. The participants appeared to spend less time watching and manipulating the simulated systems than they did the “live” systems. Part of this may have been due to the instability (e.g., jitter and bounce), variable image quality, more frequent drift of the live sensor about the target location, and somewhat slower zoom rates seen with the actual sensor. These differences may have attributed to the operator having to manually control the Bat 3 sensor position more frequently than with the virtual system. The bottom-line is that there appeared to be some difference in operator attention to and interaction with the live and virtual systems, which raises concerns with the flight test data collected in the 4-UAV condition.

### **14.10.2 Success Criteria**

Opinions have varied widely in establishing credible and challenging exit or “success” criteria for the MUSCIT program. How many UAVs should the single operator control station technology effectively support? Under what conditions? What are the appropriate measures of performance and mission effectiveness, and to what levels should the program strive for? One approach is to try to achieve equivalency of performance, effectiveness, and subject-matter expert acceptance. However, as the effort and associated control station technology take on more UAVs and under more complex conditions, the goal of reaching this equivalency may be setting expectations too high. Another opinion expressed is that drop-off of operator performance associated with any one UAV in the multi-UAV operations should be expected to some degree and that the capability or mission “success” is in the aggregate. More is potentially accomplished as more vehicles are introduced. However, this view of the system emphasizes the benefits without addressing the potential costs (e.g., missed targets, mishaps). How much drop-off in performance and effectiveness for any single UAV is acceptable? Given the somewhat exploratory nature of this domain, the MUSCIT team chose to press for equivalency as it sets a measureable level to reach for, realizing it may be very challenging to obtain with the current state of the enabling technologies and resources available.

### **14.10.3 Testing the System**

In setting up the point surveillance task and associated environment the team was uncertain on what rate of target activity was appropriate to represent a meaningful and relevant mission situation. Given there was not a prescribed level to simulate a “typical” mission, the team opted to implement a task rate that would reduce the likelihood of encountering a ceiling effect. Thus, the technology would likely support the one-UAV condition fairly well with regard to performance, but perhaps not perfectly in all cases and, similarly, the 2- and 4-UAV cases would result in less than perfect performance. In essence, the MUSCIT team chose to create a test that was likely too difficult to “ace”. Some of the participant feedback suggested that the event rate was higher than they typically encounter so perhaps the bar was set too high, and the performance disparity seen between the 1-, 2-, and 4-UAV conditions amplifies too negatively on the technology and overall capability. A “lesser” test might have resulted in more equivalent performance, effectiveness and opinion across the number of UAVs.

## **14.11 CONCLUSIONS**

The MUSCIT program is attempting to advance UAV control station technology to enable effective multi-UAV RSTA operations by a single operator. It has developed a spiral approach, combining simulation and flight test, to characterize performance, empirically derive and refine technical requirements, and advance the technology and overall capability. Through the approach, the MUSCIT program has advanced control station technology and improved single-operator, multi-UAV performance.

The MUSCIT technology demonstration for NATO HFM-170 consisted of single-operator, multi-UAV point surveillance using the Air Force Research Laboratory’s Vigilant Spirit Control Station technology. The demonstration provided the NATO HFM-170 members an opportunity to see the flight test set-up, control station technology, and flight test operations. The demonstration, along with periodic meetings, provided a forum to exchange technical information and discuss possible future collaborations in supervisory control research and development.

## **14.12 FUTURE RESEARCH NEEDS AND PLANS IN THIS AREA**

In the next spiral, the MUSCIT team will increase mission complexity and afford operator(s) more latitude with respect to “managing” the mission. Participants will be afforded an extended training opportunity so they

can become more familiar with the array of technologies and the various ways to employ the controls and displays during the prosecution of a mission. The next spiral will be less structured than the previous in that the participants will be able to employ different strategies in accomplishing the mission tasks, which is expected to provide additional insight into the control station utility and possible enhancements. The evaluation will also include an enhanced 2-operator control station design to allow for transfer of vehicle and sensor control between operators which will permit the MUSCIT team to examine crew task allocation and management methods.

### **14.13 ACKNOWLEDGEMENTS**

The MUSCIT team would like to acknowledge the contributions of the Camp Atterbury Scheduling Branch and Himsel Field Airfield Operations. Their efforts and support of the flight test activities helped make the MUSCIT demonstration possible.

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## **Chapter 15 – US-2: TECHNOLOGY DEMONSTRATOR 10: DELEGATION CONTROL OF MULTIPLE UNMANNED SYSTEMS (DELCON)**

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### **15.1 DATES**

The Delegation Control of Multiple Unmanned Systems (DELCON) demonstration was conducted on 24 April 2009.

### **15.2 LOCATION**

Recent research at the U.S. Army Aeroflightdynamics Directorate (AFDD) has focused on delegation control, and delegation interface theory, as a solution for addressing the challenges of multi-UAS control by a single operator. AFDD's delegation control work builds upon previous application of Playbook®, developed by Miller, Goldman, Funk, Wu, and Pate [1]. This research is being addressed through two complementary tracks:

- 1) A series of empirical studies to test the important tenets of delegation control; and
- 2) Demonstrations of AFDD's delegation control interface in live flight.

This section describes the first of these live flight demonstrations.

The flight demonstration was conducted at the Military Operations on Urban Terrain (MOUT) site at Ft. Ord, California (Figure 15-1). The site is located on twenty acres of 10% graded terrain. The small city mock-up contains 33 cinder block training buildings of varying heights between 1 and 4 stories high. Narrow alleyways, winding gravel roads, and vegetated surrounding slopes characterize the city.



**Figure 15-1: MOUT Site at Ft. Ord, California.**

### **15.3 SCENARIO/TASKS**

Support of troops in contact has been identified as a high priority and heavy workload mission for UAV operators due to the inherent time pressure and clear danger for troops on the ground. A Troops-in-Contact (TIC) mission for UAVs involves close air support and surveillance of an area where friendly troops are taking enemy fire. Currently, a TIC may have multiple UAVs offering close air support and surveillance over a common target. In these instances, multiple operator teams control a single UAV per team and coordinate flight paths and airspace through Combined Air Operations Center (CAOC), using mIRC and/or radio, as well as other Command and Control (C&C) channels. Delegation Control offers a solution for multiple vehicle management and coordination over a common target with reduced workload for a single operator.

An appropriate mission context to justify the use of heterogeneous unmanned systems was warranted to best exercise Delegation Control. The use of multiple unmanned assets for persistence on target in dense urban terrain is an understood necessity. As such, a TIC mission, evolving into a weapons engagement with troop re-supply was selected to showcase the capabilities of delegation control.

Initially, all air and ground assets were conducting separate and independent missions. The operator received an incoming message communication that a TIC was in progress. A TIC play was called by the operator through voice recognition control, resulting in all assets directed toward the TIC location. A follow-on communication informed the operator of a second enemy location and third location requiring ammunition re-supply. The operator responded by calling a Prosecute Target play and Quick Supply play. Assets were appropriately removed from the TIC play and new asset allocation was accepted by the operator. All changes were appropriately updated in the Play Status window. The virtual Shadow and Warrior Alpha completed a collaborative weapons engagement as prescribed by the Prosecute Target Play. In further detail, Shadow and Warrior Alpha were directed to deconflicted loiter patterns with payloads pre-pointed over a common target

and placed in notional prelaunch constraints. The operator was prompted to lock-on the target and entered laser Pulse Repetition Frequency (PRF) codes. With laser designator engaged, the operator entered weapons release codes and manually fired the missile. Upon missile impact, a pop-up text window prompted the operator to select a follow-on action. The operator selected *Conduct Battle Damage Assessment (with single vehicle)*. Consequently, battle damage assessment was conducted by the RMAX (upon completion of Quick Supply play).

In parallel, the MAX Rover and RMAX were en route to the resupply location specified by the operator. The RMAX flew in obstacle field navigation mode (scripted behavior) to the quick supply load point. The load weighed approximately 15 lbs. and was transported in a sling extending 5 meters from the bottom of the aircraft. Upon attachment of the sling, the RMAX lifted the load off the ground and took off toward the Drop Zone (DZ). At this time, the operator received intelligence that the DZ had been compromised and should drop at an alternate location. In response to this communication, the operator modified the play accordingly. The Quick Supply play was updated in real-time in the play status window and associated assets were redirected to the new DZ. After scanning the DZ for obstacles, the RMAX dropped the re-supply package. In coordination, the UGV provided overwatch security and video of the DZ and surrounding area. Once all plays were completed, the assets returned to their separate and independent missions.

## **15.4 TECHNOLOGIES EXPLORED**

### **15.4.1 Ground Control Station (GCS) Hardware**

GCS hardware consisted of all computers required to perform the demonstration safely and reliably. For safety measures, each unmanned system had a computer and an assigned backup operator to monitor system health and performance. In addition, a secondary backup operator monitored payload and telemetry functions for the RMAX.

Primary MUSIM software and Delegation Control interface resided on a 2.4 GHz Intel(R) Core™2 Quad computer with 2 GB RAM. The graphics card was an NVidia 9800GTX+. A Samsung 2333SW monitor with 1280 x 720 display resolution was utilized. Audio feedback was monitored by the operator using a Sennheiser PC 136 USB headset.

### **15.4.2 Payload Hand-Controller**

The gimballed sensor was operator-controlled via a 3D Connexion SpaceExplorer input device (Figure 15-2). This input device was pressure sensitive and required right/left and up/down twisting motions to control the starepoint of the selected active payload. A standard optical mouse was used for navigation of operator control panels and cursor control throughout the operator interface (including messaging page).



**Figure 15-2: Connexion SpaceExplorer with 6 DOF Control Movement.**

#### **15.4.3 Multi-UAS Simulation (MUSIM) Software**

MUSIM software resided on a Suse Linux 10.3 operating system. Internally developed by AFDD-contracted software engineers, the software suite was constructed utilizing OpenSceneGraph for graphics and FLTK for the graphical user interface. A simulated terrain database of Ft. Ord, correlated to the real-world was created using Creator Terrain Studio 2.2 and Creator 2.5.1. Terrain imagery was obtained from U.S. Geological Survey aerial photography. The simulation utilized 10-meter terrain data along the MOUT site perimeter and 1.25-meter terrain data within the “city” at the MOUT site. Display of sensor imagery from the virtual UASs was updated at 60 Hz.

#### **15.4.4 Voice Recognition Control**

A custom application developed by the U.S. Air Force Research Lab (Wright-Patterson Air Force Base) from an integration of two Commercial-Off-The-Shelf (COTS) products was added to MUSIM software for combined speech recognition and text-to-speech capabilities. The custom application was comprised of SRI International’s DynaSpeak 1.5.32 Speech Recognizer and integrated with Cepstral’s Text-to-Speech to accomplish voice recognition control. SRI’s speech recognizer was Linux-based, offering speaker independent capabilities with natural language in North American dialect. Text-to-speech was announced by the female voice “Callie” developed by Cepstral for Linux (v5.x).

Customized grammar including play commands, stored geographic locations, and strike window times were defined for operator use during the flight demonstration. Integration between MUSIM and the voice recognition application was accomplished through UDP messages sent from the speech recognition system to MUSIM as a set of key value pairs in a character string. At a minimum, messages always contained a “command” associated with a value [i.e., TIC (command) at Tango (location = value)]. In cases where the system was unable to recognize a voice command, the system issued a “No rec” statement via audio feedback. Operator voice commands were acknowledged with echoed verbal confirmations from “Callie.”

### 15.4.5 System Architecture and Integration

Play origination began with operator input to the Delegation Control interface. For RMAX and MAX Rover, MUSIM software propagated aircraft/ground waypoint and payload specifications to the associated vehicle control system for movement in the x, y, and z axes. Thus, complex collaborative vehicle behaviors were decomposed and relayed in a series of simple commands to the aircraft and ground vehicle. In cases where the RMAX control system possessed a resident script for a unique behavior (e.g., obstacle field navigation, safe determination and landing), MUSIM evoked script execution. Command of navigation for both RMAX and MAX Rover were executed through TCP/IP messages generated by MUSIM and sent to the aircraft and UGV control system, respectively. For RMAX navigation, Cartesian coordinates represented in the MUSIM database were first translated to UTM coordinates and then sent to the aircraft control system. For MAX Rover ground track navigation, MUSIM software communicated Cartesian coordinates which were translated by the resident control system to GPS lat./long. coordinates. Serial sensor images were sent in jpeg format from RMAX and MAX rover via UDP packets to the MUSIM computer.

### 15.4.6 Delegation Control Interface

The Delegation Control interface developed by U.S. Army AFDD for this demonstration was comprised of three separate display elements:

- 1) A digital moving map;
- 2) A Plays Multi-Function Display (MFD); and
- 3) A multi-sensor display window (Figure 15-3).



**Figure 15-3: Delegation Control Operator Interface.**

A digital moving map resided in a fixed-size window in the upper left corner of the operator display. Mission assets were depicted with vehicle shape-specific icons and uniquely color-coded. Flight paths and/or ground tracks matched the color of the related vehicle icon. In cases where dynamic re-planning of a flight path occurred, the intended flight path was depicted in white. Once confirmed by the operator, the flight path was displayed in the associated vehicle’s color. Sensor direction and field of view for each vehicle was displayed using similarly color-coded sensor “whiskers.” The sensor actively controlled by the operator displayed a sensor footprint highlighted in yellow. Direction of aircraft orbit was presented utilizing a clockwise or counter clockwise curved vector symbol. Map navigation and zoom buttons were located along the right side of the map display. Real-time vehicle position was displayed and updated at 60 Hz.

Below the map display, a Plays page was located for the purpose of building, editing, and displaying the status of a play (Figure 15-4). Before describing a play build, it should be noted that development of a multi-play library began with the definition of a single play. Plays had a data structure, assigned assets, and specific event timing. Initial defaults for altitude, loiter diameters, vehicle assignments, and sensor behaviors were defined prior to populating the play library. These assignments were given with regard to current Tactics, Techniques, and Procedures (TTPs). Consideration of cost was also important when defining the plays. Thus, vehicles navigated the shortest path to a designated waypoint, unless guided to an alternate route through operator editing. In total, the play library consisted of five previously defined plays.

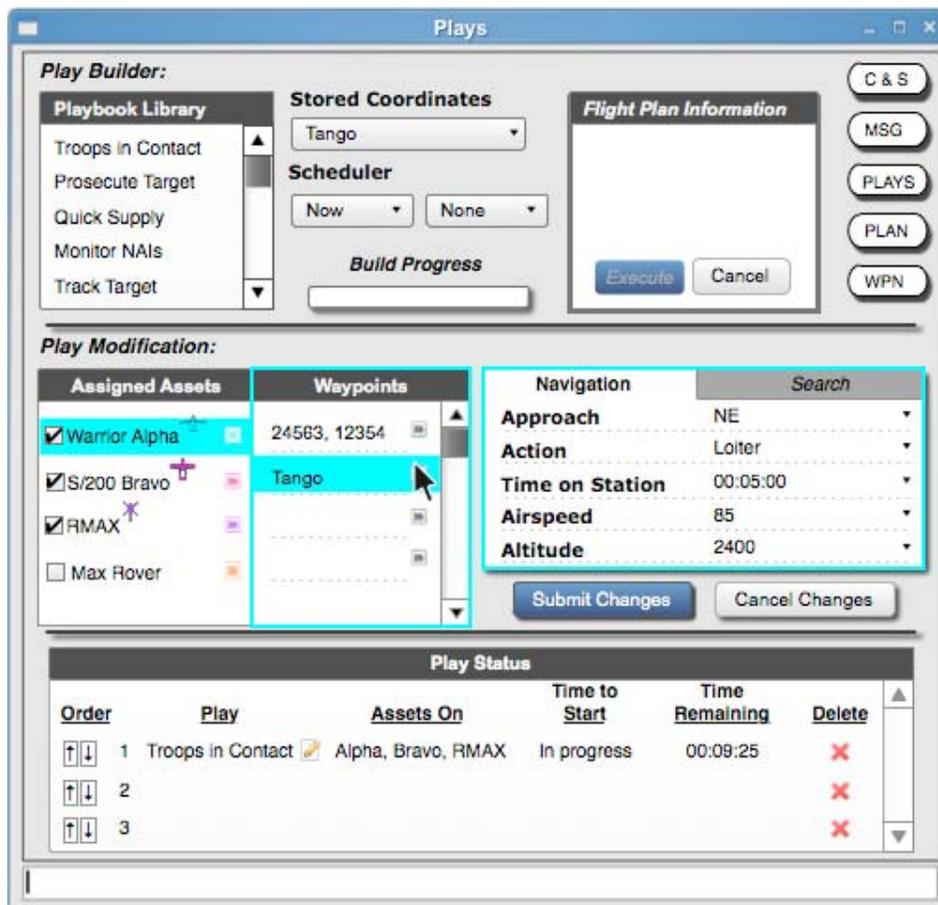


Figure 15-4: Plays MFD Page (e.g., Editing Waypoint Information Shown).

The Plays page was divided into three sections vertically:

- 1) Play Builder;
- 2) Play Modification; and
- 3) Play Status.

The top section, Play Builder, contained the menus for selecting and building a play from the Play Library. The middle section, or Play Modification section, displayed detailed information about a selected play and allowed for operator editing of navigation and sensor behavior parameters. The bottom portion of the page was reserved for display of play status and play priority order.

