DECISION ARCHITECTURES FOR UNINHABITED AUTONOMOUS AIR SYSTEMS

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Abstract

Technology for the operation of Uninhabited Air Vehicles is undergoing a major change. Hitherto, the emphasis has been on managing the change from remote or tele-operation of the vehicle's flight controls to more automatic modes of control. Such automatic modes have limits in their appropriateness and can become quite complex and unwieldy. Progression of technology to achieve appropriate responses in a wide variety of perhaps, unforeseen, circumstances, such as emergencies and failures, **and** without instant reversion to human control, is required. Development of autonomous systems – those which are capable of independent decision and action – offer a potential route towards this.

This paper describes work to understand the nature and characteristics of autonomous systems suitable for the safe and independent operation of air vehicles. In particular, it explores the nature of appropriate decision architectures and system requirements, particularly with respect to safety and robustness. It is noted that the the domain of UAV operations is characterized by supervisory control, reduced situational awareness as the pilot and the craft are not co-located, and spatio-temporal reasoning. Finally it proposes autonomous avionic system reference architecture and outlines the testing and experimental programme envisaged for the operation of a design based on that architecture in a Modelling & Simulation (M&S) Synthetic Environment (SE).

Keywords: Autonomous, Systems, Uninhabited, Decision, Avionics.

Presenting Author's biography

Charles Patchett is a former RAF fast jet Navigator and now an avionic systems engineer leading the Autonomous Systems Research Group at BAE Systems, Warton, UK. His group is currently undertaking technical R&D under the UK ASTRAEA programme in the areas of Decision Modelling, Sense & Avoid technology and Adaptive Routing. Together with inputs from Systems Health and Prognostics researchers at BAE Systems, the group has demonstrated key aspects of these technologies by developing and integrating the required sub-systems into a virtual Uninhabited Autonomous Air System (UAAS) and flying this in challenging scenarios in an M&S SE.

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1 Introduction

Although Uninhabited Air Vehicles (UAVs) have operated in the military sector for many years, there has been a recent and significant acceleration of programmes to develop, manufacture and operate them. Whilst the manufacture of small UAVs is cheap and development is relatively quick, the routine operation of these vehicles in civil airspace, currently containing only manned aircraft, is neither. This is largely due to the nature of the operating environment and the restrictions and challenges it brings. The means to overcome these aspects can be satisfied, to a degree, by having tight human control over the vehicle. The challenge today is to gradually replace the human involvement in the control process whilst retaining satisfactory operating performance and regulatory adherence. This can be achieved by transferring authority for some of the control functions normally made by the pilot or ground controller, to an onboard system able to make decisions and implement them. Such a system is conventionally known as an **autonomous system**. When such a system is incorporated into a UAV, the consequent vehicle is described as an Uninhabited Autonomous Air System (UAAS).

This paper presents work carried out to understand the nature and characteristics of architectures for autonomous systems, with specific emphasis on UAASs operating in routine, civil, un-segregated airspace. It questions whether the role, responsibilities and environment of such systems require particular architectural features and to answer the following:

- What do the issues of role, responsibility and environment force the architecture to achieve that is not found in other architectures?
- Can existing autonomous system architectures address these issues? If so, how, to what degree and why? If not, why not?
- Given that operator involvement should be reduced to the lowest level possible, how does the need for operator interaction affect the design and implementation of the architecture?

In answering these questions, several aspects have to be considered:

- Decision Making - Three general models of decision making were considered and analysed in detail: Classical Decision Theory, Recognition Primed Decision Theory and Boyd's OODA loop. By combining aspects of these models, a Unified Information Decision and Control model was formulated and this will be presented and discussed in the final paper.
- The nature and characteristics of autonomous systems and theories of distributed control – this included Man Machine Interactions and the Pilot Authority of Control Tasks (PACT) levels. An analysis of these interactions and requirements for their specification will also be presented.
- The evolution, characteristics and nature of modern avionic systems.

2 Definitions

Several definitions of autonomy and autonomous systems have been formulated and the following is offered:

"An autonomous system is one that operates within an environment and is capable of independent decision and action in pursuit of its objectives".

The concepts of decision and action are intertwined. It is difficult to understand the nature of a decision, or the point in making it, if the decision is not followed by action and in particular, action to change or influence the environment in order to pro-actively further a fundamental objective. Support for this notion, which is not universally accepted, particularly in the intelligent agent community, is given below.

