Autonomy in unmanned air vehicles

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ABSTRACT

The paper describes a key risk area threatening the widespread deployment of unmanned air vehicles (UAVs), that of attaining high levels of autonomy. Autonomy is loosely defined in the context of UAVs and the meaning of 'level of autonomy' discussed. The paper argues that the achievement of high levels of autonomy is not merely a function of increasing machine intelligence but also of maintaining the human operator's engagement with the decision making process and retaining human authority. An assumption is that a human being in the loop will be a requirement for safety, flight clearance and legal reasons on early systems. Therefore, developers of highly autonomous systems are presented with a paradox. It will be argued that the human must be placed at the centre of the design process and consequently human factors, the human machine interface and the system architecture become critical to achieving high levels of autonomy. This quality impacts on the entire knowledge acquisition and design cycle and broadens what is meant by that term placing it as a discipline firmly in the systems design community. The paper concludes by outlining the key barriers to the successful development of highly autonomous UAVs.

GLOSSARY

ACL	autonomous control level
AFRL	Air Force Research Laboratories
AI	artificial intelligence
COGPIT	cognitive cockpit
CogPit	cognitive cockpit
HMI	human machine interface
MoD	UK Ministry of Defence
OED	Oxford English Dictionary
OODA	observe-orient-decide-act
PACT	pilot authorisation and control of tasks
ROE	rules of engagement
UAV	unmanned aerial vehicle
UCAV	unmanned combat air vehicles

INTRODUCTION

Autonomous vehicles may fulfil a developing requirement in many applications and domains. Of particular interest in the defence sector, is the unmanned air vehicle (UAV). UAVs applied in combat

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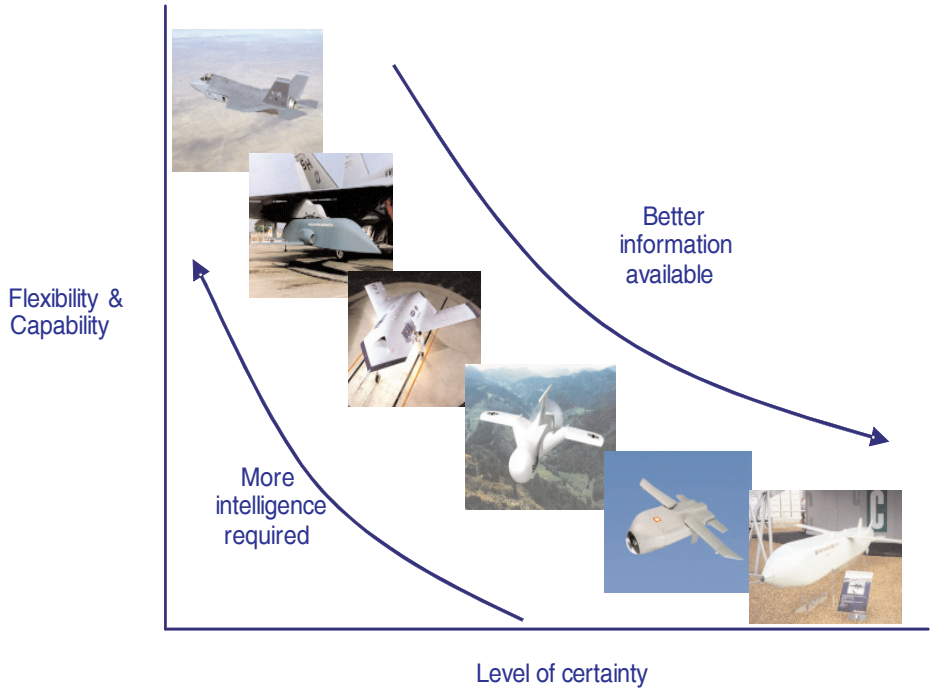


Figure 1. Capability *vs* Certainty.

roles (UCAVs) have the potential to reduce significantly the risk to aircrew in military operations and improve mission effectiveness. Moreover, in addition to the reduced risk to aircrew, the attraction of relatively low cost, highly reliable, readily available assets that are not subject to the physical, physiological and training constraints of human pilots, is self-evident. This promise has prompted studies of systems destined to provide future capability to be broadened to research UAV deployment and consider the possibility of using UCAVs in isolation, in swarms and in packages of mixed unmanned and manned platforms.