Delegation control of unmanned assets was accomplished through operator selection of a single play from the Play Library. To begin, the operator selected a play from the scrolling menu of stored plays. Next, the operator designated a location for play execution. Location could be selected from a list of stored coordinates, typed manually (e.g., numerical grid coordinate entry), or designated by clicking on a coordinate point on the digital map. Subsequently, the operator specified a time window for play execution, to include an option for immediate action (i.e., now). In the case of target prosecution, the time entry served as a strike window for earliest possible and latest acceptable time for target strike. Once the operator specified a location and time, a flight plan was generated on the digital map and the play was displayed in the Play Status window. In cases where assets were already in use on an existing play, the flight plan information box displayed the impact of allocating assets between plays (i.e., RMAX and Rover will be removed from TIC for quick supply.) During simultaneous play execution, the flight plan information box served to enhance automation transparency for the operator. When simultaneous plays competed for unmanned systems resources, the operator was required to select Execute in acceptance of the vehicle allocation before the new play initiated. No alternate remediation for vehicle allocation was offered.

Capability for real-time play modification is a central tenet of AFDD's Delegation Control over less flexible, scripted vehicle behaviors. The center portion of the Plays page was dedicated to play editing. The operator was able to modify default assets assigned to a play and waypoint navigation in real-time. To further refine the play, the operator could change navigation parameters and/or search geometry associated with a waypoint. Waypoints could be added or deleted by the operator on any play in real-time.

The lower portion of the Plays page contained a Play Status window for all plays uninitiated and in progress. Plays were listed in order from highest to lowest priority. The operator had the ability to increase or decrease a play's priority through selection of up and down arrows. As additional plays were built, both the listing of plays and priority of plays were updated. Plays were automatically removed from the status window upon completion. Details of play status included: priority order, assets assigned, time to start, and time remaining on the play. Operator changes to a play were immediately updated in the play status window. Deletion of a play was accomplished by selecting a red X, thereby "closing" the play.

The sensor display was located on the right side of the Delegation Control operator interface. The sensor display was divided into four sensor windows. Sensor windows were outlined in the correlated color of the vehicle icon offering visual cues to imagery source. In the upper left corner of each window a text description of the vehicle source was displayed. In further detail, the top sensor window displayed the actively controlled sensor. The lower side-by-side sensor windows displayed a second and third vehicles' imagery. The bottom thumbnail image contained the fourth vehicle's imagery. Although small, the fourth thumbnail display remained a live image instead of a static jpeg. Continual presence of all four sensor displays, regardless of size, was a design decision made to support the operator's situation awareness and serve as a reminder of

controlled payloads. Operator selection of a vehicle for active sensor control was accomplished by selecting a vehicle's payload feed with the mouse. Once selected, the vehicle's imagery replaced alternate imagery in the top window. Replaced imagery switched display locations with the recently selected active vehicle sensor.

Superimposed payload symbology displayed information related to vehicle heading and sensor direction on the active sensor window. Specifically, the symbology included a screen-fixed, compressed heading tape, marked in 10-deg increments and labeled in 30-deg increments. The sensor direction carrot (sensor heading) remained in the center of the 180-deg heading tape as it moved across the top of the display. A vehicle icon, identical to the moving map, depicted vehicle heading with a screen-delimiting arrow appearing when sensor and vehicle heading diverged more than 90 deg. At such time, vehicle heading was displayed to the right of the arrow as a digital readout, as this information was no longer visible on the compressed tape.

Superimposed, geo-referenced waypoint markers representing vehicle flight path / ground track overlaid sensor imagery. This use of augmented reality was intended to assist the operator in navigation and map-to-video correlation.

Crosshair symbology was displayed on vehicle sensor windows during plays involving weapons engagement. For example, during a Prosecute Target play, message prompts to ready and engage the laser designator were concurrent with the display of superimposed flashing brackets around the crosshairs. Once target lock-on was accomplished, brackets continued to be displayed without flashing. Crosshair symbology and brackets were positioned only on sensor windows of vehicles assigned to the play and disappeared with play termination. This design decision supported operator SA of vehicle collaboration in a weapons engagement.

In addition to menu selection by mouse, an operator could exercise voice commands to select a play from the Play Library. By utilizing voice commands, the operator was able to rapidly initiate a play during time-critical mission phases (e.g., response to TIC). Operators were able to circumvent mouse navigation of multi-level menus by annunciating an exact parameter to be changed. Use of voice commands was incorporated as an intuitive supplemental capability to augment Delegation Control. It was considered a time saving measure and assisted in the reduction of operator workload.

## **15.5 HUMAN FACTORS ISSUES EXPLORED**

The purpose of this flight demonstration was to successfully demonstrate delegation control of multiple unmanned air and ground vehicles by a single operator in a collaborative urban scenario [2]. In an extension of empirical studies [3],[4],[5] and flight demonstrations, it was hypothesized that a single operator could effectively monitor four unmanned heterogeneous assets with reasonable workload levels and high situational awareness using Delegation Control employment.

Specifically, demonstration objectives focused on showcasing solutions related to Human-Machine Interface (HMI) challenges involved with control of multiple payloads and vehicle platforms. Best practice solutions from human factors principles and literature were applied. A Delegation Control interface was developed by U.S. Army AFDD to support control and monitoring of four payloads. In addition, voice recognition control was implemented for multiple vehicle control in high workload mission segments (e.g., response to troops in contract.) Automation transparency was deemed significant to operator SA. Therefore, textual presentation of automation feedback related to simultaneous play execution was generated within a flight plan information window. Overall, demonstration success was defined as the ability for a single operator to execute a mission with multiple unmanned assets in collaboration with tolerable workload and high situation awareness.

## 15.6 UNMANNED SYSTEMS USED

Two live unmanned assets and two virtual unmanned aerial vehicles were used in this flight demonstration: a Yamaha RMAX helicopter modified for high-level autonomous operations was flown in the demonstration (Figure 15-5); and a Max 5A Rover Unmanned Ground Vehicle (UGV) manufactured by Senseta, Inc. and operated by Carnegie Mellon University Silicon Valley (Figure 15-6).



Figure 15-5: Live Yamaha RMAX (VTOL UAV).

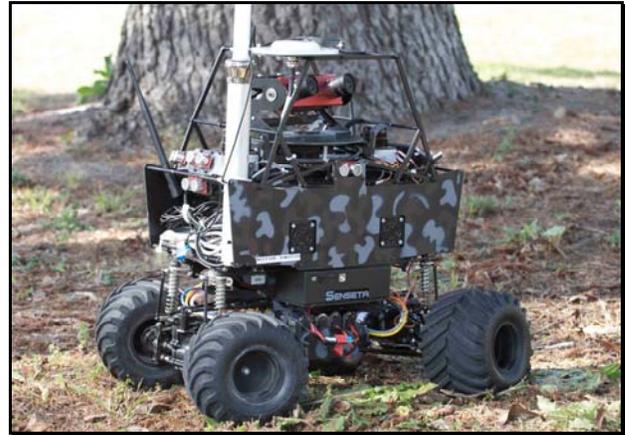


Figure 15-6: MAX Rover UGV.

A standard RMAX features a 3 m diameter rotor and maximum take-off weight of 94 kg. Additional payloads consisting of a 3D scanning hemispherical LADAR and autonomous flight control system mounted on the aircraft increased the original baseline weight to 172 lbs. Custom payload modifications were made by U.S. Army AFDD to achieve autonomous flight capabilities to include obstacle navigation. Flight controls and navigation were all processed onboard utilizing a Pentium III computer and NovAtel SPAN/LN200 Inertial Navigation Systems. Mission duration for the RMAX was approximately 60 minutes.

A UGV was a 4-wheeled, man-portable Max Rover weighed approximately 9 kg and had a cruise speed of 11 mph. The onboard computing platform consisted of a 2.0 GHz Pentium-M with 1 GB RAM.

Two virtual, fixed wing flight assets were included in the flight demonstration for the purpose of showcasing collaborative multi-vehicle plays. Nominally, a Shadow tactical UAS and Warrior Alpha were simulated. Typical altitudes, airspeeds, and payload characteristics were emulated through the U.S. Army AFDD's Multi-UAS Simulation (MUSIM) software.

### 15.6.1 Sensor Payloads/Imagery

The Yamaha RMAX was equipped with a fixed forward electro-optical, color camera with ability to pitch +10/-100 deg. 640 x 480 grayscale images were telemetered over Wi-Fi at a quality of 25% and updated at 8 Hz.

The sensor platform on the MAX Rover consisted of a Videre synchronized stereo pair system camera. Camera manipulation was accomplished in pitch (-30/+80 deg) and pan (+/-170 deg) axes. A series of jpeg images was transmitted and updated at 15 Hz to the Delegation Control operator display. Imagery capture and resolution was 320 x 240.



The virtual Shadow UAS was nominally equipped with Electro-Optical/Infrared (EO/IR) sensor and laser designator. The virtual Warrior Alpha was nominally equipped with EO/IR and four Hellfire missiles. For the purpose of demonstration, virtual sensors had 360 deg pan capability and +45/-110 deg pitch limits. Sensor slew rate was set at 60 deg/second. Zoom capabilities supported a progressive change in FOV from 2 to 16 deg (x – 8x). Precise modeling of the laser designator and weapons delivery system was not considered necessary for this demonstration. Thus, a low fidelity emulation of the weapons systems was employed.

**15.6.2 Telemetry**

The mobile ground station was equipped with two antennas for 900 MHz and 2.4 GHz telemetry. Payload telemetry for the RMAX used the 902 – 928 MHz frequency range. The 72.11 and 72.13 MHz frequencies were used for backup aircraft control. An omni-directional antenna for datalink transmissions to the RMAX was mounted on the tallest building at the MOUT site, allowing for complete site coverage. Adjacent to the RMAX antenna, a manually swiveled Yagi-Uda antenna was utilized for Wi-Fi datalink transmission to the MAX Rover.

**15.7 SUMMARY OF ANY NATO COMMUNICATIONS/COLLABORATIONS/ INTERACTIONS**

The NATO working group served as an informal crew-station working group. The demonstration plan, plays and data collection were presented, discussed and vetted at numerous meetings prior to the demo. The USAF integrated and provided technical expertise for the voice recognition system.

	<i>Planning/Design</i>	<i>Execution</i>	<i>Analysis</i>
<i>Communication</i>	<i>All</i>	<i>All</i>	<i>All</i>
<i>Coordination</i>	<i>USAF, Canada, Germany</i>		
<i>Collaboration</i>	<i>None</i>		

**15.8 SUMMARY OF TD RESULTS**

The TD demonstrated simultaneous control of multiple vehicles by a single operator. The workload was acceptable and situation awareness reasonable. These were actual vehicles in-flight and on the ground as well as virtual aircraft. This was accomplished via Playbook (DELCON) methodology. Voice recognition to “call” the plays was also demonstrated.

**15.9 LESSONS LEARNED**

Under these circumstances, a single UAS operator can simultaneously control multiple UAS. Voice recognition can be integrated seamlessly into this environment.

## **15.10 STUDY CONSTRAINTS/LIMITATIONS**

The study was limited primarily in that it was concept demonstration not a flight test. That is, it was not an actual experiment, it was demonstrating concepts previously tested in the laboratory. Further, no actual UAS operators controlled the system, they were controlled by one of the experimenters. Additional limitations included:

- Unfavorable weather conditions for flight testing of the RMAX proved to be one of the largest obstacles faced by the research team. This is being addressed in future demonstrations/flight tests through selection of a more suitable location (with more favorable weather conditions), as well as investigation of a weather impacts and route planning tool developed by ARL, called MyWIDIA (My Weather Impacts Decision Aid).
- Inability to integrate differential GPS onto the MAX Rover within the allotted timeframe, combined with limited GPS reception and safety concerns regarding road widths at the Ft. Ord MOUT site prevented the research team from allowing MUSIM to send automatic waypoints to the vehicle, despite having developed and tested this capability beforehand. Again, this limitation could be overcome by using a more suitable location, e.g., one with larger areas for transit to offset location errors, or one with better GPS reception.
- Lack of access to trained operators significantly hindered the research team's ability to collect any human performance data. This is being addressed in a future flight test by using general aviation pilots that have been trained on the MUSIM system and participated in simulation experiments in AFDD's laboratory.

## **15.11 CONCLUSIONS**

This demonstration was deemed a success for aptly showcasing Delegation Control of multiple unmanned systems by a single operator. Navigation and payload control of four unmanned systems was successfully monitored by a single operator in a collaborative urban mission scenario. Delegation Control employment strategy and interface design supported the build, initiation, modification and monitoring of simultaneous plays in progress. Use of voice recognition was considered an advantage to the operator during time critical mission phases. The operator's ability to bypass menus in favor of voice recognition control, significantly decreased reaction time to external mission events. Dynamic route re-planning was effectively accomplished while plays were in progress. In addition, play status was efficiently depicted and real-time updates were accomplished when play modification and play terminations occurred. Automation transparency was increased through messages generated by the MUSIM software that described impacts of conflicting plays. Lastly, the Play Status window was considered a significant contribution to operator SA for rapid, at-a-glance awareness of asset allocation and play scheduling.

## **15.12 FUTURE RESEARCH NEEDS AND PLANS IN THIS AREA**

This demonstration served to test and extend Delegation Control concepts initially sourced from empirical studies and Subject-Matter Expert (SME) interviews. Operational limitations of Delegation Control were explored during the demonstration without benefit of formal data collection or control comparison. Future research will include flight-tested data to support Delegation Control employment strategies over alternative control strategies. Performance data and subjective ratings of operator workload and SA will be collected in future flight tests. To ensure operationally relevant and tactically valid play definitions, U.S. Army AFDD has

plans to vet and expand play definitions with the user community. Interviews with returning warfighters will be conducted and subjective ratings collected on play usefulness, feasibility, and projected frequency of use. Modifications to the play library and play defaults will be made where appropriate. U.S. Army AFDD will continue to explore Delegation Control as an effective means for multi-vehicle unmanned systems control by a single operator. AFDD plans to continue testing Delegation Control in lab studies and flight tests. Near-term plans include the testing of the top five user-rated plays, expanding play definitions, and providing intelligent automation feedback when plays have been degraded. Possibilities for play rehearsal will also be explored. In the out- years, plans exist to implement Delegation Control from a manned platform in support of manned-unmanned teaming.

### **15.13 ACKNOWLEDGEMENTS**

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## **Chapter 16 – US-3: INTELLIGENT AGENTS AS SUPERVISORY ASSETS FOR MULTIPLE UNINHABITED SYSTEMS: ROBOLEADER**

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### **16.1 DATES**

2009 – 2011.

### **16.2 LOCATION**

Aberdeen Proving Ground, MD, USA.

### **16.3 SCENARIO/TASKS**

Urban reconnaissance.

### **16.4 TECHNOLOGIES EXPLORED**

Intelligent agent to coordinate a team of ground robots for urban reconnaissance tasks.

### **16.5 HUMAN FACTORS ISSUES EXPLORED**

#### **16.5.1 Introduction**

Future military operations will be complex and diverse. U.S. forces and its allies will be engaged simultaneously on a number of fronts under different combat conditions while fighting adversaries using a variety of tactics. Because of the changing demographics, many of our engagements will be in urban areas with entrenched adversaries who do not have to defeat us; instead they need only to out-wait us [1]. These conflicts will require the Army to put Soldiers “in harm’s way” and in the process encourage adversaries to use any means at their disposal to outlast our resolve. One possible solution will be the implementation of robotic systems that can replace Soldiers on the battlefield increasing our forces’ survivability and durability. Eventually these systems will be able to operate 24/7 in difficult terrain testing the Soldier operator’s ability to supervise these assets while conducting normal operations. Also, the possibility of a robotic battlefield creates a number of human factors as well as ethical issues related to non-human intelligence conducting combat missions [2],[3]. One obvious issue is that the proliferation of intelligent systems could easily overwhelm the current force’s ability to adequately supervise these systems. Hundreds of Uninhabited Vehicles (UVs), both aerial and ground, will share the

battlefield with hundreds of manned systems and conduct numerous missions concurrently. In these situations, the military will not be able to afford the manpower to control individual systems; instead, future missions will require single operators to supervise multiple systems. This, in turn, will necessitate some degree of UV autonomy. Unfortunately, increases in autonomy will present its own set of problems, including tunnel vision, misuse and disuse of automated systems, complacency, and loss of situation awareness [4],[5]. More germane to our current discussion, increases in autonomy will not overcome the human's span of apprehension limits related to monitoring multiple systems at the same time [6],[7].

Researchers have proposed a number of solutions to the potential issues of a robotic battlefield, such as setting up a UV call center in which robots will query the human operator only when there is a problem. The operator will make the necessary adjustments but will not be required to monitor robots continuously [8]. The obvious problem with this solution is that it assumes that the UV will be able to self-diagnose its own problems; additionally, the number of operator-robot interactions is expected to increase exponentially during the heat of combat, making the call center ineffective during the most critical time periods. As a potential safeguard, a number of researchers have suggested algorithms that share control responsibility among robots and humans as a function of either the robots' behavior or the operator's cognitive state. Closely aligned concepts involve play-book solutions that permit the operator to insert pre-programmed algorithmic solutions that control robots during difficult mission segments [9]. This generic class of adaptive systems is designed to keep operators in the decision loop while keeping the overall supervisory burden within efficient cognitive limits [9]-[12]. However, while this approach mitigates problems during high workload, it does not overcome cognitive limitations when the number of human-robot interactions surpasses human cognitive capacity [6]. We will examine two approaches that directly address the many-to-one problem:

- a) Distributed intelligence using swarm technologies; and
- b) Centralized intelligence using an intelligent agent as an intermediate supervisor.

