Replan Understanding for Heterogenous Unmanned Vehicle Teams

by

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in Partial Fulfillment of the Requirements for the Degree of

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Abstract

As unmanned vehicles (UVs) become increasingly autonomous, the current multiple human to single vehicle ratio is likely to be reversed in that a single human operator may direct a team of UVs at the supervisory control level. A single human operator supervising UVs in the context of a time-critical mission will require dynamic adaptation of the mission plan to account for emergent and unexpected events. Such dynamic replanning can be aided by an automated planner (AP), capable of assisting the operator in generating mission schedules and adapting those schedules when the mission scenario changes. Such automated decision support should help an operator evaluate the AP's proposed changes to the mission schedule in light of emergent events, as well as understand the potential consequences and benefits for enacting the proposed changes. While an AP should produce recommendations based on exogenous mission changes, the AP should also accept input allowing for human-automation collaboration, since humans may need to input parameters for which the AP cannot account. To this end, this thesis describes an interface including a schedule management decision support tool (DST) designed to allow a single-operator to control multiple heterogeneous UVs performing a search and track mission. In particular, the DST allows for the operator to both compare schedules generated by the AP and collaborate with the AP such that human input can be provided. This Schedule Comparison Tool (SCT) contains configural displays which graphically show pertinent information common to all schedules in a manner that allows for efficient and effective decision making. Two evaluations were conducted in order to examine and critique the interface which included examining cognitive processes of expected users and a functional evaluation of the interface's efficiency. The interface was shown to support a concise and effective presentation of large amounts of critical information, which allows for effective management of the search and track mission. The interface also supports mission functionalities more efficiently than a previously designed engineering interface. While increasing the accessible functions for an operator, actual interactions with the interface were reduced, on average, approximately 50%. The work presented in this thesis also includes potential areas for future research.

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Nomenclature

Acronyms

AOI	Area of Interest
AP	Automated Planner
DST	Decision Support Tool
NASA-TLX	National Aeronautics and Space Administration Task Load Index
SCT	Schedule Comparison Tool
UV	Unmanned Vehicle
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
USAF	United States Air Force
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle

Chapter 1: Introduction

1.1 Motivation

In current military operations, extensive planning is required for all missions, which is labor and time intensive. Due to the volatile nature of military environments including emerging threats, unforeseen complications, and additional mission objectives, the original plan must often be adapted once the mission commences. One such military application where mission replanning is critical is in the use of unmanned vehicles (UVs). UVs are increasingly being used to perform such military operations as reconnaissance, payload delivery, communication, surveillance, search and rescue, border patrol, and others (Nehme, Crandall, & Cummings, 2007).

For an unmanned vehicle to be used in a military mission, currently a team of human operators is needed to perform such supervisory control tasks as flying, navigation, and high-level mission planning and replanning tasks. Improvements in technology will lead to automation of many of the lower-level tasks. In the future, the current human to vehicle ratio is likely to be reversed in that a single human operator may be in charge of supervising a team of unmanned vehicles. In order to supervise multiple UVs, a human operator will be in charge of high-level mission management and will be required to adapt the mission plan to changing mission conditions. Figure 1 depicts a hierarchical control loop for a single operator mission and supervision management system with multiple vehicles.

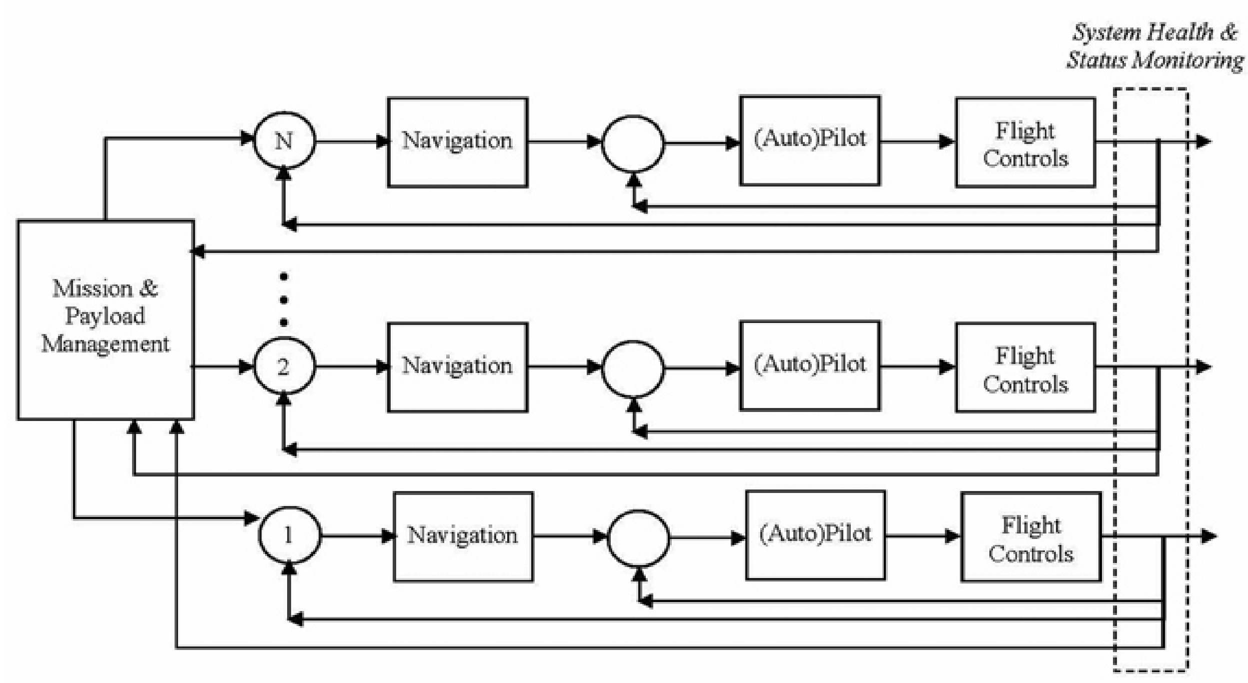


Figure 1: Hierarchical Control for Multiple Unmanned Vehicles (Cummings, Bruni, Mercier, & Mitchell, 2007)