Existing UAV systems place a large reliance on remotely situated operators with some of the larger vehicles requiring a pilot in the loop for mission phases such as landing and take-off. High levels of operator interaction with the vehicle increase the vulnerability of the UAV due to detection of electromagnetic emissions and the increased likelihood of control datalink jamming. In addition, the already intense competition for scarce bandwidth is exacerbated. Moreover, reliance on a critical communications link has safety implications with regard to the need for system redundancy to protect against single point failure with concomitant cost implications. Consequently, to reduce this interaction, many of the air vehicle sub-systems must be largely autonomous. With military aspirations towards deploying UAVs in combat roles, such vehicles must be able to operate with minimal interaction from remote operators, communicating only when human decisions are a necessity to meet constraints such as those resulting from rules of engagement (ROE).

The terms 'autonomy' and its corollary 'autonomous system' are much used and abused. Systems are often described as 'semi' or 'fully' autonomous, terms which carry little precision. The aim of this paper is to bring some clarity to the terms by describing one particular application and to outline the issues surrounding the achievement of a controllable capability which can be trusted. This paper discusses the meaning of autonomy in the context of autonomous UAVs by means of a conceptual architecture of a UCAV system. It will go on to discuss methods for calibrating autonomy by defining levels. It will also describe the proposed methods for achieving higher levels of autonomy in UAV systems. The barriers to achieving these unprecedented levels of autonomy will be discussed before concluding.

1.0 WHAT ARE AUTONOMOUS UAVS?

The introduction outlined the need for autonomy in UAVs. To aid discussion this section will define the terms introduced and postulate the likely system architecture of an autonomous UAV enabled capability.

Turning first to some working definitions of commonly abused terms:

Automatic: Performed from force of habit or without conscious thought (Oxford English Dictionary (OED 2004))

Autonomy: Ability to initiate or modify actions in the light of ongoing events. The freedom to determine one's own actions or behaviour (OED 2004). Self-governing.

Intelligence: Capacity for understanding (OED 2004) or the ability to exploit knowledge to achieve goals.

Autonomy and intelligence are terms often confused but Clough (2002) makes the point that autonomy and intelligence are not necessarily linked. For example, the Amoeba is a very simple organism that can be described as being autonomous but is also possesses very little intelligence. So are high levels of intelligence required of UAVs?

White (2002 (a) and (b))[2,3] introduces the following argument. Figure 1 shows a number of systems plotted on a graph of flexibility and capability versus certainty. In essence, as one travels down the page and to the right, the assumption is that we are more certain of the environment and situation such that less sophisticated weapons can be deployed. Conversely as we move up the graph and to the left, we are less certain of the target and situation and so must field a more intelligent system able to deal robustly with the level of uncertainty and hence the addition of the crew to provide what humans

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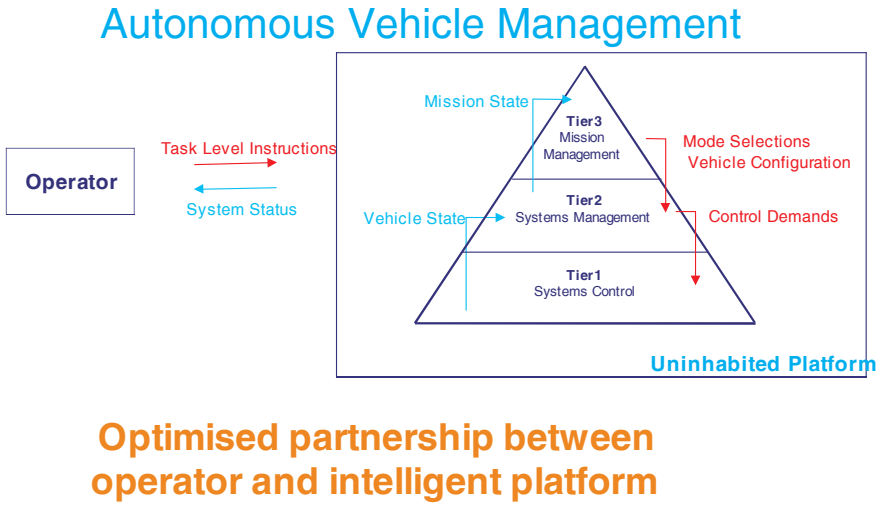


Figure 2. Operator vehicle partnership.

currently do best. In the case of the UAV, the intelligence to cope with uncertainty is now shared between the on-the-spot vehicle and the remotely situated human operator. White goes on to describe how the system autonomy is therefore achieved via an appropriate partnership between the UAV operator and the intelligent vehicle system. This conclusion is implied in the following statement taken from Lin (1994)[4] defining intelligent control:

> *'control that replaces the human mind in making decisions, planning control strategies, and learning new functions whenever the environment does not allow or does not justify the presence of a human operator.'*

So how will this decision making partnership be embodied and what is the work share? The system will contain a control station incorporating the interface to the vehicle, system-monitoring functionality, and possibly some in-built mission planning capability and decision support functionality. The system will contain one or more datalinks to the vehicle or vehicles. The vehicles themselves will possess a systems manager to control aspects of flight management, system health, sensor payload etc. High levels of autonomy may require an additional system element performing the autonomous reasoning, planning, conflict-resolution and decision making functionality. Decisions will be shared across the system (partnership) as a function of system intelligence and communications bandwidth. Critically some decisions will have to be made by human beings due to regulatory and liability issues regardless of technological capability and this implies that 'total autonomy' in the context of lethal UAVs is a non sequiter.

Breaking down further the notional architecture into levels of hierarchy aids discussion of the various elements of technology that combine to deliver the overall autonomous UAV system. Consider first Fig. 2 showing a single vehicle structure. A single operator communicates with the vehicle over a datalink. The vehicle autonomy is to be delivered using three conceptual hierarchical tiers. A description of the tier functionality is best achieved through use of an example. While the structure encompasses all vehicle subsystems the example focuses purely on the flight control aspects. In this respect Tier 1 is what is colloquially known as the 'inner-loop' and concerned with stabilisation and control of the body rates in

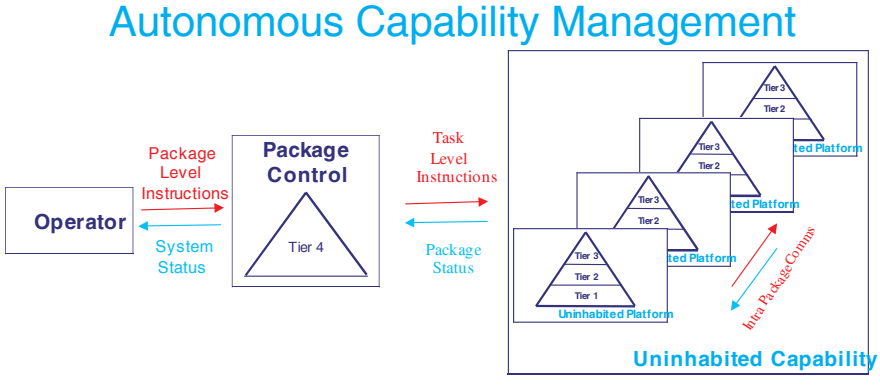


Figure 3. Operator capability partnership.

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Table 1
Alternative to the ACL (Strens 2002)

	Operator interaction	Reasoning	Knowledge	*UAV task example*
8	Long-term strategic goal	Strategic imperfect information game player. *e.g. has expectation about opponent's intention for operating air defences*	Broad battlespace understanding *e.g. has detailed models for command systems and reasons about their effective deployment*	*Long-term no-fly zone enforcement.*
7	Strategic goal	Battlespace planning or strategic behaviours *e.g. plans to achieve the strategic goal and adapts the plan in view of communicated/sensed info.*	Broad battlespace knowledge *e.g. generic predictive model for all entity types*	*SEAD with ALUAVs in high-intensity environment.*
6	Select from variety of tactical goals	Multiple specialised planning capabilities or behaviours. *e.g. separate search, surveillance, attack, BDI skills*	Generic and specialised knowledge. *e.g. tactical picture plus task-specific co-ordination models*	*SEAD with operator-intensive mission control.*
5	Tactical multi-UAV goals for heterogeneous UAV resource pool	Strong co-ordination *e.g. real-time spatio-temporal reasoning*	Local co-ordinative picture *e.g. relative position information or co-ordination functions*	*Search and attack of a mobile target given its last known location.*
4	Tactical goal for homogeneous UAV resource pool	Weak co-ordination *e.g. dynamic allocation of UAVs to tasks*	Abstract picture *e.g. platforms as resources, high-level task descriptions*	*Search a large region with an ALUAV swarm.*
3	Tactical goal for each UAV (specialised)	On-board re-planning *e.g. near real-time flight path planner*	Spatial *e.g. terrain and pop-up threats*	*Send ALUAV to reconnoitre a location.*
2	Mission planning, event-based monitoring	Adaptive control (self-regulation) *e.g. adapts trajectory; refers to operator if outside bounds*	Internal histories *e.g. distance, fuel against plan*	*UCAV vs fixed target, in all-weather.*
1	Mission planning, continuous monitoring	Plan execution *e.g. follow flight plan then deploy a weapon*	Specialised spatial *e.g. list of waypoints*	*UCAV vs fixed target in good weather*

pitch roll and yaw of the air vehicle. Tier 2 would be the 'outer-loop' and deals with such things as air vehicle trajectory control.

