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MANAGEMENT OF MULTIPLE DYNAMIC HUMAN SUPERVISORY CONTROL TASKS

STUDENT PAPER

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ABSTRACT

In network centric operations like those envisioned for future military engagements, operators will be expected to manage multiple tasks at once. However, increases in the number of available information sources, volume of information and operational tempo, all which place higher cognitive demands on operators, could become constraints limiting the success of network centric processes. In time-pressured scenarios, efficiently allocating attention between a set of dynamic tasks is crucial for mission success. Inefficient attention allocation leads to system wait times, which could eventually lead to critical events such as missed times on targets and degraded overall mission success. One potential solution to mitigating wait times is the introduction of automated decision support in order to relieve operator workload. However, it is not obvious what automated decision support is appropriate as higher levels of automation may result in a situation awareness decrement and automation bias. This paper will discuss the cognitive advantages and disadvantages of providing increasing levels of automation and how they relate to different sources of wait times. Specifically, these sources of vehicle wait times include interaction time, queues for multiple tasks, and loss of situation awareness.

1 – INTRODUCTION

The concept of network-centric operations, in which multiple human and computer-based agents are linked in order to leverage information superiority, is popular in the military command and control arena, but also can be found in other human supervisory control domains such as air traffic control and first-response team management. Human supervisory control (HSC) occurs when a human operator monitors a complex system and intermittently executes some level of control on the system though some automated agent. In future network-centric operations, it is likely that operators will manage multiple supervisory tasks at once, as HSC tasks are primarily cognitive in nature and generally do not require constant attention and/or control. For example, a single air traffic controller can handle multiple aircraft because the onboard pilots handle the flying task, while the controller is primarily concerned with navigation and deconfliction tasks that do not require constant attention. Similarly, while many operators are presently needed to control a single unmanned aerial vehicle (UAV), as technology and autonomous control improve, automation will handle the task of flying, thus enabling an individual controller to control a greater number of UAVs.

However, the primary advantage of network-centric operations, that of rapid access to information across the network, will likely be a major bottleneck and point of failure for those humans who must synthesize voluminous data from the network and execute decisions in real-time, often with high-risk consequences under significant uncertainty. Network-centric operations will bring increases in the number of available information sources, volume of information and operational tempo, all which place higher cognitive demands on operators. In time-pressured scenarios like those expected in command and control, efficiently allocating attention between a set of dynamic tasks becomes critical to both human and system performance. Inefficient attention allocation leads to system wait times, which could eventually lead to such events as missed times on targets and degraded overall mission success. One potential solution to mitigating wait times is the introduction of automated decision support in order to relieve operator workload. However, it is not obvious what automated decision support is appropriate as higher levels of automation may result in a situation awareness decrement and automation bias. In the future vision of allowing a single operator to control multiple unmanned vehicles (which could be on land, in the air, or under water), it is not well understood how operators will manage multiple vehicles, what kind of decision support will aid or hinder the operator, and how human cognitive limitations will impact overall system effectiveness. To this end, this paper will discuss recent efforts to address appropriate levels of automation for management of multiple autonomous vehicles, as well as how wait times that result from human-computer interaction will be affected by these different levels of automation (LOA).

2 – BACKGROUND

APPROPRIATE LEVELS OF AUTOMATION

In human supervisory control systems like those found in command and control domains, various levels of automation can be introduced into decision support systems. Automation allocation can range from fully automatic systems where the operator is completely left out of the decision process to minimal levels where the automation offers basic data filtering or recommendations for the human to consider. Table 1, originally proposed by Sheridan and Verplank (1978), outlines a scale used to commonly characterize the allocation of function between man and machine. Human interaction with automation represents a range of intermediate levels from 2-6 on this scale.

Table 1: Levels of Automation

Automation Level	Automation Description
1	The computer offers no assistance: human must take all decision and actions.
2	The computer offers a complete set of decision/action alternatives, or
3	narrows the selection down to a few, or
4	suggests one alternative, and
5	executes that suggestion if the human approves, or
6	allows the human a restricted time to veto before automatic execution, or
7	executes automatically, then necessarily informs humans, and
8	informs the human only if asked, or
9	informs the human only if it, the computer, decides to.
10	The computer decides everything and acts autonomously, ignoring the human.