The Tech Demo (RoboLeader) demonstrates the dynamics of an intelligent agent interacting with the human operators to coordinate a team of ground robots conducting an urban reconnaissance mission. In artificial intelligence, an intelligent agent is typically defined as "an autonomous entity which observes and acts upon an environment and directs its activity towards achieving goals" [13]. This definition covers a variety of possible uses for intelligent agents, from swarms with individual agents of limited intelligence that evince sophisticated behaviours holistically, to agents that respond to particular tasks in a manner that emulates human intelligence. As a contrast to RoboLeader's theoretical underpinnings, we will initially discuss swarms, emphasizing recent research from the Army Research Laboratory (ARL; Figure 16-1). The purpose of discussing swarms will be to delimit the theoretical possibilities for supervising multiple UVs in order to set the stage for our discussion of RoboLeader.



Figure 16-1: Swarm Display [16].

Swarm technologies are a special type of distributed intelligence wherein each component has a limited capacity to respond to its environment and the intelligence resides within the combined behavior of the group. Modeling swarms is an example of bio-inspired engineering using techniques that mimic collective behaviors of organisms such as of birds, ants and bees. Scientists have modeled swarm behavior making simple assumptions about the rules that individual members of the swarm use to permit the group to obtain its desired end states. Rules can be such simple actions as: stay close to your neighbor, avoid collisions, and move in the same direction. For example, Craig Reynolds developed an algorithm describing flocking behavior, including obstacle avoidance, to mimic avian flight paths accurately [14]. His Boids program was so successful that it was used to develop flight animations in the *Bat Man Returns* movie in 1992. A curious aspect of swarm behavior is that no single agent is in charge making the Swarm invulnerable to an individual's poor decisions. For example, in the biological domain, scout ants will go off in many directions and foragers will count those coming back in a particular direction to decide in which direction to find food for the colony [15].

More pertinent to military problems is the work that ARL researchers have conducted using swarm methods to control sentry robots for convoy protection (Figure 16-1) [16]. The robots use rules similar to the ones

instantiated for flocking behaviors to form an ellipse around the convoy, with individual robots venturing neither too close nor too far from the convoy. The algorithm had to be robust enough to account for unexpected weather, obstacles, etc., in the convoy's path. Using a simulation program with artificial obstacles, the robots were able to stay within the prescribed distance of the convoy 85% of the time. The problem with swarm technology is that swarms are most useful for simple problems wherein adaptation to novel conditions is not an important part of the problem set. Also, swarms are difficult to control because they are essentially interacting components with no clear means of supervisory control [17].

For more complex problems, hierarchical agent systems are being designed with agents that have specialized intelligence embedded within multi-layer architectures. The individual agents have specific tasks and a means of communicating with other agents. The ability to divide task complexity between senior (more capable) agents and specialized (less capable) ones allows hierarchies to adjust to greater complexity and to better adjust to change. The disadvantages are that as hierarchies become more complex, the algorithms to control them also become more cumbersome, and even then, agent hierarchies are still challenged by truly novel situations. Furthermore, the more levels involved and the more entities that need to be controlled, the more likely it is that communications among agents will become a serious problem. Carnegie Mellon University (CMU) developed algorithms using various bidding techniques in order to assign agents specific tasks. Bidding for tasks in the same neighbourhood reduced the size of auctions and it also reduced the distance that each agent was required to travel to complete its mission. In general, three levels of hierarchy were found to be the most efficient network size in order to trade-off number of agent specialties with network complexity [18]-[20].

Agent technologies with military import have been demonstrated for a number of realistic applications. For example, the L-3 Corporation and CMU used agents to successfully control multiple Unmanned Aerial Vehicles (UAV) with Received Signal Indicator (RSI) sensors to locate targets cooperatively during high fidelity simulations [21]. Researchers for the Canadian Defence Research and Development Laboratories (DRDL) demonstrated the utility of agent hierarchy technology for UAV control in a more complex simulation environment [22]. Hou and his colleagues [22] used senior agents directing working agents who in turn directed junior agents. Their simulation demonstrated agents in concert with the operator, planning multiple UAV missions, navigating UAVs to the target area, and upon arrival directing sensors to locate the targets. Similar agent technology has been used for cooperative control of multiple UAVs at the German Bundeswehr University in Munich using live UAV demonstrators [23].

### **16.5.2 Human-Agent Teaming**

An important feature of most military-related agent research is that agents are imbued with limited autonomy. Agents can perform specialized functions but authority resides with a human supervisor for safety and tactical reasons [2],[23]. Human-agent teams seem to be particularly effective for open ended missions in which not all events can be pre-programmed (i.e., most combat situations). Successful agent technologies take advantage of the differences between human and agent strengths. Human reasoning has very different characteristics than algorithmic reasoning. Johnson-Laird [24] points out that humans are rational but do not use formal logic in everyday decision making. They tend to structure problems by focusing on only some of the possible logical implications; permitting humans to rapidly but sometimes erroneously solve real-world problems (see for example, Monty Hall problem [25]). On the other hand, using inductive processes, humans are able to visualize numerous possible patterns that would overwhelm current agent technology. Also, we tend to overlook the advantages of consciousness which gives humans an acute awareness of the present and an intuitive feel for future states as well as a sense of purpose [26]. Human intuition is not an inexplicable process but rather it involves matching multiple memory traces with current cues that alert Soldiers to possible

incongruities in the environment. Experts, in particular, are able to pick up on cues that allow them to circumvent detailed analysis [27]. Also, humans can understand and react to situations in terms of overall intent rather than specified objectives. Artificial agents are able to supplement human intelligence by their use of more formal logic and their use of complex optimization algorithms to solve circumscribed problem sets. Agents also reduce workload by being able to attend to multiple functions that would overwhelm Soldiers during the heat of combat. Human-agent teams are especially important in military environments because no set of agents in the foreseeable future will be able to understand the nuanced political and ethical implications facing U.S. ground troops [2],[28].

The purpose of the below research is to better understand how humans and intelligent agents work together effectively as team to engage in military missions wherein Soldiers will be required to supervise multiple UVs during high workload combat missions [4],[29]. RoboLeader is a simple hierarchical system consisting of human operators, intelligent agents that can communicate with both the human supervisor and other agents, and less intelligent agents consisting of multiple UVs (robots) who conduct prescribed missions. The dynamics of the interactions and report of our initial findings will constitute the demonstrations and are described below.

**16.5.3 Framework Applied to HFM-170**

The purpose of our demonstration is to show the advantages of a hybrid supervisory system with a centralized agent controlling multiple UVs in an urban combat environment. RoboLeader will be contrasted with swarm systems and we will discuss research showing its advantages in controlling up to 8 robots. Past research indicates that autonomous cooperation between robots can improve the performance of the human operators [30], as well as enhancing overall human-robot team performance [31]. The current research paradigm addresses the control structure and interface requirements between the supervisory human operator and robotic agents as number of agents, workload, target mobility, and reliability level vary systemically [32],[33].

**16.6 UNMANNED SYSTEMS USED**

Simulated unmanned ground vehicles.

**16.7 SUMMARY OF ANY NATO COMMUNICATIONS/COLLABORATIONS/ INTERACTIONS**

Communications included the HFM-170 community by sharing papers and presentations. Direct interactions were with TNO Netherlands, Air Force Research Laboratory (AFRL) and DRDC Canada. Interactions with Canada include sharing software and concrete plans for joint research on intelligent agents, TNO participated in field experiments at Ft. Benning and AFRL contributed to our voice research.

	<i>Planning/Design</i>	<i>Execution</i>	<i>Analysis</i>
<i>Communication</i>	X	X	X
<i>Coordination</i>	X		
<i>Collaboration</i>	X	X	

## 16.8 SUMMARY OF TD RESULTS

### 16.8.1 Experiment 1

We investigated the effectiveness of RoboLeader, an intelligent agent that could help the human operator control a team of robots, for enhancing the overall human-robot teaming performance. We compared the operators' target detection performance in the 4-robot and 8-robot conditions [32]. The Mixed Initiative Experimental (MIX) Testbed was modified and used as the simulator [34]. The MIX Testbed is a distributed simulation environment for investigation into how unmanned systems are used and how automation affects performance. The Operator Control Unit (OCU) of the MIX Testbed was modeled after the Tactical Control Unit developed under the ARL Robotics Collaborative Technology Alliance (Figure 16-2). This platform includes a camera payload, and supports multiple levels of automation. Users can send mission plans or teleoperate the platform with a joystick while receiving video feed from the camera payload. Typical tasks include reconnaissance and surveillance.



Figure 16-2: RoboLeader User Interface.

Participants were randomly assigned to the RoboLeader group or the Baseline (no RoboLeader) group before their sessions started. Each experimental session had two scenarios, each lasting approximately 30 minutes, in which participants used their robotic assets to locate 20 targets (i.e., 10 insurgents carrying weapons and 10 Improvised Explosive Devices [IEDs]) in the remote environment. There were 4 robots available in one scenario and 8 in the other. The order of scenarios was counterbalanced across participants. When each scenario started, the robots began by following pre-planned routes at which time the operator's task of monitoring the environment and detecting insurgents/IEDs began. The robots did not have Aided Target

Recognition capability; therefore, the participants had to detect the 10 insurgents and 10 IEDs by themselves. There were friendly dismounted soldiers and civilians in the simulated environment to increase the visual noise for the target detection tasks. The participants were told that their objective was to finish reconnoitering the area using their robotic assets in the least amount of time possible. Therefore, when re-planning a route, the participant and/or RoboLeader were required to consider both the effectiveness and efficiency of the new route. In each scenario, there were six events that required revisions to a robot's current plans/route. Once an event transpired, the baseline participants had to notice that the event had occurred, and then they would re-route the robot that was affected by the event. For those in the RoboLeader condition, the RoboLeader recommended plan revisions to the operator, who could either accept the plans or modify them as necessary. In each scenario, there were 5 Situation Awareness (SA) queries, which were triggered based on time progression (e.g., 3 minutes into the scenario). The SA queries included questions such as "which areas have the robots searched?" (participants were instructed to mark the searched areas on a blank map), "which of your robots is the closest to [Area of Interest]", etc. The OCU screen was blank when an SA query was triggered, and only the SA query and the answer box were displayed on the screen.

The study was a mixed design, with RoboLeader (with or without RoboLeader [Baseline]) as the between-subject variable, and the number of Robots used in the scenario (4 vs. 8) as the within-subject variable. Dependent measures included number of targets located and identified, the operator's SA of the mission environment as well as awareness of the status of the individual robots, and the operator's self-assessed workload. A mixed-design analysis of covariance with RoboLeader (with or without RoboLeader) as the between-subject factor and number of Robots (4 vs. 8) as the within-subject factor was used to evaluate the operator's performance differences among the four conditions. Participants' spatial ability (composite score of two spatial tests) and their attentional control survey scores were used as covariates.

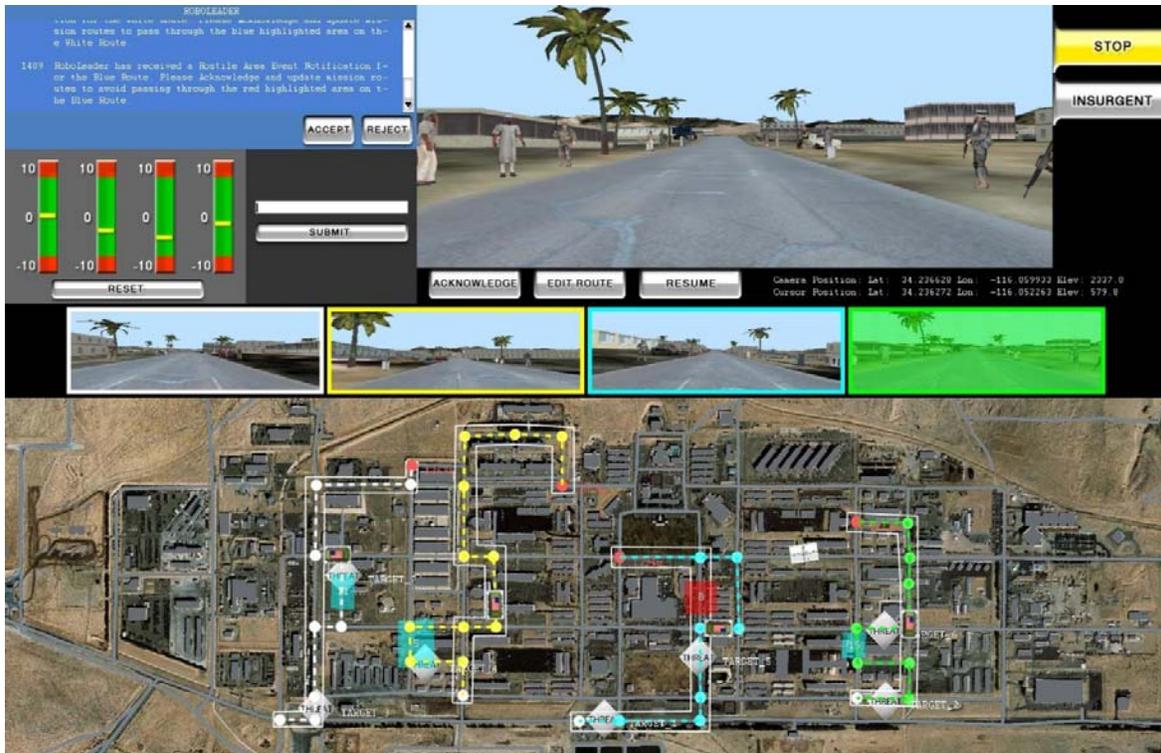
Results showed that participants detected significantly fewer targets and had significantly worse SA when there were 8 robots compared to the 4-robot condition. Those participants with higher spatial ability detected more targets than did those with lower spatial ability. Participants' self-assessed workload was affected by the number of robots under control, their gender, and their attentional control ability. Although there was no significant difference in overall target identification between RoboLeader and baseline conditions, there was a 12% reduction in mission completion time for the RoboLeader condition.

### **16.8.2 Experiment 2**

In the first experiment, the simulated reliability level of RoboLeader was 100% (i.e., no false alarms or misses). In Experiment 2, the effects of various reliability levels for RoboLeader on operator performance were investigated [32]. The participants' task, as in Experiment 1, was to manage four robots with the assistance of RoboLeader while searching for hostile targets via streaming video from the robots. The reliability of RoboLeader's solutions was manipulated to be either False-Alarm Prone (FAP) or Miss Prone (MP), with a reliability level of either 60% or 90%. Furthermore, Experiment 2 simulated a multi-tasking environment rather than a dual-tasking environment as in Experiment 1. In addition to the target detection and route revision tasks, the participants had to simultaneously perform a gauge monitoring task and a communication task. Finally, the visual density of the simulated environment was manipulated; there were twice as many entities in the high density environment as in the low density environment. The experiment is a mixed design, with RoboLeader Imperfection Type (FAP vs. MP) and Reliability Level (60% vs. 90%) as the between-subject factors and Visual Density (High vs. Low) of the simulated environment as the within-subject factor.

Participants were randomly assigned to the FAP60, FAP90, MP60, or MP90 group (with 10 participants per group) before test sessions started. The participants were informed that RoboLeader was either FAP or MP

and “fairly but not always reliable” (for the 90% conditions) or “not always reliable” (for the 60% conditions). In the MP scenarios, participants were required to notice and manually edit several routes without the help of RoboLeader. RoboLeader’s messages were displayed in the upper left corner (the blue area) of the OCU (see Figure 16-3). As in Experiment 1, participants were told that their objective was to finish reconnoitering the area using their robots in the least amount of time possible while keeping all route edits as close as possible to the original routes. Therefore, when re-planning a route, the participants and RoboLeader had to consider the effectiveness and efficiency of a new route.



**Figure 16-3: RoboLeader in a Multi-Tasking Environment.**

In the FAP60 scenario, there were five true events that required revisions to a robot’s route and four FAs that RoboLeader attempted to edit around when no events occurred. Participants could verify the validity of the RoboLeader recommendations by reviewing the map. A true event was associated with an icon (a red square for a Hostile Area and a blue square for a High Priority Area, see Figure 16-3), but FAs were not. In the FAP90 scenario, there were five true events that required revisions to a robot’s route, and one FA. In the MP60 scenario, ten true events occurred that required revisions to a robot’s route, though RoboLeader only provided solutions for two of them. In the MP90 scenario, ten true events occurred and RoboLeader provided solutions for eight of them.

In addition to the tasks described above, the participants simultaneously performed a gauge monitoring task and an auditory communications task. The gauge monitoring task (upper left corner of the OCU) displayed four gauges constantly in motion that entered an upper or lower limit at various pre-specified times throughout the scenarios. The participants were required to monitor the gauges and press a “Reset” button when any gauge entered the upper or lower limit to put the gauges back to their normal levels. The auditory communications task

presented pre-recorded questions at 30 sec intervals during the scenarios. The questions included simple military-related reasoning and memory tests. Participants used a keyboard to enter their responses for the questions into the communications panel on the OCU (adjacent to the gauges, see Figure 16-3).

Dependent measures included the number of targets located and identified, the number of routes successfully edited, the operators' SA of the mission environment, their concurrent task performance (gauge monitoring and auditory communications) and their perceived workload. A mixed design ANCOVA with Unreliability Type (FAP vs. MP) and Reliability Level (60% [Low] vs. 90% [High]) as the between-subject factors and Visual Density (High vs. Low) as the within-subject factor is used to evaluate the operators' performance differences among the four conditions. Participants' spatial ability (composite score of two spatial tests) and their attentional control survey scores were used as covariates.

