Multi-UAV Control for Tactical Reconnaissance and Close Air Support Missions: Operator Perspectives and Design Challenges

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ABSTRACT

The term 'unmanned aerial vehicle (UAV)' is a misnomer of sorts. Although the pilot is no longer onboard the platform, there remains a critical need for human involvement in order for UAVs to successfully perform missions. This is especially true for the tactical reconnaissance and close air support mission areas where tasks are often time critical, many relevant mission inputs are not digitized, target/friendly/non-combatant identification is complex and variable, mission objectives vary constantly as does the ground situation, and customers vary in training, experience, and procedures. UAV operators in these difficult, time sensitive mission areas will soon be expected to supervise multiple UAVs at the same time, requiring advances in management of mission critical information and aircraft control systems. The key to success is to identify and apply the appropriate level of human skill/attention to each mission task and to provide operators powerful and flexible automation tools so they can focus their attention at the mission execution level. This paper will detail the specific mission attributes and tasks associated with tactical reconnaissance and close air support mission areas that advocate continued human involvement, within the context of emerging multi-UAV supervisory control. Operational examples will be provided as illustrations. Based upon many years experience with real-world manned aircraft (A-10) and UAV combat operations, an operator's vision will be presented of a highly net-centric multi-UAV control station design and associated concept of operations to maximize UAV effectiveness in these complex and dynamic mission areas. Characteristics of this vision will be described including a central management station, dynamic prioritization and tasking, distributed vehicle and sensor control, multi-path information flow, sophisticated autopilot system (supporting precision high-dynamic maneuvering and other pilot moment-to-moment requirements), network integrated voice communications, design with automatic transcription and logging, and specific personnel categories involved. An incremental insertion of automation technology from system-control level to mission-management level is proposed so as to enhance, not displace, UAV operator performance. This vision will also be compared and contrasted to competing visions for multi-UAV control. Finally, this paper will identify critical human factors research issues that will need to be resolved in order to achieve this multi-UAV vision for tactical reconnaissance and close air support mission areas. These issues include human-automation interaction, task interruptions and switching, information prioritization and fusion, task-centered controls and displays, decision aiding technologies, and distributed teaming issues.

1 INTRODUCTION

Multi-aircraft control (MAC) by a single pilot or crew endeavors to multiply forces at a cost of increased system workload. Concepts for MAC tend to share a common premise: the mission conducted by the unmanned aerial vehicle (UAV) must be very simple, *or* automation must be added to handle increasingly higher levels of information management, mission management, and system control until the remaining tasks are simple enough for a human to handle across multiple missions.

It is fairly easy to multi-task if all the mission tasks are simple. But what if missions are complex and dynamically changing, requiring the full concentration of the human pilot? The aircrew must not only control the aircraft, sensors, and weapons, but also rapidly assess a complex dynamic tactical situation, process a large amount of information, and make numerous time-critical mission management decisions. The conventional solution is to add automation. However, what if the mission tasks are resistant to automation at the current state of technology? Differentiating between friendly, enemy, and non-combatants is complex, often requiring a dialogue between observers to verify. It cannot always be done with digital signature matching or just by relying on someone else to send accurate target coordinates. Mission critical information can change rapidly, be received by voice radio or unformatted text, and require manual processing before it is useful to mission-management automation. For the foreseeable future, humans will still need to perform low-level mission control in these circumstances. Additionally, mission effectiveness is not merely pass/fail; the better the pilot and the aircraft perform, the better the mission results will be--the more friendly and non-combatant lives are saved. Splitting the pilot's attention across multiple aircraft risks the lives of our ground forces or innocent civilians.

Such automation-resistant characteristics are indeed common in several combat mission types including tactical reconnaissance (Tac Recce), Close Air Support (CAS), Air Strike Control (ASC), and Combat Search and Rescue (CSAR). In these situations, the conventional approaches to MAC will not work. But with further evaluation of the mission tasks, a hybrid approach of single- and multi-aircraft control shows promise.

This paper will look further into the impact of mission requirements on the design of information management and automation systems. It will then define three categories of multi-aircraft control and propose a near-term approach to MAC for UAVs performing tactical missions.

2 THE MISSION DRIVES THE AUTOMATION

2.1 Mission Dependencies for MAC

Figure 1 diagrams in a little more detail the common MAC premise introduced above. For MAC to be effective, either the mission itself must be very simple or automation must reduce the mission complexity to a level such that a single pilot can control multiple missions. For the purposes of this paper, that automation is classified into three areas: System-Control Automation, Information-Management Automation, and Mission-Management Automation.

System-control automation is defined as automation used to control the aircraft, the ground control station, the communications system, sensors, weapons, and other associated parts of the unmanned aircraft system. It includes all the levels of autopilot from basic heading hold to following (but not planning) multi-leg three dimensional routes. For sensor control, it includes basic operations like slew and zoom through more complex operations such as locking onto a operator-designated contrast source (target) and tracking it. What

system-control automation doesn't do is make decisions such as where to fly or what target to track.