For routine operations, higher levels of automation in general result in lower workload, while the opposite is true for low levels of automation (Kaber, Endsley, & Onal, 2000). The relationship between workload and performance can be seen in Figure 1, which is adapted to the Yerkes-Dodson Law (Yerkes & Dodson, 1908). This illustration shows that optimal human performance occurs at moderate levels of workload, and as a consequence, it is possible to have a LOA too high or too low. If the LOA is too high, HSC problems could include: 1) manual or mental skill degradation, 2) loss of situational awareness, 3) automation brittleness and literalism, and 4) increased time and difficulty to diagnose failures and manually take over when required (Billings, 1997; Parasuraman, Sheridan, & Wickens, 2000). If the LOA is too low, potential HSC problems could include: 1) cognitive and working memory overload in routine tasks under time pressure, 2) human decision biases and heuristics, 3) lack of repeatability and consistency, 4) complacency and boredom, and 5) greater human interdependency and chaos under failure (Billings, 1997; Parasuraman et al., 2000). As a consequence, care must be taken to consider each of the roles human and machine should perform in a given task, and automation should only be introduced when there is a specific need to do so. This will ensure better overall performance across the dynamically changing set of responsibilities assigned to operators with complex tasks to perform.

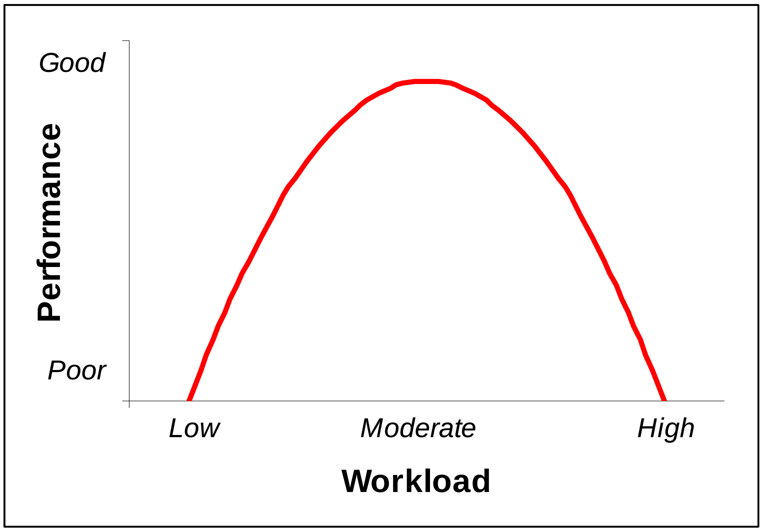

Figure 1: The Yerkes-Dodson Law

WAIT TIMES AND HUMAN SUPERVISORY CONTROL

In previous work modeling human-robot (ground-based) interaction and operator capacity, it has been proposed that workload as measured by the number of robots a single individual can control is a function of neglect time and interaction time (Goodrich, Quigley, & Cosenzo, 2005; Olsen & Goodrich, 2003; Olsen & Wood, 2004). Neglect Time (NT) is the expected amount of time that a robot can be ignored before its performance drops below some acceptable threshold, and Interaction Time (IT) is the time it takes for a human to interact with the robot to ensure it is still working towards mission accomplishment. While originally intended for ground-based robots, this work has direct relevance to more general human supervisory control tasks where operators are attempting to simultaneously manage multiple entities, such as in the case of UAVs.

Modeling interaction and neglect time are critical for understanding human workload in terms of overall management capacity, but there remains an additional critical variable that must be considered when modeling human control of multiple robots, regardless of whether they are on the ground or in the air, and that is the concept of Wait Time (WT). In HSC tasks, humans are serial processors in that they can only solve a single problem or task at a time (Chapanis et al., 1951), and while they can rapidly switch between tasks, any sequence of tasks requiring complex cognition will form a queue and consequently wait times will build. In the context of a system of multiple vehicles or robots in which two or more vehicles will likely require attention simultaneously from a human operator, wait times are significant in that as they increase, the actual number of vehicles that can be effectively controlled decreases, with potential negative consequences on overall mission success. Figure 2 illustrates how wait times could impact an overall system. In multiple vehicle supervisory control, operators interact with a robot to bring its performance to some acceptable performance threshold and then neglect it until such time that it requires assistance. Point A in Figure 2 represents a discrete event that causes the robot to require operator assistance such as system failure or the need for clarification of a goal state. The robot must wait while the human recognizes the problem, solves the problem internally, and then communicates that goal to bring the robot to another acceptable state.

While interaction and neglect times are important in predicting human capabilities for handling multiple robots, for those domains that are time-critical and high risk like UAVs, WT becomes a critical point for possible system failure. While most robots and vehicles can be programmed to follow some predetermined contingency plan if they do not receive required attention, mission success will likely be significantly degraded if wait times grow unexpectedly.