In Multi-Attribute Decision Theory, a decision is defined as:

> *"A decision is the commitment to irrevocably allocate resources. A decision is a commitment to act. Action is the irrevocable allocation of resources [1]".*

Similarly, in the Lexicon of Decision Theory published by The Decision Analysis Society [2]:

> *"A decision is an allocation of resources. It can be likened to writing a check and delivering it to the payee. It is irrevocable, except that a new decision may reverse it".*

As far as the rest of this document is concerned, the above definitions of a decision, which are believed to be equivalent to each other, will be used.

3 The Nature of Decision Making in an Airborne Environment

If we accept that a decision is followed by action, and some do not, it is reasonable to ask what comes before the decision. Fortunately there are many, and three in particular, generally accepted theories which explore this area:

- Classical Decision Theory (CDT),
- Klein's Recognition Primed Decision Making (RPDM) Theory
- Boyd's Observation-Orientation–Decision-Action (OODA) cycle.

CDT requires the formulation of alternative courses of action (COAs) which are assessed according to the Decision Maker's (DM) values. The COA that gives the greatest expected utility is chosen (the decision) and then embarked upon (the action). Unfortunately, CDT assumes that the derivation of acceptable alternatives is the starting point in the process but it certainly recognises the key elements of **values** and **objectives**. So we can now infer, from CDT, that the choice of a plan alternative i.e. the decision-action pair, is one that ultimately gives the greatest chance of (ultimately) achieving a fundamental objective. RPDM is very different from this in that it assumes, and requires, full or sufficient Situational Awareness (SA) of the problem at hand. The achievement of SA has been described as a continuing sequence of perception, comprehension and projection (or prediction). So the full recognition primed decision action cycle is one of SA – Decision - Action.

The OODA cycle is very similar. The process is Observation-Orientation–Decision-Action.
Observation and Orientation, or “what is going on in the world and how it is relevant to me”, can be seen to be equivalent to the SA process described above. Indeed, the whole OODA cycle can be viewed as more general Information – Decision – Action (IDA) cycle.

If we accept that the notion of action when applied to a vehicle can described as a control, then the above processes can be combined into a single unified decision model which operates over the contexts of objectives, consequences and constraints. This can be called an Information – Decision - Control model as shown below:

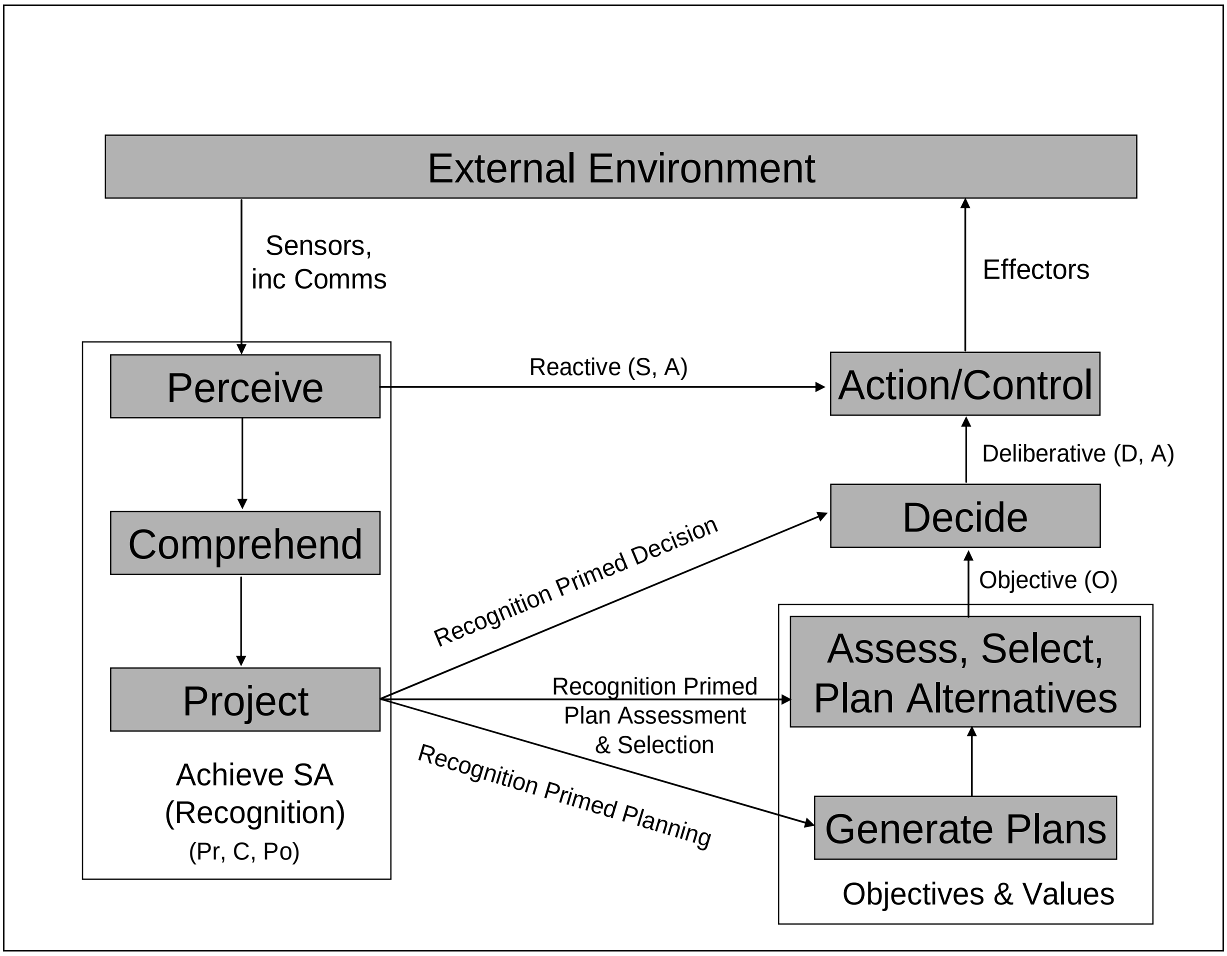

Figure1 A Unified Information - Decision – Control Model

It is believed the above mechanisms for control are a full and complete set with the exception of those directly ordered by an external operator. Therefore, ideally, architecture for the control of a UAAS should encompass all the above mechanisms including the latter i.e.:

- Direct Sensor to Effector Reactive Control
- Direct Operator to Effector Control – in effect, a control override
- Deliberative Effector Control using:
- Recognition Primed Decision Making – this mechanism constitutes a direct decision consequent to the recognition of a particular situation. This mechanism could be effected by a rule based system e.g. IF Under Attack,

THEN Turn by 180 degrees, or by a more sophisticated and complex method such as Case Based Reasoning (CBR) by retrieving a suggested Course of Action from the best fit of input conditions to a case database.

- Operator Decision Making – this can be effected by presenting the Operator with inferenced situational data in order that value judgments can be reached, and accepting his decision as the pre-cursor to a control override.
- Recognition Primed Plan Assessment and Selection – The result of the Situational Assessment is used to draw up a list of applicable plans to that situation and select the most appropriate, either by on the basis of maximum expected utility or by some other mechanism.
- Maximum Expected Utility (Value) Plan Assessment and Selection – the generation of alternative plans to achieve a perceived objective and scoring these plans from value metrics and probability of outcome
- Operator Plan Assessment and Selection – as above but allowing the operator to select the plan
- Recognition Primed Plan Generation – the generation of a plan to achieve an objective within a perceived situation.
- Objective Based Plan Generation – using plans based on applicable objectives; initiating a take off sequence for instance.
- Operator Commanded Plan Generation – the acceptance of a plan override commanded by the operator.

4 Existing Architectures and Requirements

With the above in mind, the work reviewed many existing architectures for decision making and control, irrespective of the environment for which they were intended. From this analysis, the suitability of these architectures for airborne decision making and control was determined. The architectures examined included:

- Specific and Generic Robotic Architectures, particularly the Three Layer Architecture (TLA).
- Control Architectures, including: 4D-RCS, the Coupled Layer Architecture for Robotic Autonomy CLARAty) and Integration of Behaviour and Rational Planning (InteRRaP).
- Intelligent Agent (BDI) Architectures, including JACK and JAM.
- Avionic Architectures, including the J-UCAS architecture and Common Operating System.

Of the above, it was considered that the TLA, J-UCAS and InteRRaP architectures were particularly suitable for further consideration and the key aspects of these were incorporated into a cardinal system requirement and characteristics set as follows:

- Decision making and Control Processes – a variety of processes derived from the Unified Information, Decision and Control model should be used.
- Certification - the system must be safe and therefore capable of handling safety related functions and be robust for the air environment. This can be achieved if the system follows the general requirements of an avionic system.
- Competency - the system must be able to conduct missions, handle emergencies, failures and other unforeseen events and respond appropriately to produce successful outcomes where possible.
- Distribution of Control Authority - the system must be capable of determining whether it has the authority for committing a decision into action. This authority can be likened to a meta-control under the jurisdiction of the human operator.

