# Chapter 1 – INTRODUCTION

This Working Group was formally initiated in 2004, with the genesis and rationale contained in a Pilot Paper written in September 2002. It is appropriate, therefore, to start with some thoughts from that document. The document cited a need for stressing the system engineering process. As the focus changed to the current report title, it became more obvious that unmanned vehicles would be a primary focus. With the increased interest and emphasis on unmanned systems over the last decade, the question arises as to whether totally new design and development processes are required. While there are competing views, the authors of this report believe that while unmanned vehicles open new areas of "design space", the systematic engineering disciplines associated with their development remain largely unchanged and may be extended from those already existent for comparable manned systems. The area which has opened for new development tools and techniques is the integration of individual vehicles and (where applicable) control stations into a system of systems. In many cases, the individual elements of this system of systems are dissimilar from each other and other components of a broader set (such as a force structure) with which they must be integrated. In some cases, the individual elements (vehicles) may even operate in dissimilar media – land vehicles may be integrated with airborne vehicles and water (or even submarine) vehicles. The authors did attempt to address the similarities or differences between air, land, and sea systems. However, in spite of those differences, the authors assert that the classic systems engineering processes, properly understood and applied, may be used as the "jumping off point" for the larger systems of systems development and integration challenge.

It is intended that this report should be a tool for scientists and engineers working both in research and development and in systems acquisition. For the former, it should denote areas where knowledge, technology or tools are poorly developed or even lacking. These areas become candidate areas for research. For the latter group, it is intended that this report represent a compendium of best practices and state of the art from the NATO technical community.

## 1.1 TERMS OF REFERENCE AND DEFINITION OF SCOPE

There have been a variety of recent activities within RTO devoted to control issues. Task Group SCI-026 focused on design issues of air vehicle control and produced a Best Practices Guide for design of flight control systems (Anon 2000). In May 2000, the AVT Panel held a symposium devoted to 'Active Control Technology' (Reference Anon 2001). In this symposium, papers discussed various extensions to classical flight control. As the Technical Evaluation Report said: "Within the realm of aircraft technology, this symposium was of very high quality". But then a further comment was: "It is suggested that a symposium would be possible in another five years and show similar progress. At that time we should include the technologies of all vehicle classes".

The most recent effort was Task Group SCI-053, "Vehicle Dynamics, Modelling and System ID, Control and Handling Qualities". This Task Group produced a Technical Report in 2002 (Reference Anon 2002) with a significant advance by identifying similarities and differences in those subjects between land, air and sea domains. In addition, a symposium in May 2002 (Reference Anon 2003) with papers in the four TG subjects addressing land, air, sea and (minimal) space aspects. That report contains a very good coverage of vehicle related issues. It was suggested that there be a requirement to address higher-level issues of controlling vehicles in a system of systems.

The subject area of vehicle control continues to expand rapidly. New techniques have been developed, plus major improvements in how this expertise can be applied to solve new problems. Continued development of this core competency is essential to harness these technological advancements. Even greater benefits can be achieved if we integrate the technology developments across all vehicle

classes and domains, including the cooperative operation of dissimilar vehicles. It is no longer appropriate to design military vehicles as individual entities, they must operate in the total system environment. The ultimate payoff is design processes to achieve equal or better system capabilities at more affordable cost.

The emergence of RTO as the organisation to co-ordinate research and technology activities over the breadth of all the NATO military environments (land, air, sea and space) presents a unique challenge. The core competencies embodied in the technical areas of vehicle control, command and control, and automation are at the heart of the mission performance of all military vehicles. The experts currently active in RTO activities and in the process of solving aircraft issues and performing research in these areas have counterparts addressing analogous issues for land, sea and space vehicles. These experts all face similar challenges, and the co-ordination of the different activities will have benefits that can be applied to all environments.