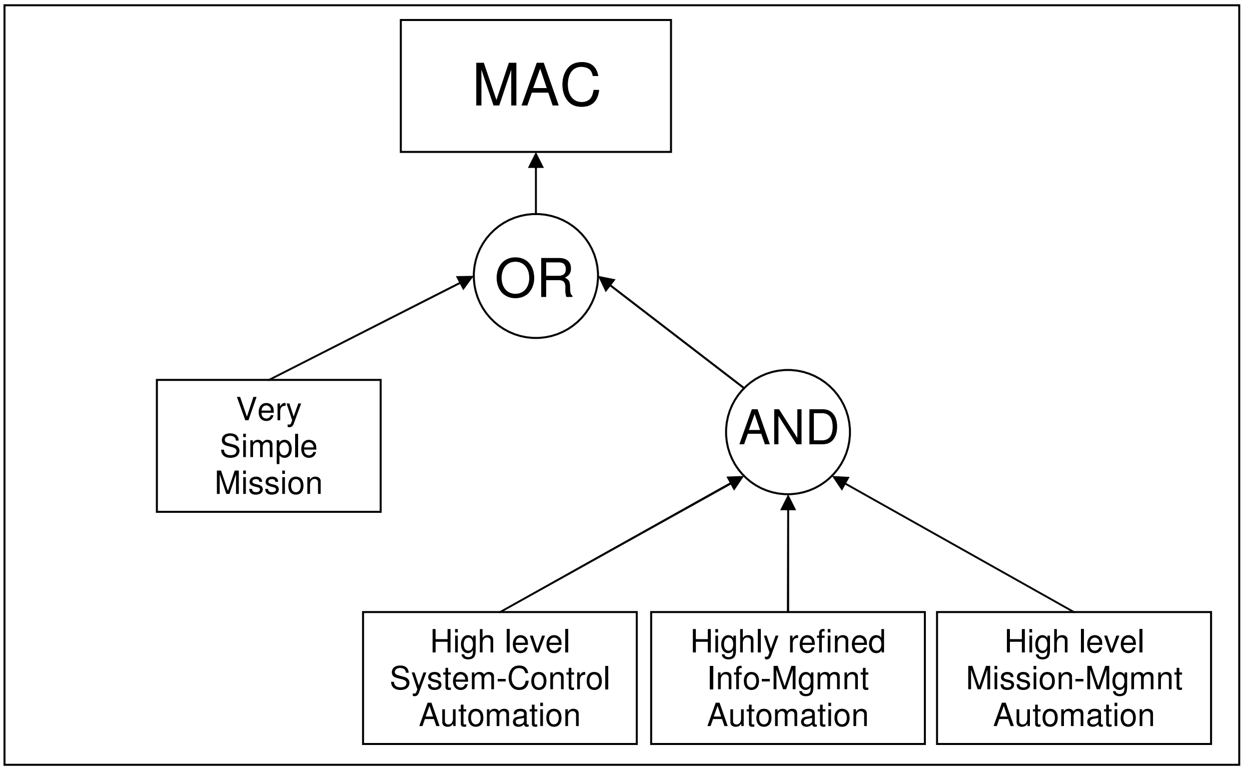

Figure 1: Mission Characteristic Dependencies for MAC

The information-management automation provides information to the crew on the aircraft systems and the tactical mission. It includes the data returned from the aircraft, stored reference data such as maps, and external mission information such as control directives, airspace restrictions, threat locations, etc. Well designed systems will present information in a clear and concise manner and include such elements as information filtering, fusion and prioritization, task-centered interfaces, and advanced situation assessment tools.

Mission-management automation is that which is capable of making decisions or providing options to the crew to aid in conduct of the mission. Examples include automatic calculation of new mission routes, automatic target recognition and cueing, and weapons cueing on automation-determined targets.

2.2 Selected Examples of Mission Types

Note: What follows are some examples of combat mission types. Each mission description includes a notional scenario intended to illustrate the mission's adaptability to multi-aircraft control In real world environments, missions can be much more complex and dynamic than described—a notion which itself bears on the ability to control multiple aircraft.

2.2.1 High Altitude Intelligence Surveillance and Reconnaissance

Suppose one or more UAVs are assigned to an Intelligence Surveillance and Reconnaissance (ISR) mission. The purpose is to take images of predefined targets, although occasionally ad hoc targets will be inserted during the mission. The aircraft flies above 60,000 feet where very few other aircraft can fly, few weather problems occur, and many mobile threat systems cannot reach.

Such a mission type is ideal for MAC. Most targets are pre-planned and identified by accurate coordinates. Ad hoc targets arrive at a low and normally manageable rate. The aircraft operates in a benign environment, at an altitude above most other aircraft and weather concerns. Given the well-defined nature of the environment with few variations, the essential mission tasks (routing, aiming camera, etc.) are highly amenable to automation.

2.2.2 Suppression of Enemy Air Defenses

Now consider the mission of suppression of enemy air defenses (SEAD). In this notional scenario, one or more aircraft proceed to a predefined search area and scan for the electromagnetic signatures of enemy air defense systems. When a signal is detected, it is compared to a library of signatures, classified, and geo-located. If multiple threat systems are found, they are prioritized by a predefined rule-set based on their capabilities and location. The threats are targeted with weapons or electromagnetic counter measures based on predefined tactics and rules of engagement.

These essential mission tasks are highly amenable to system-control and mission-management automation. The targets are not preplanned, but the search area is. The targets can be located and classified by automated on-board equipment or cued automatically by off board sensors. The mission objectives are clear and consistent.

But there are some complications with the SEAD mission as compared to High Altitude ISR. As a weapons-bearing tactical aircraft, the SEAD aircraft may fly in the same airspace as other unrelated tactical aircraft. Airspace coordination is not currently automated. It could be automated between cooperative aircraft, but for the foreseeable future, there will always be aircraft that don't participate. Weather is another issue. On-board sensors could keep the aircraft out of trouble, but may not provide a big enough picture of weather throughout the airspace. Automated off-board weather information is not yet available in sufficient fidelity to guide an aircraft in real-time. Diversions due to weather or pop-up threats may conflict with time critical tasking, necessitating real-time assessment of conflicting goals (aircraft safety versus target prosecution). An additional issue is collateral damage. An enemy threat system can be placed amongst innocent civilians, requiring detailed imagery inspection and judgment prior to strike clearance.

Technology can and should be pursued to address these issues, but SEAD missions will likely require significant human involvement for the foreseeable future.

2.2.3 Close Air Support

The final mission example is close air support (CAS). In this mission, the aircraft is directly supporting a ground unit engaged in combat. The ground commander prioritizes and assigns targets for the CAS aircraft to attack. This mission is very complicated for several reasons.

- The ground environment is very fluid. Friendly, enemy, and non-combatant locations change

constantly.

- The ground commander's objectives change rapidly in response to changes in the ground environment and enemy actions.
- Identification of friendly, enemy, and non-combatant entities is difficult and cannot be done solely with on-board sensors or use of target coordinates. A dialogue with the ground unit is often required.
- Coordination is still primarily by voice radio and is sometimes conducted with personnel of varying experience levels and knowledge of the situation at hand. Efforts are underway to pass some of the information by data link, but progress is slow and not expected to totally replace voice coordination.
- Airspace deconfliction is complex. Numerous aircraft can be involved in a small area. Aircraft must avoid overflight of friendlies during weapons deliveries and also deconfict from ground launched weapons and weapons delivered from other aircraft.

To be useful in CAS operations, mission-management automation will require digitization and integration of the ground and air battle at a very detailed level. It is more than just designing a good system for a particular aircraft—all of the aircraft, ground vehicles, personnel, weapons, tactical objectives, airspace, terrain and urban features; friendly, enemy, and non-combatants must be integrated in a digitized network. That is a highly desirable goal which would aid the mission immensely. But it is unreasonable to expect any such networked data system to contain all of the information and directives needed to conduct CAS in the foreseeable future [1]. For example, enemy forces will actively resist being detected, classified, and placed on an automated mission plan for disposal; they will discover and exploit weaknesses in our systems and develop technologies to counteract them; insurgents will appear as civilians. Essential mission inputs are not yet digitized and may never be. Even if they were, mission-management automation would be highly stressed to correctly analyze and interpret the tactical situation for all possible conditions and rules of engagement (ROE). Trained human aircrew are currently superior to automation in "filling in the gaps" of tactical situation awareness, rapidly assessing ambiguous situations within the ROE, and forming flexible solutions. Considerable human decision-making is still required in the conduct of close air support missions.

Another characteristic of CAS is that the results are proportional to the effort applied. There is no black line cleanly dividing success and failure. Even assuming our ground forces win the battle, success can be measured in the number of friendly lives lost, the number of innocent civilians killed, the loss of enemy combat capacity, and the impact on the enemy's will to continue fighting. Because there is no line demarking "good-enough", there is also no metric denoting the excess mental capacity of the pilot that can be dedicated to other missions in a MAC environment. Any diversion of mental capacity from one mission to another can reduce the quality of results.

3 MAC DESIGN CONCEPTS

3.1 Questions to Consider in Design of a MAC System

The mission examples above illuminate several operationally-inspired questions a designer should consider when developing a multi-aircraft control system. They are not necessarily questions of whether a given UAV *should* be enabled for MAC, but rather are intended to provide insight on *how* the MAC system should be designed. These questions are listed and described below.

