Research Considerations for Managing Future Unmanned Systems

Ciara Sibley[1], Joseph Coyne[1] and Jeffrey Morrison[2]
[1]Naval Research Laboratory, 4555 Overlook Avenue SW, Washington, DC, first.last@nrl.navy.mil
[2]Office of Naval Research, 875 N Randolph St, Arlington, VA, jeffrey.g.morrison@navy.mil

Abstract

The next generation of unmanned systems (UxVs) will require a significantly different relationship with operators than what is implemented to date. Unmanned systems will perform an increasing number of missions in the future, with expanded capabilities. Furthermore, there is a major push to reduce the manning requirements for UxV missions from what is typical today. Operators of these next generation systems will become supervisory controllers of increasingly advanced automation. Research is required to better understand the information requirements for operators to effectively supervise these new systems. Metrics and concepts of employment are required to define what it means to safely and efficiently conduct missions in this future supervisory control context. We contend that establishing context dependent, operator state and mission performance metrics will be critical for assessing different control paradigms and user interfaces. Additionally, realistic synthetic environments are necessary to adequately assess the performance impacts of the various mission contexts an operator will encounter. This paper suggests research foci that would be useful in defining the roles and information requirements for human operators of these next generation unmanned systems.

Introduction

The last fifteen years has seen a proliferation in the use of unmanned systems within the Department of Defense (DoD). Unmanned systems experienced an over 40-fold increase in the DoD inventory between 2002 and 2010, by which time they accounted for 41% of all DoD aircraft (Gertler, 2012). This rapid growth has been paralleled by advances in the automation in these systems. As automation and reliability continues to increase, the role of the operator interacting with the systems has been transitioning from one of manual control of specific subsystems (e.g., payload or avionics) to supervisory control of multiple UxV platform systems. This change is already happening in many of today's unmanned systems where stick and rudder piloting is being replaced by mission management via maps and the plotting of waypoints for the autopilot system.

Despite this paradigm shift towards supervisory control of unmanned systems, most current Unmanned Aerial Vehicle (UAV) operations require three human operators to supervise one UAV, where each operator maintains one of three distinct roles: Mission Commander (MC), Air Vehicle Operator (AVO), and Payload Operator (PO). In a typical team set up, the MC is primarily responsible for mission management, requesting access to controlled airspace, communicating with external customers and interested parties (effectively consumers of the services provided by the UAV), as well as disseminating information to the AVO and PO. The AVO is principally responsible for navigating and monitoring the vehicle's health and status, and ensuring the vehicle travels from waypoint to waypoint. The PO manages the system's sensors and relays relevant information to the MC and/or customer. The DoD recognizes that the current UAV manning requirements and team structure is sub-optimal as it is resource intensive and does not scale, particularly when compared to manned military aircraft such as the F/A-18-E Super Hornet which has a crew compliment of one and can accomplish a wider range of missions.

The tasking demands for current UAV operators are highly variable and often unbalanced across the different team members. This is partly attributable to increased automation causing significant down-time for some of the roles (MC, AVO, PO) during certain mission phases (i.e. take-off, enroute, over target, landing). For example, missions requiring a UAV to loiter over an area of interest for an extended period of time may require no interaction from the AVO (since loitering can be performed automatically), whereas the PO is likely continuously moving the camera sensor from one object to another. There are also many situations in which the entire crew is engaged or underutilized. For example, a wide area surveillance and mapping mission tasked to provide updated high resolution imagery of an area of interest requires little to no human input once the system is airborne. However, a mission providing direct support to troops in contact or requiring weapons release requires substantial human input and attention. All of these missions currently call for the same amount of manpower, despite the team in the former mission scenario being highly under-utilized. Concerns about how to address emergency situations are one of the primary drivers for requiring the same manning requirements across all missions with the same vehicle.

