Application of Intelligent Aiding to Enable Single Operator Multiple UAV Supervisory Control

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Abstract

Under the sponsorship of the Air Force Research Laboratory, a development team has been defining a set of intelligent tools that will enable a single non-rated operator to provide supervisory control of multiple unmanned air vehicles (UAVs) engaged in tactical support to ground forces. Early work has defined concepts for the operator-system relationship, identified functional requirements, and produced analytical estimates of the relative effectiveness of three alternative levels of automated assistance to the user. The results suggest that higher levels of automated support will significantly leverage the span of attention and span of control of the operator, while reducing workload to a manageable level

Introduction

The Air Force recognizes that providing rated pilots to continuously attend a UAV ground control station for long duration missions is an unsustainable practice(Miller 2004; Drury, Riek, and Rackliffe 2006; Cummings and Mitchell 2005; Calhoun, Draper, and Nelson 2006; Quigley, Goodrich, and Beard 2004). There are insufficient numbers of qualified pilots to use them in this way. An emergent manning strategy focuses the assignment of rated aviators to Launch and Recovery Element (LRE) positions where stick-to-surface flight control demands their skills for takeoff and landing, while the management of platforms in the tactical operational area will become the responsibility of a new class of operator the On Station Operator (OSO) - located in a (possibly remote) Mission Control Element (MCE).

The OSO will not be a rated pilot, but will be prepared to navigate the platform(s) in a sector of responsibility through autopilot mediated commands, and will be skilled in payload operation to support client ground forces. The LRE pilot can only be expected to fly one platform at a time. The OSO, in contrast, will be assigned a particular geospatial segment of the battlespace rather than with a particular UAV platform.

The OSO will control all UAVs in the assigned airspace. There, the focus will be on maintenance of situational awareness and coordination with other force elements. The the OSO mission will be to allocate the mix of available assets - to include all unmanned aircraft that may be in the sector - to best meet evolving tactical requirements. When required to manage the operations of this mixed collection of platforms, each with its unique mission, capabilities, limitations, and control protocols, a toolset of intelligent aids for planning, monitoring, workload relief and decision aiding become essential components of the OSO user interface.

Recognizing this emergent manning strategy, the Air Force has launched an R&D effort called AIMS to identify and develop the toolset and the user interface that the OSO will need to operate it. The toolset must enable the OSO to:

- Accept supervisory responsibility for UAS platforms from the controlling LREs as the aircraft enter the OSO sector,
- Navigate UAS platforms to locations of employment,
- Make plans to employ the mix of platforms to meet the changing needs of sector clients,
- Monitor and manage execution of ongoing UAS missions ,
- Re-plan and re-allocate resources to adjust to changes in the battlespace environment, client needs, and platform availability,
- Navigate UAS platforms to handoff locations for returning supervisory control to the respective LRE's for recovery, and,
- Operate the UAS payloads to accomplish mission objectives, to include weapon delivery,

AIMS Program Objective

The objective of the AIMS (Adaptive Interface and Management System) program is to enhance multi-UAV operator performance by the provision of this toolset of task-oriented job performance aids, decision aids, and intelligent agent assistants. A team headed by Perceptronics Solutions, Inc. that includes the

Carnegie-Mellon Robotics Institute and the George Mason University Arch Laboratory is under contract to the Air Force Research Laboratory to define and develop AIMS.

AIMS Developmental Scenario

Perceptronics strongly believes in the use of a scenario as an instrument to inform the design, development, and testing of system concepts. As a design tool, a tactically realistic and vetted scenario provides means for developers to ensure that the system is responsive to the functional requirements of the problems it addresses. The AIMS developmental scenario that has been created brings to focus the tasks that a single operator of multiple UAVs must perform as the MDMP process results in mission plans, execution, and assessment of success.

Planning/re-planning, allocation of resources, continuous decision and control, battlespace coordination, and payload operation are must be completed in the tactical flow within the time, space, and resources available often simultaneously. METT-TC factors, changes in environment, and unanticipated platform system availability issues complicate the operators task. Beyond identification of application areas, by analysis of the scenario, we have attempted to reveal functions for which automation or performance aiding returns the greatest payoff by enabling or expanding the capacity of the operator for multiple platform management. This disclosure establishes the priority for AIMS technical development.

As the automation/aiding processes are defined, the scenario is in use as our vehicle for demonstration of the anticipated gains in human-system performance in mission context. During the initial effort, we have made analytical estimates; during continuing development, we intend to verify these predictions by exercising a prototype first in a simulated environment, then in field tests with live platforms.