1) Is the UAV's system-control automation capable of adequately conducting its essential mission tasks?
2) Can the aircraft take care of itself when things go wrong?
3) Are the mission objectives well defined and constant?
4) How are necessary mission inputs provided?
5) Can the mission-management automation adjust for environmental impacts or mission exceptions?
6) What is the duty cycle and mental load of the required human tasks?

Realize that designers may not have a blank sheet of paper and an unlimited budget. They may be required to design a MAC system for an existing UAV operating in the existing communications and command and control environments. It is virtually certain though that adapting a current UAV to MAC will require upgrades to the system-control automation and information-management automation, and will likely require the addition of some level of mission-management automation. Issues surrounding the design of effective human-automation systems then become critical, such as functional allocation of tasks between the operator and the system, human vigilance effects, clumsy automation, system flexibility, mode awareness, trust/acceptance issues, failure detection, automation biases, etc. [2, 3, 4].

3.1.1 Is the UAV's system-control automation capable of adequately conducting its essential mission tasks?

Essential mission tasks are, of course, driven by the mission. Common essential tasks include the ability to stay safely airborne and navigate along an assigned course. If the mission is ISR, can the UAV accurately point its camera at a target at a useful zoom level just based on coordinates or is a human required to fine tune the aim? Can it independently position itself to get the desired look angles and stand off ranges or must a human program those parameters?

Significantly, it is not only the *level* of automation that matters, but the *quality*. Where capability gaps exist, humans must fill in. In the experience of this author, even when the automation meets the stated performance requirements on essential mission tasks, pilot intervention is still common. As a consequence of simplifying system control, automation by its nature reduces the system response space. It uses default turn and climb rates, sets presumed optimal gain and contrast for imagery, establishes standardized holding patterns and so on. Global Hawk pilots, for instance, often choose to fly in a heading override mode. When a mission calls for higher performance, the human can and should exploit the unused response space of the automation. The mission requirements and quality of the system automation determine how often this happens.

3.1.2 Can the aircraft take care of itself when things go wrong?

This question addresses the need for contingency management. Things always go wrong. Aircraft systems fail. Control links are lost. Icing appears where it is not predicted. Other aircraft cross your programmed flight path. Is a human required to intervene when these exceptions occur? Can the aircraft begin the initial response while screaming for help from the pilot? More abstractly, how does the aircraft address contingencies and present resulting mission impact to the aircrew for assessment and higher level action?

3.1.3 Are the mission objectives well defined and constant?

Can you program the aircraft to image a set of targets for this mission and let it go? Or will the targets change in flight with new target coordinates and imagery requirements passed real-time throughout the mission? Can the target even be defined by coordinates or must the aircraft locate and track mobile personnel and vehicles? Will the aircraft fly an ISR mission or a CAS mission today—or can it be diverted from one to another? Aircraft designed for a single unvarying mission can have highly refined automation designed specifically for the predefined mission tasks. It is considerably more difficult to develop the same level of refinement for an aircraft which must be ready for a broad range of mission objectives.

3.1.4 How are the necessary mission inputs provided?

One of the biggest impacts to task loading for the Predator pilot is not controlling the aircraft, but coordinating, filtering, and transcribing essential mission information from off-board sources—none of which can be transferred directly to the UAV computer systems except by human transcription. Target identification, for example, is an essential mission input. A SEAD aircraft may be able to identify enemy threat systems with internal sensors or with a machine-to-machine interface to off-board sensors. A CAS aircraft on the other hand may view a group of personnel. The crew must identify that group by observing their behavior or by coordinating with on-site observers via radio or computer chat.

3.1.5 Can the mission-management automation adjust for environmental impacts or mission exceptions?

Environmental impacts and mission exceptions can be pop-up thunderstorms, the unexpected loss of airspace as the Army starts firing artillery, the jamming of global positioning signals, or the failure of a primary sensor. How flexible is the automation in handling these events? How reliable is it?

3.1.6 What is the duty cycle and mental load of the required human tasks?

Many examples of human intervention have been discussed. How often to they happen? When they do happen, how long must the pilot focus on the issue before he/she can turn to other tasks? Do they require a level of concentration that excludes monitoring other missions? Humans need to remain engaged, even with highly automated systems, in order to maintain situation awareness and prevent out-of-the-loop performance decrements [5, 6]. However, MAC may sometimes require simultaneous human engagement with two or more UAV systems and at other times require no active engagement for extended periods. Both of these situations are known to reduce the effectiveness of human-automation systems [5, 6].

3.2 Approaches to Controlling Multiple Aircraft

To help in designing MAC solutions to the mission requirements and considerations discussed above, the authors have defined three approaches to MAC: interleaving, sequential, and simultaneous. The approaches are primarily distinguished by the mental model the pilot must use in performing MAC. It is unlikely that any MAC design will use only a single approach. But by considering the mental models, developers can design the information and control systems to better meet the needs of the crew.

3.2.1 Interleaving Control

Interleaving control is characterized by the pilot repetitively switching back and forth between aircraft to provide detailed control of each mission. The pilot must process and remember the status of multiple

missions and their associated UAV systems. Suitable information systems must be provided to give the pilot rapid access to the breadth of data across all missions. Control systems must be designed so pilots can coax the UAV into the desired behavior as quickly and accurately as possible, allowing them to switch their attention to the next mission.

3.2.2 Sequential Control

Like interleaving control, sequential control also has the pilot switching between aircraft. But the pilot focuses on one mission at time, usually for a much longer period, and is not expected to retain knowledge of the other missions. This is needed for more complex missions where the pilot's full concentration is required. When the time comes to switch to a new mission, the pilot starts with a blank page and must have information systems suitable to rapidly indoctrinate to the new situation.

3.2.3 Simultaneous Control

With simultaneous control, the pilot supervises a collection of aircraft on interdependent missions. Mission changes for one aircraft can have ripple effects on other aircraft. For example a group of three UAVs on an ISR mission can be programmed for optimal coverage of a preplanned set of targets. When an ad hoc target is added, the pilot (hopefully with the help of automated planning software) reroutes one of the aircraft to the new target and re-optimizes the remaining target set between all the aircraft. The key difference with this type of control is that the pilot must consider the impact that any change to one aircraft will have on all of the others.

4 DESIGN VISION FOR TAC RECCE AND CAS

As an illustration, let's apply these concepts to a MAC design for the MQ-1 Predator aircraft in the tactical reconnaissance and close air support missions. Note that the Predator currently has a MAC system built as a technology demonstration system [7]. This paper builds on lessons from this system but returns to core principles for design of a new system. The paper will describe the mission as currently flown by the Predator, answer the design consideration questions presented above, and follow up with a design vision.

4.1 The Predator Mission

Although the Predator has flown multiple mission types including traditional ISR and interdiction, its most common missions are tactical reconnaissance and close air support. The Predator mission objectives are typically controlled in real time by the end user (Army command post, Marine forward air controller, etc.) who needs the information.