This inefficiency and inflexibility has influenced the DoD's desire to invert the ratio of operators to UAVs (DoD, 2009). Specifically, the 2011 Navy S&T plan calls for "the development of a distributed system of heterogeneous unmanned systems relying on network-centric, decentralized control that is flexible in its level of autonomy, with the ability to get the right level of information to the right echelon at the right time" (ONR, 2011, p. 15). Decentralized flexible control means that an operator will no longer be assigned to control a subsystem of one specific platform for a single mission, but rather that groups of operators will perform a common set of tasks for multiple platforms at different points on the platform missions. The result will be shared control of a larger number of unmanned systems that is dynamically assigned based on theater mission requirements vice simply vehicle requirements. To increase flexibility and manning efficiency, the operators will not be statically assigned to a specific task or vehicle, but will instead be able to directly or indirectly interact with a vehicle and task which will best accomplish overall mission objectives.

Such a decentralized, flexible system of control represents a significant change in how individuals must interact with autonomous systems, and what information they would require to support mission requirements. A new suite of capabilities will be necessary to allow the transition to supervisory control; these include better decision support, alerting, and monitoring tools. In order to adequately assess the potential benefits and costs of these new technologies, though a comprehensive set of metrics needs to be identified. This set of metrics is especially important since novel capabilities are likely be introduced over time. The DoD established the UAS Control Segment (UCS) working group to develop an architecture for the control systems of future UAVs that utilizes the principles of service oriented architecture (SOA). The SOA approach will enable future control platforms such as the common control station (CCS), to incorporate a modular design allowing for components (i.e. services) to be easily replaced. This future design model for control stations is very different from today's UAV control stations. To expound, the DoD originally procured unmanned systems as a combination of ground control stations and unmanned vehicles. This process has led to stove piped systems that are incompatible with each other, significantly increasing training and procurement costs as well as limiting innovation (Chanda et al., 2010).

In addition to considerations about future UAV control, the DoD and its NATO allies are moving towards both standardizing the unmanned systems' user interface (i.e. common control layout) and increasing interoperability (i.e. ability for a ground station to communicate with multiple platforms). This goal and the communication protocols required are outlined in NATO's Standardization Agreement (STANAG) 4586 (NATO, 2012). STANAG 4586 also discusses the need for interface standardization, however no details on how that interface would look were provided. The DoD (OSD, 2012) released a style guide to provide system designers recommendations for how to display information within a UAV control station. However, this information does not get at the bigger question about what information needs to be displayed, particularly as automation increases and direct interaction decreases. For example while an attitude indicator provides useful information to a pilot directly controlling a platform it is unclear what value, if any, it provides when flying by waypoints. Addressing design and implementation questions such as these requires test and evaluation with UAV operators and the capability to systematically compare performance costs and benefits. This ability to assess is surprisingly challenging.

Operator and Mission Performance Metrics

Each year the DoD funds new ideas for tools which purport to improve warfighter performance in one capacity or another. Despite these large investments, questions remain as to the utility to the warfighter (i.e. how does the tool impact mission success and warfighter performance? Is the impact generalizable to all mission types?). Identifying suitable performance metrics within UAV operations is dependent upon the mission context, which includes a very broad range of factors including phase of flight, mission requirements, operating area (e.g. contested vs uncontested), mission intent, type/number of assets, mission priorities, environmental constraints, time restrictions, etc. Without the use of carefully documented and defined metrics for assessing user and mission performance and a common nomenclature for documenting the specific mission context, it isn't possible to accurately compare across different UAV team control structures or system interfaces.

The ability to assess the costs and benefits of any new automated system, display component, or team structure requires a comprehensive set of metrics. In the operational environment, performance is often considered primarily in terms of mission success, however the operator's interaction with the system is a large influencer in how successful a mission will be. A 2012 U.S. Unmanned Aerial System Report to Congress stated human causal factors were present in approximately 68% of UAV mishaps (Gertler, 2012; Williams, 2004). Many of these incidents were attributable to factors such as extremes in workload leading to channelized attention and/or lapses in Situation Awareness (SA), and generally poor operator interface design causing automation state confusion and alarm fatigue (Chen, Barnes, & Harper-Sciarini, 2011; Giese & Chahl, 2013; Parasuraman & Manzey, 2010; Parasuraman, Sheridan, & Wickens, 2008). Limiting metrics to traditional performance-based measures of accuracy and response time will provide only a partial assessment when evaluating human performance issues within new technologies.