Results showed that the type of RoboLeader unreliability (FAP vs. MP) affected operator's performance of visual scanning tasks (target detection, route editing, and situation awareness). There was a consistent effect of visual density for multiple performance measures. Participants with higher spatial ability performed better on the two tasks that required the most visual scanning (i.e., target detection and route editing). Participants' self-assessed attentional control was found to impact their overall multi-tasking performance, especially during their execution of secondary tasks (communication and gauge monitoring). The most important finding was the target identification superiority for the FAP condition compared to the MP condition. This was most likely caused by the visual accessibility of the route map making FA verification relatively easy, whereas the lack of alerts in the MP condition required participants to scan the map constantly thus missing the targets on the live video. This was reinforced by the finding that MP conditions resulted in better overall SA which is consistent with increased scanning.

### **16.8.3 Experiment 3**

In 2010, the capabilities of RoboLeader were expanded to deal more specifically with dynamic re-tasking requirements for persistent surveillance of a simulated urban environment based on various battlefield developments as well as coordination between Unmanned Aerial Systems (UASs) and Unmanned Ground Vehicles (UGVs) in pursuit of moving targets in urban environments (Figure 16-4). In Experiment 3, we manipulated the level of autonomy of RoboLeader and examined its effect on the operator's performance (i.e., plan revisions for the robots, the concurrent target detection task, and SA of the mission environment) and workload [33]. The four levels of manipulation were as follows: Manual (no RoboLeader), Semi-Autonomous without Visualization, Semi-Autonomous with Visualization, and Fully Automated. The Semi-Autonomous condition was divided into two conditions so that the effect of the visualization tool could be evaluated. The visualization tool informed the participant of the synchronization of the robots as well as overall entrapment effectiveness of the target based on the movement of the target.



Figure 16-4: RoboLeader User Interface in Experiment 3.

During the scenarios, participants used their four robotic assets to pursue a primary moving target (a truck traveling at about 3 MPH) while monitoring the streaming video from the robots in order to find additional (secondary) targets (insurgents carrying weapons) in the mission environment. When the scenario for the Manual condition started, the participants entered waypoints for each UGV manually and adjusted the waypoints based on the movement of the primary target. In the Semi-Autonomous conditions, the participant selected an end point/location for the UGV at which time RoboLeader provided an optimum solution for reaching the desired destination. In the visualization condition, the user could consult the bar graphs as an indicator of whether their point selections were effective in terms of synchronization of the robots and entrapment of the target or if the plans needed revisions. The scores displayed in the visualization area were calculated based on the RoboLeader's encapsulation algorithm. Without visualization, the participant had to determine if they were properly cornering the target for capture. In the Fully Automated condition, RoboLeader provided the recommended end points as well as intermediate waypoints for each robot. The participant could accept, modify, or reject the plans. In each scenario, there were hostile areas (indicated by red squares on the map) that the robots needed to avoid. The order of experimental conditions was counterbalanced across participants.

The study was a within-subject design with RoboLeader's level of autonomy as the independent variable (with four levels: Manual, Semi-Autonomous without Visualization, Semi-Autonomous with Visualization, and Fully Automated). Dependent measures included the participants' performance of encapsulating the primary target (the encapsulation scores), the percentage of secondary targets (insurgents) detected, the participants' SA of the mission environment (percentage of SA queries answered correctly), and the participants' perceived workload. A repeated-measure analysis of variance with RoboLeader as the within-subject factor was used to evaluate the operator performance differences among the four conditions.

Results showed that RoboLeader (Fully Automated condition) was more effective in encapsulating the moving targets than were the human operators (when they were either without assistance from RoboLeader or when they were partially assisted by RoboLeader). Participants successfully encapsulated the moving targets only 63% of the time in the Manual condition but 89% of the time when they were assisted by RoboLeader. Those participants who played video games frequently demonstrated significantly better encapsulation performance than did infrequent gamers; they also had better SA of the mission environment. Visualization had little effect on participants' performance. Finally, participants reported significantly higher workload when they were in the Manual condition than when they were assisted by RoboLeader.

The difficulty levels of the tasks in the current study were fairly moderate. Instead of comparing the 4-robot and 8-robot conditions, the study could have investigated the effect of task difficulty. Different outcomes could have been observed in terms of the effectiveness and usefulness of RoboLeader.

## **16.9 LESSONS LEARNED**

The lessons learned were many. Specifically for agents with less than perfect reliability having an easily verifiable display space mitigated problems with false alarms but not misses for the primary task of target identification. Most interesting was the superiority of experienced gamers for overall situation awareness. Future experiments will investigate mitigating factors for situation awareness well as target identification.

## **16.10 STUDY CONSTRAINTS/LIMITATIONS**

The experiment was conducted in a virtual environment, not with actual robotic vehicles.

## **16.11 CONCLUSIONS**

We concluded that future battlefields will be rife with manned and unmanned vehicles that will overwhelm the Soldiers' ability to conduct their assigned missions effectively unless technologies are developed to alleviate their multi-tasking requirements. This is particularly important because logistic efficiency will require Soldiers to conduct their missions in a many-to-one configuration. The purpose of the RoboLeader simulations was to understand how to develop a synergistic relationship between human supervisors having final decision authority and intelligent agents who supplies algorithmic solutions for many-to-one control problems. The initial experiment established the feasibility of using RoboLeader to control up to eight robots during a reconnaissance mission. The second experiment focused on RoboLeader's reliability level and type of possible errors. Surprisingly, operators were able to intervene more successfully with False Alarm Prone (FAP) error rates than with Miss Prone (MP) error rates contrary to previous findings in the literature. The apparent reason for this was that the more compact interface used in the current experiment allowed FAP verification to be accomplished more efficiently. In contrast, MP errors required operators to constantly scan the map reducing their target detection scores on the video displays. The final experiment showed the efficacy of RoboLeader in aiding the operator conduct more complex missions which required four robots to entrap a moving target.

## **16.12 FUTURE RESEARCH NEEDS AND PLANS IN THIS AREA**

The capabilities of RoboLeader are currently being expanded to deal more specifically with dynamic re-tasking requirements based on battlefield developments (e.g., individual robots need to be re-tasked to search for a high-stake target) for persistent surveillance in urban environments.

## **16.13 ACKNOWLEDGEMENTS**

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## **Chapter 17 – US-4: UNMANNED SURFACE VEHICLE CONTROL AND MONITORING HUMAN-COMPUTER INTERFACE FOR AMPHIBIOUS OPERATIONS**

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### **17.1 DATES**

The US Navy is investigating the usability of Remotely Piloted small Unmanned Surface Vessels (USVs) to support mine warfare missions. The demonstration focuses on the Human-Computer Interface (HCI) for the Multi-Robot Operator Control Unit (MOCU) software developed at the Space and Naval Warfare Systems Center Pacific in San Diego California USA. Human performance studies are being conducted to investigate alternate design configurations relative to optimum human performance and decision-making. In April 2009, the first technology demonstration illustrated two versions of the HCI, a baseline version and an integrated map-video version. A third version was created following initial end-user review of the map-video version and additional testing was completed in March 2011 to allow comparison of results in a dynamic simulation across the versions. The goal of the technology is to safely and efficiently control simultaneous operations of two USVs and to identify human performance shortcomings that may be mitigated by advanced HCI concepts.

HFM-170 Concept Demonstration 1 was conducted April 22 2009. Concept 2 usability testing was performed August 5 – 12, 2010, and Concept 3 usability testing was performed February 28 – March 10, 2011. Further testing is planned for summer 2011.

### **17.2 LOCATION**

Concept Demonstration 1 was conducted April 22 2009 at the US Naval Submarine Base Point Loma, San Diego California. Concept 2/3 usability testing was conducted in the User Laboratory of SPAWAR Systems Center – Pacific, San Diego CA.

### **17.3 SCENARIO/TASKS**

The USV HCI test scenario consisted of a simple navigation route tracking which simulated both ingress and egress from a “host ship”, e.g., the US Littoral Combat Ship (LCS) to an operational area. The USV scenario picked up after a simulated post-launch from the host ship at a control point where the on-deck launch operator would hand-off the launched USV to the Organic Off-board Vehicle Operator (OOVO). The MOCU HCI allowed the user to shift between automatic waypoint-following control mode to manual control mode. Upon completion of the test scenario the USV would begin a slow search pattern for mine hunting.

The remaining mission phases were deemed to duplicate the first phase for human performance impact and not included in testing. These phases included mission sensor search and transit to a recovery dock for retrieval.

The scenario used to test Concepts 2 and 3 in 2010 and 2011 followed a simulated mission scenario with simulated USVs. Participants in both sessions were USN enlisted personnel, most of whom had previous experience operating USVs. The scenario required them to respond to a series of pre-determined conditions and events as they transited two USVs from the host ship to the mission operations area. The scenario was designed to elicit performance of critical tasks derived during previous task analysis interviews with subject matter experts. In several instances scenario events were purposely scheduled in close time proximity to heighten mental workload and assess attention management capabilities under challenging conditions. Performance measures were developed for each task, which usually specified a window of time for completion. The scenario required the subjects to perform the tasks listed below:

- Take control of USVs;
- Download and execute pre-planned routes;
- Set emergency maneuver actions;
- Activate radar and display contacts;
- Switch between driving modes (manual and auto);
- Start/stop engines, including set to idle;
- Drive USV in manual mode;
- Make waypoint reports at each waypoint;
- Monitor for and report contacts (radar and visual);
- Respond to stationary contacts in path (emergency and non-emergency);
- Respond to moving contacts in path (emergency);
- Respond to vessel in pursuit;
- Use Point, Tilt and Zoom (PTZ) camera to assess contacts; and
- Report/respond to system status alarms.

## **17.4 TECHNOLOGIES EXPLORED**

Demonstration Concept 1 utilized the MOCU HCI with a live robotic USV. Later testing used the HCI with two simulated robotic USVs. In all cases the technology focus was on visualization strategies and dynamic visual and audio feedback during user monitoring and control of missions. In addition to visualization methods, use of hand-held controller technologies was investigated in Concept 3.

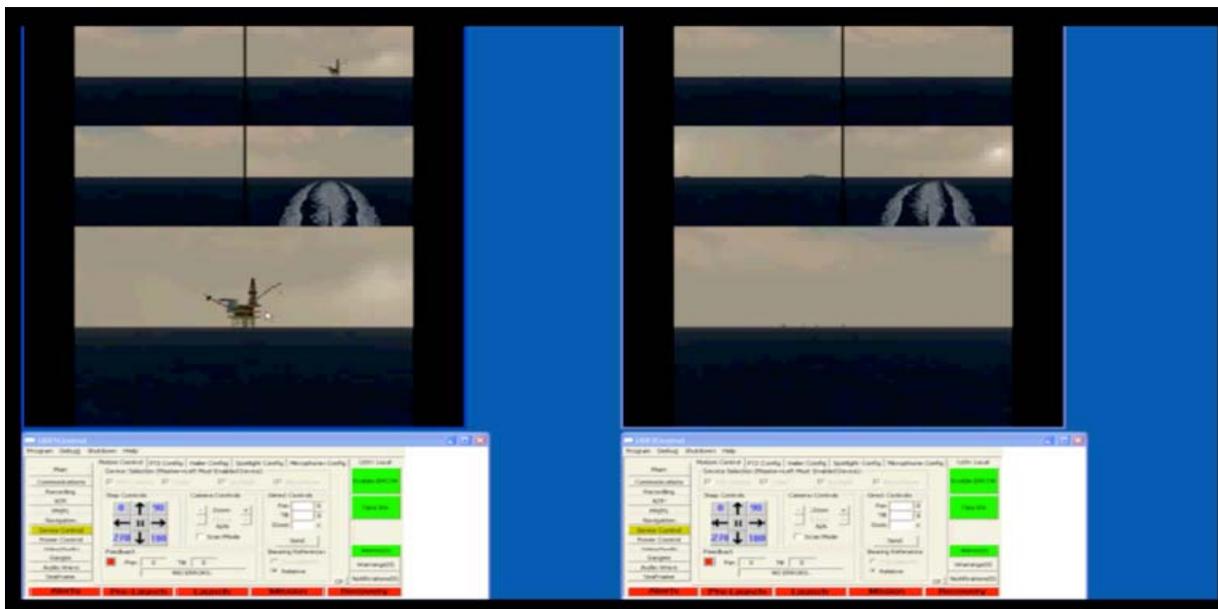
The integration of visualization methods within the HCI challenges the end-users visual workload and attention management skills by the use of several sets of cameras with various visual focus domains. These domains include:

- 1) Pan-tilt-zoom camera;
- 2) 360 degree camera; and

- 3) Rear-view focus camera (rear-view available on some USVs).

Other sensory inputs include Digital Nautical Charts (DNC) that display information about known geographic features including algorithms that compare objects on the chart to the depth of the USV keel to determine if a hazard exists. Color coding on the chart display indicates nearby geographic hazards. Radar returns are overlaid with the digital chart information.

The HCI concept demonstration was conducted using a PC-based simulation program developed by the Space and Naval Warfare System Center Pacific Unmanned Systems Group. The simulator incorporated video graphics from a customized commercial software nautical gaming simulator integrated with the MOCU-based user interface displays and controls. In Concepts 1 and 2 video graphics simulating forward/aft/starboard and port camera views (as well as PTZ) for each of the two USVs were displayed on the upper console monitor with USV#1 displayed on the left and USV#2 displayed on the right (see Figure 17-1). The lower monitor included an integrated Digital Nautical Chart (DNC) showing landmasses, radar contacts as well as routes and waypoints for both USVs. (See Figure 17-2) Operational information (speed, heading, location) was shown for each USV. In Concept 3, video graphics were displayed in an integrated “windshield” style display (see Figure 17-3) on the lower console and the DNC was displayed on the upper console (see Figure 17-4).



**Figure 17-1: Upper Display for Concept 2 Baseline Version of MOCU Multi-USV Video Information.**

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Figure 17-2: Lower Display for Concept 2 Baseline Version of MOCU Multi-USV Chart Information.

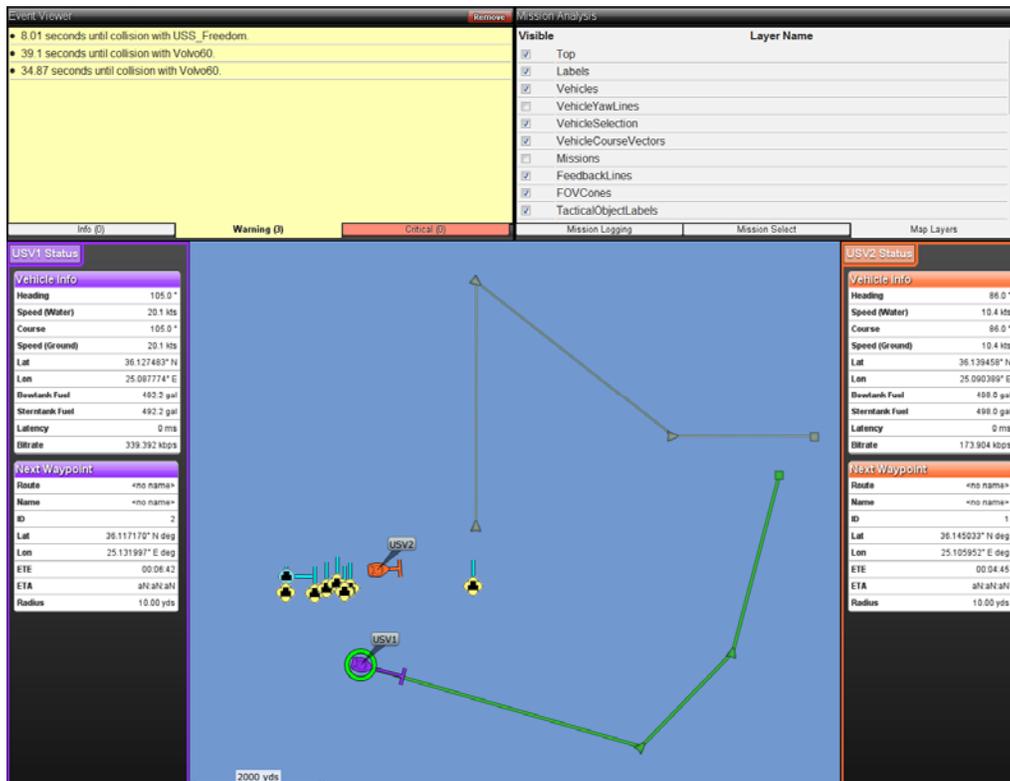


Figure 17-3: Upper Display for Concept 3 Version of MOCU Multi-USV Chart Information.



Figure 17-4: Lower Display for Concept 3 Version of MOCU Multi-USV Video Information.

The modularity and flexibility of the MOCU software architecture allows for relatively quick turnaround in implementing design improvements, therefore the software is well suited to an iterative test and development effort.