The Predator is launched and recovered by a flight crew in theater using a line-of-sight transmitter (Figure 2). The launch crew consists of a pilot and a sensor operator. After takeoff, the launch crew passes control to the mission crew which again has a pilot and sensor operator but adds a mission coordinator who interfaces with the tasking agencies. Predator control stations are not networked together so the handover process is an involved procedure of manually configuring ground control stations, coordinating between the two crews, and switching the data feeds. The mission crew receives their first target location, coordinates with air traffic control for safe passage, and performs inbound battle checks to ensure all the aircraft systems are properly configured and the weapons and sensors are functioning properly.

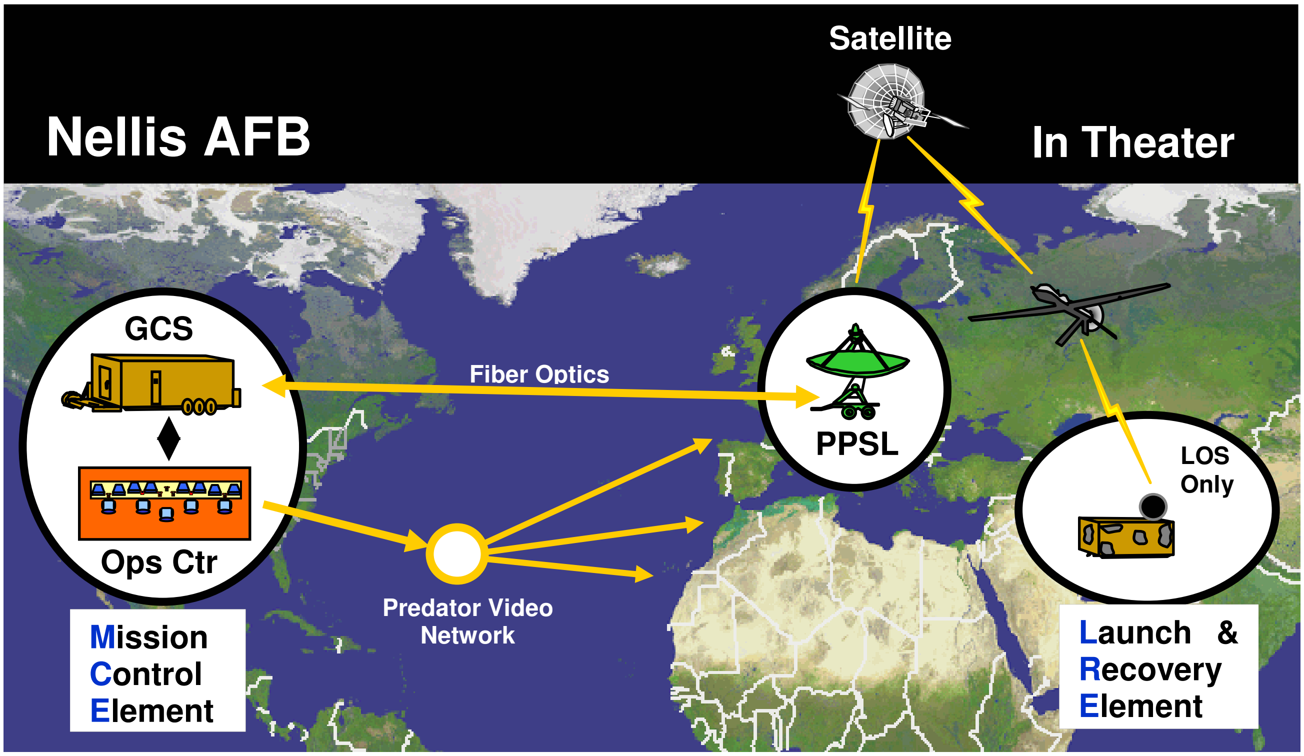

Figure 2: Predator Remote Operations

The mission crews coordinate with the launch crews, airspace controllers, command and control agencies, and the end users via several methods. Most common is a secure internet-relay chat system which ties together all of the agencies in different chat rooms. Two separate chat applications are run, one for secret and one for top-secret communications. Secure voice over IP (VOIP) and secure phone are available with certain agencies. And pilots can converse by voice with air traffic control, other aircraft, and ground parties using an on-board UHF/VHF radio.

In its Tac Recce mission, intelligence collection managers at forward-based army and marine units view the video as the mission is flown and provide low level direction to the Predator crews. This direction typically comes across chat, but crews can also use VOIP or secure phone with certain end users. A typical 20 hour mission can be dedicated to one user or split into blocks to serve multiple users. Switching users requires the crew to open new chat rooms, often switch computer screens as security levels change, and key off of new user callsigns. It also typically requires the aircraft to move to a new location, necessitating coordination with air traffic controllers.

The Tac Recce mission can, at times, be slow paced. Predator crews will sometimes spend several hours circling one building. Sometimes the end user will have the Predator crews move back and forth between several targets within a few kilometer radius, necessitating frequent manipulation of the cameras, but few large movements of the aircraft. At other times, Predator crews can be very busy following target vehicles through crowded urban areas, necessitating coordinated control of the aircraft and sensor.

The close air support mission is typically very busy, requiring full concentration and coordination of the whole crew. The Predator pilot will often feed the sensor video down to a combat controller. The combat

controller is embedded with the front line troops and carries a portable video receiver (Figure 3). The pilot and the combat controller typically coordinate by voice radio to sort out friendly locations from enemy and non-combatant. They coordinate weapons delivery plans and timing for the Predator crew to fire their AGM-114 Hellfire air-to-ground missiles. If more or larger weapons are required, the Predator pilot can coordinate with other strike aircraft to mark targets with one of two types of laser, data link target coordinates, or just perform a visual "talk-on".