Furthermore, there are many extended periods of time during UAV operations where traditional operator performance metrics (i.e. reaction time and accuracy) cannot be obtained, such as when a vehicle is enroute to an objective or loitering over an objective for an extended period of time. During this time the pilot's tasking is to monitor/scan the system's sensors and maintain high levels of SA. He/she has no direct interaction with the system and therefore no performance measures that can be assessed. This is concerning since problems with degraded SA are increasingly likely (given the future unmanned vehicle control paradigm of increased automation) and studies have shown decreases in SA can increase time for an operator to re-engage with a system (Endsley & Kaber, 1999).

One solution for gathering a more complete picture of operator performance is to augment traditional metrics of mission performance with measures of operator state, which can widely vary throughout the mission. The ability to assess an operator's state throughout a mission will provide valuable data for predicting mission success, particularly in situations where the operator's interaction with the system is limited but those few interactions could be critical (e.g. if an operator is fatigued and hasn't been scanning display panels for the last 9 minutes, as a piece of chat information has been waiting unnoticed in a string of correspondence that reveals a high priority target nearby).

Remote, off the head eye trackers are becoming less expensive and could be a viable option for assessing an operator's attention allocation, fatigue, and cognitive workload. Ratwani, McCurry and Trafton (2010) demonstrated that eye gaze data could be used to ascertain where a user is allocating attention during a supervisory control task. They used this information to predict when an operator was losing SA and consequently made an error. Furthermore, they discussed how this information could be used in real-time to alert an operator and prevent errors.

Measures of fatigue such as percent eyelid closure (PERCLOS), frequency and duration of blinks are reliable indicators of fatigue (Caffier, Erdmann, & Ullsperger, 2003) and as such are currently being used to monitor and ensure safe use of construction equipment (Solon, 2013). These kinds of systems will soon become commonplace in civilian automobiles, as car manufactures are installing low-cost systems in new vehicles (Gallen, 2014). Fatigue is likely to become an increasing problem within UAV operations as automation increases and the operator's role shifts to monitoring systems for extended periods of time.

Cognitive workload is another operator state measure which can be assessed using eye-tracking and is a valuable predictor of mission performance (Tsai, Viirre, Strychacz, Chase, & Jung, 2007; Marshall, 2007). An extensive amount of research since the late 1960's has shown that pupil diameter increases as cognitive workload (or mental effort) increases (Beatty, 2000). Sibley, Coyne and Baldwin (2010) used pupillometry to assess mental effort within a simulated UAV task during training. The researchers found that pupil diameter decreased as performance increased, suggesting that as skills are honed an individual doesn't have to expend as much mental effort to perform a task well.

Heart rate sensors are also a low-cost viable option for assessing user state, since heart rate can be collected non-invasively and remotely; even smartphone cameras can be used to detect blood volume changes during a cardiac cycle, from which heart rate variability (HRV) can be further calculated (Altini, 2014). HRV has been extensively researched and shown to correlate with measures of mental stress, which consequently impacts task performance (Hjortskov et al., 2004).

Even less invasive, simply collecting operator input into the system can provide meaningful information for assessing operator state. Cummings and Nehme, (2009) demonstrated that key stroke analysis could be used to create a metric of operator utilization within a supervisory control task. The researchers defined utilization as the percentage of time the operator was "busy" interacting with the system and performing tasks; they did not consider monitoring or scanning (i.e. updating SA) as time when the operator was busy, since this requires no interaction with the system. Using this metric, they identified that performance was best when operators were at a middle range of utilization with performance dropping at both ends of the scale, consistent with well-documented findings on the effect of arousal (i.e. mental stress, cognitive workload, mental effort) and performance (Kahneman, 1973).

