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).

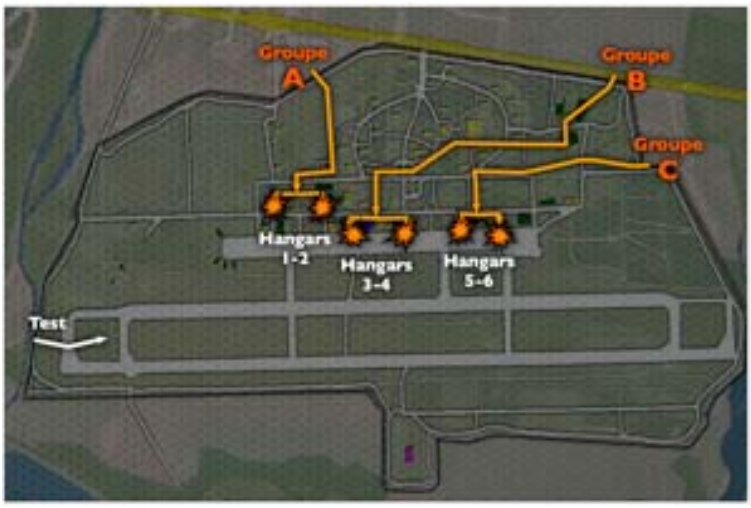

Figure 6-2: Intrusion Scenario Played on Simulation.

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×(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, he 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 ale 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 location2, 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).

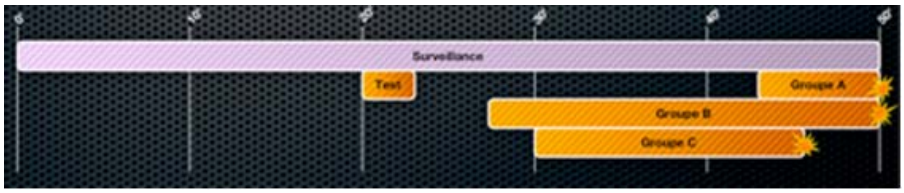

Figure 6-5: Time-Line of Scenarios.

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		**Insure a permanent surveillance of punctual target (restricted version of area monitoring).**	**Detect fixed or moving target present on a line. Can be extended to the monitoring of a graph.**	**Detect fixed or moving objects close to a given contour. Special attention may be put on objects crossing the contour.**	**Detect fixed or moving objects within a given area.**
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).		**Avoid (or get the UAVs out of) a given area.**
Find	**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.**	**Determine the position of one or several punctual targets known to be present on zone.**	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	**Keep one (or several) moving target's) under detection/ tracking range. Can imply to remain simultaneously out of range for security of UAV.**				
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.

	Planning/Design	***Execution***	***Analysis***
Communication	*X*	*X*	*X*
Coordination	*?*	*?*	*?*
Collaboration	*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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