Chapter 6 – CONCLUSIONS AND RECOMMENDATIONS

The work of SCI Task Group 144 has been presented in detail in the previous chapters. The original title of the activity was "System-Level Integration of Control, Plus Automation". There was a presumption that development of unmanned vehicles required that the control system would need to be addressed at the system level. As the group members met and exchanged initial ideas, it became a consensus that a general re-focus would be more productive. The emphasis of the work was changed to "Integration of Systems with Varying Levels of Autonomy". The effort has been to collect and correlate experiences in the design and operation of unmanned vehicles, but also in other areas where autonomy has a primary impact.

The report begins with a historical background starting with man-machine integration. This presents data from the many years of addressing pilot-aircraft interactions. There are then case studies presented discussing examples for land, sea, air and space vehicles. The intent is to discuss success and problems that have been found, plus show similarities across this range of vehicles and any differences. This leads into a chapter discussing systems engineering and then to recommended best practices. Then the report presents supporting information across the complete range of the subject.

This final chapter presents a simple background discussion of the original focus, i.e. the incorporation of an increasing number of automatic functions into flight control systems. There is then a discussion of the issues of systems of systems of unmanned vehicles. The final recommendations are very generic.

6.1 BACKGROUND: ACHIEVEMENTS IN FLIGHT CONTROL SYSTEM DESIGN AND THEIR USE FOR FUTURE AIRCRAFT

The technical progress is defined by the requirements to the production and goals in their development, by achievements in different technologies, sciences and means used for realization of the goals. The main goals and requirements in aviation are the improvement of flight performances (flight effectiveness) and flight safety; all these obtained by improvements in aircraft design, electronics, simulation, feedback control theory, hydraulics, aerodynamics, etc. Many new principles and tools were developed in flight control system design in the area of automation, and will be used in design of the next generation of aircraft. Some of them are briefly summarized below:

- Increased number of functions of control fulfilled by automatic systems. The limitation of maximum bank or pitch angle, normal acceleration, improvement of handling qualities, collision avoidance and others are related to such functions. The number of such control functions for the different periods of recent history in development of civil aircraft is shown in Figure 6.1 for illustration. The tendency shown leads to conclusion that in the near future, if the tendency continues, then aircraft flight will be automatic. The pilot's function in that case will be limited by monitoring only. This requires consideration of transfer from the automatic system to a human operator as discussed in Chapter 2.1.1.
- Improvement of flight performances by the use of flight control system. It is achieved by increasing static instability up to 10 – 20% allowing decreased weight and increased maneuverability. Flight control system provides necessary stability and controllability, in addition, active control systems can be used for large transport and passenger aircraft to control the lift force in maneuver and to suppress response to atmospheric turbulence.
- Increased number of control surfaces (for example, canard, thrust vectoring control) allows the implementation of super maneuverable flight at low speeds and high angle of attack and new types of maneuvers including 360º loops. New actuation techniques allow the distribution of control signals among the control surfaces in an optimal fashion as a function of piloting task.

Moreover damage of any surface has now built-in hardware redundancy allowing continuation of primary mission.

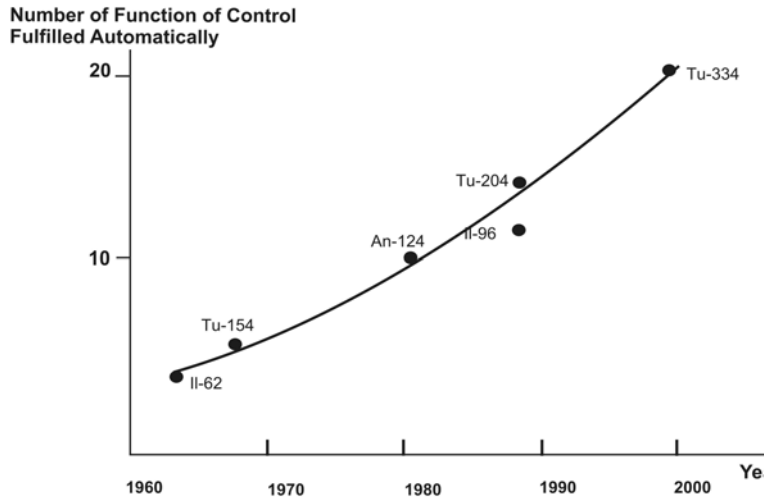

Figure 6.1: Automation Functionalities vs. Time.

- The purpose of a flight control system changes from stability augmentation and flying qualities improvement to provider of necessary/required flying qualities. For the future generation of aircraft this might become the principle of optimization of flying qualities as a function of piloting task and pilot characteristics.
- Usage of fly-by-wire (or fly-by-light) technology. This principle leads to a revolution in flight control system technology: allowing the use of new types of actuators, processors, etc.
- Integration of different control systems: for example integration of flight control with fire control or with critical regime and barrier systems. This principle allows to increase the potentiality of each system, aircraft effectiveness and flight safety.
- Appearance of intelligent systems features, for example the adaptation in flight control system and its elements design. This principle produces increased flight safety and the ability to continue a flight even in case of considerable damage or failure.

6.2 ISSUES AND CHALLENGES

The UAV cooperative team problem can be highly complex, even for relatively small teams. Generally the available theories and approaches can address only one or two aspects of the problem at a time. We are often more interested in a fast, feasible, and robust solution, rather than an optimal one. Since there are many UAV scenarios of moderate size that are of interest, say four to eight vehicles, approaches such as MILP and stochastic dynamic programming may be sufficiently fast at this scale, where a centralized optimal solution is possible. Thus, algorithm scalability may not be the limiting factor.