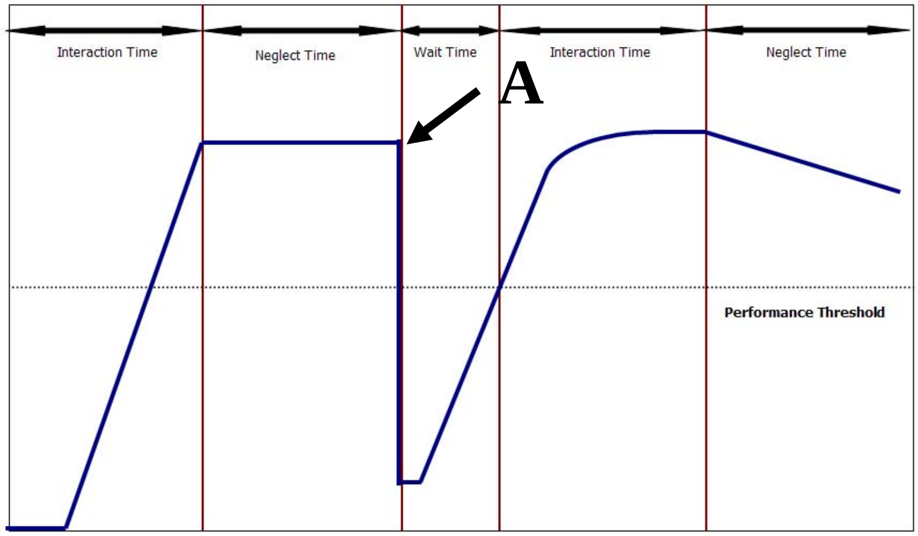

Figure 2: The relationship between interaction, neglect, and wait times

From the robot or vehicle perspective, WT imposed by human interaction (or lack thereof) can be decomposed into three basic components: 1) wait time in the human decision-making queue (WTQ), 2) interaction wait time (WTI), and 3) wait time due to loss of situation awareness (WTSA). For example, suppose an operator is controlling two robots on a semi-autonomous navigation task (much like the Mars Rovers). While typical operations involve human interaction with a single vehicle, there will be times when both vehicles require attention simultaneously or near-simultaneously. When this occurs, if the human operator begins assisting the first robot immediately, the first robot must wait while the operator solves the problem and then issues commands to it (WTI_1). For the second robot, the time it waits in the queue (WTQ_2) is effectively WTI_1. If an operator does not realize a robot or vehicle needs attention, the time from the initial onset of the event to actual operator intervention could range from seconds to minutes. This wait time induced by lack of recognition for required intervention is an example of WTSA.

3 - THE EFFECTS OF AUTOMATION ON WAIT TIMES

It is not clear what effect the level of automation of a human supervisory control task has on the various types of wait times, and what the overall system effectiveness will be as these wait time components change in magnitude and proportion to one another. For example, at high levels of automation where the system takes over execution of some or all functions, overall wait times are expected to decrease as automation can generally make faster decisions than humans and the number of opportunities for skill-based human errors is reduced. Superficially it seems that the system should perform well at higher LOAs, but under abnormal, unexpected conditions, automation could fail, possibly causing a catastrophic event to occur. This is particularly problematic under uncertain or novel conditions because the human operator may not understand the situation well enough to determine if the automation is working correctly and if it requires intervention.

In order to investigate the impact of levels of automation on operator performance as measured by the different wait time components, an experimental interface, termed the Multi Aerial Unmanned Vehicle Experimental (MAUVE) interface was developed. The MAUVE interface provides a simulation test bed for operator control of up to 4 UCAVs. It consists of two displays: one contains an overhead map view and allows mission planning and execution (Figure 3), while the other contains air tasking order (ATO) decision support, system messages and a chat box tool (Figure 4). An ATO provides a schedule of events and resources needed for these events to be allocated over a period of hours and/or days. Examples of information contained in an ATO are which aircraft have been assigned to certain strikes, times on targets, way points that must be flown on those strikes, and call signs to be used on those missions. As air tasking orders often involve a large number of aircraft, they are complex and hard to interpret, particularly under time pressure. Despite this, operators are still expected to extract the information they need from them in a timely manner.