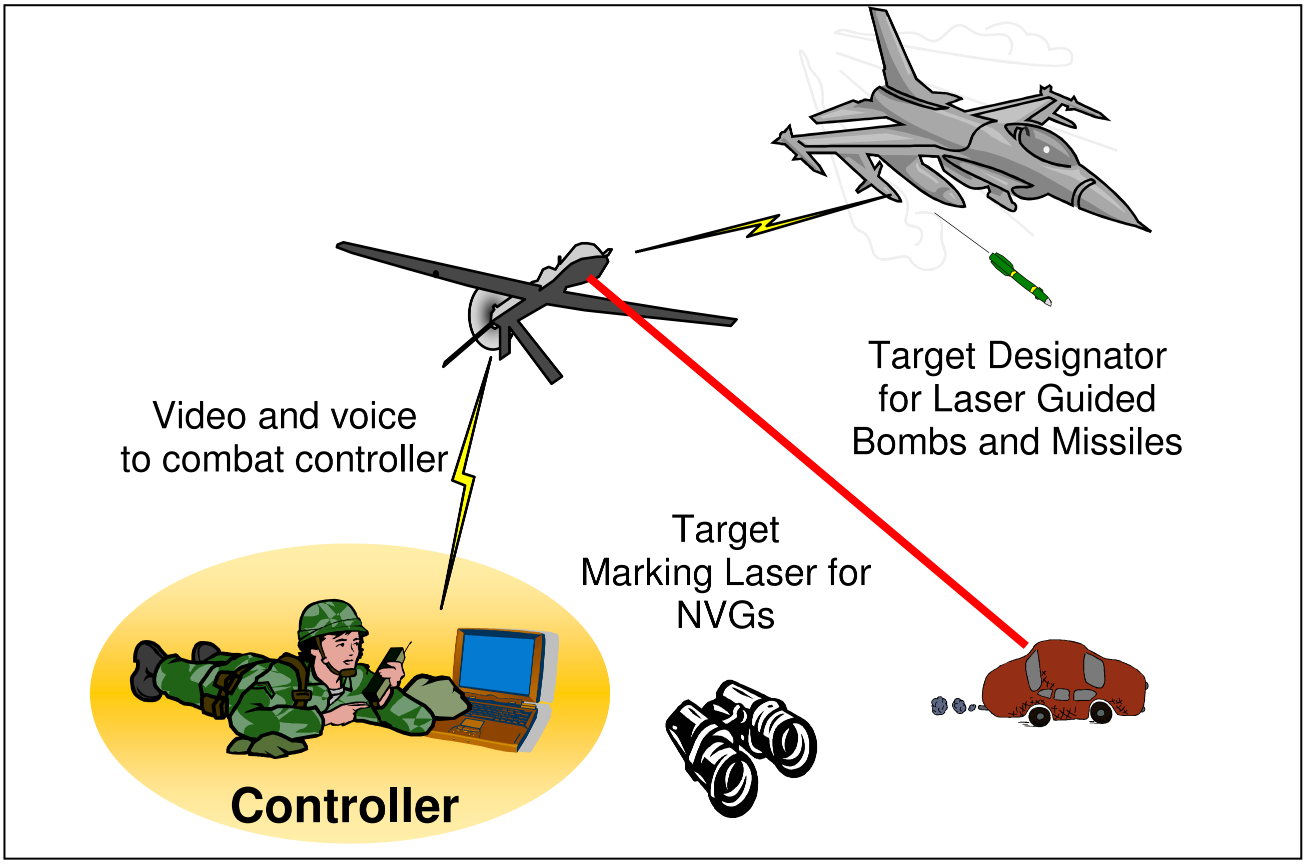

Figure 3: CAS Coordination

4.2 Evaluating the MAC Design Questions

4.2.1 Is the Predator system-control automation capable of adequately conducting its essential mission tasks?

The Predator system-control automation is currently very dependant on pilots and sensor operators to successfully accomplish essential mission tasks. For multiple reasons, the aircrew will not cue the sensor solely off of target coordinates. Sensor operators will fine tune the device as they zoom in to useful levels for reconnaissance. The positioning tools for the aircraft are sufficient for some targets but not for others. The preformatted holding patterns are not optimal for reconnaissance. Pilots can manually construct holding patterns, but must continually monitor the aircraft response to ensure it does what the pilot expects. Aircraft handovers to other control stations are complex and time consuming. Weapons employment is a manual

process. Many of these suboptimal tools can and should be improved to support MAC.

4.2.2 Can the Predator aircraft take care of itself when things go wrong?

The Predator has an automatic response mode for loss of command link which performs well in most respects. The initial set up is manually intensive as each turn point on the return route must be programmed. The pilot also must update entry points manually throughout the flight. The Predator can also carry an automatic anti-ice system which releases glycol across the wings when icing conditions are entered. Finally, the Predator has redundant GPS, airspeed, and attitude systems, but in some situations they must be switched manually. The Predator currently has no sense-and-avoid system for other aircraft nor any automatic responses for other common problems such as overheat of flight control servos.

4.2.3 Are the Predator mission objectives well defined and constant?

The mission objectives vary constantly through out the mission. The specific requirements must often be coaxed from end users as they have little training in how to direct a Predator mission.

4.2.4 How are necessary mission inputs provided?

There are no machine-to-machine inputs to the Predator system from outside sources. The control system is not attached to any external computer network. But there are several external planning and coordination tools.

Figure 4 illustrates some of the planning and coordination tools used by the Predator pilot. These are strap-on computer screens hooked up to external networks. The pilot and sensor operator must assess the mission information and manually enter any control inputs to the Predator system. On the left side of the illustration are four chat windows for air traffic control, mission coordination, CAS coordination, and launch and recovery coordination, although there are several other windows that could be selected. On the right side is the pilot's mission planning and mapping tool. It displays maps of various sizes, airspace coordination information, location of targets, data linked positions of other aircraft and a track of the crew's own aircraft. Along the bottom of the screen are buttons for other applications such as websites with relevant mission information, fuel and flight time logs, maintenance logs, and airspace deconfliction tools.

Note also that mission inputs come from three different levels of security (unclassified, secret, and top secret) as well as multiple special access programs. This creates a mix of different monitors and paper based products. The flight crew must mentally fuse the information from each of these systems.

Considerable effort will be needed to integrate all of these types of mission inputs across multiple security levels into a mission management system that would support effective MAC.

4.2.5 Can the Predator mission-management automation adjust for environmental impacts or mission exceptions?

The Predator currently has no mission-management automation as defined by this paper.

4.2.6 What is the duty cycle and mental load of the required human tasks?

The current design of the control interface artificially extends the duty cycle and mental load. The interface uses a mixture of function key controls and mouse control of drop down menus. The function keys control a

multi-level menu that must be memorized to use effectively. Accidentally moving one's finger one key to the left as they start a sequence of key strokes has caused more than one Predator accident. Consequently pilots must be slow and deliberate. Setting up and validating an autopilot flight plan can take several minutes.