If more decentralization is desired, the primary limitation is task coupling. Task coupling can be reduced if a myopic or receding horizon procedure is used where not all tasks are addressed up front. However, this can have a significant impact on performance and even feasibility. Also, in the drive for localization, algorithms such as auction and distributed constraint satisfaction can incur extensive message traffic for all but the weakest task coupling. Finally, false information and communication delays can completely negate the benefits of cooperation, similar to losing the benefits of feedback when the sensors are noisy and consequently open loop control is preferable.

It is necessary to study more actively different aspects of human behaviour (manual control, monitoring, decision making) taking into account that integrated, intelligent vehicle control systems has to emulate human capabilities with respect to planning, learning and adaptation.

We have to work for synthesis of concepts, technique and tools defining the information technologies for intelligent system design. The most important goal of such synthesis is to define general scheme that might be called "semi soft computing" (SSC) model. This model must allow to obtain partial models for various branches of the SSC, namely for artificial neural networks, fuzzy logic, generic algorithms, multi-agent systems as well as mathematical modelling by putting into appropriate requirements and conditions.

6.2.1 Systems Level Challenges

Figure 6.2 shows that the work on cooperative control draws from three established disciplines: control, operations research, and computer science, as well as elements of many other disciplines, including estimation, statistics, and economics theory. The research challenge has been to combine these disciplines together to form the beginnings of the new integrated discipline of cooperative control.

Figure 6.2: Cooperation is at the Intersection of Disciplines.

Following is a list of observations made over the course of the research effort that hopefully will provide some insight into what has been done and what yet needs to be done.

- A comprehensive theory of cooperative control must include: uncertainty, communication costs, the consideration of local vs. global information structures, nested vs. non nested information patterns, control decentralization, task coupling, predictive models, adversary action, false information/false targets and false positives, and well reasoned performance measures.
- It is not always beneficial to cooperate, particularly if there are long delays or the sensed or computed information that is communicated is very noisy or error prone.
- It is possible to obtain the optimal solution only for moderately complex operational scenarios.
- Decomposition is a necessary attack upon complexity, but guarantees of optimality are forfeited and, more importantly, oftentimes feasibility is not guaranteed, leading to the possibility of task churning.
- Jacobi auction type assignment algorithms are an iterative form of network flow algorithms which yield a degree of decentralization, but at the expense of possibly much more communications.

- The evaluation of different solutions is problematic. Comparisons can be made, but all solutions may be far from the optimum. There is a need to obtain analytical solutions for small scale problems which should help benchmark the array of heuristic "algorithms"/recipes/procedures currently developed.
- Aside from optimality, feasibility is an even more important concern: In general it will not be possible to prove a procedure will not generate infeasible results.
- The "truth" might never be known because in general there are critical states that are not observable. Hence, randomization/mixed strategies are called for, as are Monte Carlo based simulation studies.
- Due to sensitivities to random disturbances, adversary action, operator performance characterization provided in the form of statistical data, and randomized strategies, extensive simulation studies are required for objectively evaluating competing cooperative control schemes.
- As per the employment of feedback, the benefits of cooperative control are questionable when measurement noise and bad or delayed information are dominant factors. Networks are specifically good at rapidly spreading bad information.
- False target attack rate dominates the wide area search and destroy scenario.
- Highly reliable target recognition is *the* critical capability to make autonomous attack vehicles a reality.
- In general, a strongly decentralized controller cannot recover centralized controller performance except if the tasks are nearly independent, that is the optimization problem at hand is virtually decoupled – a rather trivial cooperative control problem.
- For highly coupled tasks, a strongly decentralized controller will need vastly more messages than a centralized controller due to the need to constantly resolve conflicts. This introduces a degree of vulnerability.
- State estimation is the central actor in addressing partial information. In the absence of observability, the illusion is created of being able to provide state estimates from recursive Kalman filters, whereas in reality the provided complete state estimate exclusively hangs on prior information – adding additional states and augmenting the filter does NOT help to update the information about the missing states.
- Only very rarely can optimal performance be achieved with strictly local controllers – unless one can predict the unobserved state.
- Adversary action can be correctly modelled using the game theoretic paradigm. The problem statement is then rigorous, however there are few cases where solutions have been derived.
- Adversaries will resort to information warfare. The objective is to gain information about the true intention of the adversary without revealing any information. This is done by lying, deception, the use of decoys, and diversion tactics/gambits. This further complicates attempts at using game theoretic formulations to realistically address adversarial action.

6.3 CONCLUSIONS

We can start by posing the question: what can be done to support current and future projects? Learning the right lessons from the past can support future projects, by aiming to understand the real reasons for past problems and successes. Exchange of experience, thereby being as open as possible, is strongly recommended. Design cycles are becoming longer, and any designer is faced only with a few designs during his career and, therefore, experience can only partly be gained by learning from the experience of others. To bridge the gaps between projects, an environment has to be established that allows young

engineers to acquire past experience rapidly and reliably. The establishment of databases is recommended that contain bad and good examples of projects from the past. It is important to also consider the establishment of education methods, curricula and training environments in this context.

The system design problem has to be understood as a multidimensional multidisciplinary problem that can only be solved with proper co-operation and mutual understanding between different disciplines and communities. It is therefore important to spend sufficient time at an early stage, to talk to everybody who is involved in the design process, and to consider whether the group has the right constitution. Then the group should understand the 'Best Practices' as documented in Chapter 3. Modern communication and information technology may help to improve the design process, but another real question is how to integrate research communities in order to contribute in this area? New design techniques have been and are being developed, which may aid the designers. An important contribution of the research community could be to make these methods more accessible for the wider design, implementation and testing communities. The gap between science and practical application needs to be narrowed. Modern information and communication technologies could be very helpful in this respect.