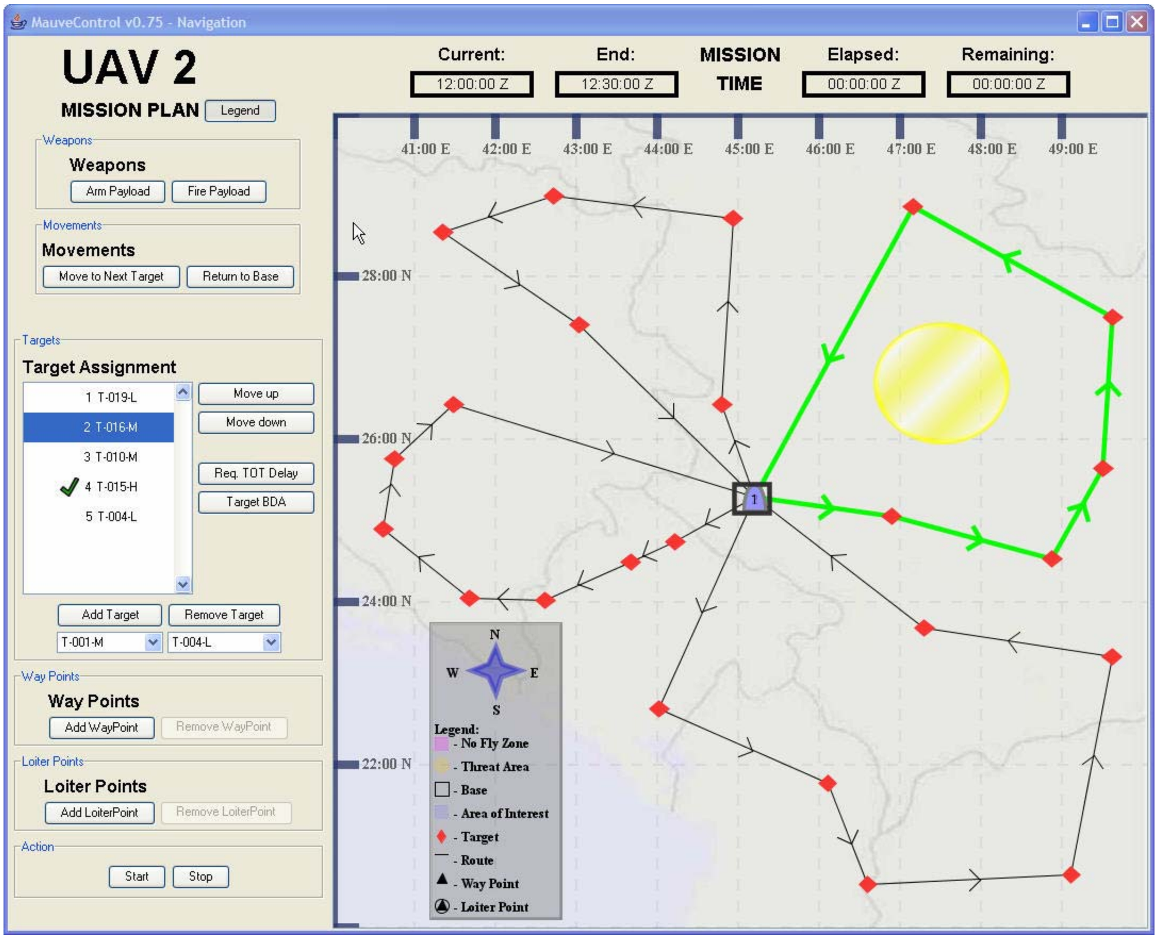

Figure 2: The MAUVE navigation, mission planning and execution interface

Potential decision support in MAUVE takes on 4 separate forms, which are termed 1) manual, 2) passive, 3) active, and 4) super-active levels of automation, and correspond to Sheridan and Verplank LOAs of 1, 2, 4, and 6 respectively (Table 1). Under the manual level, the user is provided with a simplified ATO that provides information such as the deadlines (otherwise known as time on targets or TOTs) for all future targets assigned to each UAV, and serial expected actions. The passive level of automation transforms this information into a horizontal timeline format that is color coded by action (Figure 4). Table 2 outlines the colors assigned to each high-level action UAVs are capable of performing in the simulation. The active level of automation uses this same timeline and runs a basic search algorithm on it to identify future time periods of high workload. It then outlines potential areas of concern and directs attention to them through a reverse shading technique. This draws users' interest to the appropriate areas of the timeline without loss of any information. The highest level of automation, termed super active, is a management-by-exception approach where the UAV automatically executes all actions according to the original mission plan unless the human intervenes.

Ruff et. al (2002) conducted a study that looked at the effects of a subset of these levels of automation on human interaction with 1, 2, and 4 UAVs. They found that a medium level of automation corresponding to approximately LOA 4 (equivalent to the active level in the MAUVE interface) provided performance and situation awareness advantages over LOAs 1 and 6 (manual, super-active) supervisory control schemes. However, significant interactions of independent variables were noted. Through maintaining a constant number of UAVs under control in the MAUVE study (4), we hope to demonstrate clearly both human and system performance differences due to increasing LOAs, as well as increases in workload.