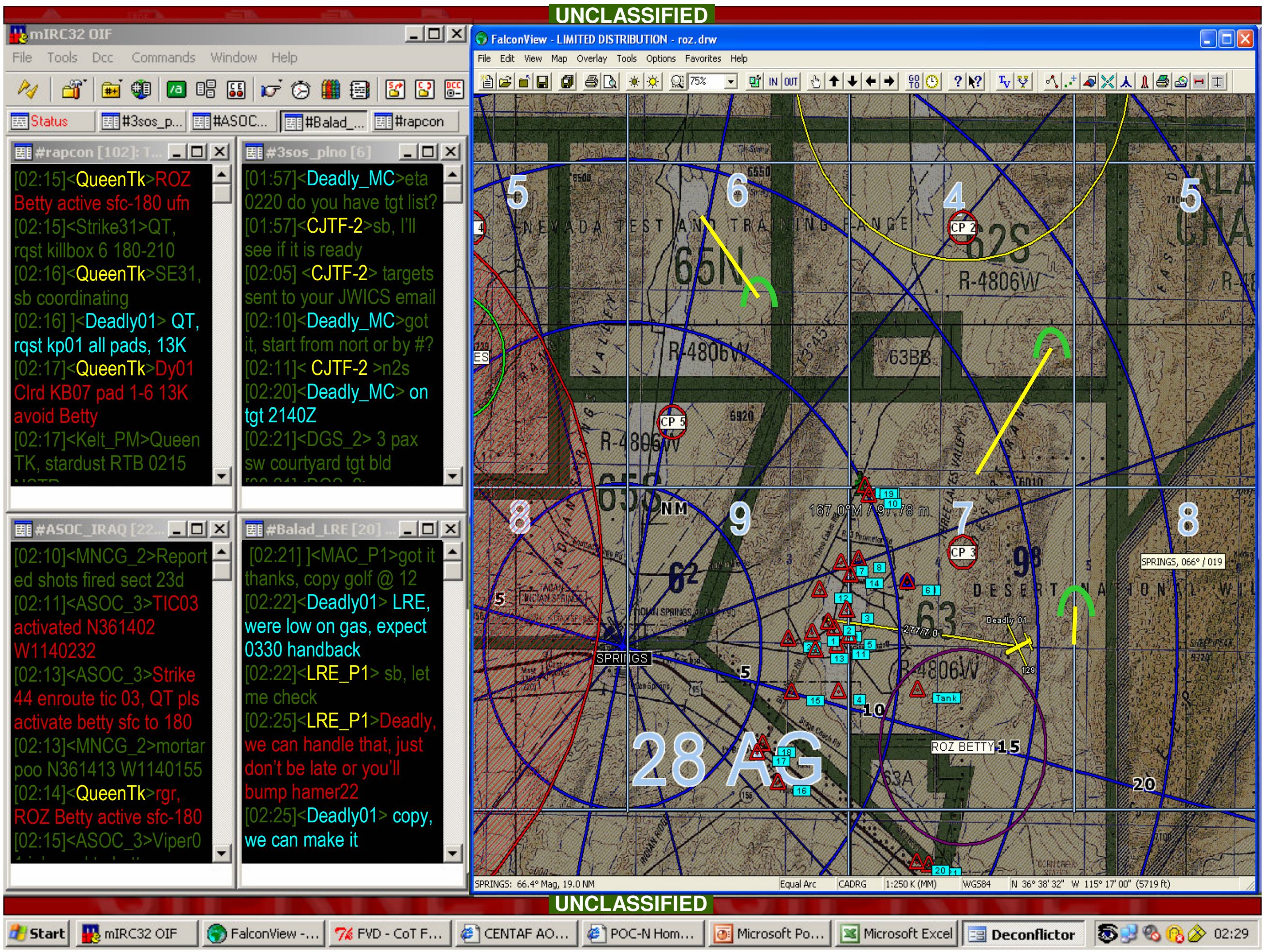

Figure 4: Predator Pilot Mission Management System

From a mission perspective, the Predator system needs some level of human involvement at almost all times. Both pilots and sensor operators can have low duty cycles during transit periods, but each is still required because the pilot cannot control the sensor to avoid weather and other aircraft. Once set up on long "stakeout" watches of a single target, the pilot role can reduce to a system safety monitor. The sensor operator's most difficult tasks are complete and the remaining tasks are often simple slew and zoom controls.

Handover procedures, initial setup on target, initial coordination to switch targets, CAS, aircraft emergencies, and weather avoidance are all high task-load events which take high levels of concentration by the crew. Formal measurements have not yet been taken for the percentage of time crews currently spend in high task load events. But subjective assessments have it varying across missions from 30% to 70%.

4.3 Conceptual MAC Design

This analysis points to three main recommendations to enable a high function, networked MAC capability for the Predator or any other UAV engaged in the Tac Recce and CAS missions:

- Improve system-control automation and develop mission-management automation to improve the quality of essential mission tasks and reduce crew attention and workload requirements.
- Improve mission integration by developing an information management system that fuses mission inputs and outbound communications in a single mission-optimized interface and integrate it with the ground control station for machine-to-machine data transfer to support mission-management automation.
- Develop a networked aircraft control system allowing multiple aircraft to be simultaneously controlled from a single MAC station and allowing rapid handover to dedicated crews in single-aircraft control stations or distributed control of low-level sensor functions to end users.

Under this concept, all Predator aircraft would be networked under the control of a central supervisor (**Error! Reference source not found.**). Using the simultaneous control concept introduced earlier, a central MAC station would track each of the aircraft and control them during low-dynamic phases of their mission. This station would likely have a map-based interface with no stick or throttle—high-level control only. As UAV missions become more highly dynamic (such as the onset of a CAS mission), this MAC supervisor would handover the UAV to a dedicated control station. These single-aircraft control stations would build an immersive flying environment for the crew to focus on accomplishing a single complex mission, under the sequential control concept. An improved information management system would allow crews to step into a new mission and rapidly come up to speed on the ground situation, mission goals, aircraft status, airspace, weather, and who to coordinate with.

There are many possible instantiations of this MAC configuration. One pilot may be able to manage several aircraft in low-dynamic parts of their missions. Some missions (such as Tac Recce and CAS) or parts of missions will require the dedicated attention of a highly trained pilot—not just for maneuvering of the aircraft but for the conduct of the tactical mission. This is referred to as the “one mind, one mission” concept. Some periods may not require the full attention of a pilot, but will require a lesser qualified but fully trained sensor operator. Some very simple missions may require skilled crews to first establish the aircraft and sensors, but then the simpler functions of sensor control (slew and zoom) can be remoted to minimally trained operators in the field. A single sortie can switch between these employment options several times before it is complete.

With many options such as these, a central supervisor is required to evaluate tasks across the multiple missions and dynamically assign the appropriate level of human attention. This supervisor must be able to track the location and status information for all the aircraft as well as receive the mission tasking information needed to determine how to allocate human resources. A MAC station situated in a UAV operations center could provide that level of information and control.

Single-aircraft control stations should provide an immersive environment where a pilot or a sensor operator could focus on a single mission without the distraction of monitoring other aircraft or missions. Even though it is optimized for a single mission, it still needs access to mission information for other aircraft to allow quick switching between missions as priorities shift or aircraft emergencies occur.