AIMS System Concept

The development of a functional concept for any system in which there is vested machine intelligence must consider the nature of the relationship between user and system. The configuration of the user interface must be appropriate to support the roles that the user and system assume in their collective execution of mission tasks. Several types of relationships can be defined; they differ in the level of supervisory abstraction of the control task, in the degree of autonomy and delegated authority granted to the automated components of the collaboration, and in the technological demands of implementation. We have examined three concepts for comparison:

Basic AIMS Concept In our most simple concept, AIMS is an operator interface configured as a user invoked set of tools that make no presumption of intelligent capacity to 1) perceive the state of the battlespace, 2) comprehend mission status and objectives, 3) sense the need for and make decisions, or 4) execute the mission by automated sequencing of scripted military behaviors and detecting deviations from plan expectations. The entire responsibility for all of these functions remains with the human operator who determines when a system behavior is needed and proactively initiates it, a form of mixed-initiative interaction(Ferguson, Allen, and Miller 1996; Hartrum and DeLoach 1999). While the toolset includes planning aids and/or performance reporting, the responsibility for discovery of behavioral anomalies, course of action selection, and for translating plans into directed action remains with the user. This basic implementation makes maximum demands upon the user to maintain situational awareness, to discover the need to make decisions or to take action, and to assess the results of action taken. This is the most workload intensive relationship from the human point of view and requires the operator to remain involved with the most granular aspects of platform performance and mission supervision.

AIMS as an Executive Agent In the intermediate concept, AIMS is an executive of scripted behaviors; AIMS is required to:

- Collect state information from the battlespace and from platforms under control,
- Comprehend the immediate goals of behavioral scripts either individually or in sequences,
- Compare current and objective state, and,
- Supervise the execution of behavioral primitives when invoked by plan or by user directed action.

While this implementation of AIMS is not intended to autonomously select the behavioral scripts appropriate to realizing higher order objectives, a system with this capability is expected to leverage the span of attention/control of the human supervisor by monitoring the execution of programmed behaviors, detecting deviations from expectation, and by summoning operator attention for decision making by exception rather than as a continuous responsibility. This ability to compare system performance to expectations provides an initial basis for mixed initiative supervisory control in which either the system or the user can identify a need for action. It offers supervisory workload relief to the operator if the automated monitoring of execution is reliable, if the quality of situational awareness is adequate, and if the timeliness and efficiency of intervention when operator control action is needed is satisfactory.

This higher degree of abstraction elevates the framework for operator action decisions from platform system control to platform tactical behavior specification. It can have a significant positive impact on the ability of a user to time-share attention between competing supervisory control demands because it reduces user need to decompose/translate mission level state performance deviations to detailed platform system commands. The user is still required to maintain awareness of individual platform roles and behaviors, but need not be focused on what the platforms must be doing [internally] to execute the directed behaviors. Provision has to be reserved, however, to enable the human supervisor to penetrate the abstraction and to drill down to platform level control when necessary.

In this implementation, AIMS can be perceived by its user to be a tactical autopilot with limited ability to independently plan, to monitor the tactical situation, to execute directed behaviors, and to raise issues requiring operator attention.

AIMS as a Tactical Colleague In this most sophisticated concept, AIMS is a capable peer that permits the users frame of reference to remain at the tactical level - to a degree unconcerned with platform level specifics. AIMS here provides an operational capability executed by the population of resources over which it has been delegated control, and responds to tactical direction in the same way a subordinate unit leader responds to a commander. User directives need not specify which assets should be tasked to particular roles rather, AIMS is directed to execute a higher level mission such as attack a [specified] target or provide force protection overwatch of a [specified] ground unit.

Supervisory responsibility for the platform assets under control is delegated to AIMS, which knows how to execute tactical directives in accordance with doctrine, local SOPs, and the current state of the battlespace. AIMS must still make available a rich set of situational state information, including, if the operator desires, detailed platform state data that would be required for the most manual implementation described above. Further, although in the normal course of operations, most supervisory directives originate in the automation, certain activities such as weapon delivery must be surfaced for operator consent in accordance with doctrine, legal obligations, and rules of engagement. The operator must have the ability to penetrate the control abstraction to make directives to platforms at the behavioral level and at the system/subsystem level if necessary.

This implementation concept is expected to have the greatest impact on expansion of operator span of attention/span of control while minimizing workload demand, but it also presumes a great deal of elegance in the machine intelligence.