As technology advances, onboard systems will be increasingly automated, accompanied by cross-platform forms of automated management for high-level aspects of the mission. Current areas of research that can be incorporated into such UV systems include automated path planning, e.g., (Shanmugavel, Tsourdos, Zbikowski, & White, 2006), cooperative dynamic target tracking, e.g., (Zengin & Dogan, 2006), and task assignment (Brunet, 2008). In all of these computational approaches, adding mission-specific constraints and requiring multivariate optimization only further exacerbates mission complexity (Schumacher, Fulford, & Kingston, 2005), which is costly both in terms of computation efficiency, and as this thesis will demonstrate, human interaction.

Although utilizing high levels of automation can assist human operators in successfully performing missions while meeting various constraints in a time-pressured environment, increased automation has been shown to produce opacity, lack of feedback, and mode confusion (Billings, 1997) (Parasuraman, Sheridan, & Wickens, 2000). These effects can seriously impact the success of a mission, but well-designed user interfaces have been shown to mitigate these detrimental effects. However, UV interfaces designed to represent pertinent information graphically in concise forms have been shown to produce better decisions and situation awareness for complex, time-critical missions (Brzezinski, 2008).

Understanding the current schedules of multiple UVs in order to replan them (including insertion of new tasks, and modifying and deleting current tasks) is an important cognitive requirement of multiple UV systems (Cummings & Mitchell, 2006) (Cummings, Brzezinski, & Lee, 2007). Automation can aid operators in the schedule management task by generating complete schedules for each UV. Such automation-generated schedules can guarantee all mission constraints are met and be generated at any time during the mission to account for emergent events. However, because automation is inherently brittle (Billings, 1997), human operator interaction is critical in ensuring the automated solutions are actually desirable, as automation of this nature has been shown to produce sub-optimal solutions (Vandermeersch, Chu, & Mulder, 2005).

Thus, as automation aids human operators in supervisory control of multiple UVs in dynamic mission environments, a primary task for the operator will be to analyze schedules produced by the automation and provide intelligent feedback. In performing this task, it will be particularly important for operators to fully understand what the automation's proposed schedule has to offer over the current mission plan, and if it is possible to improve on the automation's proposal. Operators may have difficulty understanding the consequences versus benefits of accepting such a proposed schedule. Thus, decision support is needed to help multi-UV operators collaborate with automation at high-level mission management. This thesis examines the human factors challenges of allowing a single human operator to supervise multiple UVs during a dynamic mission. To understand interface requirements, an example interface will be presented and ways to improve on the example interface will be investigated.

1.2 Problem Statement

The primary question investigated in this research effort is whether a decision support tool that allows both a comparison of mission schedules and collaboration with an automated algorithm helps multi-UV operators supervise the mission and effectively manage the vehicle schedules.

1.3 Research Methodology

The problem statement was investigated via the following research objectives (each will be elaborated upon in subsequent sections):

- Objective 1. **Develop a user interface for controlling multiple UVs in a previously-developed multiple UV simulation environment.** Following a human-systems engineering approach, display requirements were generated through a cognitive task analysis (Chapter 3), and a resultant interface was developed to enable a human operator to interact with the simulator to control multiple UVs.
- Objective 2. **Develop a Schedule Comparison Tool consisting of configural displays for viewing and comparing different schedules of multiple UVs.** Configural displays, defined in Chapter 2, were chosen for their ability to support efficient perceptual processes. Deciding

between multiple, time-critical schedules necessitates displays requiring little contemplation to understand the information and make decisions. A more detailed description of the resultant configural displays is given in Chapter 4.

- Objective 3. **Evaluate the interface.** Human subject experiments were performed with this new interface, in comparison with a previously-existing human interface not explicitly designed to support cognitive requirements. Chapter 5 details this comparison.

1.4 Thesis Organization

The remainder of this thesis is organized as follows:

Chapter 2, *Background*, summarizes research done in the areas of autonomous multi-UV control and related human factors issues in interface design.

Chapter 3, *Cognitive Task Analysis*, describes the hybrid Cognitive Task Analysis process and the requirements developed that guided the design of the decision support tools and interface.

Chapter 4, *Design*, introduces the main interface and the Schedule Comparison Tool, a decision support tool. The various human factors elements utilized in the design of the interfaces will be examined.

Chapter 5, *Cognitive Walkthrough*, analyzes the cognitive processes required to perform the various functions of the interface.

Chapter 6, *Functional Comparison*, compares the original engineering interface with the newly designed interface. Overall functionality of the interfaces will be compared, concentrating on effectiveness and efficiency.

Chapter 7, *Conclusion*, summarizes the motivation, objectives, and key findings of this research initiative. Suggestions for future work are also provided.

Chapter 2: Background

This chapter first introduces multi-UV research that is focused on completely autonomous control of multi-UV systems. In addition, recent research on those human factors issues involved in adding a human into the highly automated multi-UV control loop will be discussed. This overview highlights the need for the development of decision support tools for multi-UV mission management. Configural displays will be introduced as a method for graphically representing complicated information as a part of decision support tools. Finally, research surrounding video game interfaces and their relationship to real world multi-UV mission management interfaces will be examined. Because of the similarities between the two domains, multi-UV displays can be made to both look and function like video games interfaces to give users an intuitive environment for learning how to supervise a team of UVs.