Table 2: Color Coding of UAV Actions in MAUVE

UAV Action	Color
Enroute	Blue
Loitering	Orange
Arming Payload	Yellow
Firing Payload	Red
Battle Damage Assessment	Brown
Return to Base	Green

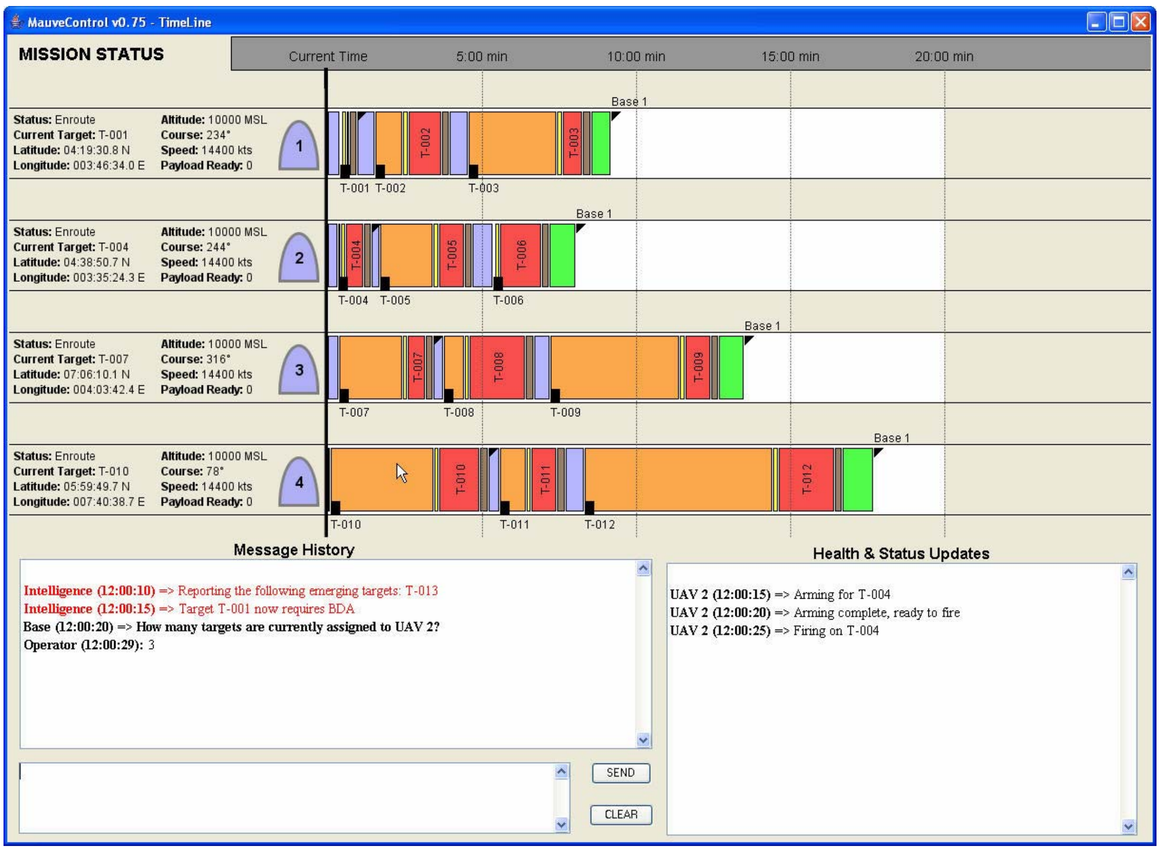

Figure 3: MAUVE decision support with passive automation

3.1 – Interaction Wait Time (WTI)

Interaction time (IT), which was previously defined as the time it takes for a human to interact with a robot (or vehicle), can be further decomposed. IT is the time during which a human's attention is focused on a single vehicle in order to solve a problem or induce some change to improve performance above a specified threshold. From the human perspective, IT includes the time required to discover a vehicle needs attention, determine the nature of the problem, solve the problem, and communicate that solution to the vehicle, with some type of feedback. Olsen & Goodrich (2003) described these four components of IT as 1) vehicle monitoring and selection, 2) context switching and acquisition, 3) planning or problem solving, and 4) command expression. Interaction wait time (WTI) is a subset of IT that occurs when any or all parts of these stages take place while the vehicle requires human input.