The AIMS Vision

To enable a single operator to provide supervisory control of multiple heterogeneous UAS platforms, we must find means to leverage operator span of attention/span of control and to manage workload. As the design advances along the relationship continuum, we expect to achieve greater success in realizing these objectives, however the association between the level of supervisory autonomy and the degree of development risk has not yet been assessed in the current effort. Table 1 summarizes the functional responsibility allocations for the three AIMS implementation alternatives.

Proof-of-concept demonstration

As a capstone to the AIMS initial concept definition work, the development team utilized pre-existing user interface components and planning/reasoning tools to create a limited working demonstration of AIMS functionality at each of the three levels of automation. A vignette extracted from the developmental scenario provided a framework for the simulated operation. In the demonstration, multiple UAVs are tasked with conducting a collaborative attack on a ground target when it is discovered that an essential platform capability on one of them has failed. This necessitates re-planning and reallocating resources, relocating the aircraft, and then completing the attack. The demonstration highlights the differences between the human-system interactions in the differing automation aiding concepts, and establishes the basic feasibility of integrating intelligent tools into the tactical workflow to expand operator capacity. Figure 1 depicts the demonstration situation.

AIMS Functional Requirements

Our initial analysis of objectives for the AIMS toolset and specific capabilities required by the development scenario and operator-system relationship revealed a set of functional requirements for a mature AIMS implementation, as follows.

General Requirements To reduce operator workload, AIMS must provide assistance in a context sensitive fashion; tools and capabilities most likely to be needed must be offered most conspicuously as paced by the mission context. To achieve this, AIMS must understand the mission intent, the plan for accomplishing it, and the state of progress in the execution of the plan. AIMS can then prioritize the presentation of display and control elements to favor those information items and response mechanisms most relevant to the immediate tasking of the user.

As a further measure to relieve the operator, AIMS must maintain the transactions with the user at the mission context level, and provide whatever translation and decomposition of these abstract exchanges that may be required to effect behavioral sequences onboard the differing platforms through automation. The user should be able to express the intent to execute a complex sequence of activity such as attack target, and from this expression, AIMS, through its portfolio of templated behaviors and augmented by machine reasoning, must decompose this abstract command into the set of elemental behaviors necessary to complete the directive. We refer to the collection of pre-scripted aggregate behaviors as the playbook, and to the individual action options within the collection as plays.

Planning and Re-planning Requirements AIMS must be capable of producing course of action alternatives for consideration by the operator when making planning

Table 1: AIMS Autonomy Levels and Responsibilities

Functional Responsibilities In Alternative Relationship Configurations	AIMS User-System Relationship Concept Functional Responsibility			
	Perception	Comprehension	Decision Making	Execution Oversight
Current Technology	Operator	Operator	Operator	Operator
AIMS as an Executive of Behavioral Scripts	AIMS	AIMS	Operator	AIMS
AIMS as a Tactical Colleague	AIMS	AIMS	AIMS	AIMS

decisions. Beyond that, the system must monitor the course of execution of a selected plan, detect when the actual situation is deviating from expectations, sense the need for re-planning, iterate the planning process, then alert the operator by calling attention to the divergence, proposing alternative subsequent courses of action, and providing a recommended choice and rationale for its selection.

In the general case, the AIMS planning function product will be alternatives for consideration in human decision making; AIMS must also provide capability for intelligent agents to plan their own behaviors and to make decisions when the user delegates responsibility for supervisory control. AIMS plan products must specify:

- Plan objectives and success criteria
- Resources to be employed,
- How, and in what roles they are to be used,
- What tactical behaviors are to be exercised by each participant,
- What the triggers for these behaviors are to be,
- Contingency actions and criteria for invoking them,
- Rule of engagement constraints and verification criteria,
- Technical data such as communications conventions to be used, routing constraints, timing and synchronization criteria, weapon delivery parameters, etc.
- Execution validity parameters and tolerance, and milestone events.

Resource Allocation Requirements AIMS must assist the operator in allocating available assets in a way that maximizes the probability of mission success as defined by stated mission objectives and constraints. Considerations in the assignment process reflected in allocation recommendations include:

- Specific capabilities of various platform and payload types
- Resources in hand and their status (capabilities, consumables state, etc.)
- Resources available for acquisition
- Economy of forces and the level of competing demand for asset services
- Chain of command directives and command intent
- Mission factors such as time and distance constraints
- Environmental factors such as weather and terrain

Continuous Decision and Control Requirements Supervisory control of mission execution requires determining that participating elements are performing assigned functions consistent with expectations, that the current status and health of those platforms supports belief that they will continue to do so, and that, given the disposition of the battlespace environment and flow of the tactical activity - including that of the enemy, the plan remains responsive to current objectives. AIMS must monitor the appropriateness and execution of plan or operator directed behaviors in the context of command intent, confirm conformance with predictions, and alert the operator when divergence is detected.