2.1 Fully Autonomous Multi-UV Research

There has been much multi-UV research focused on controlling the autonomous vehicles with little to no human interaction. Research on completely autonomous multi-UV control has included path planning (Shanmugavel, Tsourdos, Zbikowski, & White, 2006), cooperative dynamic target tracking (Zengin & Dogan, 2006), and real-time task allocation with moving targets (Turra, Pollini, & Innocenti, 2004). In addition to the lower-level tasking of multi-UVs, other research has focused on higher level goals such as automated task assignment. Completely autonomous multi-UV cooperative task assignment methodologies include quasi-decentralized (Ousingsawat, 2006) and decentralized (Alighanbari & How, 2006) task assignment and genetic algorithms (Shima & Schumacher, 2005).

A drawback common to these task assignment algorithms is that they frequently suffer from sub-optimal mission plans (Vandermeersch, Chu, & Mulder, 2005). Current systems utilize overly simplified representations of the mission environment with very limited abilities to update the system when changes occur. Additionally, there have been very few efforts directed toward real-time mission replanning algorithms for coping with emergent and unexpected events. Current algorithms designed for satisfying time constraints for task assignments can be run during a mission to generate new plans. These new plans accommodate some aspects of the changing environment, but a human operator would provide support for aspects of the mission not represented by the algorithm. While human operators are critical in managing these automated planning and scheduling systems due to automation brittleness, they also need assistance from decision support tools because of the complexity involved in managing multi-UV mission plans and the required computation times.

2.2 Human Factors Research in Multiple UV Control

When studying a single human operator supervising multiple UVs, mission performance, operator workload, and situation awareness are principal concerns (Brzezinski, 2008). Mission performance is a measure for how well the operator and UVs perform the mission. Operator workload refers to the operator's capability to perform primary system functions (Wierwille & Eggemeier, 1993). Situation awareness (SA), essentially the awareness of the operator, can be dissected into three levels (Endsley, 1988). Level 1 SA is the perception of elements in an environment within time and space. Level 2 SA is the comprehension of the meaning of those elements. Level 3 SA is using an understanding, of the current state to project future states.

Research with regard to a single operator supervising multiple UVs has focused on how the operator is affected by the number of supervised UVs (Lefebvre, Nelson, & Andre, 2004) (Ruff, Narajanan, & Draper, 2002) (Nelson, Calhoun, & Draper, 2006), by different automation levels (Ruff, Narajanan, & Draper, 2002) (Nelson, Calhoun, & Draper, 2006) (Malasky, Forest, Khan, & Key, 2005) (Ruff, Calhoun, Draper, Fontejon, & Guilfoos, 2004), and by supervision from manned aircraft (Miller, Goldman, Funk, Wu, & Pate, 2000) (Howitt & Richards, 2003) (White, 2004). However, little has been done to examine how to design a decision support tool to promote collaboration between the human and the automation in the replanning and schedule management tasks. While Cummings et al. (2007) showed that a graphical decision support tool can improve operator performance in multiple UAV schedule management, this research only focused on independent UAVs, and did not account for the collaborative nature of intra-vehicle planning. The Adaptive Levels of Automation (ALOA) test bed (Nelson, Calhoun, & Draper, 2006) used an automated algorithm to present alternative routes for individual UVs to the operator. Although individual UV routes can be important for certain mission types, the mission used for research in this thesis focuses on higher level schedule management goals, of which alternative routes are a subset.

2.3 Configural Displays

Complex systems such as multi-UV control systems require operators to understand large quantities of abstract data while managing their workload. One approach in designing a human-automation interface for such a complex task leverages novel information visualization techniques. Information visualization designs represent abstract data using visual elements in order to aid understanding (Shneiderman, 2005). They generally offer compact graphical representations of data rather than text-based displays which can be perceived and analyzed faster, thus potentially reducing workload. Configural displays, a type of information visualization that is central to this research effort, are especially suited for time-pressured, multivariate decision making scenarios. As will be discussed in detail, configural displays support perceptual reasoning processes, which are significantly less costly than cognitive processes that require iterations across data sets to generate solution alternatives.

Configural displays map several individual data variables into a single geometrical form, providing an integrated display of the information (Bennet & Walters, 2001). As a data variable changes, the corresponding part of the geometrical form associated with that variable changes shape, providing a graphical presentation of changing system properties (Bennet, 1992). Additionally, by integrating the data needed for comparison and computation into a common geometrical form, configural displays support the proximity compatibility principle (Wickens & Carswell, 1995). Close display proximity can minimize dividing attention between analyzing pieces of information from more than one source and aids in mental integration, producing better understanding of the information.

Configural displays support direct perception-action, which is when a display allows for direct perception of a system state, such that an immediate action can be identified. Direct perception-action enabled the use of efficient perceptual processes instead of more cognitively demanding processes that rely on memory, integration, and inference (Gibson, 1979). Designing interfaces to provide users with direct perception-action has been shown to improve performance in complex tasks (Buttgieg & Sanderson, 1991) (Sanderson, 1989) (Smith & Cummings, 2006), and also in UAV schedule management tasks (although in the independent vehicle case (Cummings, Brzezinski, & Lee, 2007)). The goal of this research is to extend those lessons learned in applying configural displays to UV schedule management to the multiple collaborative vehicle case with a global mission manager.