The contents of this technical report start with a background of matured technologies such as man-machine integration. It was decided to consider a variety of subjects and current efforts: Swarms of Unmanned Vehicles, Safe Mixing of Manned and Unmanned Vehicles, Automated Mission Performance of Unmanned Vehicles, and Optimizing Vehicle Convoy Performance. There is then a discussion of future potential benefits from system-level controls integration, automation and optimization, e.g.: Fully Intelligent Control, and others. An objective of the report is a complete interchange of expertise/information between land/air/sea/space communities considering 'control' as only a component in a system-level approach to the war fighter needs.

## 1.2 SYSTEM COMPLEXITY AND THE NEED FOR A NEW APPROACH

Complex systems consisting of single vehicles or multiple vehicles have to operate at several levels. These levels describe the capability of the systems within the appropriate domains. To illustrate this, consider Figure 1.1.

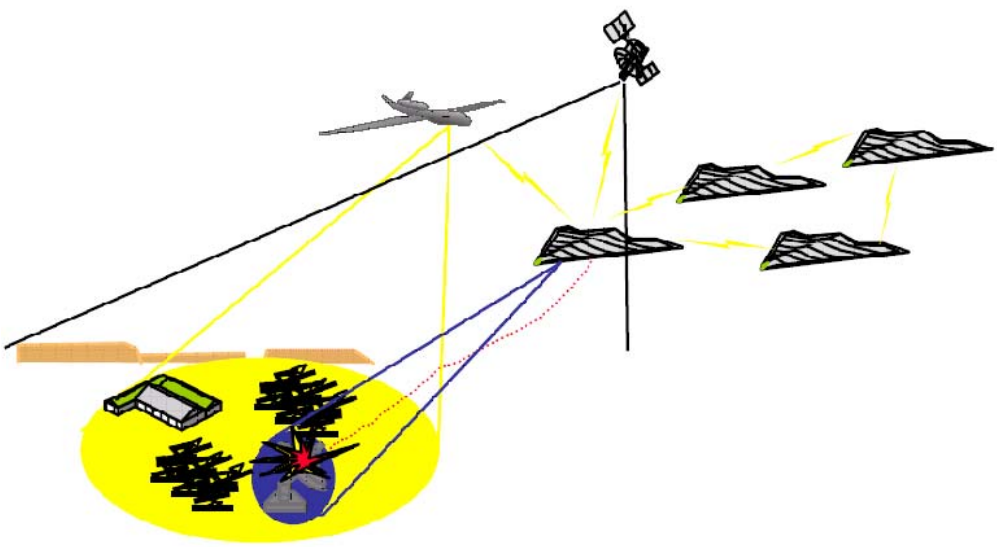

**Figure 1.1: Pictorial Representation of Multiple Vehicles (Land, Sea and Air) Communicating and Coordinating.**

This shows the operation of a vehicle or collection of vehicles which is mobile in an uncertain, unstructured environment with a set of sensors that inform the system about the vehicle state and the

external environment. The information generated within the individual vehicles and that shared over the totality of vehicles is inherently different in quality, accuracy and latency. Hence such a multi-vehicle system becomes actually a system of systems. There are several layers of complexity within each system and sub-system that need to work effectively together in a well behaved and predictable manner from the design perspective. Additionally, if this system has some degree of autonomy, it will have to perform deliberate actions as well as reacting to the environment in a capable manner. Hence the design of these complex systems is that of designing capability such that the system will perform and react in a controlled recognizable manner. The overriding requirement is to design the system such that no unexpected behaviour should result. If this system is controlled and operated by a human, its behaviour should be recognizable and enable the operator to recognize capability and be able to use and exploit it. This principle can also be applied to the structure of the complex system itself.

To illustrate the above concepts, consider a single autonomous vehicle within an autonomous multi-vehicle system. In order to function, several layers of activity are required, each layer having a technical domain in which problems have been posed and solved mainly in isolation in the literature. A typical structure is shown in Figure 1.2.