## 17.5 HUMAN FACTORS ISSUES EXPLORED

Human Factors performance issues with two simultaneous semi-autonomous USVs include the following:

- 1) **Attention Management and Attention Allocation** – Autonomous systems such as USVs that may be in fully auto or fully manual control modes require the user to know where and how long to focus on information pertaining to each USV. Also, the user must shift attention between USVs. The user's strategy must be aligned with the environment (e.g., traffic congestion) and speed of the USV and mission tempo (pace of mission events). Attention management and human vigilance is subject to errors in allocation and fatigue. Initial tests of the baseline 1 model in 2008 indicated the probability of error was high and that visual feedback in terms of type of information coding was not adequate. Also, the point-and-click type of control implementation required full visual attention. Further testing in 2010 indicated significant performance decrement issues if baseline visual cues were used. The Concept 3 version shown in Figure 17-3 and Figure 17-4 included the reconfiguration of displays and use of additional visual cues.
- 2) **Mental Model of Robot and Mission State** – The user must maintain an awareness of USV mission status and USV equipment status. Situation Awareness includes an accurate mental model of mission

objectives (reaching waypoints, deploying sensors) and safety (approaching danger from fixed or moving objects). The test scenarios for Concepts 2 and 3 included verbal reports for mission waypoints to superior officers. The verbal reporting activity adds to overall user workload. Position awareness and orientation requires understanding of each USV relative to the ship platform, and with two USVs potentially three different course and speeds simultaneously.

- 3) **Performing Emergency Maneuvers** – The user may need to respond to an unexpected safety issue or threat requiring a shift from automated to manual control and a corresponding course and speed change to avoid collision. If the user cannot quickly orient and respond to an emergency event the mission and USV could be at significant risk of collision and mission failure.

Correlation of real-world stimulus associated with multiple camera views has been a significant design challenge. The camera views distort the perception of approaching and crossing objects (e.g., other vessels). A successful HCI design requires an integration of information that minimizes visual scanning and shift from one display to another. The design problem for afloat USVs differs from both unmanned air and surface (ground robots) in the dimensions, approach and characteristics of obstacles and ability to detect and avoid obstacles. The water operational space is not controlled as air space is and the water surface is constantly moving with waves and floating objects, including submersed objects.

To mitigate human performance risk of errors and improve performance efficiency, several enhanced design attributes were implemented and tested. These attributes include:

- 1) Attention cues to aid in shifting of attention between USVs.
- 2) Orientation of map display and camera views to provide synchronized visual feedback to aid in maintaining an ongoing mental model of USV position.
- 3) Improved visual feedback as mission waypoints approach and are passed.
- 4) Integration of a hand-held “game” controller to replace point-and-click methods to reduce visual workload associated with manual control. This allows the users visual resources to maintain a camera view focus while a maneuver is made.
- 5) Overlay and integration of key status information with ongoing dynamic information from cameras and maps to reduce visual search and scanning.
- 6) USV-specific color coding of video display window borders and vessel status information to reduce confusion between USVs.

## **17.6 UNMANNED SYSTEMS USED**

The live demonstration used a laboratory model USV that was comprised of a commercial craft modified for remote control radio with sensors mounted onboard.



**Figure 17-5: Unmanned Surface Test Vehicle.**

The following components are part of the demonstration:

- Unmanned Surface Test Vehicle is a lightweight Length: 20' 6" / 6.25 m, weight: 3,250 lbs / 1,474 kg consumer (non-ruggedized) craft containing sensor packages.
- Sensors include: Digitized marine radar, Video (stabilized or non-stabilized), Stereovision (3D range data), Monocular vision for obstacle detection.
- Automatic Identification System (AIS) (receive-only currently, Uncooled thermal imager (in future possible laser range scanner).
- Multi-robot Operator Control Unit (MOCU) baseline version software and HCI package enabling user monitoring and control of one or more USVs.
- Radio transmitter and receiver for video and communications to/from vehicle.
- Obstacle detection and avoidance software and methods were disabled.

For simulated tests in the laboratory, the MOCU simulation used the larger 11-meter "fleet" class USVs designed for operational missions. The simulation also replicated the types of cameras available on the operational model. These USVs weigh approximately 7700 kilograms. The USVs are designed to be remotely operated from the LCS host ship. Although each USV will be equipped with radar, current plans do not include onboard obstacle avoidance capability.

## **17.7 SUMMARY OF ANY NATO COMMUNICATIONS/COLLABORATIONS/ INTERACTIONS**

- 1) USN received design guidelines from Canada Defence R&D Canada – Toronto on Intelligent Adaptive Systems.



- 2) Received guidelines on visual display symbology from US Army HFM-170 member.
- 3) Posted guidelines for command and control mission flow visualization to all members.
- 4) USN, Canada, Netherlands – discussed generalization of results to Explosive Ordnance Disposal robot applications.
- 5) USN, USAF – Discuss speech and voice technology applications for robot control.
- 6) USN, US Army, Discussion of playbook and work process visualization for mission supervision.

	<i>Planning/Design</i>	<i>Execution</i>	<i>Analysis</i>
<b>Communication</b>	1) USN and Canada 2) USN, Canada, NE		
<b>Coordination</b>	2) USN and US Army		
<b>Collaboration</b>	2) USN and all	Potential USN and US Army future collaboration in upcoming cargo air robot project	

**17.8 SUMMARY OF TECHNICAL DEMONSTRATION RESULTS**

The operational demonstration was successfully completed in April 2009 [1],[2] using the integrated map and video version of MOCU. The demonstration had several caveats regarding validity of results. First, the users were not end-users (Navy operators) but instead were project engineers. Second, the mission scenario and course was limited to a small range and area due to safety precautions, with a live human operator available on the USV to take over control in case of emergency. Overall the demonstration showed the validity of the initial HCI design concepts and demonstrated a test capability to conduct further testing and analysis.

Subsequent testing sessions in 2010 [3],[4] and 2011 [5] evaluated Concept 2 (baseline) and Concept 3 HCI designs in support of multiple robot operations. Overall, the testing showed that Navy operators had difficulties in attending to two USVs simultaneously, however performance was significantly improved for Concept 3 with the addition of the enhanced design attributes described above. User performance across three task areas is discussed below:

- Responding to contacts in emergency situations – Each scenario included four events requiring the subjects to observe and maneuver around one or more vessels stationed or moving in the direct path of one of the USVs. In Concept 2 testing, all subjects failed to avoid collision in at least one instance and most were involved in multiple collisions, resulting in an overall collision rate of 67%. Subjects typically noticed the contacts too late to take effective evasive action – even though all contacts were visible in at least one video window for at least 30 seconds prior to impact. In three instances, subjects failed to notice the contact at all and took no evasive action whatsoever as they were monitoring other video windows or performing other tasks. In Concept 3 testing, subjects not only showed an improved

capability to detect contacts but also demonstrated improved capability to successfully execute avoidance actions, resulting in a decline in the overall collision rate to 27%. This rate is still significant for operational conditions. Thus, an upgraded Concept 3.1 will be generated and tested.

- Responding to system status alarms – During the scenario a system status alert was turned red and flashed indicating a high engine temperature alarm. Operators responded by making a report to the mission supervisor. In Concept 2 testing, reports were made within the designated response window only 33% of the time. In Concept 3 testing however, the response rate improved to 63% with improvements also noted in the ability of subjects to take appropriate action (i.e., shut down engines) in a timely manner.
- Making verbal waypoint reports to command – Operators were directed to make reports to the mission supervisor as each waypoint was reached along the pre-planned routes. In Concept 2 testing, timely reports were made 90% of the time for the first and last (4<sup>th</sup>) waypoints on the routes (typically reached during times of low scenario activity when subjects had few distractions), and 77% of the time for waypoints 2 and 3 (which occurred during periods of high scenario activity and heightened mental workload). In Concept 3 Testing, subjects completed waypoint reports successfully 97% of the time for waypoints 1 and 4, and 84% of the time for waypoints 2 and 3.

In addition to the improved performance noted on objective measures for the Concept 3 HCI design, subjective measures collected during an exit survey also showed a strong user preference for the Concept 3 controls and display configuration.

## **17.9 LESSONS LEARNED**

The initial findings of this study demonstrated that the baseline Concept 2 interface would not safely support simultaneous operation of multiple USVs and identified a number of specific opportunities for improving the overall HCI that were incorporated into a Concept 3 design. Although subsequent testing of the enhanced design showed dramatic improvement across all performance measures, operator errors were still observed at an unacceptable level and additional opportunities for design improvements were noted, including:

- Increased collision avoidance aiding tied to attention alerting cues (the need for advanced obstacle cues may require placement of additional sensors onboard USV platforms).
- Prominent urgent alarm messaging, to include the addition of audio alerts.
- Improved color coding to depict route graphics.
- Refinement of hand held controls to reduce joystick sensitivity and prevent inadvertent shifts in driving mode.
- Enhanced indication and control of PTZ camera magnification levels.
- Additional engine status indication and independent start/stop controls.

## **17.10 STUDY CONSTRAINTS/LIMITATIONS**

The primary limitation of this usability testing was the fidelity of the simulator and the realism of the mission scenario. Several aspects of the simulator differ from the actual system including:

- The substitution of digital animation for live video;

- Non-functionality of many secondary screens that operators would normally have access to;
- The actual shipboard hardware with alternate video monitors; and
- Substitution of a mouse for trackball control.

Although every attempt was made to build a realistic mission scenario, it must be recognized that the initiating events and responding actions represented in the scenario would in actuality unfold over several hours as opposed to the 30 minutes it took to simulate the mission. When questioned about the realism of the simulation most subjects (including the most experienced USV operator who was involved in developing the Operational Procedures for the real system) indicated that it was “pretty close” or “not far off” and that fidelity level would be sufficient to serve as a “useful training aid”.

## **17.11 CONCLUSIONS**

The results of the usability studies confirmed the existence of many human factors concerns that had been identified through previous heuristic reviews and HCI design walkthroughs of interface displays. Based on the results of the testing in which even experienced operators demonstrated degraded performance, the researchers concluded that the baseline Concept 2 design interface would not safely support simultaneous operation of two USVs. Design Concept 3 shows great promise but is not yet at a level that would support safe and reliable operation of multiple USVs simultaneously. Concept 3.1 will be generated and tested in 2011.

## **17.12 FUTURE RESEARCH NEEDS AND PLANS IN THIS AREA**

Further design alternatives will be explored in developing an improved interface that will be tested and compared to previous versions. The goal of the studies will be to measure performance of the current USV sensor package, with the HCI improvements. Another configuration will include obstacle avoidance aids that are technically feasible. These aids will be simulated and tested for comparison with the lower cost, lower fidelity sensor package. A design trade-off between USV cost, risk and user performance can then be accomplished.

## **17.13 ACKNOWLEDGEMENTS**

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## Chapter 18 – CONCLUSIONS

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This underlying report describes how HFM-170 successfully developed and demonstrated pertinent supervisory control human-system interface design practices and operator interface concepts for Uninhabited Vehicles (UVs) network-centric operations. In a series of 14 specific Technology Demonstrations (TDs) it was shown that the operator's role is becoming more supervisory of nature since future UVs will be increasingly automated (e.g., autonomous capabilities, multiple systems, systems of systems), on the other hand it was demonstrated that new sensor and control technologies enable operators to be closer in the loop in a telepresence situation. The applications addressed varied in degree of autonomy from manual robotic control to highly autonomous, swarming UVs. A variety of critical issues were addressed including multi-vehicle control, manned-unmanned teaming, human-automation interaction, telepresence interfaces, delegation interfaces, vehicle hand-offs, operator workload adaptive systems, variable levels of autonomy, authority sharing, situation awareness aids, cognitive workload assessment, swarming interfaces, and dynamic mission management. HFM-170 also concentrated on the identification and demonstration of successful supervisory control methodologies and interface design practices for enabling single operator control of multiple UVs.

Based on these TDs the following conclusions can be drawn:

- Live-demonstration of UV supervisory control methods and enabling technology as experienced within NATO HFM-170 is a complex undertaking which requires serious preparation. These TDs were well received by the entire Task Group. [ALL]
- These demonstrations, along with periodic meetings, provided a valuable forum to exchange technical information and discuss possible future collaborations in supervisory control research and development. [ALL]
- The developed 7 Dimension Framework model held the most promise for satisfying the ends of the Task Group. This model was largely descriptive, but it captured several dimensions relevant to the many alternate supervisory control systems, relationships and usages we were examining. While the specific dimensions examined need to be refined, and the scales for characterizing them might also be improved upon, this multi-dimensional description of alternate systems seemed to provide the right level and type of information for conveying how a set of supervisory control systems are similar and different from each other. [ALL]
- Hand-off demonstrations between two UV supervisory control crews, as well as between an external pilot (flying manual control) and a supervisory control station was successfully verified. [CAN-1]
- Self-organization and protection capabilities of multiple autonomous ground vehicles through Artificial Impedance Control for local autonomy including collision avoidance and trajectory generation showed

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excellent results. Expanding this with formation control and flocking control through computer simulation showed promising results. [CAN-2]

- A technology demonstration called OmniSense showed the efficacy of a multi-modal display (i.e., the presentation of visual, auditory, and tactile information) for enhancing supervisory control of an automated UAV. The benefit of OmniSense is anticipated to be particularly evident in an increase in the detection of critical events, a reduction of response times to critical events, and increased situation awareness. This suggests that the OmniSense solution will be more effective than a visually-only GCS interface. [CAN-3]
- Swarm intelligence seems to be a promising approach for multiple UVs control in terms of algorithmic performance and robustness, as long as human factors and especially man-machine communication and interaction are properly adapted. [FRA-1]
- A program demonstrating new means of cooperation and interaction between Humans and Automates (“Authority Sharing”) showed that it is possible to optimize the workload of existing UAV systems by allocating dynamically the operators’ functions, allowing thus the integration of multiple UAVs and payloads without necessarily increasing the number of operators required to manage. The operators appreciated the human-machine interface, in particular the “draggable vector tool”. Regarding the “authority sharing” engine, the overall performance does not change with or without the activation of the engine, but the test panel was too small to statistically confirm this data. [FRA-2]
- The demonstration of a generic approach in the development of a knowledge-based assistant system adapted to the domain of manned-unmanned-teaming focused on guidance of multiple UAVs from the commander’s workplace in a helicopter cockpit aided by an assistant system. This approach was evaluated through experiments in the helicopter simulator. The introduction of the assistant system improved human factors related variables like situation awareness and workload, improved performance and safety, and was well accepted. It is also concludes that the next steps to further improve the assistant system performance and acceptance should be to refine the knowledge models for operator overtaxing estimation, current task recognition and cost prediction, and to refine the action and decision support for tasks. Finally, the cooperation and variable task assignment between commander and pilot flying have to be further investigated and regarded within the concept. [GER-1]
- An experimental research collaboration between the US Army Research Lab and NL TNO where robots were used for reconnaissance of a remote area revealed:
  - 1) No difference between the Mono-Headtracking condition and the Mono-Joystick condition in accuracy of target identification. However, more time was required for target identification when using joystick control.
  - 2) The Telepresence condition (that included 3D audio) increased the percentage of correctly identified targets by approximately 23% compared to the Mono-Headtracking condition (using a directional microphone). In addition, target identification took approximately 35% longer without having the 3D audio functionality available.
  - 3) The Telepresence human-robot interface decreased identification/localization times for audio stimuli by approximately 42% as compared to currently commonly used interfaces. In addition, target identification performance increased by about 26% when using the Telepresence human-robot interface. [NL-1]
- A test of a new framework for managing UAV task and workload allocation between various operators in a mission scenario revealed improvements of optimal in-the-loop inclusion of operators

for the successful application of multi-UAV systems. Further testing, with simulated scenarios, will provide new insights over the real capabilities of the proposed framework. [PT-1]

- A demonstration/test where an operator had to mainly manually navigate one, two, or three partly autonomous UGVs to pre-designated inspection points in a simulated urban environment showed that the limited autonomous function was insufficient to significantly improve the operator to vehicle ratio. The operators were saturated even when only controlling two UGVs in a basic navigation task. More advanced autonomous functions or control station interfaces that reduce the attention demands are therefore necessary to improve the operator to vehicle ratio. [SWE-1]
- A demonstration/test revealed that partly autonomous UGV functions can improve the operator to vehicle ratio if there are weak dependencies between the task that an operator performs and the task that the partly autonomous function performs. However, these task dependencies also depend on the operators' task experience, as well as the formal task properties. The operators' control strategy showed that they were rather naïve towards the complexities of tactical reconnaissance tasks. More experienced operators may therefore find different task dependencies. [SWE-2]
- Demonstration and test of the Dynamic Airborne Mission Management (DAMM) program developed a set of principles, interfaces and interactions for the delivery of effects, enabled by advanced digital networking and mission enabling technologies, providing a distributed, collaborative and adaptive mission capability for stability and dominance in a dynamic environment. DAMM synthetic environment and flight trials provide evidence with high levels of proof for real benefits of a full suite of collaborative decision support tools across multiple tiers of the networked dynamic Command and Control (C2) architecture. This work has shown that as data rate, confidence and context increase/improve, nodal (micro) and system (macro) C2 decision loop activity transposes from slow serial to concurrent-NRT speeds. Consequently, kill-chain timeline, fratricide and collateral incidents should reduce. [UK-1]
- The Multi-UAV Supervisory Control Interface Technology (MUSCIT) program demonstrated several advances in UAV control station interface technology that enables effective single-operator, multi-UAV performance for surveillance and re-routing tasks. Interface enhancements included a novel tactical situation (map) display, speech recognition, synthetic overlays, mission and sensor automation, integrated information displays tailored for supervisory control, and support tools for multi-sensor management tasks. The control station technology was demonstrated in a four-vehicle configuration made up of two actual UAVs in flight along with two simulated UAVs, all controlled by a single operator. The operator interface was iteratively developed using a spiral approach; combining simulation and flight testing to characterize operator and mission performance, empirically derive and refine technical requirements, and refine operator interface technology. Empirical results from simulation and flight evaluations reveal specific costs to operator performance, situation awareness, and workload as a result of increasing the number of UAVs a single operator is required to manage. [US-1]
- Delegation Control of multiple heterogeneous UVs by a single operator was successfully demonstrated. Navigation and payload control of four unmanned systems was monitored by a single operator in a collaborative urban mission scenario. Delegation Control employment strategy and interface design supported the build, initiation, modification and monitoring of simultaneous plays in progress. Use of voice recognition was considered an advantage to the operator during time critical mission phases. The operator's ability to bypass menus in favor of voice recognition control, significantly decreased reaction time to external mission events. Dynamic route re- planning was effectively accomplished while plays were in progress. In addition, play status was efficiently

## CONCLUSIONS

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depicted and real-time updates were accomplished when play modification and play terminations occurred. Automation transparency was increased through messages that described impacts of conflicting plays. Lastly, the Play Status window was considered a significant contribution to operator situation awareness for rapid awareness of asset allocation and play scheduling. [US-2]

- The results of two experiments using RoboLeader, using simulations to understand how to develop a synergistic relationship between human supervisors (having final decision authority) and intelligent agents (who supplies algorithmic solutions for many-to-one control problems) showed that operators were able to intervene more successfully with False Alarm Prone (FAP) error rates than with miss Prone (MP) error rates, contrary to previous findings in the literature. The apparent reason for this was that the more compact interface used in the current experiment allowed FAP verification to be accomplished more efficiently. In contrast, MP errors required operators to constantly scan the map reducing their target detection scores on the video displays. The final experiment showed the efficacy of RoboLeader in aiding the operator to conduct more complex missions which required four robots to entrap a moving target. [US-3]
- The results of usability studies to investigate alternate design configurations relative to optimum human performance and decision-making in USV supervisory control confirmed that the baseline concept design interface showing video graphics simulating forward/aft/starboard and port camera views for each USV would not safely support simultaneous operation of two USVs by a single operator. A design concept displaying an integrated “windshield” style display showed great promise but is not yet at a level that would support safe and reliable operation of multiple USVs simultaneously. The latter concept will be further tested. [US-4].