Figure 5 summarizes how the four components of WTI are affected in different ways by increases in levels of automation, and how there is a decreasing trend of WTI with increasing LOA. Vehicle monitoring and selection (VMS) is the component of WTI where the user decides to interact with a particular vehicle. In general, increasing levels of decision support should decrease vehicle selection time, as a primary goal of automation in this context would be to more quickly identify problem states. Vehicle selection is aided in MAUVE primarily through the color-coded format of the timeline that provides a visual representation of critical temporal information regarding specific UAV tasking, according to the ATO. Vertical stacking of the timelines and status display also makes it possible to observe all vehicle actions simultaneously. The active level of automation augments this by further drawing attention to predicted high workload blocks of time, and making recommendations for specific UAVs to alleviate the workload bottleneck. The super-active automation takes the vehicle selection decision away from the human, thus decreasing subtask selection to nearly zero.

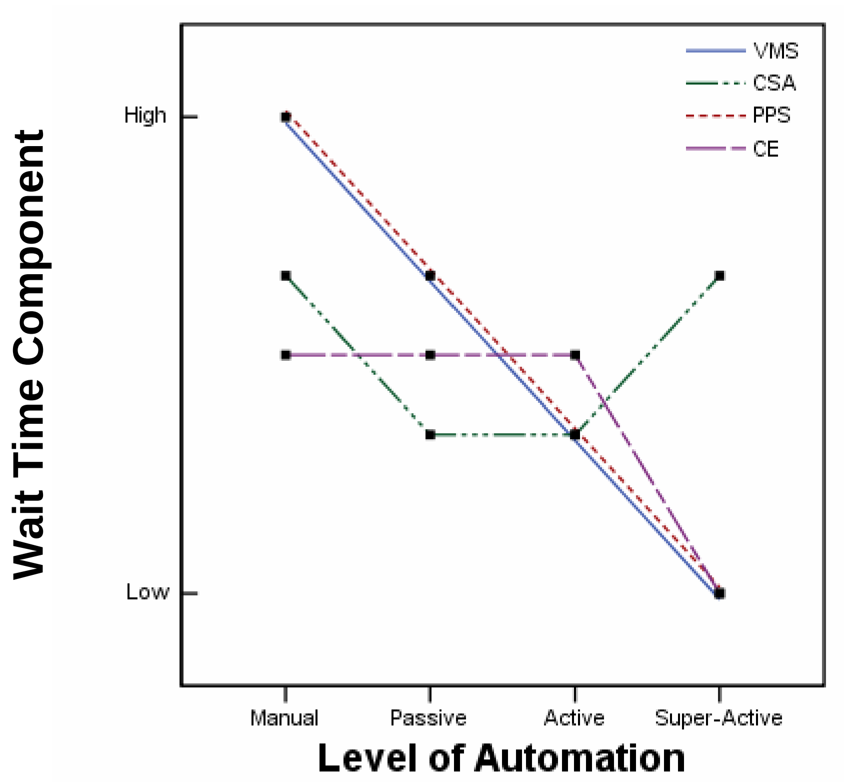

Figure 5: Predicted Effects of Increasing LOA on WTI Components

Context switching and acquisition (CSA), the next step in the interaction process, occurs when operators attempt to update their knowledge of the new vehicle's current goals and problems. The process of CSA in conjunction with VMS can incur a "switching cost" in which switching between tasks incurs added cost in terms of wait time because of the cognitive need to orient to the new problem. Switching costs are not incurred simply as a function of change detection, but occur as an operator regains the correct mental model and situation awareness needed to solve the new problem. Switching costs in terms of added wait times occur because in the control of multiple UAVs, operators spend time monitoring unfolding events, but periodically engage in interactive UAV control tasks. This need to concentrate on a task, yet maintain a level of attention for alerts causes operators to have a conflict in mental information processing. Interrupt-driven processing, needed for monitoring alerts, occurs when people are sensitized to possible problems and expect distraction. This is the mode operators supervising multiple UAVs will nominally find themselves when missions are executed according to plan. Concentration on a task, like that needed for UAV intervention, requires task-driven processing which is likely to cause decreased sensitivity or attention to external events. While interrupt and task driven processing can both be present in a person, attention must be shared between the two and switching can incur cognitive costs that can potentially result in errors (Miyata & Norman, 1986). Switching costs are expected to be higher for the super-active and manual levels of automation than moderate LOAs. Increased switching costs result from the greater demand for task-driven processing in the manual mode, while under the super-active LOA the opposite is the problem.