Tier 3 is the functionality traditionally brought to the air-vehicle by the aircrew and partially delivers the flexibility and robustness discussed already.

For example, focussing on the human contribution to the operation of a twin seat ground attack aircraft, whilst there are levels of automation within the cockpit for both the pilot (automatic pilot modes) and the navigator (navigation systems), the scheduling and initiation of these systems is still carried out by the crew. Moreover, real-world uncertainties in the kinds of environment in which this aircraft operates frequently mean that sub-system failures and damage must be compensated for such that, ideally, the mission continues. In the case of the UAV this Tier 3 functionality is now shared between a remotely situated human and the UAV based capability. In order to formulate a view on who does what in the partnership it is necessary to understand how human beings think.

Rasmussen (1983 and 1986)[5,6] proposes a model of human cognition known as the Skills-Rules-Knowledge model. In this model low level reflexive and motor skills are generally executed without thought (changing gear in a car for example) and initiated according to established rules (approaching a junction so change down through the gear-box). When unfamiliar situations arise, humans are adept at building new rules from knowledge to cope with the new situation (skidding on the approach to the junction for example). In the case of the UAV/human decision making partnership then it would seem logical to automate the lower level skills involved (Tiers 1 and 2) and then share as appropriate the higher level rules and knowledge levels. Unfortunately there is no clearly defined 'decision surface' between these levels. Therefore in the case of UAVs, having removed the aircrew from the vehicle, the functionality lost must now be shared between any on-board intelligent capability (Tier 3) and the remotely situated operator. This sharing of the decision making between the operator and vehicle partnership will be discussed in greater detail later in what follows and is referred to in the literature as a mixed-initiative system.

Having discussed the single vehicle system architecture the aspiration is for a system where a single operator now controls a number of UAVs. The level of abstraction with which the operator interacts with the UAVs is increased by the addition of a Tier 4. Tier 4 carries out the 'pooling' tasks and resource allocation. An assumption is that the operator now deals with an uninhabited capability comprising a number of platforms and is no longer concerned with the individual platforms. The intelligent system is defined such that the mission is designed around a pool of UAV resources by default and only operator intervention will take resources from the pool to divert them to additional tasks. Synthetic Environment based human in the loop trials have shown that this assumption is sound up to a point. There are instances where the autonomous behaviour exhibited by the 'pool' is not exactly that required by the operator and so he or she will interrupt and begin to draw single platforms from the pool to carry out additional tasks. Clearly this requirement begins to indicate the level of sophistication required of Tier 4.

In order to understand the relative sophistication required of various autonomous UAV systems it is necessary to first explore more fully potential degrees of autonomy.

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2.0 HOW DO WE MEASURE AUTONOMY IN UAVS?

The autonomous control level (ACL) matrix was developed at the US Air-Force Research Laboratory Air Vehicles Directorate at Wright-Patterson Air Force Base as part of the Fixed-Wing Vehicle Initiative by researchers across US Services and industry[3]. The matrix is an attempt to place arbitrary levels on an autonomy scale but with the added dimensions of the 'OODA' loop. The observe-orient-decide-act loop was adopted in an attempt to map the autonomy level to a capability. Moreover, a number of technologies exist to increase autonomy levels whose strengths and weaknesses constrain their application. The added OODA dimension allows for comparison of such methods and subsequent judgements to be made in respect of their capabilities and likely contribution to increasing the level of autonomy. Indeed, it is understood that the matrix has been used as a Balance of Investment tool.

Strens (2002)[7] pointed out that the decision column of the ACL Matrix essentially provided definitions for the level descriptors. i.e. it was an input to the table. For example, ACL 7 (battlespace knowledge) is defined to mean capability for 'group accomplishment of strategic goal with minimal supervisory assistance'. The orient and decide requirements are the fundamental elements of autonomy, whereas the observe requirements must support these processes by providing the necessary information. Continuing his critique in the context of theories for optimal interaction used in robotics research he advanced alternative dimensions to autonomy having first defined an autonomous agent being one that can, without intervention, sustain robust behaviour for a period of time or until a goal is reached. He advanced that high autonomy implies accomplishment of a strategic group goal without intervention, and lower levels of autonomy imply intervention is required to set subgoals (e.g. for different phases of a mission or different agents in a group). Clearly definitions of strategic goal will differ application to application.