On occasion, it will be necessary to suspend preplanned activity and to command a platform to execute an immediate tangential action responding to a tactical need. AIMS must facilitate the process by offering a menu of high-level doctrinal behaviors (the playbook) from which the operator can select. These behavioral templates (plays) together with parametric metadata specify common actions quickly and efficiently with reduced operator workload. To accommodate novel situations, AIMS must also provide means to edit existing behavioral templates or to create new ones that can be added to the option list.

When the plan of execution must be modified to reflect acquisition of state information that was uncertain at planning time, AIMS must invoke its planning capabilities informed by newly acquired data, and present the operator with course of action options and a recommendation and rationale for the option selection decision. During periods of high workload, at the direction of the operator, AIMS must be capable of assuming responsibility for common functions such as mission monitoring. To do so, AIMS must understand mission goals, mission status, and task objectives/criteria/dependencies. AIMS must have the ability to make low-level mission management decisions and to implement them autonomously, while providing the operator with situational awareness updates and means to intervene when in the judgment of the operator it becomes necessary.

Battlespace Coordination Requirements On occasion,

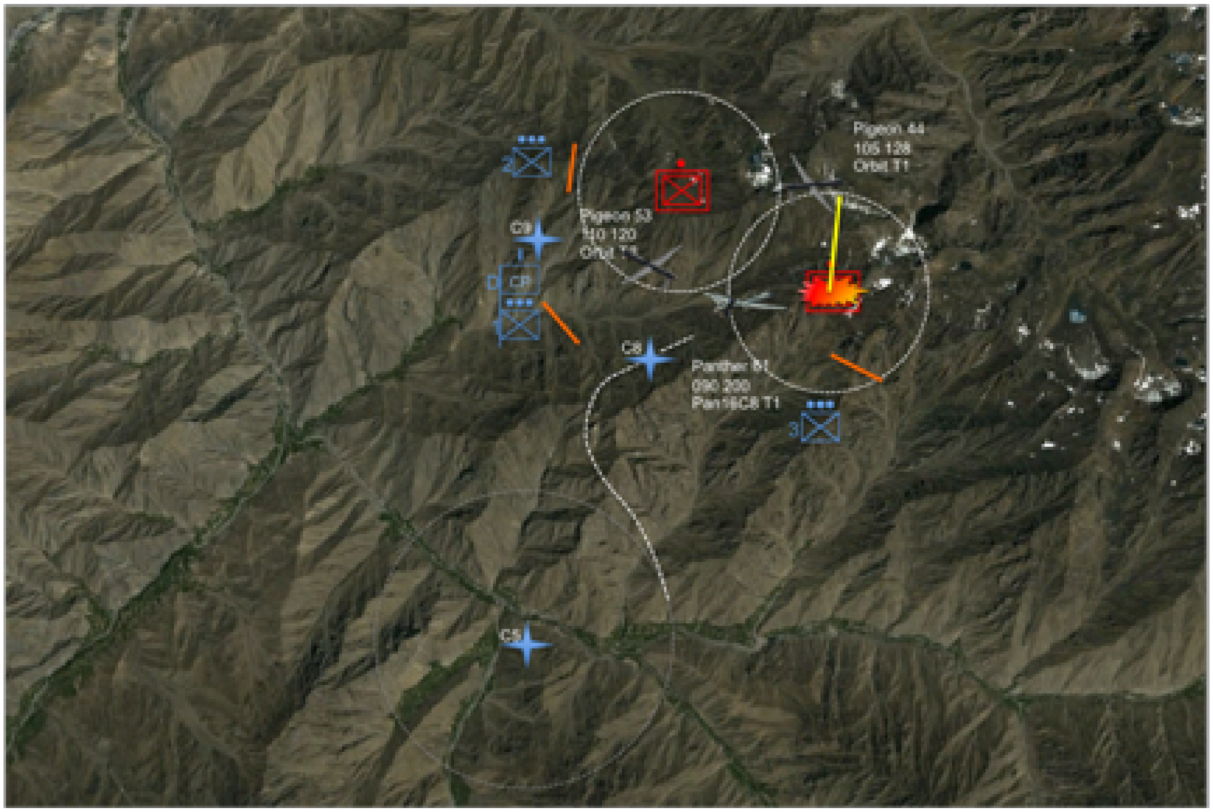

Figure 1: Starting situation for the demonstration scenario.

it is necessary for the user of AIMS to coordinate with other humans or with external systems in the course of mission planning and execution. AIMS must facilitate these transactions by alerting the operator when they are needed, and by supporting the mechanics of these information exchanges over the tactical network.