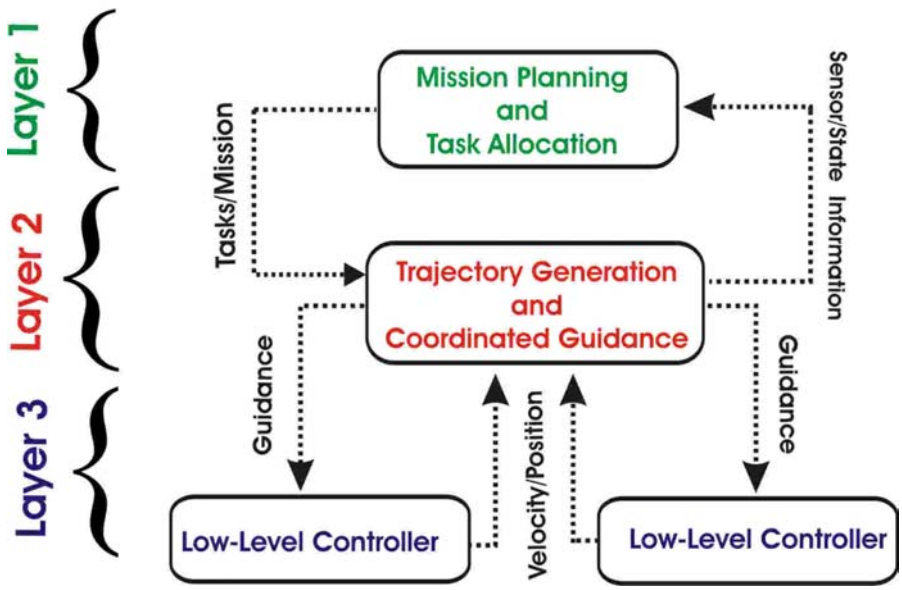


**Figure 1.2: Typical Structural Hierarchies for Multiple Autonomous Vehicles.**

To function well as an autonomous system each level in the figure should be able to recognize, use and exploit the capability of each level below it. The lower layers should in turn, have knowledge of the upper levels, sufficient to describe their own capability in terms that the upper layers can exploit. Hence the interface that translates between levels requires special attention, in that a common view of the capability exists across the boundaries. Hence control at each level needs to be integrated with levels both above and below its own level.

Each level will have its own language, whether that is a mathematical framework or an experiential description that will need to be integrated sufficiently to enable the overall system capability to be understood. The mathematical tools for each level are fundamentally different and it is unlikely that a grand unifying approach will capture the system design process. Hence continuous differential equation representations are useful at level 1, where autopilots and parametric robustness, parametric identification techniques are used. Level 2 is primarily kinematic in that planning routes through uncertain environments, re-planning as pop-up threats and other obstacles are detected and collision avoidance is performed. The top

level deals with decision making and mission planning, where event driven reactive behaviours are dealt with, together with deliberative behaviours in fulfilling tasks. The mathematical framework for each of these levels is fundamentally different, but assumptions about the behaviour of each level are made in each framework. For example, for route planning assumptions about manoeuvre capability of the airframe enter at level 1 in the form of limits on lateral acceleration or incidence. At level 2 this will be translates into the kinematic domain as a constraint on trajectory curvature. This will promulgate into level 3 as a constraint on immediately reachable areas. It seems important that these different descriptions are consistent, and easily used and exploited at each level. Essentially, the structure is the same as for a single vehicle, with the difference being in the abstraction level of the information, together with the latency.