Having first interpreted the ACL in the context of three dimensions of requirements

(*i*) operator interaction;

(*ii*) agent reasoning ability (to support this interaction); and

(*iii*) the level of knowledge needed by the group of agents (to support this reasoning). He also went on to argue for a reduction of the number of levels and proposed the scale of autonomy shown at Table 1. As has been described, at least two scales of UAV system autonomy exist. Focussing on the scale proposed for Table 1, at least two difficulties remain;

(*i*) the mapping of technologies to an appropriate level and

(*ii*) the mapping of levels to the achievable military capability.

The former is an issue in that it has been shown that achievable levels of autonomy are a function of a number of different technologies of differing maturity level and the challenge of integration of those technologies. The lack of a well defined application requirement further adds to this challenge. In developing Table 1 it is clear that some assumption has been made about the 'context' in which the system will be operated. This is a further dimension to autonomy level that allows meaningful discussion about the user's expectations of the system and comparison with other 'autonomous' systems. Often autonomy is assumed to be a function of flight management alone.

In the case of the second difficulty it is not known what level of investment is required to optimise the mix of operator, available bandwidth (a dynamic quantity), technology maturity and the concomitant military capability. This lack of knowledge stems from the nature of current procurement programmes in that the user's requirements are, at this stage, aspirational depending largely on the 'art of the possible'. Without a true understanding of costs it is not a foregone conclusion that UAVs of the type discussed here are tenable in any future force-mix. The required concepts of use are based on operational assessment studies that are untested other than in SE trials. The nature of such trials makes them constrained and relatively expensive such that the entire mission space can not be explored. Consequently, it is extremely difficult to extrapolate across this mission space to the extent that a clear picture of the technological needs and capabilities is understood such that the cost versus capability relationship is apparent.

The key to use of Table 1 comes in deciding the command level of abstraction which in turn comes from understanding the 'context' of the system's application. The UAV task column briefly describes some typical tasks at the appropriate level of abstraction. These tasks can be read across to the operator interaction required and the implied information requirements for the appropriate decision making. Thus giving insight into the required command and control architecture and required technologies.

3.0 HOW DO WE REALISE HIGHLY AUTONOMOUS UAVS?

Having discussed both the nature of UAV autonomy and the measurement of degree of autonomy, some ideas about how these required levels are achieved are presented. The methods consider the hierarchical Tiers already described and the interface to the human operator.

Two concepts associated with safety should be introduced at this stage of the discussion, mission critical and safety critical decisions. These concepts will be returned to later in this paper but for now it is worth pointing out that currently in manned aircraft, a proportion of the risks to safe flight are mitigated merely by the presence of the crew. For example, the 'see and avoid' philosophy of collision avoidance, the ability of the crew to spot potential collision hazards is a cornerstone of current operations under visual flight rules – the ability to minimise flight over populated areas or to manoeuvre clear in an emergency for example. Mission critical decisions are those whereby the success of the mission is compromised – due to sensor failure for example – but crew safety or collateral damage is not necessarily a risk. In the case of mission critical case the crew are required to make the appropriate decision to abandon the mission.

Safety criticality is a key issue and barrier to the deployment of highly autonomous UAVs. To this end, and to capitalise on many years research into the automation of aspects of manned flight, the philosophy adopted in the work underpinning this discussion is to use where possible, tried and tested technologies. In this respect Tiers 1 and 2 rely on well-established design methods for inner and outer loop control with regard to flight management aspects of autonomy. Similarly other system aspects of autonomy such as sensor control, communications system control, weapon control and so on may not have specific parallels in the manned flight world but do not, it is felt, represent significant technological challenges for mainstream automation methodologies. A possible exception is aided (or augmented, but not automatic) target recognition (ATR) where novel approaches may well have increased utility and the subject as a whole remains a challenging research issue. However, notwithstanding the case of ATR, the real challenges appear at Tiers 3 and 4, the boundaries between Tiers 3 and 2 and the decision sharing partnership described earlier.

The methods to increase autonomy can be split into those techniques to increase overall system robustness by endowing the vehicle part of the partnership with greater intelligence and those allowing a true mixed-initiative approach.