2.4 Video Game Interfaces

There has been a growing interest in designing interfaces for systems comprised of unmanned vehicles to resemble video game interfaces (Drury & Richer, 2006). Many current video games place the player in the position of a military commander surveying a mission involving numerous simulated troops. The player is given the ability to order these troops to perform various tasks, and the troops perform these tasks with varying levels of autonomy. To ensure mission success, adequate situational awareness must be maintained throughout the entirety of the mission. A video game's success hinges upon its ability to provide the player with pertinent information and effective controls in an entertaining manner.

Research has shown that those skills promoted by such video games can produce superior performance (Green & Bavelier, 2003). In addition, research has shown that designing interfaces for controlling multiple autonomous robots to resemble those of current real-time strategy games gives both new and experienced users an intuitive way of observing and interacting with the system (Jones & Snyder, 2001). Point and click operations allowed users to select robots and tasks, and pop-up dialogs clearly showed allowed actions. Such systems have allowed new users to, with very little training, comfortably operate the robots.

2.5 Conclusion

Supporting an operator in supervising multiple UVs in a time-sensitive, dynamic mission is not an easy task. Existing fully autonomous systems operate as black boxes with little room for input and little to no feedback (Brunet, 2008). Integrating a human operator into such a system presents many challenges, especially in the area of schedule management. The algorithms the system uses need to allow for operator input, but the complexity of such computational environments, including the number and relationship of variables, can quickly overwhelm an operator, particularly in a time-pressured setting. Thus, some kind of decision support interface is needed that simplifies the data representation through a graphical format and provides for intuitive interaction like that promotes effective video game strategies.

Towards the development of such an interface, the next chapter describes a cognitive task analysis of a system which utilizes multiple UVs to search for and track vehicles in an area of interest. The analysis results in display cognitive requirements needed for a successful interface.

Chapter 3: Cognitive Task Analysis

This chapter presents the detailed analysis of the cognitive processes involved in managing multiple unmanned heterogeneous vehicles performing a search and track mission, assuming the existence of a centralized automated planner[1]. The analysis was accomplished through a hybrid cognitive task analysis that was performed on the system in order to generate both information and functional requirements. The concepts captured from this analysis are critical elements to any interface that will support multi-UV control with a focus on path-planning or replanning. The hybrid CTA process is explained and the results are discussed below.

3.1 Hybrid Cognitive Task Analysis

An existing domain can be analyzed via a Cognitive Task Analysis (CTA) to generate design requirements for creating an interface that specifically focuses on operator cognitive needs The CTA is described as "the extension of traditional task analysis techniques to yield information about the knowledge, thought processes, and goal structures that underlie observable task performance" (Schraagen, Chipman, & Shalin, 2000). A CTA traditionally requires analysis of existing systems and interviews with subject matter experts. Unfortunately, for a futuristic system like the one examined in this thesis, no predecessor system exists nor are there subject matter experts. Because of this limitation, a conventional CTA cannot be applied (Cummings & Guerlain, 2003). The hybrid CTA was developed to specifically account for this constraint (Nehme, Scott, Cummings, & Furusho, 2006). To compensate for the lack of subject matter experts and a predecessor system, the hybrid CTA takes the following steps to generate design requirements: 1) Generating scenario task overviews, 2) Generating event flow diagrams, 3) Generating situation awareness requirements, and 4) Generating decision ladders for the critical decisions.

[1] This system, called OPS-USERS (Onboard Planning System for UAVs in Support of Expeditionary Reconnaissance and Surveillance), represents a collaborative effort between MIT and Aurora Flight Sciences.

From these four steps, information and function requirements can be extracted. Figure 2 presents the hybrid CTA's sequence of processes.