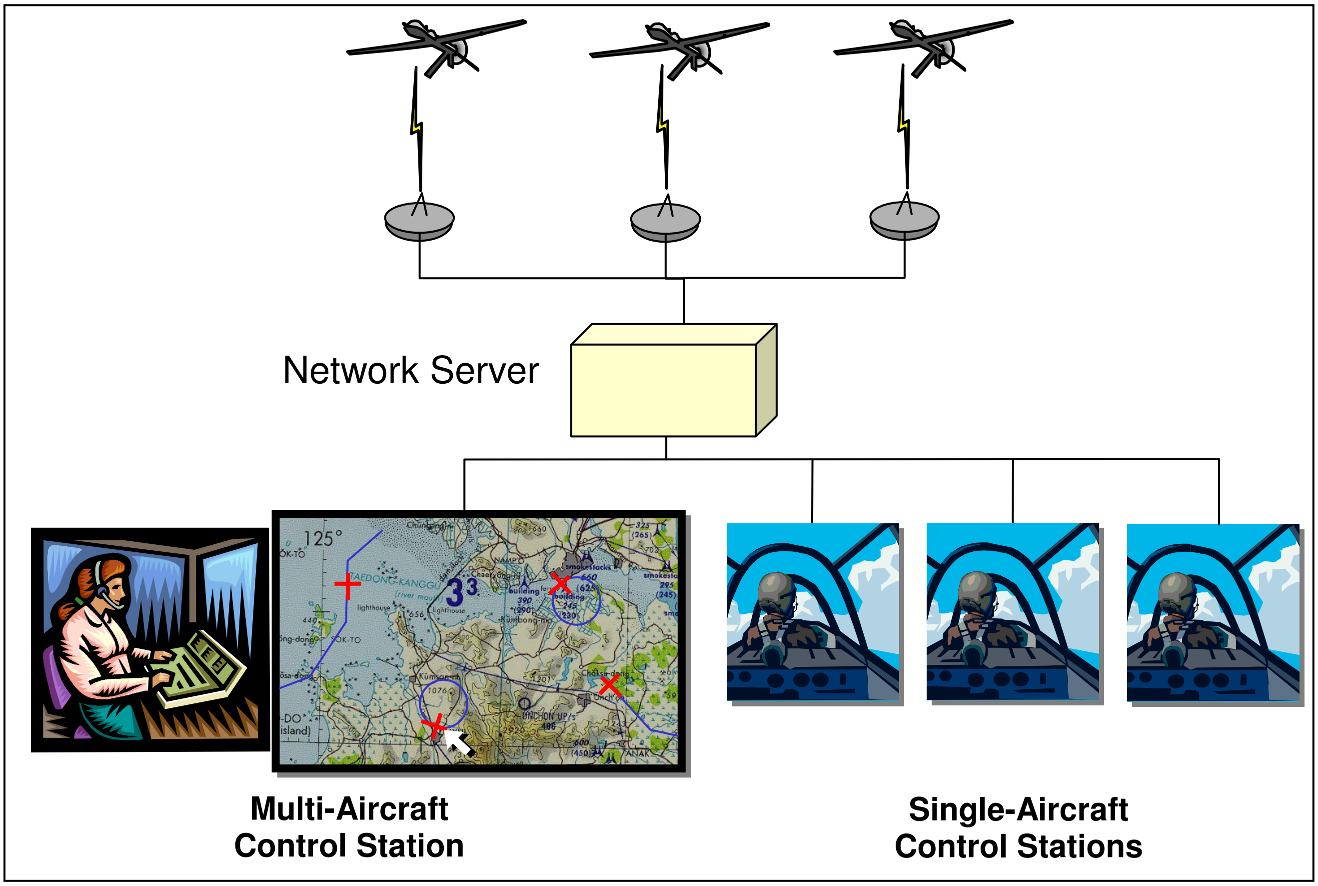

Figure 5: Networked Multi-Aircraft Control

For very-low dynamic periods, simplified control of the slew and zoom functions could be ported across a network or radio link to a forward-based intelligence manager or a combat controller in the field. But it is important that control is not over delegated from pilot to sensor operator to end user. Flying aircraft, employing weapons, and controlling sensors require specific training in both the systems and the tactical environment no matter how simple the control interface can be made.

4.4 Human Factors Challenges

The above described conceptual MAC design is a significant departure from the predominant conventional mindset regarding UAV MAC, which envisions a single operator (or crew) as always in charge of multiple UAVs simultaneously. The DARPA UCAV/JUCAS program was a prime example of the conventional vision, focusing heavily on the SEAD mission as well as highly automated UAV cooperative control [8, 9]. However, as stated earlier, the Tac Recce and CAS missions are completely different from SEAD; much more impromptu, ambiguous, and dynamic in nature. Additionally, the current level of autonomous technology development cannot support the tasks associated with CAS and Tac Recce missions. Therefore, the new conceptual MAC vision is much more human-centric in the key areas of dynamic function allocation, task prioritization, and tactical mission accomplishment. It is a human-centric approach to a very human-centric

problem. Described below are several human factors challenges associated with this new vision.

4.4.1 Central MAC Supervisor Station

This new vision requires a central MAC supervisor, who would be the nexus of the entire operation. The job of this supervisor is to act as mission monitor for all assigned UAVs, and to manage the allotment of individual missions to crews under his or her direction (dynamic functional allocation). Thus, this supervisor must be both highly qualified and experienced in many areas including tactical situation assessment, task prioritization, task allocation, crew resource management, contingency management, and distributed multi-talker communications.

As stated earlier, this supervisor will require constant global situation awareness of all managed aircraft within the theater of operations, likely achieved through an information-fused map display and other relevant net-centric feeds. Information must include those UAVs currently assigned to distributed operators along with pertinent information on each operator (pilot, sensor operator, or trained operator in the field). The supervisor must be able to rapidly gather additional information on any selected UAV to support various decision-making needs.

This MAC supervisor must immediately recognize when a UAV needs to 'go dynamic' in order to solve time critical mission needs (via specialized attention directing cues). This activity will require the MAC supervisor to have constant, reliable communication with all the potential users within the area of responsibility (either directly or through intermediaries). Additionally, the supervisor will need constant and reliable communication to the pilots and sensor operators under his/her direction, including those operators who are already assigned to missions and those that are available for new tasking. Obviously, communications will be a critical aspect of the MAC supervisor's job. Technologies will likely be needed to assist in this area, including spatialized audio for improving speech intelligibility in multi-talker systems [10, 11]. Knowledge of crew qualifications and/or experience will be required for optimal assignment of task to crew, possibly contained as part of a more comprehensive 'crew status' display or through a decision support aid. A predictive display estimating planned time until each tasked crew's return to availability may also prove beneficial for task allocation.

4.4.2 Single Aircraft Control Stations

Individual crews will likely receive fewer simultaneous competing tasks than that expected with the conventional (JUCAS) MAC vision of simultaneous control, due to the "one mind, one mission" sequential nature of assignment to dynamic, complex missions. However, task interruption and task switching costs will likely become critical. In some situations, individual crews may need to switch between UAVs frequently. This constant context switching has been shown to result in significant performance decrements if not accounted for [12, 13, 14, 15]. As a result of vehicle switching, operators might not have time to build an accurate awareness of the current tactical situation or they might commit errors due to a negative transfer of context from the previous mission to the current one. Specialized situation displays will be required to facilitate the rapid refocusing of the operator away from the previous situation and towards the new situation. Key contextual information will include both spatial and non-spatial elements. Critical information, tailored to the immediate task at hand, should be highlighted during transitions. Recent historical information regarding that mission/situation should be retrieved and presented to the operator in an intuitive manner to assist in the refocusing. Negative effects of task interruptions should be minimized through the use of mission-specific change detection tools that highlight recent changes in the key state variables of interest [12].

4.4.3 Improved Automation

Although this new MAC vision is more human-centric than the conventional (JUCAS) vision of MAC, it remains a highly automated concept and improved automation will be required over currently available levels to ensure success. Rather then following the "leftover" principle of attempting to automate everything and assigning to the human only those tasks that cannot be reliably automated, automation should be designed from the outset around the needs of the human operator as primary decision maker. Automation should support continual human engagement and maintained situation awareness. Automation must be flexible and allow visibility into what it is doing and why. These and additional general guidelines for the design of effective human-automation systems are readily available elsewhere [2, 4], however some specific, operationally-based recommendations regarding system-control and mission-management automation are identified below.