Turning first to increased intelligence, any survey of research areas associated with autonomy will show a vast range of techniques, often under the 'Artificial-Intelligence' umbrella. It is advanced that the techniques are often limited (in the application

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Table 2
Pilot Authority and Control of Tasks (PACT)

Primary Levels	Secondary Levels	Operational Relationship	Computer Autonomy	Pilot Authority	Adaptation	Information on performance
AUTOMATIC	5	Automatic	Full	Interrupt	Computer Monitored by pilot	On/off Failure warnings Performance only if required.
ASSISTED	4	Direct Support	Action unless revoked	Revoking action	Computer backed up by pilot	Feedback on action. Alerts and warnings on failure of action.
	3	In Support	Advice, and if authorised, action	Acceptance of advice and authorising action	Pilot backed up by the computer	Feed-forward advice and feedback on action. Alerts and warnings on failure of authorised action.
	2	Advisory	Advice	Acceptance of advice	Pilot assisted by computer	Feed-forward advice
	1	At Call	Advice only if requested.	Full	Pilot, assisted by computer only when requested.	Feedforward advice, only on request
COMMANDED	0	Under Command	None	Full	Pilot	None, performance is transparent.

discussed here) in that they are applicable where so-called classical established techniques are already adequate[8,9]. Moreover they are often targeted at a very small part of the overall UAV autonomy problem. For example, artificial neural nets may be applicable in image recognition but may not deliver a high level tactical decision maker operating with partially observable information. For example, it is the difference between the methods to allow the UAV to decide that to successfully attack it is going to be vulnerable to attack from a ground threat and reasoning to resolve the evident conflict, and methods to model vehicle characteristics to understand that damage has resulted in a loss of performance. Both methods may be needed to achieve an overall capability level but both will adopt different technologies to realise the functionality. Consequently, greater intelligence in the vehicle will only be achieved by a range of approaches and thus making architecture a key issue. It is believed that the real risk-reward area for research into UAV intelligence is more likely to be found amongst agent oriented methods which provide a useful framework to express task management and execution of asynchronous events in the face of uncertain information.

Being mainly concerned with task execution, agent based systems are not best placed to carry out planning tasks. To carry out planning the agent based system will delegate the task to a subordinate planner. So for example, the overall task might be for the multi-platform based capability to carry out a search for a mobile target. Only the last sighting would be known and the approximate speed of the vehicle and knowledge of the terrain over which the vehicle is moving may be gleaned from a digital map database. The planner's job is to offer a series of routes for each platform such that the search area is efficiently covered given available resources. Boundary conditions on the problem exist in the form of fuel limitations, performance limitations in respect of platform and sensors. The planned solution might be passed in a series of waypoints via Tier 4 over a datalink to each platform Tier 3 and thence to the Tier 2 waypoint following system for each platform. A planner with such capabilities is a non-trivial requirement particularly when one considers that the mobile target is not likely to be co-operative and use tactics such as hiding under bridges, doubling back etc to confound the UAVs.

Again it is clear that architecture is an issue to successfully integrate the different techniques. In this application, the appropriate agent architecture must be developed to cater for mixed-initiative control of the capability made up of multiple UAVs. The architecture needs to robustly cater for the fact that the decision making team is distributed over a series of datalinks and that the team plan may be interupted and the team split by the human operator into sub-capability teams deployed on different tasks.

Turning to the other aspect of increasing UAV autonomy level, the human interaction aspect is addressed. Having advanced an argument in respect of the mixed initiative approach to UAV autonomy, the Human machine interface (HMI) requires discussion. In this context the HMI refers rather to the philosophy of how the operator manages the level of autonomy of the vehicle rather than the construction of the display media and control station.

Norman in Harris (2003)[10] captured what makes an automated [autonomous] system hard to control [trust] in terms of two so-called gulfs:

- The gulf of execution – Does the system allow actions that correspond to the intentions of the operator?
- The gulf of evaluation – Can the operator monitor the state of the system and what is the difference in state from that intended?

where the square brackets are suggested alternatives for the UAV application. Crossing these 'gulfs' would seem to be the objective of any mixed-initiative decision making system. Given the Skills-Rules-Knowledge based model discussed earlier, a boundary between the human and machine decision making was implied in the rules and knowledge layers of the human-machine system. Intuitively this interface must change position according to the desired level of autonomy. In simulation work[11,12,13], operators

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expressed a desire to be able to select an appropriate autonomy level with respect to mission elements and sub-systems. That is, there will be times where the operator is overwhelmed with new information and would be prepared to accept a higher level of autonomy to remain in overall control – still able to bridge the gulfs!