The list of potential metrics of operator state described here are not meant to be comprehensive and additional research is needed to understand how they relate to UAV mission performance across different mission contexts.

Supervisory Control Testing Environments

Two of the current challenges within supervisory control research for unmanned vehicles are that these systems do not yet exist within the DoD, and the future Concept of Operations (CONOPS) is not well defined. The research community has developed several simulated test beds such as the Human and Automation Laboratory's RESCHU testbed (Nehme, 2009) and the Air Force Research Lab's Adaptive Levels of Automation (ALOA) testbed (Johnson, Leen & Goldbegr, 2007) to simulate some of the different types of tasks an operator might have to conduct. These tools have provided some valuable initial information on some of the potential benefits and challenges associated with different types and levels of automation within supervisory control (e.g., Calhoun, Draper & Ruff, 2009).

One of the limitations of these testbeds, however is that the tasking was developed to be quickly learned and tested on untrained populations. As such, the complexity is lacking in some of the tasking and is not especially representative of the tasks a current or future operator would be performing (i.e. decision making under uncertain contexts). Additionally, most supervisory control research has focused on scenarios with sustained high levels of workload where participants complete 6-7 tasks per minute (e.g., Kidwell, Calhoun, Ruff & Parasuraman, 2012). This consistent level of tasking provides a near continuous measurement of performance, which while ideal for research, does not reflect the real environment. This task level only represents a narrow range of UAV mission contexts. There are many contexts in which a UAV operator will have limited interaction and must sustain their attention and SA for extended periods of time.

Assessing levels of automation and display formats within a single mission context limits the generalizability of the supervisory control research results to future operations. In order to apply our scientific knowledge of supervisory control towards future systems, it is essential to assess tools and concepts within realistic, synthetic environments which can model the broad range of scenarios and contexts which an operator would actually encounter (e.g. denied/degraded communications, sustained monitoring, target-asset allocation under uncertain conditions).

The Naval Research Laboratory (NRL) developed the Supervisory Control Operations User Testbed (SCOUT) to begin to address some of these research needs. SCOUT represents the tasks that a future operator would engage in while controlling multiple UAVs (e.g., prioritizing targets, communicating with customers and dealing with airspace restrictions). SCOUT also gathers and synchronizes all task/mission performance data with detailed information on the user's behavior (i.e., eye gaze data, interactions with the system) and the user's physiological state (e.g. pupil size, heart rate and respiration rate).

In addition to traditional mission performance metrics, SCOUT includes two methods of assessing SA. These include an SA probe in which the simulation is paused and the screen disappears, leaving operators with a new screen which assesses knowledge of where assets and objective are, as well as where they are going (similar to Endsley's (1988) SAGAT methodology). Additionally, SA is assessed in SCOUT via chat messages which request information on the current state as well as probe the operator's ability to predict future states (similar to Durso & Dattel's (2004) SPAM methodology).

While SCOUT can be configured to require frequent interactions it is designed to represent a broad range of mission contexts, including those which have long transit time and sustained operations over an area which require little interaction with the system.

The second challenge within supervisory control research is that there is no common concept of operations (CONOPS) for future UAV supervisory control operations. That is, it is unclear what the role of future operators will be. There are many basic questions such as how many vehicles might an operator manage, will there still be specialized roles (e.g. payload), will operators be assigned to a vehicle (reflecting current operations) or will they be assigned to a mission. In fact, it may be that the specific mission context defines what the role of the operator or operators are.

Identifying what the best CONOPS is for a particular set of missions requires both a set of assessment metrics and a simulation environment capable of representing a range of different missions. Furthermore, the implications of poor environmental conditions and emergency situations need to be considered, such as operating in bad weather, dealing with an engine failure or attempting to operate in regions with low bandwidth. Clearly research is needed within this area before implementing any new UAV control paradigm, to ensure both high performance, efficiency and safety during unmanned missions.