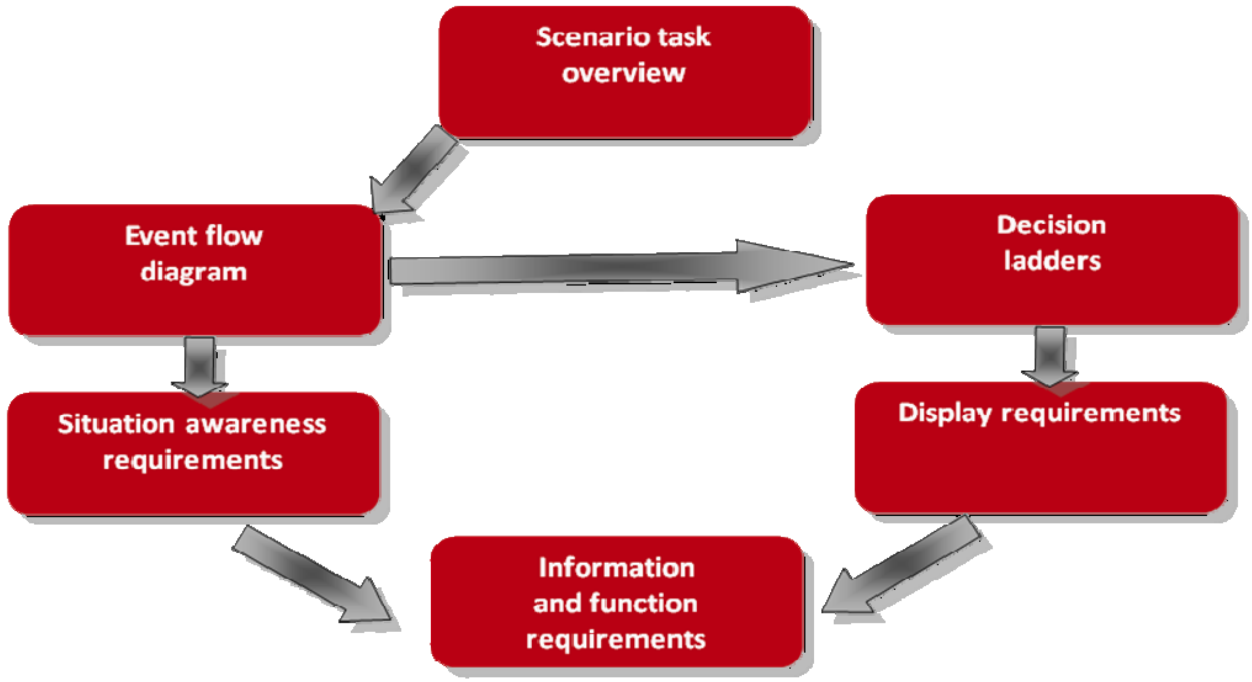


Figure 2: Hybrid Cognitive Task Analysis Process (Bhattacharjee, 2007)

In the following sections, the hybrid CTA technique (Nehme, Scott, Cummings, & Furusho, 2006) is applied to the multiple unmanned heterogeneous vehicles performing a search and track mission.

3.2 Scenario Task Overview

In the search and track mission scenario, an operator is given an area of interest (AOI) and multiple unmanned vehicles (UV). Using the UVs, the operator is charged with finding hostile targets in the AOI and maintaining coverage of these vehicles over the course of the mission. The UVs have limited fuel, so as they survey the AOI, they must make frequent stops at a refuel station within the AOI. To perform this mission, the operator is given the aid of an automated planner (AP) which calculates schedules. These schedules include specific plans for each UV to search the AOI, track found targets, and schedule times for refueling.

The AP uses a primarily centralized task assignment algorithm to create individual schedules for each UV. These individual schedules are then combined into a complete mission schedule. This centralized approach allows schedules to be calculated with a global view of the state of the mission. Once individual schedules are passed to each UV, the AP utilizes a decentralized approach for further optimization. Although each schedule calculated by the primary centralized algorithm accounts for the various constraints such as refueling, each UV has an onboard AP which constantly recalculates waypoints and refuel times. When each UV's onboard AP performs these calculations, the resulting waypoints and refuel times are sent back to central command only to support the centralized algorithm's global view of the mission.

The decentralized approach offers a more robust system by allowing UVs to periodically travel out of communication with central command. The onboard AP's also off-load computational workload, allowing the centralized algorithm to produce quicker and more optimal schedules. An example of the decentralized approach working to ensure UV safety is when unforeseen speed limitations force a UV to return to base to refuel before reattempting to travel to a location.

Given the many tasks needed to be assigned, the centralized AP attempts to assign all the tasks in the order of priority as specified by the user. The AP has been designed to accept modifications from the user. Specifically, the user may input to the algorithm a particular task that the user wishes to be performed, essentially giving it highest priority. The algorithm then computes a schedule based on the new priority.

The schedules produced by the algorithm are often sub-optimal, because as an operator performs the mission, priorities can change, which may or may not be weighted correctly by the AP. For example, the operator may want to search an area within the AOI for additional targets, but the algorithm may return schedules that only track already-found targets. In this case, the operator has chosen to prioritize searching the AOI over tracking targets, but the algorithm has defaulted to tracking known targets.

In terms of system and UV autonomy, the following assumptions apply:

- The UVs are intelligent in the sense that they are capable of following the waypoints generated by the AP while avoiding obstacles.
- The UVs are capable of searching for targets as they travel with no assistance.
- The UVs are capable of intercepting and tracking a moving target.
- All schedules proposed by the algorithm account for refueling.
- Refueling is performed completely autonomously at the base location within the AOI.
- The UVs are always in communication with each other and with central command.

3.3 Event Flow Diagram

Following the scenario task overview, the event flow diagram ties the various cognitive events required to perform the mission together into temporal relationships. To do this, the event flow diagram categorizes the cognitive events extracted from the scenario task overview into three categories:

- Loops, which represent processes that occur repeatedly with a predetermined stopping condition.
- Decisions, which can be simple yes/no decisions or can be more complicated, requiring knowledge-based input from the operator.
- Processes, which are tasks requiring human-computer interaction to fulfill a mission sub-phase.

The event flow diagram for this scenario is shown in its entirety in Appendix A. A subsection of the overall event flow is depicted in Figure 3 to highlight those decisions and processes that are required to support collaboration between the operator and the AP.

At the start of the mission, no tasks exist because the operator has not added any, and no targets have yet been found. The operator only adds search tasks when the onboard APs do not schedule pertinent areas to search. At this stage, as depicted in Figure 3, the operator is strictly monitoring the automation to ensure it is performing to some degree of satisficing (Simon, Hogarth, Piott, Raiffa, Schelling, & Thaier, 1986). As tasks are added via the initial decentralized approach and targets are found, the centralized AP begins calculating schedules.

Because of the level of complexity involved in creating a schedule for each UV (i.e., fuel constraints and efficient AOI search patterns coordinated across with all UVs), all initial task assignments to individual UVs are done by the AP. This AP scheduling represents a critical decision posed to the operator, i.e., whether or not the latest proposed schedule can improve performance?