It should be noted that the two scales of autonomy discussed earlier tend to be meant for use as descriptors rather than a practical implementation of a variable level of autonomy. Some work has been undertaken to define and measure autonomy levels[14] as applied to the robotics field where the agents may be less constrained by the need for continual human involvement, for reasons of safety or legality, in the task . However, as has been described, for this application some key decisions may be mandatory for humans. More applicable is the work done on the Pilot's Associate programme[15] that covered some of the earlier Pilot Authority and Control of Tasks (PACT) work that will be discussed next.

This is a pragmatic approach to bridging the gulfs described earlier and has hitherto been applied to increasing pilot capacity within the context of a single seat fast jet[16]. The PACT framework was realised in that application within the UK MoD's COGPIT programme and showcased the role of adaptive automation and intelligent decision aiding in a future manned military aircraft. The PACT system provides a logical, practical set of levels of automation, ranging from fully manual, assisted, to fully automatic modes, with four levels of automation assistance which, in the combat aircraft implementation, can be changed adaptively or by pilot command. The four assisted levels provide progressive support of pilot situation assessment and decision action. Table 2 below shows the revised PACT system as modified by Taylor and Bonner[16].

In the fast jet application the pilot forms a PACT contract with the automation by allocating tasks to PACT modes and levels of automation aiding. This allocation was made either by default settings set prior to flight and/or during mission planning, or by prior authorisation of level changes following agreed onset and triggering conditions or events, or alternatively by making changes to levels by command in flight.

The application of PACT to the control of UAVs is a new development[17]. The PACT system as applied to the UAV application aids the control of the multi-vehicle capability and is related solely to the control of higher level UAV activity. In initial work[18] the principal focus was the heavy workload target location and identification tasks. The underlying philosophy of the PACT applied in this work is that:

- skill based tasks should be automated first (PACT levels 4 and 5),
- rule-based tasks should be automated where possible (PACT 3, 4 and 5)and if not able to be automated they should be supported by decision-aiding (PACT 2) and
- knowledge-based tasks should be supported by decision-aiding (PACT 1 and 2).

This philosophy corresponds to the 'KRS' paradigm as discussed earlier in this paper. The key point here is that the level of human interaction is variable on a task by task and mission by mission basis. A further point is that the required technologies to achieve PACT levels 2 and a proportion of 1 may well increase significantly the overall software costs of the system. Trials work (op cit) has yet to establish a need for this technology. The desired 'PACT level' is set as a function of:

- regulation due to safety clearance or legality such as RoE
- technological capability – e.g. do we trust aided target recognition for target identification?
- bridging the 'gulfs' to keep the operator engaged at the correct level of arousal and in control
- the command level of abstraction as defined in loose terms in Table 1.

In summary, higher levels of autonomy in UAV systems will be achieved by the appropriate mix of technologies, using an agent based architecture to build intelligence built around a mixed initiative approach that accepts from the outset the partnership between the user and the intelligent machine. A key risk area is the establishment of a suitable architecture to facilitate this approach.

4.0 WHAT ARE THE BARRIERS TO HIGH AUTONOMY IN UAVS?

The previous sections have discussed in some detail what autonomy is and how it might be measured. The argument that the level of autonomy is a function of the degree of human interaction was presented. Furthermore, the robustness of the system in the face of uncertainty together with a workable level of decision sharing is delivered through the increased intelligence of the air vehicle capability and a variable autonomy interface.

To achieve high intelligence in vehicles an agent based software architecture has been argued as the obvious approach and this presents a number of barriers to wide adoption. Agent based methods, where modern Java type development environments are used, represent a significant departure for the generally conservative aerospace domain. The ability to use the agent based approaches will make a huge difference to the life-cycle costs of UCAVs as they are designed specifically for this representation of a problem and the rapid development of appropriate behaviours. Using such means tends to fly in the face of the accepted approaches of using methods such as ADA and its sub-sets. However, while it is almost certainly possible to achieve high intelligence using traditional ADA based approaches, it is argued that it becomes prohibitively expensive to do so.

It should be noted however that UAV tactics will change on a mission by mission basis as target sets, weapon and sensor fits change. This may mean that tactical behaviours will also need to be changed to reflect system changes on a daily basis. Moreover, as doctrine changes throughout any campaign then so, it may be inferred, must the UAV behaviours. Therefore, it is a key requirement that both architecture and software can accommodate this without compromising the overall system safety case and without limiting system flexibility throughout the system life. The process must be rapid, safety clearable and cost effective.