5 Functional Partition of the Architecture

In order to achieve the above, the functionality of the complete system is large and must cover several areas, not only for carrying out its intended role, but also for satisfying regulatory and safety related aspects. It is therefore prudent to partition the system into functional sub-systems, including the decision making system, described below as the Master Executive. The partition proposed is:

- A Mission Master Executive – responsible for all cross partition plans, decisions and actions. To act, in conjunction with the human control element based at the remote Ground Control Station (GCS), as the surrogate pilot controller.
- An Information System – responsible for:
    - The management, processing and dispersement of external data to provide the necessary information for Situational Awareness.
    - The collection of internal data from contributing sub-systems.
    - The retrieval and storage of data from/to databases

  - Flight data recording

- A Vehicle System – responsible for all non avionic sub-systems such as hydraulics, electrical power and airframe systems (undercarriage, flaps, brakes etc.).
- A Flight Management System – responsible for the directional control of the aircraft and operation of the engines.
- A Navigation System – responsible for all navigational aspects including the flight (including route) plan and fuel plan.
- A Communications System – responsible for all communications plans and actions
- An Air Safety System – responsible for the recognition and avoidance of threats such as weather cells and other air traffic (Sense and Avoid).
- System Health Management System (SHM) – responsible for monitoring and reporting system health by diagnosing and predicting failures and proposing plans for remedial action.
- Sensor System – responsible for operation of all sensors.

6 Proposed Reference Architecture

Following the above considerations, a Reference Architecture for the combined avionic and autonomous system is presented:

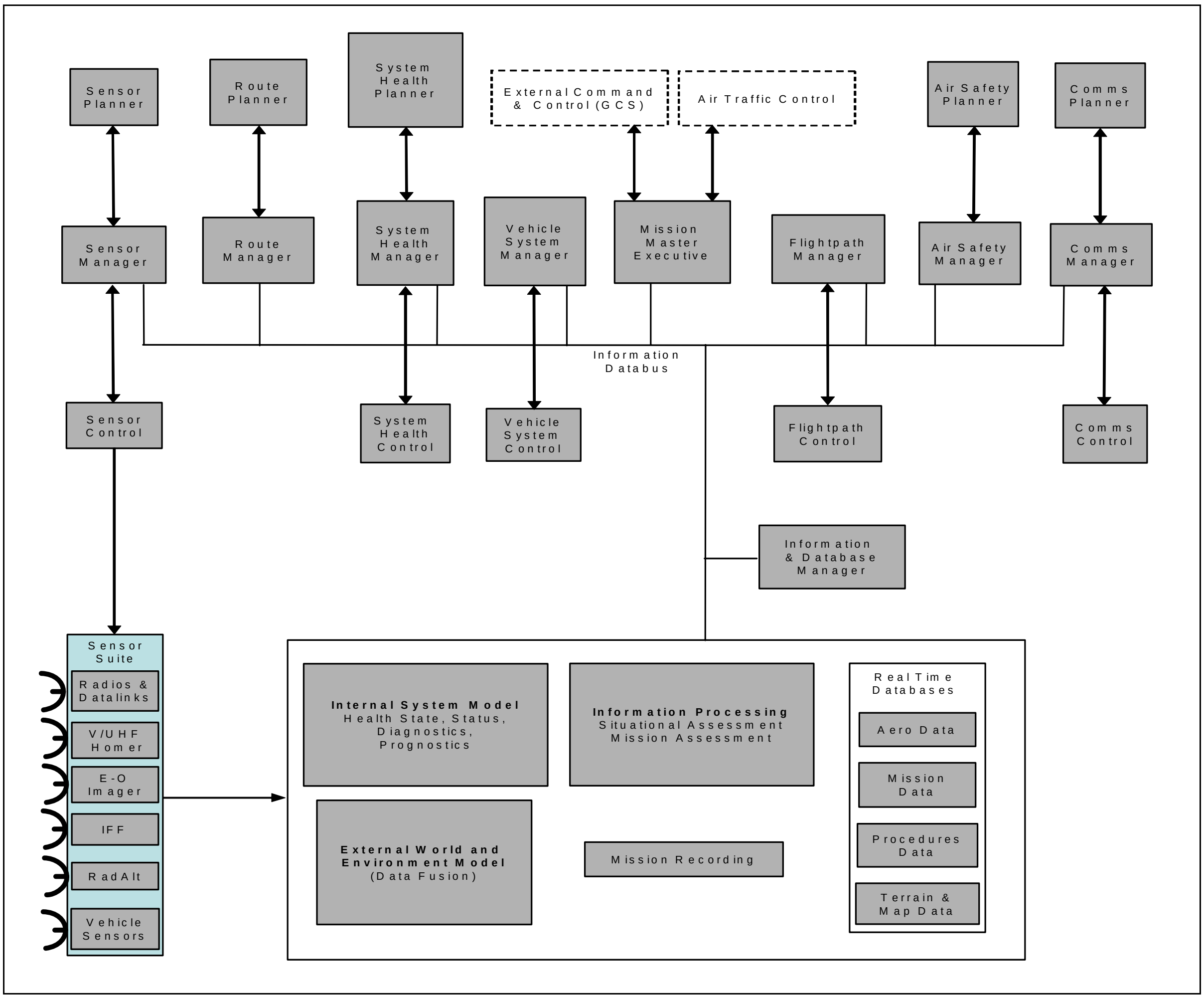

Figure 2 - Proposed Reference Architecture

An avionic system design based on this architecture was implemented (except for the SHM system) using a proprietary integration and development environment. The software was distributed across three computing areas and integrated with an in-house synthetic vehicle system. These systems were networked to a Command and Control Ground Station (GCS) and the whole system was embedded in a M&S SE as described in the next Section.

7 Modelling and Simulation Synthetic Environment

The M&S SE laboratory at BAE Systems, Warton, UK provided the representative operational context in which the integrated vehicle and avionic systems were evaluated. This laboratory provides a suite of modelling and simulation tools comprising of Operational Analysis models, detailed vehicle and systems models, correlated environments and various visualisation and logging/ analysis tools. The SE comprehensively models a variety of atmospheric situations including weather, precipitation, lightning and visibility. This facet enables a high degree of realism for the Master Executive (the decision processor) to reason about, especially when faced with emergency situations. All of models in the SE can be federated (using DIS/HLA) either as part of LAN or WAN solutions. Processes for use of the capability as part of a wider strategic drive towards Rapid Engineering/ Synthetic Environment Based Acquisition (SEBA) are also being evolved.

8 Operation of the Model Architecture in an M&S Environment

The complete vehicle and avionic systems, controlled internally by the Master Executive and externally by the GCS, were demonstrated for the first time in December 2006. This demonstration involved flying a routine Search and Rescue Mission in the M&S SE at BAE SYSTEMS, Warton, England.

During 2007/8, it is intended that the above system is further developed and used in the M&S SE to fly a transit mission from Aberporth (Wales) to Sumburgh (Orkneys) using many classes of UK airspace. During this transit mission, the UAAS will be commanded to re-task to a Search and Rescue (SAR) mission to search for, prioritise and report the positions of, survivors from yachts involved in a hypothetical Round Britain Yacht Race disaster. This forcing mission is designed to require the UAAS to:

- Re-plan its route and fuel.
- Optimise its usage of fuel between searching for survivors, avoiding weather cells and other aircraft and the constraint of having to land at its pre-planned base with a minimum fuel weight. To do this it will need to consider different landing site options and make effective decisions on whether to divert.
- Handle in flight emergencies and show good airmanship in progressing these through to a successful outcome.
- Deal with routine operation in different classes of airspace (and therefore operating rules).
- Do all of the above in conjunction with, but with minimum help from, the human controller.

Following this, a series of trials are planned to estimate the degree of competency of the decision making processes by the following assessment methodology:

- Conduct real incident/accident analysis based on published material from the CAA and EASA to formulate appropriate responses.
- Review aircrew experience by conducting crew interviews to add to the above
- Design and implement system or architectural modifications that will deal with typical incidents and situations.
- Estimate the theoretical or expected system response to a subset of these incidents.
- Real time testing and evaluation:
- Incident and emergency generation during missions and scenarios simulated in the SE.
- Comparison with aircrew actions and responses facing identical situations using a cockpit simulator.

These trials, together with experience of flying the above missions, should allow us to generate valuable evidence on the safety of the vehicle in flying in routine un-segregated civil airspace and in its ability to handle unexpected and emergency situations through to a safe conclusion.

9 Study Project

This study is currently being conducted under the ASTRAEA project, which is a joint UK Government, Industry and University civil research and demonstration programme to progress the operation of Uninhabited Autonomous Air Systems (UAASs) in routine, non-segregated civilian airspace.

10 References

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