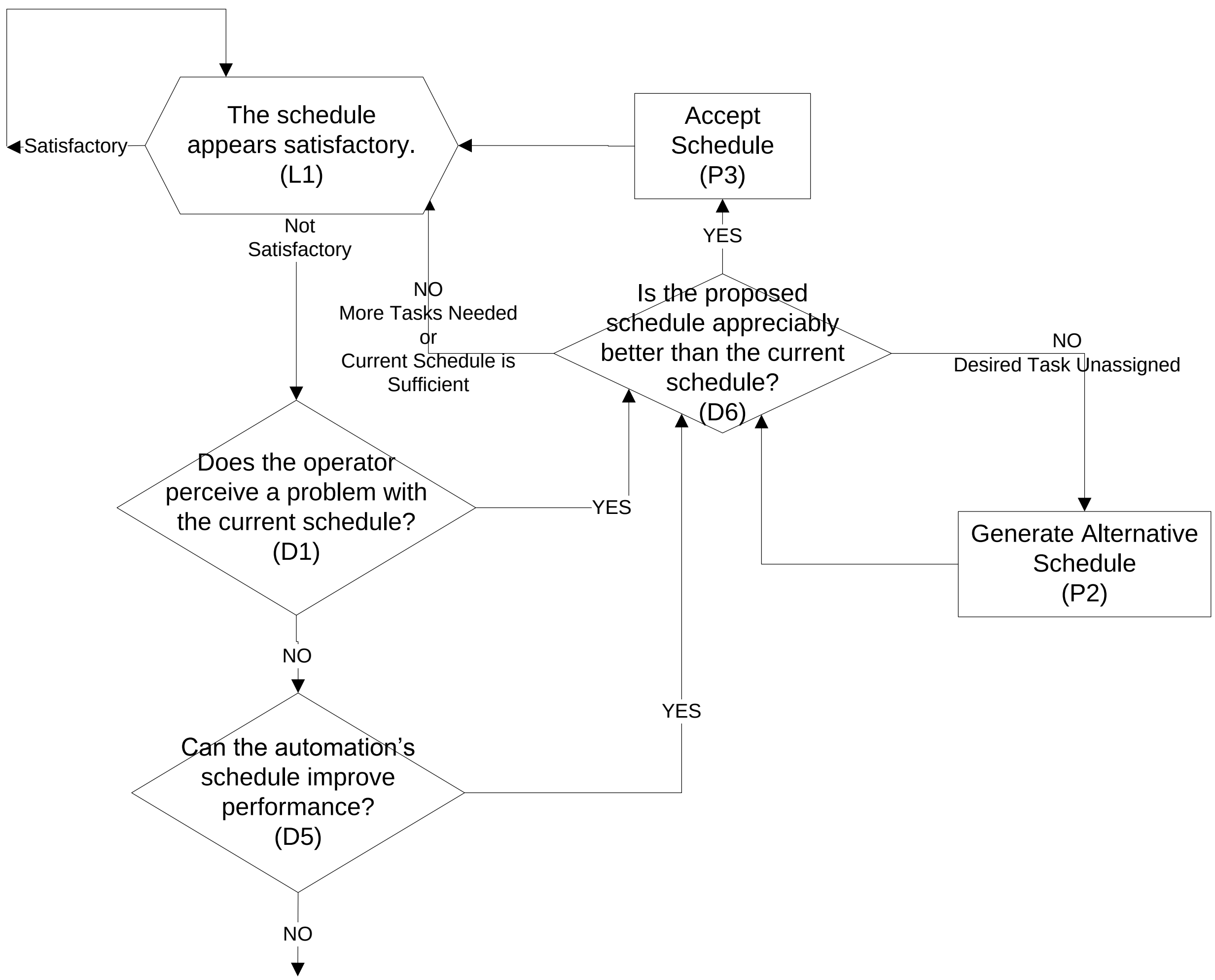


Figure 3: A decision block in the event flow diagram

The first decision regarding the algorithm's schedule (D5) is a simple decision decided by the AP or the human. From the AP perspective, given the current schedule and the latest proposed schedule, it can perform a simple comparison based on projected AOI coverage and percentage of targets tracked and make the decision based on a quantitative score. The AP can then notify the operator to examine the proposed schedule. The operator can also elect to analyze the proposed schedule at any time, but for workload mitigation, the AP will alert the operator in the case of a possible better solution. Regardless of who makes the decision to reschedule, the operator enters the schedule management decision (D6) for further analysis of the schedules. If the proposed schedule does not pass the initial, baseline comparison, the operator is directed to assess the various tasks present in the AOI and add tasks as needed until the proposed schedule is better than the current schedule. The schedule management decision (D6) will be discussed in greater detail below.

3.4 Decision Ladders

Decision ladders take the critical complex decision events from the event flow diagram and expand them into a detailed description, capturing the information and knowledge requirements needed to support a correct decision (Bell & Lyon, 2000). In addition to showing the information and knowledge needed for the many cognitive processes involved in the decision, a decision ladder also includes display requirements. These display requirements are included in the decision ladder and each requirement connects to its corresponding element in the ladder.

Decision ladders for the three complex decisions identified in the event flow diagram have been constructed: 1) The decision regarding searching the AOI (D2), 2) The decision regarding determining if all found targets are scheduled to be tracked sufficiently (D3), and the decision regarding schedule management (D6). The schedule management decision will be discussed in detail below (Figure 4). The two other complex decision ladders appear in Appendix B.1 and Appendix B.2.

3.4.1 Schedule Management Decision

The schedule management decision is the most important decision the operator must face in performing the search and track mission. The decision involves comparing two abstract schedules on concrete metrics: AOI coverage and percentage of targets tracked. To perform an adequate comparison, significant amounts of information need to be perceived and comprehended about both schedules. In addition to comparing each metric across schedules, the schedules need to be compared across metrics. This is no simple process and necessitated the in-depth analysis provided by the decision ladder.