Many missions will be success-dependent upon temporal synchronization of activities of collaborating elements such as ground forces and their UAV support. AIMS must understand these dependencies, monitor status of the collaborating elements, and alert the operator when conditions are either set for, or were scheduled to be but are not suitable for continued execution of the mission plan.

Payload Operation Requirements The operation of payloads on differing UAS platforms involves an idiosyncratic command vocabulary and syntax that pose a challenge to the operator particularly for infrequently used variants. AIMS must provide relief by permitting the operator to express payload operation intent in common, high-level terms, then decomposing and translating these operator directives into platform/payload specific low-level commands to invoke the specified payload behavior.

Mission success will often be contingent upon operability of the UAS payload. AIMS must monitor payload health and status, and alert the operator when payload capabilities are incapable of supporting mission expectations. To do so, AIMS must understand mission payload performance expectations and continuously compare them with the reported capabilities onboard the assigned assets.

GOMS Modeling and Performance Estimates

To estimate the effectiveness of the AIMS system, we created engineering models comparing AIMS operating concepts in the proposed scenario. Performance models for AIMS were developed within the well-established GOMS (Goals Operators Methods and Selection) framework that provides quantitative predictions of human performance and can be used in place of empirical user data to compare systems in the prototype phase(Card, Moran, and Newell 1983).

GOMS Methodology

GOMS models are based on the Model Human Processor theory of cognition(Card, Moran, and Newell 1983) and assume that the user engages in goal-directed behavior. GOMS also assumes expert performance and derives cognitive, perceptual and motor-based time estimates from empirical motion-time studies as well as an extensive theoretical literature. The table below shows an example of a GOMS top-level goal. Example of a method in the GOMS framework.

Method for Goal: OSO orders [UAV ID] to fly to [Waypoint ID]

1. AG: Select [UAV 1 for tasking]
2. AG: Select [go_to command for execution]
3. AG: Select [waypoint]
4. AG: Select [transmit]
5. Watch for confirmation/acknowledgement
6. Monitor vehicle for departing towards waypoint
7. Return with goal accomplished

Results

The GOMS analysis produced important results. The three conditions were compared on several dimensions including complete mission execution, task execution, option generation, and methods called. Task execution refers to time spend by the OSO to task UAVs and to interact with the system. Option generation refers to time spent by the OSO to generate options for re-planning. All time was estimated in seconds.

GOMS predicted time reductions for both AIMS automation aided conditions compared to the basic configuration. For complete mission times, AIMS as an Executive produced a savings of 74.9% and AIMS as a Tactical Subordinate showed a savings of 93.8% compared to the basic implementation. Table 2 summarizes the results of the analysis.

Conclusion

The GOMS analysis demonstrates substantial benefits for introducing AIMS automation in the OSO scenario. If the time estimates developed here are valid, and if the assumption can be made that there is an inverse linear relationship between the time demand for supervisory control of a given platform and the number of platforms that an operator of fixed capacity can manage, the results suggest an approximate gain of 4:1 for the AIMS Executive implementation over the basic case, and a gain of approximately 10:1 for the AIMS Tactical Subordinate concept. These time savings are on the order of minutes, which can have dramatic effects when operators are under stress and time constraints. Experimentation and interaction with the AIMS prototype will produce the data to validate the predictions produced here.

As well as having application to control of UAVs, we believe this research will shed light on appropriate control for other cooperative robot systems, including those for urban search and rescue(Wang et al. 2009; Casper and Murphy 2002) and surveillance(Elmaliach, Agmon, and Kaminka 2007; Elor and Bruckstein 2009).

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Table 2: GOMS Analysis Results

Tasks	Baseline (B)	Scripted (S)	Tactical Subordinate (AT)	B-S Gain	B-AT Gain	S-AT Gain
Complete Mission	433.6	109	26.7	74.9%	93.8%	75.5%
Task Execution	335.8	49	33.3	85.4%	90.1%	32.0%
Option Generation	97.8	60	60	38.7%	38.7%	0.0%
Main Methods Called	16	9	4	43.8%	75.0%	55.6%