The planning/problem solving (PPS) stage of interaction time occurs when the operator plans a course of action for the selected vehicle. In general, increasing levels of automation should lower planning times because the computer takes progressively more decision options away from the human and/or aids the human by executing some of the planning steps. As the human is presented with fewer or no alternatives, they have a smaller problem space to explore, though this limitation may result in less than ideal solutions. Features of MAUVE that help to decrease planning time include recalculation of real-time UAV arrival times based on movable waypoints and routes on the map display, and computer suggestions at the active level of automation and above. In the case of super-active automation, the UAV performs all major tasks but the route planning for the human. This includes weapons arming, release, and if required, battle damage assessment.

The last stage of interaction wait time is the execution or command expression (CE) stage. Regardless of the level of decision support, the level of effort required to communicate decisions to the UAV through MAUVE commands remains constant, except for the super-active LOA in which the human has 30 seconds to veto automated decisions. Thus, increasing LOAs have no effect on execution times, save for the super-active phase.

3.2 – Wait Time in The Queue (WTQ)

In the context of human supervisory control and multi-UAV simulation, the elements of an operator's queue are tasks that the operator must perform, such as firing on a target, re-planning a route, or assigning an emergent target to a particular UAV's mission plan. In the context of queuing theory, the operator's tasking can be thought of as a preemptive priority queue with a single server. The time of the service rate, the average time an operator takes to attend to a vehicle, is essentially the average WTI. As previously mentioned, WTI for the vehicle in service corresponds to additional queuing wait time for all the vehicles in line. From the above discussion, WTI is predicted to decrease with increasing levels of automation, so the same trend can be expected with service rate. The arrival rate is the average time between tasks that the operator must perform, and is dependent upon the scenario complexity and the number of UAVs to be controlled, amongst other things. Within this framework, it can then be seen that utilization of the operator will decrease with increasing level of automation, and therefore average wait time in queue will decrease, potentially in a non-linear way. A small increase/decrease in individual vehicle WTI can have a much larger impact on WTQ, particularly as the number of vehicles in queue becomes large. The implications of this are that there could be a much steeper increase in WTQ at the lowest levels of automation, such as under the manual decision support.

3.3 – Situation Awareness Wait Time (WTSA)

WTSA is perhaps the most difficult wait time component to model because it represents how cognitively engaged an operator is in the task. Situation awareness (SA) is generally defined as having three levels, which are: 1) the perception of the elements in the environment, 2) the comprehension of the current situation, and 3) the projection of future status" (Endsley, 1988; Endsley, 1995). An example of a WTSA would be the failure of an operator to notice a message from a UAV that notified them of a failure rendering it useless for the remainder of a mission, such as an inability to release weapons. The time it takes for the operator to process the message and task the appropriate UAV to return to base would be a WTSA. While notifications and critiquing devices included in decision support systems can help to alleviate added wait time due to loss of SA, it is still an event that at the very least, should be included as a probabilistic model in a larger model of wait time for human interaction with multiple vehicles.

As an operator's level of SA can decrease under high workload due to competition for attentional resources (Wickens, 1995), but also decrease under low workload due to boredom and complacency (Rodgers, Mogford, &

Strauch, 2000), it can be concluded that optimum level of operator SA occur under moderate levels of workload. It is predicted that WTSA will follow the opposite trend. Therefore, medium levels of automation, such as the passive and active levels, should have the lowest accumulated WTSA, while the manual and super-active levels should be higher. In particular, total accumulated WTSA for the super-active level of automation should be greater than the active and passive levels of automation, but lower than that for the manual level of automation.

The super-active level of automation should eliminate any wait time due to the loss of SA, but only for *planned* events. A primary concern with management-by-exception systems is that when an unanticipated event occurs, automated systems often arrive at erroneous solutions and humans do not have enough SA to recognize the failure mode. Because of the propensity of human towards automation bias in command and control settings (Cummings, 2004) and with the loss of SA, it is likely that the human will not veto a erroneous automated actions, thus causing some potentially catastrophic event. Indeed, this problem was seen recently in the 2004 war with Iraq when the U.S. Army's Patriot missile system engaged in fratricide, shooting down a British Tornado and an American F/A-18, killing three. This avoidable loss of life occurred because human operators did not recognize the guidance system had erroneously locked onto aircraft instead of enemy missiles. It is exactly in this kind of instance where automating the system to reduce wait times caused by humans should be very carefully considered.

As opposed to the super-active level of automation, under the manual level of automation in MAUVE the operator is responsible for both execution and re-planning. With very little automation assistance, these dual responsibilities increase workload, which could induce low levels of operator SA. As SA decreases, there is no guarantee that wait times will occur, only that the probability of WTSA occurrence is more likely. However, given the greater number of opportunities for this human error to occur under manual decision support, it should have the largest total amount situation awareness wait times amongst all LOAs.