The decision ladder begins with the alert seen in the box labeled “Activation”: the operator has either perceived a problem with the current schedule or seen that the automation’s proposed schedule is *appreciably* better than the current schedule. This comparison is performed by the AP and is based on a simple calculation using projected AOI coverage and the number of targets tracked. In other words, the activation of this decision ladder is from answering “yes” to either of the previous decisions (D1 & D5): “Does the operator perceive a problem with the current schedule?” or “Can the automation’s schedule improve performance?”

If the proposed schedule is *appreciably* better than the current schedule, the operator can compare the schedules in more detail to get a better idea as to how much better the AP’s proposed schedule is. There are numerous metrics that produce the single score for the AP’s determination of what constitutes a better schedule such as projected AOI coverage, the percentage of targets tracked, and the percentage of overall task completion. The specific threshold can be varied to match desired priorities in changing environments. After the operator is notified that the proposed schedule is in some way better than the current schedule, the operator's judgment is needed to resolve the AP's ambiguities. The left side of this decision ladder shows the process of formulating a decision with data processing activities, represented by boxes, and the following states of knowledge resulting from the data processing, represented by ovals.

Once the operator has perceived the various differences between the schedules and understood the implications of switching to the proposed schedule, the operator must make a decision. This is shown in the uppermost "Decide" box. The operator must decide if the proposed schedule's projected AOI coverage, projected target coverage, and projected task completion perform the operator's current mission goal better than the other schedules. If it does perform better, the operator can accept the proposed schedule and return to monitoring the mission.

However, if the proposed schedule is not better, the operator can analyze the portion of the mission tasks not covered by the proposed schedule. The operator is given the ability to query the algorithm to determine if one or more of the unassigned tasks could produce significantly better performance if assigned. This process realigns the priorities the algorithm uses to generate schedules with the operator's current priorities for the mission. The AP then recalculates a schedule based on the user-specified new priorities and, once finished, presents the schedule to the operator. This cycle of querying the AP and restarting the analysis of the proposed schedule is shown in Figure 4.

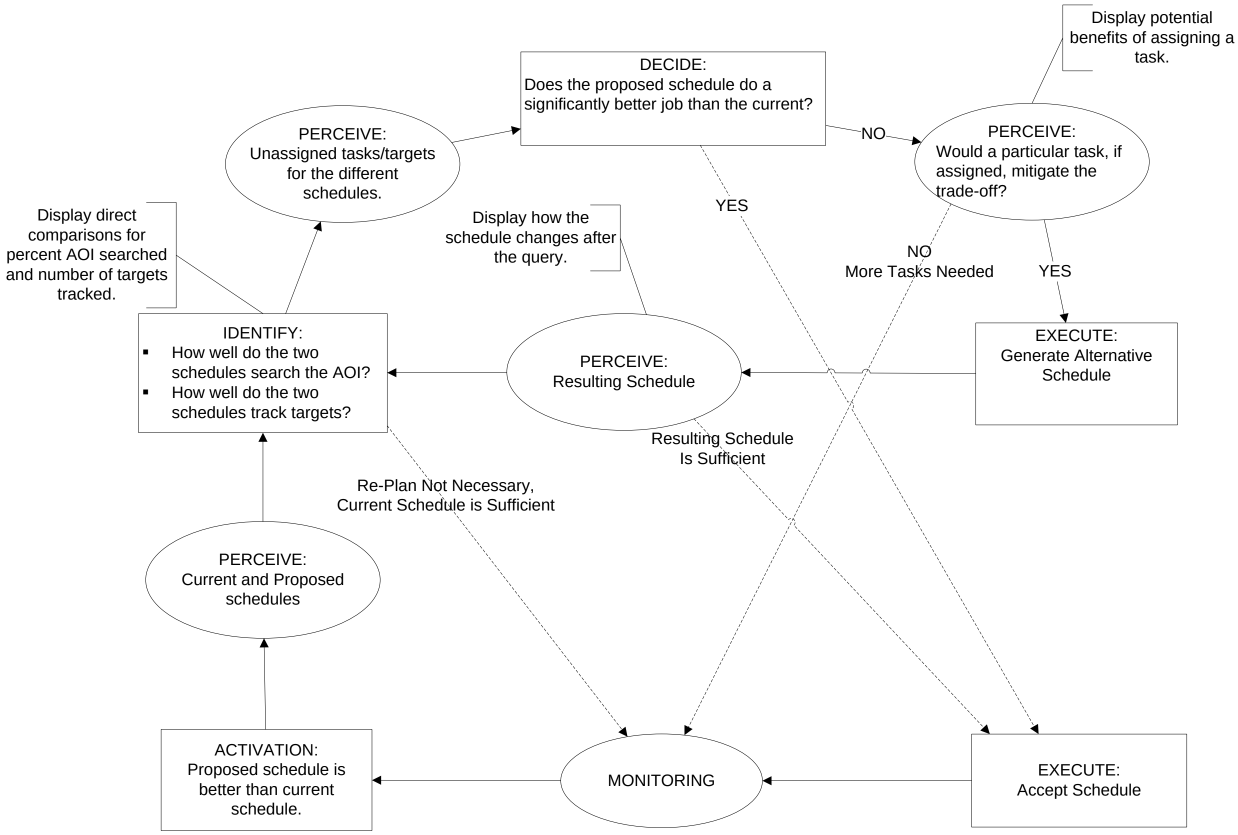


Figure 4: Decision Ladder with Corresponding Display Requirements

The detailed analysis of the cognitive processes involved and the knowledge states required in the decision making process leads to the development of functional and information requirements, that will be presented in a subsequent section. The next section address the situation awareness requirements generated from the event flow diagram and the decision ladders.