All TDs were very successful and well received by the Task Group members. It is therefore recommended to disseminate results and lessons learned associated with the technical demonstrations of HFM Technical Task Group HFM-170, Supervisory Control of Multiple Uninhabited Systems – Methodologies and Enabling Human-Robot Interface Technologies. The aim is to bring together representatives of the research and operational communities at invitation, to present technical demonstration results, and to review progress in this important area.

## Annex A – DYNAMIC AIRBORNE MISSION MANAGEMENT: LESSONS LEARNT

### A.1 DYNAMIC AIRBORNE MISSION MANAGEMENT

Fundamentally, DAMM is primarily concerned with adaptation of mission command, mission flow and effects delivery to changes in the mission context. In UK MOD operations, the mission context for tactical missions is customarily briefed in terms of the “4 Ts” – Tasks, Targets, Threats, Tactics – and the observed impact on timeliness for a co-ordinated and precision engagement mission. Thus, the 4T’s provide an operationally relevant representation and high level decomposition of the key elements of the mission context. A simple representation of the functional flow model for DAMM in relation to the 4Ts is shown in Figure A-1 below.

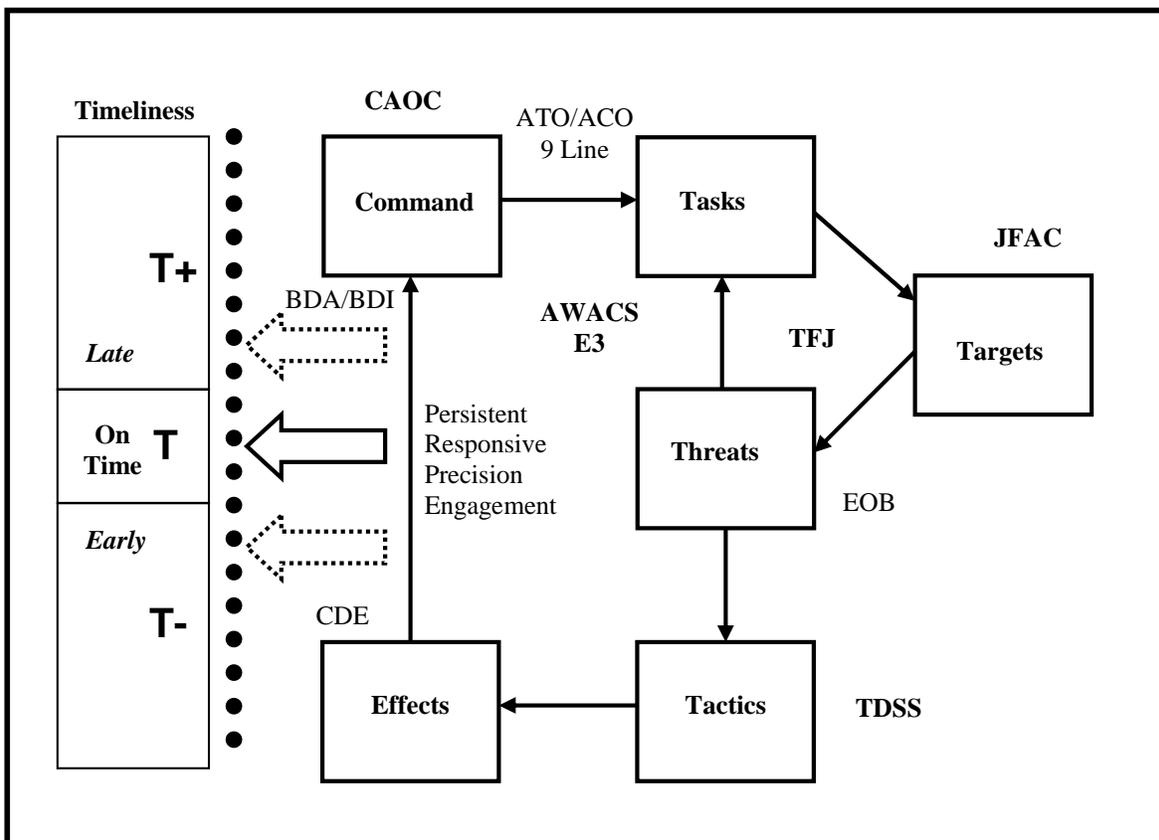


Figure A-1: Functional Model of DAMM.

The functional flow model of DAMM illustrated in Figure A-1 provides a useful framework for planning of DAMM test and evaluation studies. This framework has utility for defining test variables and metrics, with potential discriminative power for diagnostic and prognostic analysis. All 4T’s, coupled with command intent and the timeliness of effects, should be considered as essential mission variables and sources of metrics for comprehensive studies of DAMM advanced digital networking and mission enabling technologies.

## **A.2 MISSION CONTEXT**

Measurement and control of the complexity of the mission context provides a basis for standardisation, comparison and balance in test design. The “4 T’s” – Tasks, Targets, Threats, Tactics – with timings of effects, provide an operationally relevant framework for the description, decomposition, and measurement of the mission context. The frequency of individual tasks, targets, threats, tactics (and affected timings) can be controlled, observed and measured directly. Additionally, given the familiarity of operators with the 4T’s framework for briefing missions, it seems sensible and potentially useful to try to elicit from participant operators, or from observer subject-matter experts, estimates of the demands on operators workload arising from changes in mission T’s. Accordingly, in the both 1<sup>st</sup> and 2<sup>nd</sup> US-UK Strike Warrior SE Trials, rating scale estimates (using 7-point Likert scales) of Change Management Demand for Tasks, Targets, Threats, and Tactics (Times 1<sup>st</sup> Trial only) were obtained from the participants for individual trial runs. The mission T’s change demand ratings data showed evidence of systematic and sensible trends (Tasks>Targets>Threats>Tactics>Times) and some statistically significant beneficial effects of advanced system architectures (Baseline>Threshold>Objective). It was noted that Target and Threat demands arose directly from the external environment and mission scenario. In contrast, Tasks, Tactics and Times were mitigation responses mediated by the system architectures and mission management.

## **A.3 SCALE**

In the operational environment, DAMM involves complex interactions and interfaces between air packages, C2 elements and air-land co-ordination. In planning realistic technology demonstrations and operational testing, the scale of the tested operations and architectures, and the degree of uncertainty or volatility in test missions, are major determinants of the validity, reliability and generalisability of test findings. Scale is a major study cost driver. More affordable small-scale, sub-system studies provide simpler effects and easier measurement, but risk low generalisability of findings. More costly large scale, system-of-system realistic demonstrations can be convincing and impressive, but the more complex effects arising can be difficult to quantify and verify, in particular with regard to repeatability and reliability. A mixed approach is probably preferable, using progressive development and testing of prototypes, for better managing the risks and costs of scale. This can be provided by a series of development and test phases, with increasing complexity, and prioritisation of core capabilities, critical interactions and essential interfaces. A progressive approach can be facilitated by exploiting any inherent scalability in the technical system and testing scenarios. The DAMM architecture afforded progressive building and extension of the horizontal (effectors packages) and vertical (tactical/operational command) C2-MM system components. The DAMM scenario afforded incremental development of mission complexity by the addition of tasks, targets, and threats.

## **A.4 VOLATILITY AND UNCERTAINTY**

DAMM seeks to enable adaptation and stability in a dynamic environment. The scenario and missions were designed to allow White Force to vary volatility and create uncertainty through injection of unexpected and disruptive information and events via tasks, targets and threats. Variability in the volatility and uncertainty of the missions is necessary to stress and test human component capabilities:

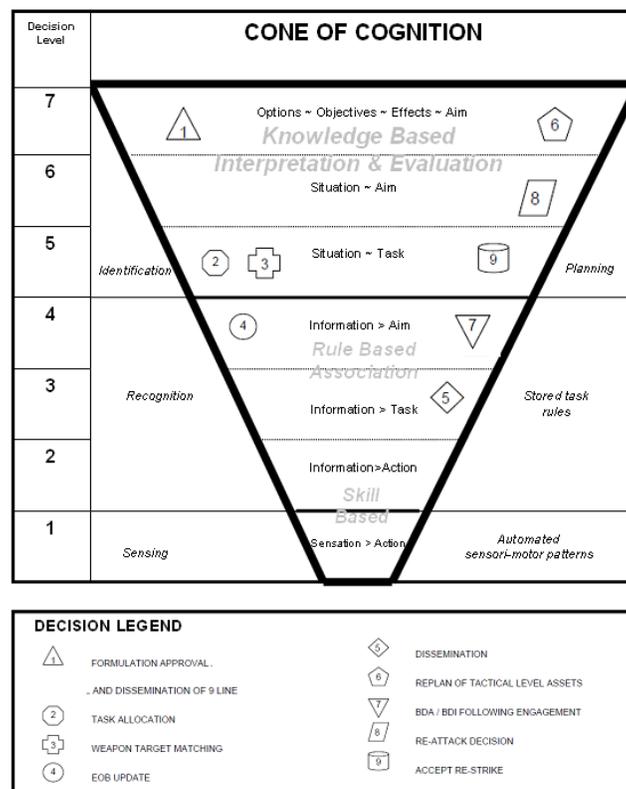
- To exercise and challenge the operator’s use of DAMM tools, and application of skills, rules knowledge underpinning Mission Essential Competencies (MEC);
- To mitigate operator learning;

- To provide military operational variety and realism; and
- To enable participant engagement and immersion.

Control of the scale of volatility and uncertainty in the test scenario missions provides a further basis for standardisation, comparison and balance in test design. The frequency of injections of changes affecting tasks, targets, threats, and tactics afforded by the vignettes can be observed and measured directly to provide direct measurement of the mission volatility. Estimates of Change Management Demands associated with the 4Ts provide indirect measurements of the resulting uncertainty. However, these are confounded with the mitigating effects of the DAMM system architectures. The scenarios were designed with a set of vignettes (typically 3+) to provide variety and challenge, with progressive complexity and volatility. In practice, the degree of volatility and uncertainty appropriate for stressing and testing effectively the DAMM tools relied heavily on military judgement. Generally, vignette complexity was matched to the DAMM capability under test. White Force used more complex vignettes and injected more volatility and uncertainty on Objective architecture runs, expecting better mitigation and adaptation. The Baseline architectures were tested with relatively simpler vignettes.

### A.5 DECISION MAKING

In the development of the DAMM CMDM assessment approach, it was useful to consider how DAMM CMDM task MECs were structured with reference to existing cognitive frameworks. Figure A-2 illustrates the structure of individual CAS/TST CMDM task MEC examples within a Skills–Rules–Knowledge (SRK) cognitive framework.

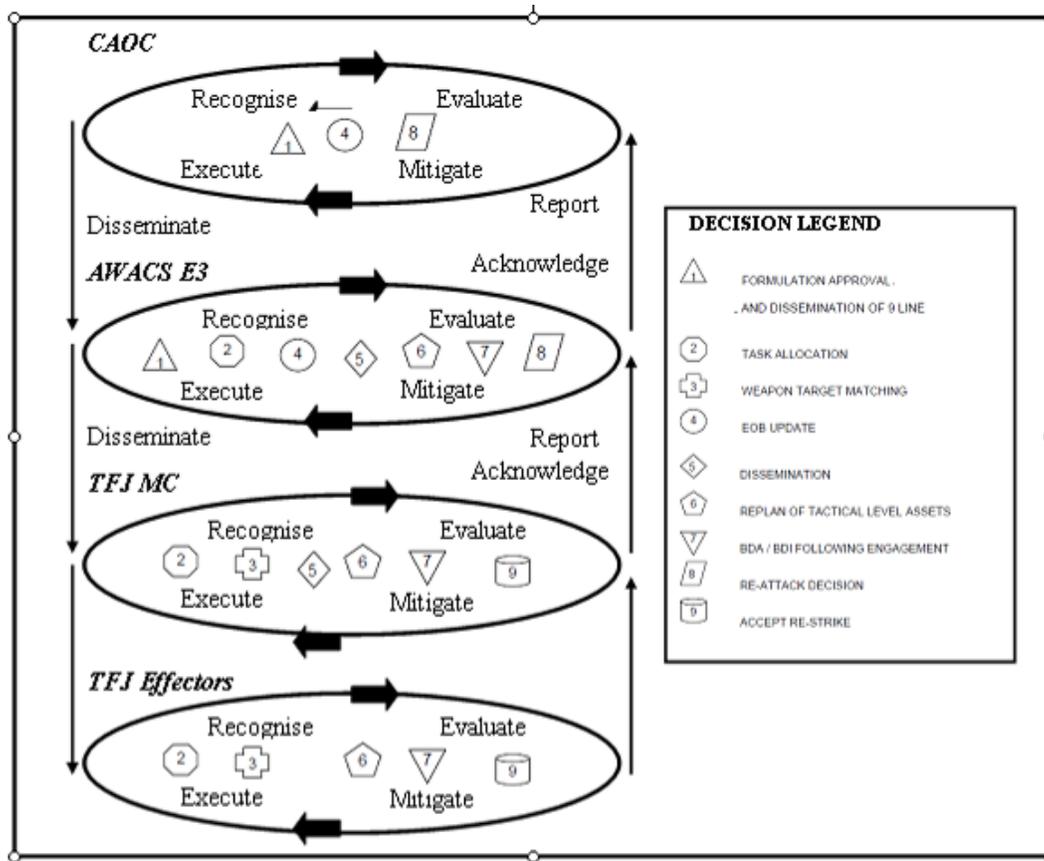


**Figure A-2: DAMM Decisions in the SRK Cognition Framework.**

The SRK framework draws distinctions between automatic and naturalistic or recognition-primed decision making, and deliberative, analytical and evaluative decision making. In Figure A-9, the nine CAS/TST CMDM task MECs are shown as residing at the rule-based association level, and at the knowledge-based interpretation and evaluation level.

The SRK framework concerns cognition at the level of the individual. DAMM concerns individuals working collaboratively within a distributed, hierarchical C2 process. So, it was also considered useful to examine how DAMM CMDM task MECs were structured with reference to C2 framework. Cognitive control theory represents cognition as a layered process of multiple control loops. Figure A-3 illustrates a representation of the structure of the CAS/TST CMDM task MEC examples within the Operational and Tactical C2 architecture C2 OODA (Observe>Orient>Decide>Act), or “COODA loop” layered control system. Here, the REMDAER\* framework provides the components for multi-player, distributed, or team, decision making cycle.