One issue that will be important for these multiple vehicle systems is the integration, i.e. command and control, of totally dissimilar vehicles. Representative time scales (defined as L/U, where L is typically length, and U is forward speed) and masses for some vehicle categories of interest are compared in Figure 1.3, (Reference Anon 2002). Since this is a variation of the classic transport efficiency diagram, the two variables are reasonably well correlated for each vehicle category. However, there is some distinction between the ranges for military and civilian fixed-wing aircraft because of speed, and between military and civilian surface ships because of mass. Note that the time scale covers several orders of magnitude. In addition, if L/U represents a medium length time scale for a particular vehicle, then the system design problem includes a number of other different time scales to consider, such as:

- Time to complete a representative manoeuvre – typically long.
- Vehicle responses – roll period, etc.: typically medium scale.
- Time history (memory) effects – trailing vortex interactions, etc.: typically medium.
- Vehicle subsystem responses – land vehicle suspension period, etc.: typically short scale, but can vary considerably.
- Sensing and control system responses – short to very short.

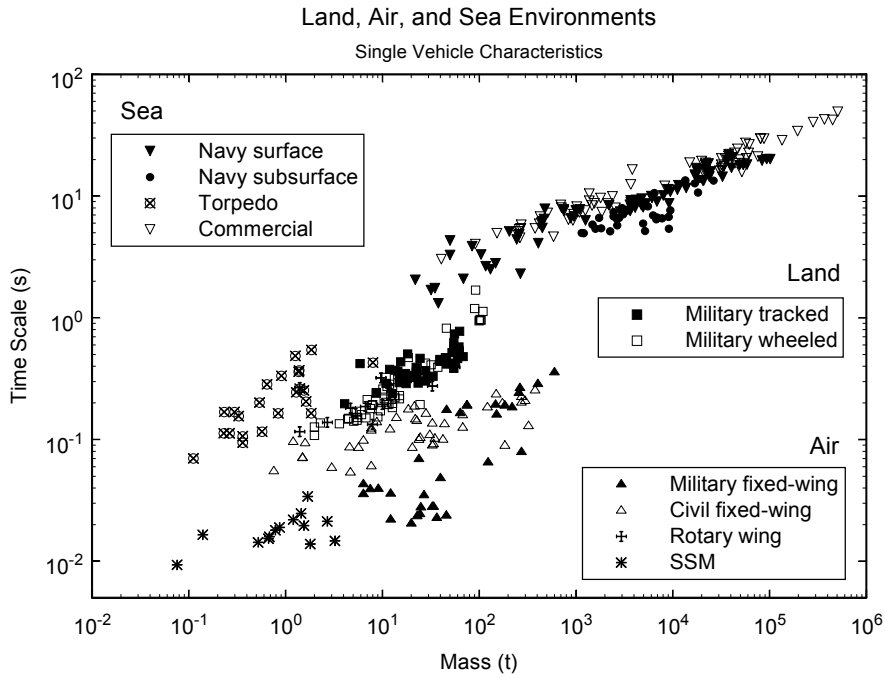


**Figure 1.3: Time Scale (Sec) vs. Mass (Tonnes) of Some Representative Vehicle Types in the Land, Air, and Sea Environments.**

In a few cases, subsystem characteristic time scales e.g., that of a tow cable, may be much longer than that of the vehicle(s) in the system.

Including the full control bandwidth will generally add one or two lower orders of magnitude to time scales in a simulation. Such a variation, or even the variation in fundamental time scales in a multi-vehicle simulation, will result in “stiff” equations of motion that require relatively inefficient and complex implicit methods to integrate.

For multiple vehicle systems there will also be issues related to effective communication between vehicles. For a single vehicle the design structure will be fixed and usually fit for its purpose. Hence, each layer will have a communication speed and protocol that will integrate by design. For multiple vehicle systems communication will be more problematic in that there will be bandwidth limitations, availability of channels and possible interference from natural hazards such as weather, buildings, terrain or deliberate jamming and spoofing. Such multiple vehicle systems must therefore have integrated capability under all conditions. This will range from each vehicle operating as an independent autonomous system to full linked capability when coordinated control and actions give more effective performance. The multiple vehicle system must be capable of defined performance and capability over the complete spectrum of integration conditions.

The design challenge is to review existing techniques and to propose new approaches to the design of autonomous control systems in such an unstructured and uncertain operating environment, and this will be presented in the next chapters.