The NRL is currently extending SCOUT to allow multiple operators to share control of and operate systems within a networked environment. The limited research on team performance in supervisory control shows that teams with more flexible operator roles are better able to handle unplanned events which are typical during real missions (Mekdeci & Cummings, 2009; Donmez, Nehme, & Cummings, 2010). This study also revealed however that increased flexibility in tasking results in an increased amount of time spent coordinating tasking and activities within the team.

In order to eliminate the need for coordinating tasking among team members, this flexible future model necessitates automated task monitoring and scheduling tools. Tools will also be necessary to monitor and predict operator and asset utilization and dynamically distribute tasks across assets and team members to maximize mission performance, safety, and efficiency. The DoD already recognize the need for better planning tools (DoD, 2009, p. 16) in future missions, but it is critical that these tools are developed, assessed and validated within a broad range of mission contexts and team structures.

Supervisory Control Display Design

As platforms become more interoperable, different users and operators will have access to different levels of direct and indirect interaction with an unmanned system. While the five levels of interoperability defined in STANAG 4586 were meant to outline communication requirements between a control station and an unmanned vehicle they are also important in defining information needs for different types of users. For example, in support of a user's mission he/she could subscribe to information (i.e. sensor) feeds (level 1-2); directly control specific payloads (level 3); or redirect an asset's path (level 4-5).

Highly interoperable systems and a flexible control paradigm will lead to potentially high levels of task switching and impair a user's SA and subsequent decision making. The increased platform and sensor hand-offs envisioned in a distributed control environment enhances mission flexibility, however the information requirements to successfully enable transfers between operators needs to be understood. As such, research is needed to identify the information requirements for maintaining high levels of performance, assuming an operator may only be responsible for an asset for a limited timeframe. Demonstrating and assessing the costs and benefits of this type of flexible control model is a critical next step towards the DoD's goals.

Some of the new challenges and tasks supervisory control may introduce over control of a single asset are associated with planning. Either the operator or the automation will have to determine how to allocate the different assets to complete the different objectives associated with a mission. New display concepts need to be designed to meet new challenges such as how to represent multiple plans associated with each vehicle, as well as differentiate between old and new plans, and automation-developed versus user-developed plans. Additionally understanding how to represent the different assets over time is another new potential information need within supervisory control.

Summary

As DoD and its NATO allies move towards unmanned systems which are both increasingly interoperable and autonomous there will be a shift in the current UAV control paradigm. Having a validated set mission performance and operator performance metrics is critical to the DoD fully capitalizing on these new unmanned system capabilities. A failure to understand how a new piece of automation impacts the user and mission under all contexts can lead to problems similar to those in today's systems where operators have excessive periods of down-time or are unable to respond to a critical events due to excessive workload or poor SA.

Since human performance suffers at both low and high levels of workload, assessment of future systems must take place across the range of task loads a future operator may encounter. It is not sufficient to assess mission performance under high levels of workload alone. In fact, displays and levels of automation which improve performance in a high workload context might cause more errors and/or degrade operator SA in a scenario with a low levels of tasking. Furthermore, it is still unclear how different control paradigms (e.g. any operator can perform any task on any vehicle vs. an operator maintaining control of all of one vehicle vs. an operator conducting all communication tasks on all Predator UAVs) will impact mission success under different scenarios and contexts. These kinds of research questions needs to be addressed before new operator control paradigms or interfaces are employed, rather than simply learning through mistakes.

Experimentation within synthetic environments can help understand the implications of different control paradigms and the utility of various decision support, monitoring and alerting tools. To fully understand the efficacy and impact of new systems though a broad range of mission contexts must be incorporated and well documented in all evaluations. Furthermore, the research community should converge on a common nomenclature and taxonomy for decomposing and documenting mission context and performance, both of the operator and mission, so that results across different experiments can be compared and assessed.

As the DoD continues to increase automation and move towards supervisory control of unmanned systems, the research community must continue to assess the impact of these new capabilities. Evaluating mission performance and operator state (e.g., attention, fatigue, workload, and SA) across a range of potential mission is critical to the success of these future systems. Without carefully designed assessments and meticulous documentation the DoD will likely repeat many of the problems associated with current vehicle control.

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