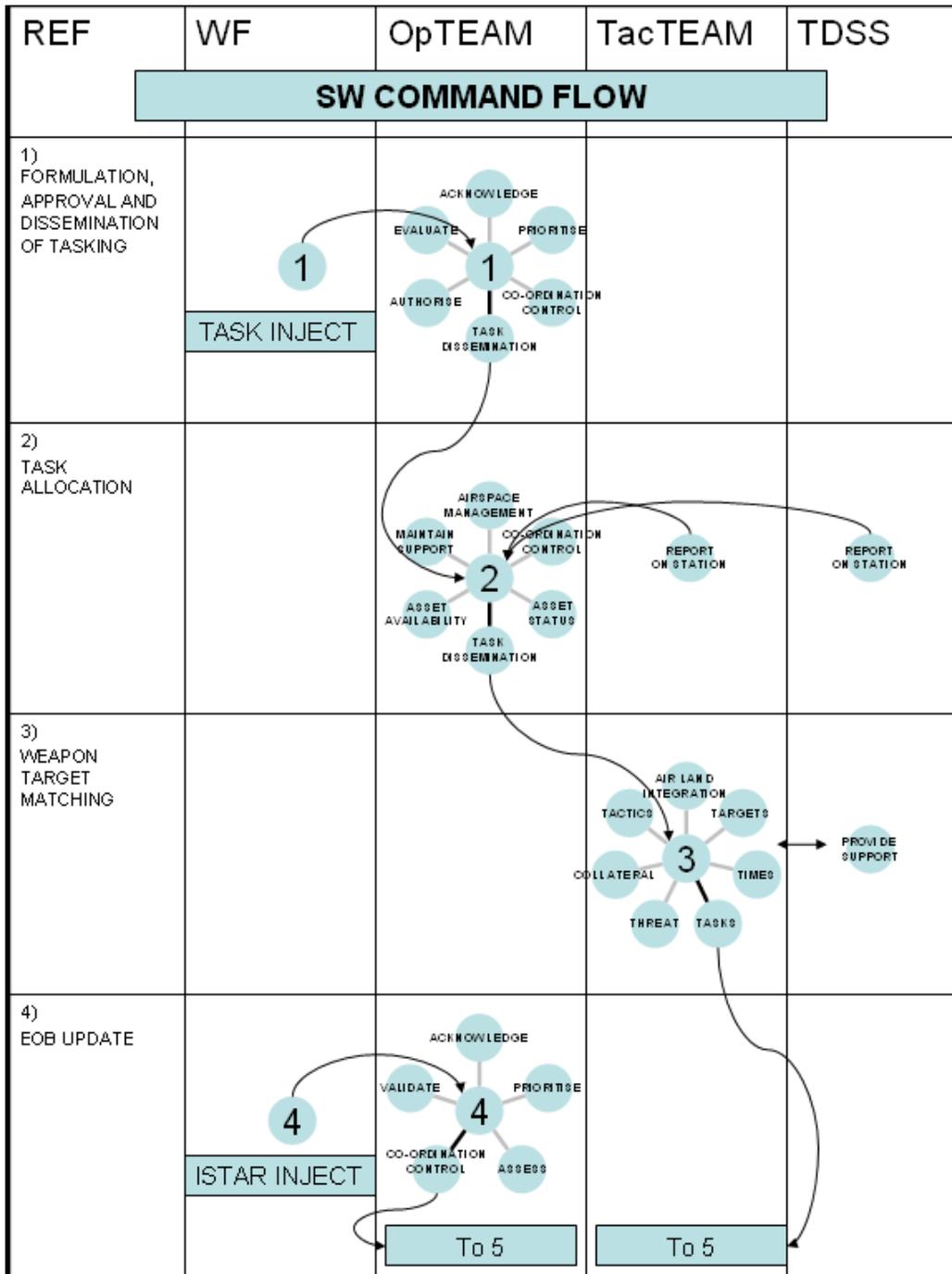
*\*Recognise>Evaluate>Mitigate>Disseminate>Acknowledge>Decide>Execute>Report.*



**Figure A-3: DAMM Decisions in the REMDAER Framework.**

In the development of DAMM capability, and in planning and reporting of trials, it was found to be useful to provide system-of-systems views and system architecture representations of DAMM CMDM derived from MODAF/DODAF system architect tools. Figure A-4 illustrates a representation of the structure of decision making using a systems architecture framework view approach (MODAF/DODAF), with CAS/TST CMDM

examples depicted in sequential order, with the *Command Flow* across the architecture tiers (CAOC White Force; E3 OpTEAM; TFJ TacTEAM and TDSS), and with the *Mission Flow* within Tiers. This approach is more suitable for identifying CMDM characteristics such as influencing factors, prioritisation, and alternative Courses of Action (CoA).



**Figure A-4: DAMM Decisions in Command and Mission Flow Framework.**

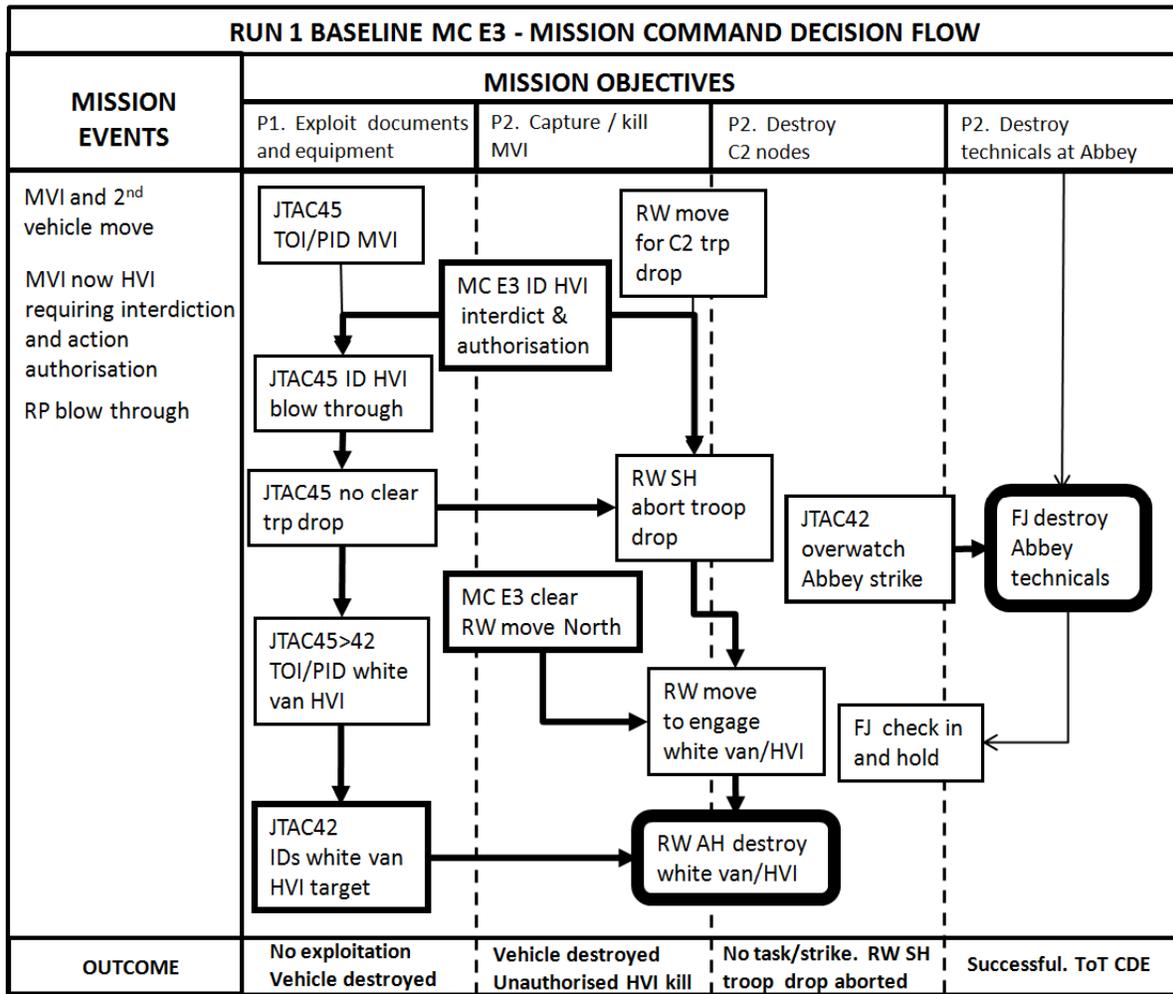
In DAMM SE trials workshops, the impact of DAMM on mission command flow was frequently discussed and debated, in particular the increased potential for distributed adaptive decision making providing support for the role of Mission Commander. It was hypothesised that in more highly networked collaborative architectures, SSA might be more widely and better distributed, and that mission command decision making processes might not necessarily need to be centralised, as illustrated in Figure A-5. As reported earlier, in the 2<sup>nd</sup> Joint US-UK SE Trial, September 2010, four different MC positions were tested, and the Objective architecture provided relatively good adaptability proficiency with the MC in all four positions, consistent with good communications and SA. Individual runs showed benefits of distributed and adaptive decision making, afforded most by the networked Objective architecture. Further work is needed to more fully understand the implications of DAMM for Mission Commander MECs.

<b>MISSION COMMAND</b>	<i>BASELINE</i>	<i>THRESHOLD</i>	<i>OBJECTIVE</i>
<p><b>DECISION HOLD</b> PACT In Command Participants provide MC with information and advice, and MC decides course of action</p>			
<p><b>DECISION TIGHT</b> By Consent PACT In Support Participants provide MC with advice and action information, and if approved by MC, participants perform advised Action</p>			
<p><b>DECISION FREE</b> By Exception PACT Direct Support Participants provide MC with advice and action information, and perform advised action, unless revoked by MC Dynamic Adaptive</p>			

**Figure A-5: Effect of DAMM Network Architecture on Mission Command.**

## **A.6 DYNAMIC MISSION ACTIVITY REPRESENTATION**

In analysis and reporting of successive trials, the need was recognised to develop improved methods for the representation of the missions. Mission representations needed to highlight the important relationships between system components, participants, tasks, goals, events, decisions and outcomes. This was needed in a manner that captured the structure of the dynamics and flow and afforded measurement of performance. Illustrations of the forms of representation that evolved under DAMM, and that were found to be useful, is shown in Figure A-6 to Figure A-8 below.



**Figure A-6: DAMM Mission Command Decision Flow.**

**ANNEX A – DYNAMIC AIRBORNE  
MISSION MANAGEMENT: LESSONS LEARNT**

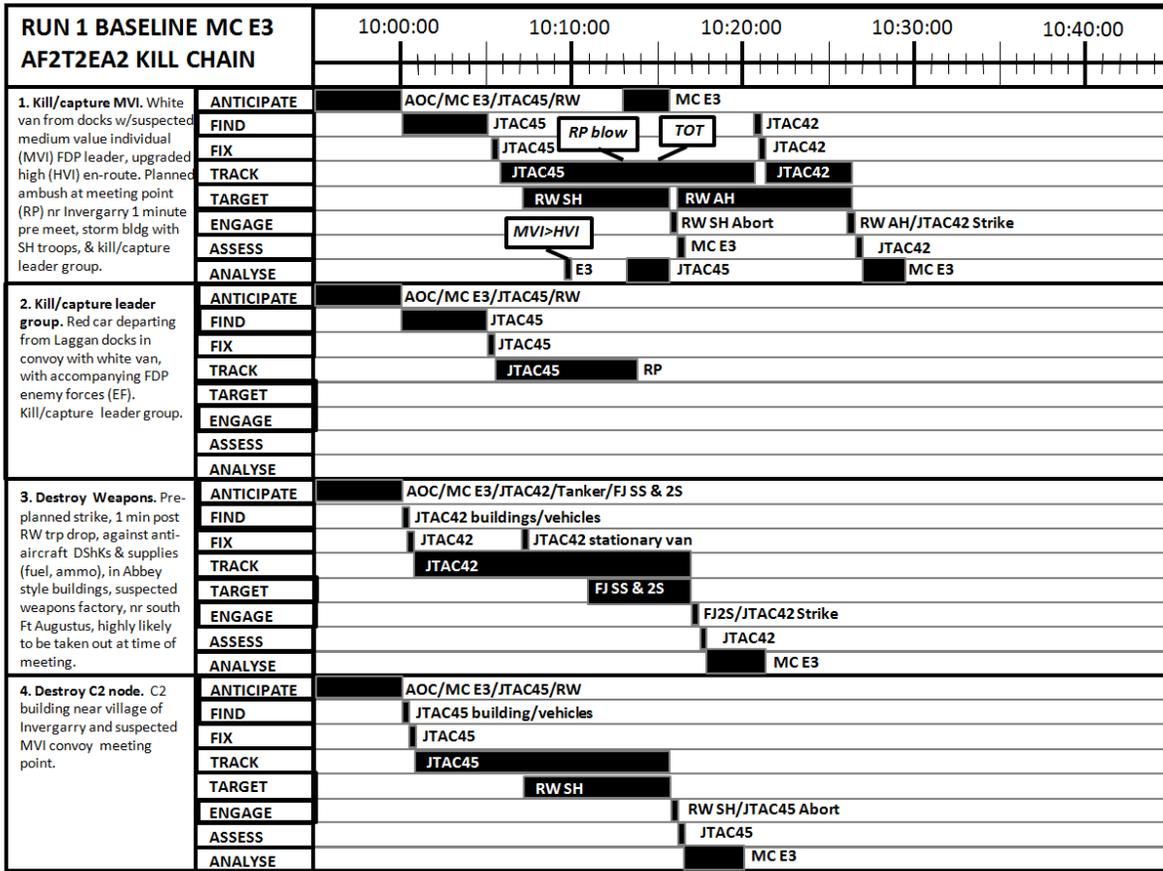


Figure A-7: DAMM AF2T2EA Kill Chain.

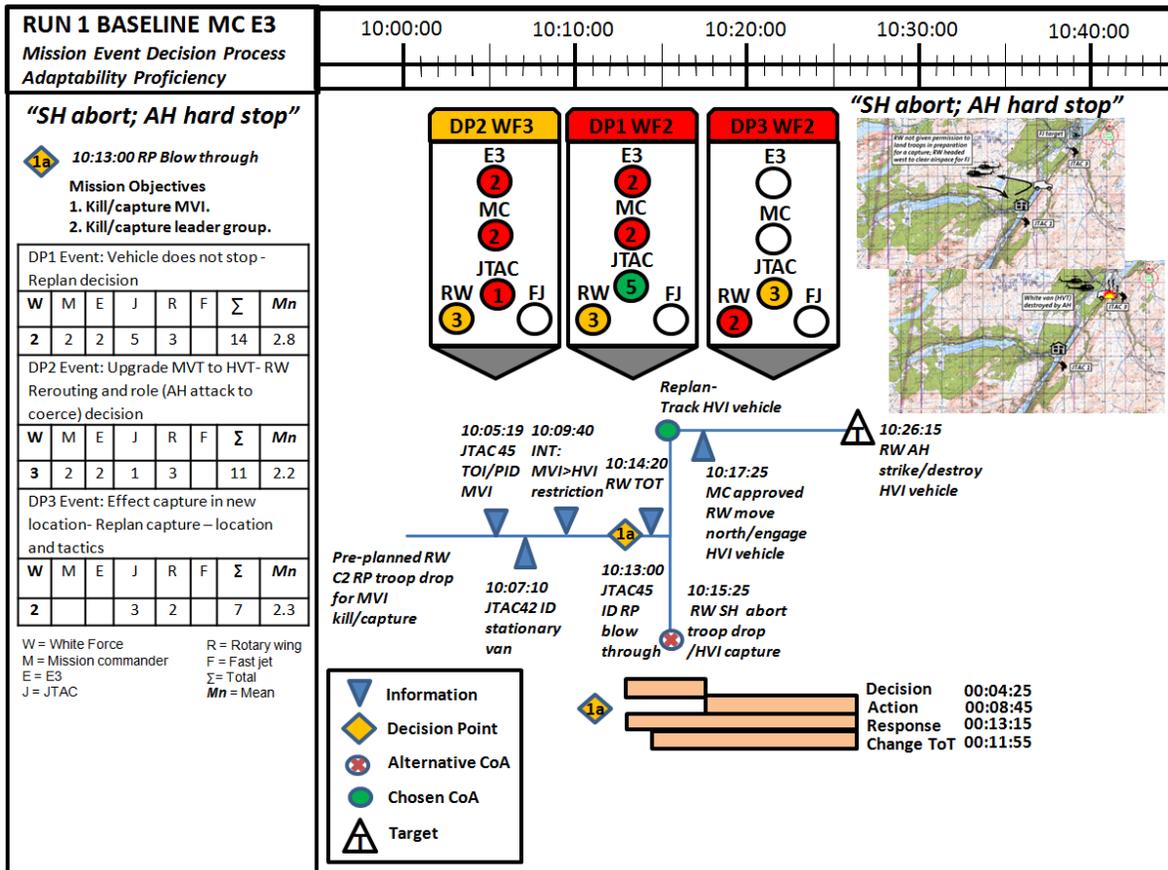


Figure A-8: DAMM Adaptability Proficiency Decision Mapping.

## A.7 TOOL USAGE

The creation of scenarios and missions that properly and fully exercised the envisaged use of the DAMM tools proved problematic. This arose because of difficulties in effectively mandating DAMM tool use during the test trials. Variability in tool usage is partly a training issue. However, although the DAMM tools are regarded as enabling technologies, fundamentally they are designed to provide operator aiding and decision support. Tool use is optional. Simple mission management tasks can be completed “manually” without the aid of DAMM tools (c.f. Baseline architecture), relying only on the operator’s airmanship and tactical knowledge and skills. Whether or not the DAMM tools actually get used in a realistic trials environment is dependent on the operator’s training and perceptions of utility, benefit, and ease of use, as judged in the mission context. Mitigation of the risk of non-usage of tools can be achieved by identification of strong tools use cases, and by integration of validated use cases into the trials scenario missions.

## A.8 LEVELS OF PROOF

The DAMM programme of work involved progressive development and test with increasing levels of proof and evidence of integration de-risking and system performance. The work progressed from laboratory bench

testing, through Synthetic Environment (SE) trials, to Live, Virtual and Constructive (LVC) environments and flight test. The levels of proof and weight of evidence required for technology demonstration and test are associated with the Technology Readiness Level (TRL) of the systems under test, and the needs for risk reduction and cost/benefit assurance. For progressing development of concept prototypes at relatively low TRLs 1 – 4, laboratory bench testing and SE evaluations of mission enabling technologies can be appropriate, using only core sub-systems, semi-realistic missions and part-task simulations, comparing only essential equipment, messages and links, and varying critical characteristics of the operating environment, missions, stresses and tasks. Here, relatively low levels of evidence of performance and effectiveness can provide necessary and sufficient for proof of progress and assurance of concept validity, e.g., nominal/ordinal qualitative data level metrics, aircrew subjective ratings, operator usability questionnaires. At high TRLs (5+), demonstrating de-risking and readiness for exploitation in real systems, LVC and flight test of mission enabling technology are needed, using real environments and stresses, current equipment and systems, with objective measurement of performance and effectiveness on realistic operational missions and tasks, and demonstrations of real effects.