Implementation of the UAV behaviours (derived from tactics) using an agent based task execution framework, as has been discussed, represents a key challenge to the overall design philosophy in terms of architecture and software engineering, if system flexibility is to be maintained.

The barriers to use of agent based approaches become therefore:

- Trust: will the community come to accept these novel approaches?
- Clearance: can methods be found to clear these approaches in a safety critical sense to the satisfaction of the authorities?
- Expertise: is there sufficient expertise in these methods within the UAV/aerospace domain?

The situation is exacerbated by the need to use an array of methods to achieve appropriate parts of the overall requirement. The road search example highlighted the need for at least two distinct approaches. Clearly when mapped across the foreseeable mission space the required specialised planners may be key. Furthermore, novel methods to fully realise the Tier 3 and 2 elements of the decision hierarchy may need to be developed.

The likely decision space (the range of all possible decisions that would be shared between operator and UAV capability) for a range of

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missions has, thus far in this document, been considered largely in the reactive sense in that decisions are made on-line based on current information. One must also consider the a-priori decision making (currently embodied in the mission planning process) and the exact interplay between decisions to be made *a-priori* and those on-line in real time. The nature of this relationship makes the difference between capability represented by systems such as that in the bottom right of Fig. 1 and those of the top left and reflects why it is we need UCAVs at all. Another example might be Inter-planetary space based vehicles. These may appear to be the apotheosis of autonomous technology but one must consider the scale and length of the pre-planning and support during missions to cater for contingency, but also need high levels of intelligence to cater for significant system latency. While UCAVs may arguably enjoy less latency they can not afford the scale of a-priori planning found in space projects.

In order to integrate the various software components of the system a suitable architecture is required. The architecture must consider the philosophy of autonomy described in this document but must also recognise:

- the technological constraints imposed – sensor fit and performance for example
- concepts of use and tactical behaviours – do we need to fly a figure of eight and possibly linger too long within a threat area
- doctrine – what are the decisions deemed critical that may necessitate a human decision maker for reasons of safety or legality
- safety – that the distinction is made between safety critical and mission critical functionality such that inevitable changes to the mission critical aspects can not impact on the safety critical aspects
- flexibility – the ability to grapple with these issues as they change on a regular basis and having accepted that almost by definition the fielded system will not meet requirements on day-one of any conflict

Clearly a suitable architecture, a process by which its requirements are captured and the system developed becomes a significant barrier to the realisation of highly autonomous UAVs.

Finally, the key to targeted autonomy such that the 'gulfs' are bridged is the knowledge acquisition (KA) process. This is the process whereby the user's requirements are captured in a form such that they are readily understood by the developer of the architecture and the intelligent software. It is a skill traditionally associated with the developers of knowledge based systems but in the context used here refers to the whole process of the UAV system design. Given that in essence no operational UCAV is currently in service then the KA process can not be applied in the traditional sense. KA is usually applied to a known process where an expert exists and the aim is to capture that human's expertise or a sub-set of it such that an artificial process can duplicate the functionality. In this UAV application the vehicle concepts, technological capabilities, mission types, role of the operator and UAV tactical behaviours are all the subject of research and the 'art of the possible' being developed in parallel. Consequently no 'expert' exists and a new process is required that embodies more of the overall system design process than hitherto within intelligent systems design. This too represents a barrier to realising highly autonomous UCAVs.

5.0 CONCLUSIONS

This document has described a view on what is meant by an autonomous UAV. It has also gone on to define and discuss the degree of autonomy whilst proposing a measurement matrix in order to bring some clarity to the imprecise terms such as highly autonomous and semi-autonomous. The paper then discussed a hierarchical autonomous system architecture to aid discussion before going on to recommend how high autonomy may be achieved and finally what might be the barriers to achieving high autonomy.

In conclusion, from the literature, it is clear that there is a need for highly autonomous UAVs. High autonomy is a complex function of the:

- overall system architecture,
- available technologies and their capability,
- nature and level of the decision sharing between the human and intelligent machine,
- desired capability.

Autonomy level is a function of the system context, the level of human interaction, the system reasoning capability and the knowledge.

Three key barriers to successful development of highly autonomous UAVs are

1. the need to adopt agent based software methods
2. the process by which the software architecture is defined to meet foreseen and unforeseen needs
3. the knowledge acquisition process in the absence of 'experts'

It is clear that research must continue to:

1. Find ways to allow the adoption of agent based software in safety critical applications.
2. Continue to refine knowledge acquisition processes to allow seamless requirements capture and system realisation in a rapid manner.

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