The first goal of improved system-level automation should be to perform the essential mission tasks to a level of quality such that the crew would prefer to use the automation rather than perform the tasks manually. Intuitive and flexible controls should allow the crew to very rapidly induce the desired behavior without making mistakes. Every second trimmed from controlling the systems is a second that can apply to accomplishing the mission. The automation should be designed from the bottom up. High-level mission automation loses much of its luster when the pilot has to fly the aircraft manually.

In addition to addressing the previously described issues, specific suggestions for system-control automation include the following. Procedures for setting up control stations and handing-over control between launch crews, the MAC station, and single-aircraft control stations should take under a minute—ideally no more that two or three button pushes or mouse clicks. This means the systems must be networked together and aircraft configuration information passed automatically.

The communications delay across the satellite link dictates the need for a more sophisticated autopilot system. At times, pilots will need to wring the last ounce of performance out of the aircraft. They need an analog control method (stick and throttle) combined with flight path prediction aids that let them maneuver the aircraft in a rapid, precise, and instinctive manner despite the control lag time.

The sensor suite needs to automatically recognize and cue certain crew-selected target types. Improved tracking of moving targets and lag-compensating prediction tools are needed. The sensor suite should include a laser spot tracker and automatically generate weapons-quality coordinates for CAS support. An auto scan mode should rapidly generate a wide area mosaic for situational awareness.

Mission-management automation should include auto-routing to plot flight paths around complex airspace while optimizing the order of targets. It should also set up optimal holding patterns based on target stand off and view angle criteria. During lost link situations, mission-management automation should follow preprogrammed routes home, but be flexible enough to avoid other air traffic and adverse weather and to adapt for low fuel states. In all cases, the control station should tell the pilot where the aircraft is and what it will do during lost link periods by predicting the aircraft logic, integrating radar returns from the theater, etc.

4.4.4 Improved Mission Integration

UAV operators live on data feeds. The information management tools described above are difficult to manage even in a single-ship environment. In a multi-aircraft environment, this information must be consolidated, filtered, and presented in a single interface that connects to the ground control station. The data must be fused from unclassified, secret, top-secret, and special access sources without compromising the source networks.

This must also be a two-way flow of information as the crew often needs to send information out to air traffic control, other aircraft, end users etc. without compromising security (Figure 6).

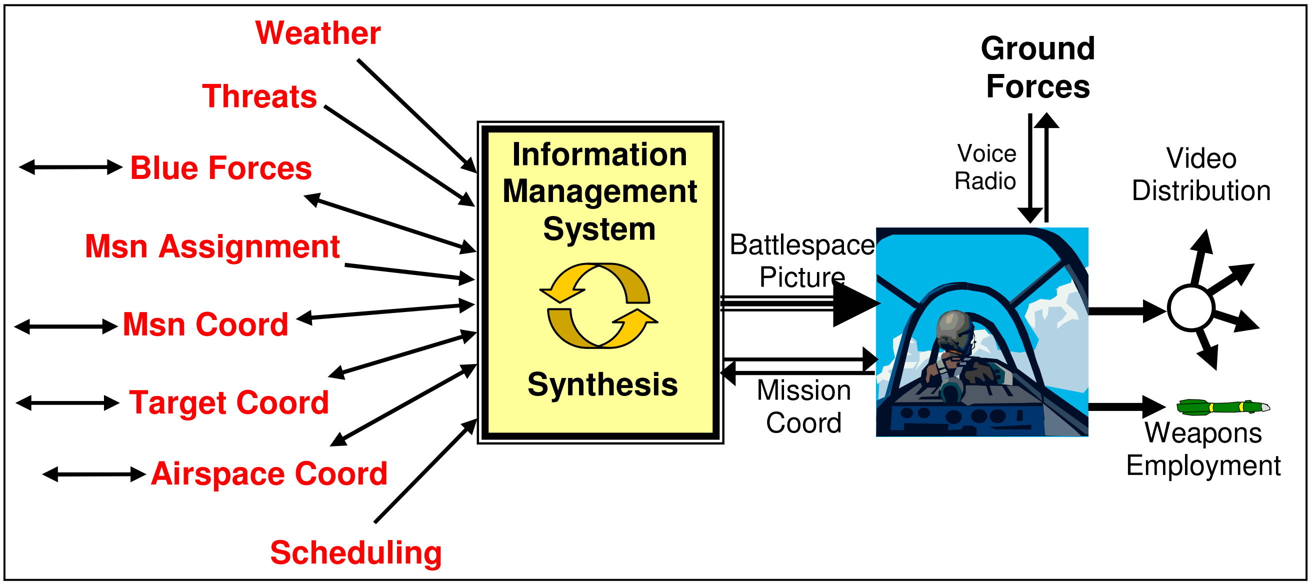

Figure 6: Mission Integration Concept

To the maximum extent possible, data should be sent machine-to-machine to avoid transcription efforts. Still, much of the information needs to be in a dialogue format. Voice communications seem to convey complex information more quickly and precisely than text entries in chat. (Chat entries are often short and abbreviated to save typing, thus providing less complete information than people would normally pass by voice.) On the other hand, chat provides a great historical documentation tool. When a pilot takes control of an aircraft, it is very convenient to scroll back in chat to review previous coordination. Conference VOIP is a good tool for voice communications. But a system that combines VOIP with automatic voice transcription and logging would aid both goals. In a multi-aircraft environment where each aircraft has multiple communications devices, it can be difficult for the crews to ensure they are always communicating on the right device for the right aircraft. A good human interface design is critical.

Finally, general human factors challenges apply. The desire for a useable, error-resistant design implies the need to follow a user-centered design process of iterative design, test, and refinement throughout system development [16]. Key issues of workflow, situation awareness, and workload must be addressed by the design. New ways must be found for filtering, prioritizing, fusing, and presenting the mass of information so crews can quickly locate the needed information for the task at hand. Work-centered interface designs and intelligent decision support systems may offer potential solutions in this area [17].

5 CONCLUSIONS

This paper attempts to rectify the desire for UAV MAC force multiplication within the limitations of current automation technology and the requirements of complex tactical missions such as Tac Recce and CAS. Operational experience suggests the need for a human-centric MAC vision due to complexities associated with tactical missions, time critical tasks, the lack of digitized mission inputs, target/friendly/non-combatant

identification, varying mission objectives, dynamic and ambiguous tactical situations, and communication with multiple customers of variable training, experience, and procedures. A highly net-centric multi-UAV control station design and associated concept of operations were detailed to maximize UAV effectiveness in these complex and dynamic mission areas. Key aspects of this vision are human dynamic function allocation and the premise "one mind, one mission" for complex tactical missions. Force multiplication, though reduced from the conventional MAC vision of constant simultaneous multi-UAV control, is still achieved through the assignment of multiple benign missions to a single pilot, and single benign missions either to trained sensor operators or remote operators in the field. Finally this paper identified several critical human factors research issues that will need to be resolved in order to fully achieve this multi-UAV vision for Tac Recce and CAS mission areas. These issues include improved system-control automation, human-automation interface design, task interruption and switching, digitization of mission inputs, information management (prioritization, filtering, and fusion), task-centered displays, decision aiding technologies, and distributed teaming. Different UAV systems and missions will have different requirements for MAC. The essential message of this paper is: let the mission, and required mission effectiveness, drive the specific MAC design.

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