In an advanced simulated environment, features and components can be varied up to high levels of fidelity and representativeness, within constraints of time and cost. In a programme with progressive test and evaluation, not all the system features need necessarily simulated at a uniformly equivalent level of fidelity, e.g., co-ordinated aircraft behaviours, outside world visual resolution, sensors and communications performance, C2 procedures, cockpit/crew workstation layout, HMI. For mission systems testing, the design of the SE test environment representativeness should provide the standard of fidelity necessary and sufficient to accomplish the specific test objectives. Higher levels of SE representativeness should be needed for features involved directly in the performance of critical mission functions. For networked critical mission system functions and associated tasks, interactions and procedures, particular consideration needs to be given to the requirements for representativeness of SA and tactical information, and data link communication of tasks, threats, targets, tactics, and positions of other assets, routes and airspace.

The Operator-Mission Interface (OMI) is a critical component of DAMM. Involvement of experienced military operators is essential at all the levels of mission system development, test and evaluation. Experienced aircrew are needed to build credible and realistic test scenarios and missions. They are needed to design representative stressing missions and events to test and stress the mission systems and aircrew under evaluation. Experienced operators are needed to adapt and apply realistic, current or developmental CONOPS, training, Tactics, Plans and Procedures (TPP). Mission system test trials need scenarios and missions to focus on crew information quality, decision making, prioritization, mission command and interoperability issues. Critically, they are needed to provide imagination, creativity and expertise to develop new tests for new concepts and technologies, where for DAMM the focus is on the efficiency and effectiveness of distributed adaptive decision making in a highly dynamic networked environment.

## **A.9 MEASUREMENT AND METRICS**

Assessment approaches should use a combination of objective metrics of mission performance, and operator provided expert judgments captured using subjective rating scales. Experience has shown that subjective ratings of aircrew and system performance, captured using simple, reliable and proven methods, provides valuable quantitative evidence and insight on decision making performance, that aids and reinforces the interpretation of objective data. Metrics of should include ratings of decision quality, specifically survivability, effectiveness and timeliness, in addition to SA and workload.

The DAMM programme sought to develop a sensible and practical set of simple rating scale protocols for data capture, during both real-time on-line assessments by SME Observers, and from crew participants during post-run de-briefings. Several versions of the basic structure were employed across the trails. Item content was varied and refined following feedback from users and statistical evidence of item sensitivity and discriminative power. The evidence indicated the value of Team Work metrics, in addition to measurement of individual Task Work, for measuring operator performance in distributed, collaborative networked operations. The protocols used towards the end of the DAMM programme, and the associated metrics structure, are shown in Figure A-9 to Figure A-12 below.

SELF ASSESSMENT OF PARTICIPANT WORKLOAD AND PERFORMANCE																		
Date:		Time:			Trial Run Description:						Participant Role:							
RATING SCALE	WORKLOAD Time Pressure-Mental Effort-Stress-Team Workload				REPLAN TASK LOAD Decision-Action		SA Attention Demand Supply-Understanding			DECISION QUALITY Confidence-Survivability-Effectiveness-Timeliness				PERFORMANCE Task Performance-Tools Utility-Adaptability Proficiency-Probability of Mission Success				RATING SCALE
	TP	ME	ST	TWL	DEC	ACT	DEM	SUPP	UND	CON	SURV	EFF	THM	TP	TU	AP	PRS	
HIGH 7																		7 HIGH
6																		6
5																		5
4																		4
3																		3
2																		2
LOW 1																		1 LOW
NOTES:																		

PARTICIPANT PROTOCOL RATING SCALE INTERPRETATION									
LOW ANCHORS	DIMENSION							HIGH ANCHORS	
	Low1	2	3	4	5	6	7High		
<b>WORKLOAD</b>									
<i>Slow/Leisurely/No time pressure</i>	<b>WL Time Pressure</b>						<i>Rushed/Rapid/Frantic</i>		
<i>Very little/Extremely easy</i>	<b>WL Mental Effort</b>						<i>Extremely hard/Stretched</i>		
<i>Relaxed/Placid/Tranquil/Calm</i>	<b>WL Stress</b>						<i>Anxious/Worried/Up tight/Harassed</i>		
<i>Light/Quiet/Unpressured</i>	<b>Team Workload</b>						<i>Heavy/Busy/Pressured</i>		
<b>REPLAN TASK LOAD</b>									
<i>Forgiving/Simple/Easy</i>	<b>Replan Decision</b> <i>Recognise-Evaluate-Mitigate</i>						<i>Difficult/Demanding/Complex/Exacting</i>		
<i>Forgiving/Simple/Easy</i>	<b>Replan Action</b> <i>Disseminate-Acknowledge-Execute-Report</i>						<i>Difficult/Demanding/Complex/Exacting</i>		
<b>SITUATION AWARENESS</b>									
<i>Stable/Simple/Fixed</i>	<b>SA Demand on Attentional Resources</b>						<i>Unstable/Complex/Variable</i>		
<i>Relaxed/Inattentive/Spare Capacity/Singular</i>	<b>SA Supply of Attentional Resources</b>						<i>Alert/Concentrated/Full capacity/Divided</i>		
<i>Uninformative/Meaningless/Unfamiliar</i>	<b>SA Understanding</b>						<i>Informative/Meaningful/Familiar</i>		
<b>DECISION QUALITY</b>									
<i>Indecisive/Doubtful/Guess</i>	<b>DQ Confidence</b>						<i>Decisive/Confident/Obsvious</i>		
<i>Dangerous/Vulnerable/Risky</i>	<b>DQ Survivability</b>						<i>Safe/Unthreatening/Secure</i>		
<i>Ineffective/Un-useful/Unproductive</i>	<b>DQ Effectiveness</b>						<i>Effective/Capable/Useful</i>		
<i>Behind/Late/Pressurised</i>	<b>DQ Timeliness</b>						<i>Ahead/On-time/In control</i>		
<b>PERFORMANCE</b>									
<i>Unsatisfactory/Unacceptable/Failure</i>	<b>Task Performance</b>						<i>Perfect/Successful/Satisfied</i>		
<i>Useless/Complicated/Difficult</i>	<b>Tools Utility</b>						<i>Easy/Intuitive/Effective</i>		
<i>No backup plans/ Insensitive/Unresponsive</i>	<b>Adaptability Proficiency</b>						<i>Sensitive/Responsive/Timely effective backup plans</i>		
<i>Fails to meet any mission objectives/0%</i>	<b>Probability of Mission Success</b>						<i>100%/Successfully achieved all mission objectives</i>		

**Figure A-9: DAMM Participant CMDM Assessment Protocol.**

# ANNEX A – DYNAMIC AIRBORNE MISSION MANAGEMENT: LESSONS LEARNT



SME OBSERVER ASSESSMENT OF PARTICIPANTS PERFORMANCE															
Date:			Time:			Trial Run Description:					Observed Participant Role(s):				
RATING SCALE	DECISION QUALITY Survivability-Effectiveness-Timeliness			TEAMWORK Communication-Shared SA-Leadership-Support-Team Workload					PERFORMANCE Task Performance-Collaboration-Influence Power-Adaptability Proficiency-Probability Mission Success					RATING SCALE	
	SUR	EFF	TIM	COM	SSA	LDR	SUP	TWL	TP	COLL	IP	AP	PMS		
HIGH 7															HIGH 7
6															6
5															5
4															4
3															3
2															2
LOW 1															LOW 1
Notes:															

### OBSERVER PROTOCOL RATING SCALE INTERPRETATION

LOW ANCHORS	DIMENSION							HIGH ANCHORS
	Low1	2	3	4	5	6	7High	
<b>DECISION QUALITY</b>								
<i>Dangerous/Vulnerable/Risky</i>	DQ Survivability			<i>Safe/Unthreatening/Secure</i>				
<i>Ineffective/Useless/Unproductive</i>	DQ Effectiveness			<i>Effective/Capable/Useful</i>				
<i>Behind/Late/Pressurised</i>	DQ Timeliness			<i>Ahead/On-time/In control</i>				
<b>TEAMWORK</b>								
<i>Silent/Unclear/Confused/Slow/Uninformative</i>	Communication			<i>Clear/Timely/Coherent/Concise/Rapid/Informative</i>				
<i>Uninformative/Meaningless/Unfamiliar</i>	Shared SA			<i>Informative/Meaningful/Familiar</i>				
<i>Indecisive/Unassertive/Confused/Uncommunicative</i>	Leadership			<i>Commanding/Directing/Guiding/Initiating</i>				
<i>Ignoring/Hindering/Blocking/Criticising/Conflicting</i>	Support			<i>Monitoring/Advising/Correcting/Assisting</i>				
<i>Light/Quiet/Unpressured</i>	Team Workload			<i>Heavy/Busy/Pressured</i>				
<b>PERFORMANCE</b>								
<i>Unsatisfactory/Unacceptable/Failure</i>	Task Performance			<i>Perfect/Successful/Satisfied</i>				
<i>Separate/Independent/Divided/Conflicting</i>	Collaboration			<i>Joint/Shared/Coordinated/Cooperating</i>				
<i>Powerless/Weak/Irrelevant/Not Involved</i>	Influence Power			<i>Influential/Powerful/Forceful/Decisive/Critical</i>				
<i>No backup plans/ Insensitive/Unresponsive</i>	Adaptability Proficiency			<i>Sensitive/Responsive/Timely effective backup plans</i>				
<i>Fails to achieve any mission objective/0%</i>	Probability of Mission Success			<i>100%/ All mission objectives successfully achieved</i>				

Figure A-10: DAMM Observer Assessment Protocol.

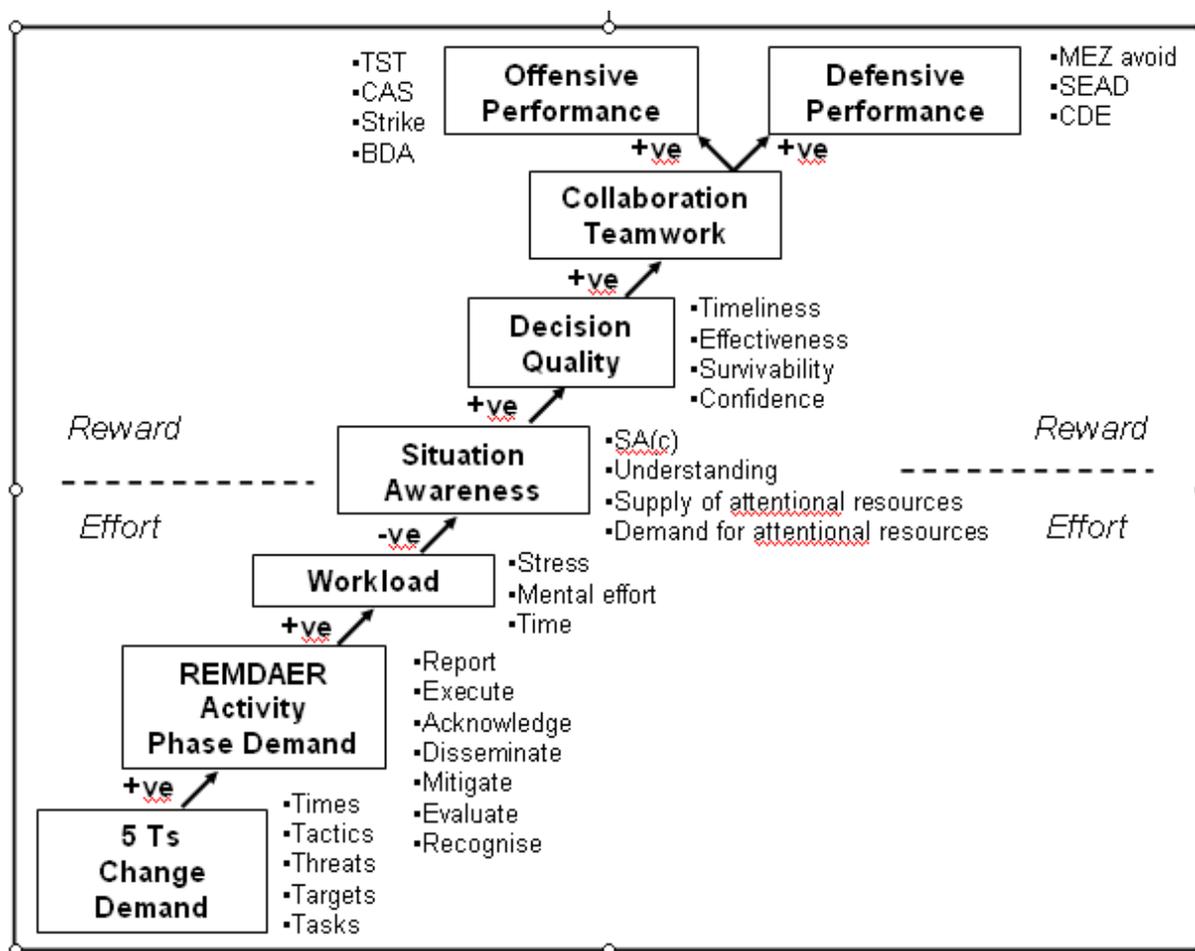


Figure A-11: Reward/Effort Metrics Structure.

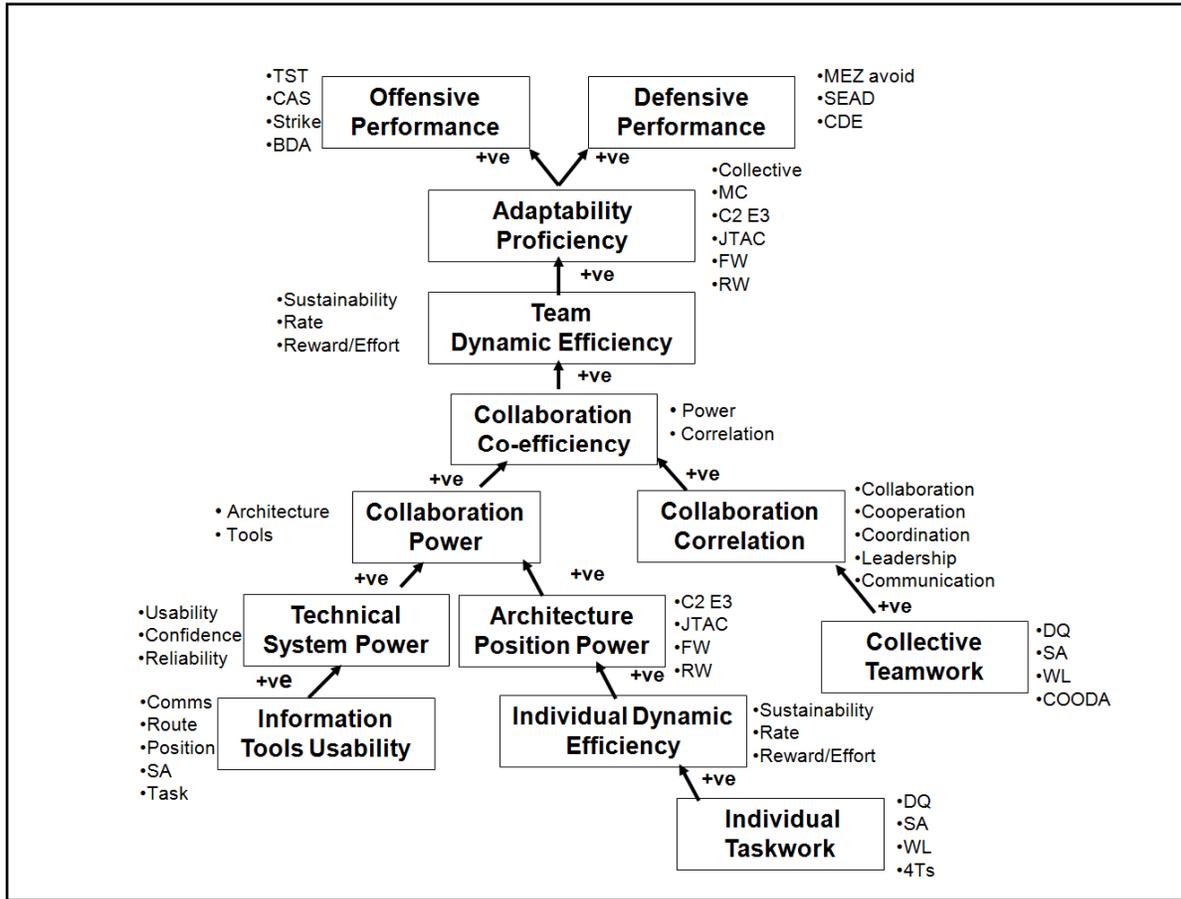


Figure A-12: Collaboration Metrics Structure.

<b>REPORT DOCUMENTATION PAGE</b>																											
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<b>14. Abstract</b>	With increasingly automated Unmanned Vehicles (UVs), the operator's role will become more supervisory in nature. HFM-170 identified and demonstrated successful supervisory control methodologies and interface design practices for enabling single operator control of multiple UVs in network-centric operations. Fifteen Technology Demonstrations are summarized and a supervisory control framework developed by which to characterize and communicate research within the supervisory control domain.																										





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