3.4 – DISCUSSION

In general, increasing levels of decision support should result in lower aggregate levels of WTI and WTQ, while WTSA will be lower at moderate levels of automation and higher at the extremes (Figure 6). It is not clear which of these components dominates total wait time, or even if a single component dominates across all factor levels for management of multiple autonomous vehicles like UAVs. Increasing workload and uncertainty will likely increase WTI and WTQ, while WTSA may be contextually dependent.

The preceding discussion on wait times has not mentioned their *cost*. A wait time cost measure is needed because wait times alone don't quantify how much impact they have on a particular mission. It can be inferred that higher wait times are related to higher costs in performance, but the threshold at which they incur a cost needs to be identified. In addition, the context in which wait times occur may have an even greater influence on overall system performance. For example, a typical mission for a UAV in a MAUVE scenario involves striking targets at precise times. If the mission planner has built in additional "slack" time into a route so that the UAV may incur wait times without missing its deadline, then the cost of wait time in this instance is relatively low until all of the slack time is used, whereas any additional wait time will cause the UAV to fail to destroy a target on time. This could have a very high potential cost if the target was of strategic importance. Freed et al. (2004) has quantified wait time cost with respect to UAV surveillance for the purpose of evaluating computer algorithms, but more research is needed in this area.

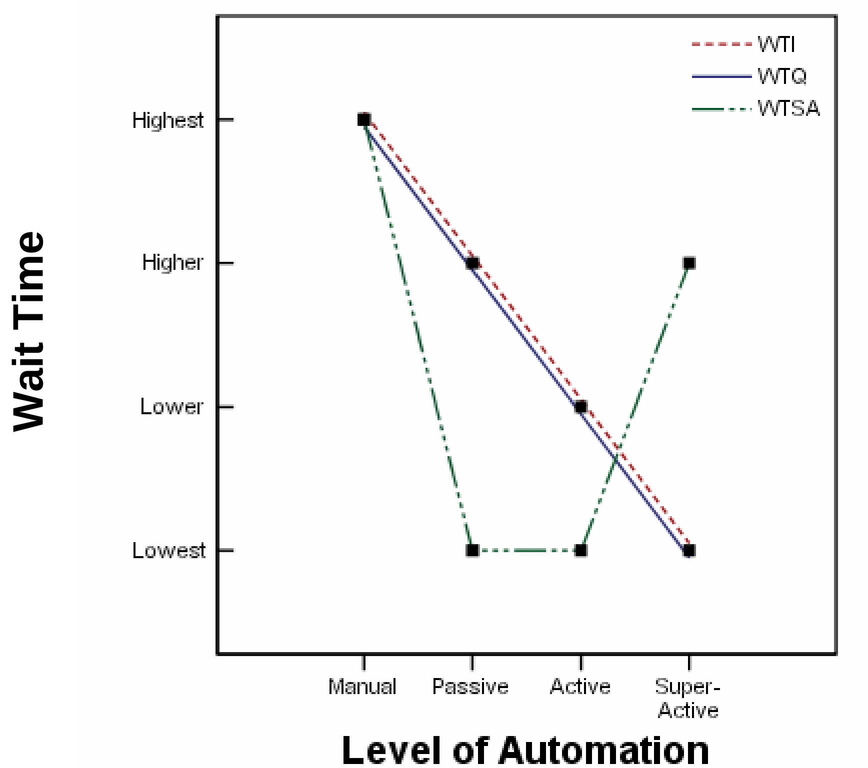

Figure 6: Predicted Trends for each Wait Time Component with LOA

4 – CONCLUSIONS

The ability for a single operator to effectively control multiple agents such as UAVs, UGVs, and UUVs is a fundamental component of the military's future vision of network-centric warfare. However, if not well understood and accounted for in design strategies, human cognitive limitations could be a significant source of degraded system performance and possible failures. When modeling operator workload, it is important to model the sources of wait times, especially since these times could potentially lead to system failure. Specifically, these sources of system/robot wait time include interaction time, queuing, and loss of situation awareness. The impact of increasing levels of automation on overall wait times is unclear, but some trends can be identified for individual wait time components. In particular, wait times due to interaction and queuing will decrease with level of automation, while those due to situation awareness will increase only at very low or high levels of automation. While this paper outlines general concepts in wait time modeling and makes predictions concerning the impact of increasing levels of automation on wait times, more research is needed in the development of wait time, switching cost and wait time cost models. Ongoing research in this area will attempt to address these areas and provide experimental data from which to validate the predictions made in this paper.

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