3.5 Situation Awareness Requirements

Situation Awareness (SA) can be generally defined as “the perception of the elements in the environment within a volume of time and space, comprehension of their meaning and projection of their status in the near future” (Blanchard & Fabrycky, 1998). This definition divides SA into three levels: perception, comprehension and projection. Maintaining these three levels of SA is a critical aspect in successfully performing missions involving multiple UVs.

The first level of SA is the perception of information. Efficient perception of the necessary information can produce correct mental pictures and efficient cognition of a scenario. The second level of SA is comprehension. Comprehension is the integration of multiple pieces of information and the ability to determine their relevance to one's goals. The third level of SA is projection, where an operator uses the knowledge of the current state of the scenario to anticipate future states and events, allowing for timely and accurate decision-making.

Based on these three levels of SA, a requirements matrix was created, derived from the event flow diagram. Next to each SA requirement is the particular decision or process in the event flow diagram from which the requirement was derived. For example, a D1 next to a requirement indicates that the requirement was derived from the decision in the event flow diagram with the same D1 identification. Similarly, a P1 indicates that the requirement was derived from the process labeled P1. Table 1 shows the full SA matrix for this hybrid CTA.

Table 1: Situation Awareness Requirements

Level I (Perception)	Level II (Comprehension)	Level III (Projection)
Task Management		
- Task Locations (D2, D3, D4, P1) - Task Priorities (D2, D3, D4, P1) - Task Window of Start Times (D2, P1) - Is task assigned or unassigned (D2)	- If unassigned, should the task be assigned (D2) - Show which UVs are allowed to perform a task (P1, D2, D6) - Show which UVs are capable of performing a task (P1, D2, D6)	- If assigned, estimated time of completion (D1, D2)
Target Management		
- Target last known location (D3, D4) - Target last known velocity (D3, D4) - Target's likely location (D1, D3, D4, P1)	- Is target assigned or unassigned (D1, D3, D4) - Is target found, recently lost, or lost (D1, D3, D4) - Show each target's obstacles (D3, D4)	- When will the target be considered lost? (D3, D4) - If assigned, estimated time of completion (D1, D3)
Schedule Management		
- When is the automation's proposed schedule appreciably better than the current schedule? (D5, D6) - Confirmation that a schedule has been accepted (D6, P3) - Indicator that a task has been given to the automation as a query (D6, P2)	- Comparison between the current schedules' and proposed schedules' estimated coverage of the AOI (D6) - Comparison between the current schedules' and proposed schedules' ability to track the targets (D6) - Show unassigned tasks for each schedule (D6, P2)	- Show potential benefits for assigning each unassigned task (D6)
Mission Management		
- Show UV locations and fuel values (D1, D2) - Show each UV's obstacles (D2) - Show estimated position of targets - Show UVs position history (D1) - Show UV sensor ranges and capabilities (Search vs. Track) (D1) - Show UV range (D1, D2, P1)	- Determine when each UV will need to refuel (D1) - Determine when the UVs will be occupied (D1)	- Show UV's current range given current fuel and distance away from base (D1, D2, P1) - Show for how long a UV is estimated to be occupied into the future (D2)

3.6 Functional and Information Requirements

The hybrid CTA results in the functional and information requirements for decision support design. The functional requirements specify system behavior and required operations (Blanchard & Fabrycky, 1998). The various information requirements support each system function by specifying what needs to be presented to aid the operator's cognitive processes.

The functional and information requirements have been derived from the event flow, decision ladders, and finally the SA requirements matrix. Table 2 shows the primary functional requirements grouped with corresponding sub-functions. Table 3 shows the information requirements which correspond to each primary function.

Table 2: Functional Requirements

Functions	Sub-Functions
SEARCH AOI	▪ **Add and Edit Search Tasks** - Specify Task Location - Specify Task Priority - Specify Window of Opportunity - Specify UVs allowed to perform task ▪ **Delete** - Delete Task
TRACK TARGETS	▪ **Edit Track Tasks** - Specify Task Priority - Specify Window of Opportunity - Specify UVs allowed to perform task
MANAGE SCHEDULE	▪ **Accept Proposed Schedule** ▪ **Assign Task / Query Automation**

Table 3: Information Requirements with Corresponding Functions

Functions	INFORMATION
SEARCH AOI	- Show all UVs' locations and fuel values - Show all UVs' schedules - For all assigned tasks, indicate which UV will perform the task. - Show UV's sensor range - Show UV's obstacles - Show UV's range - Show all search tasks' locations - Show when each task is scheduled to be performed - Show each task's priority - Show each task's window of start times - Show each task's allowed UVs
TRACK TARGETS	- Show all targets - Indicate how long a target has been lost. - Show all targets' last known position and last known heading - Show best estimation for where each target is likely to be and where UVs have already searched.
MANAGE SCHEDULE	- Efficient visualization for comparing schedules – specifically each schedule's ability to cover the AOI and each one's ability to track all targets. - Specifically show tasks unassigned by a particular schedule. - Indicate that a schedule has been accepted. - Indicate which task has been queried to the AP. - Indicate that the AP has been queried. - Show specifically how the schedule changes as a result of assigning a particular task.

3.7 Summary

The hybrid CTA details the functional and information requirements that any interface must support in order for an operator to successfully complete a multi-UV search and track mission with embedded automated planners. The next section presents a proposed conceptual interface designed for this research initiative, and shows exactly how the various requirements generated from this analysis have been incorporated into the interface.

Chapter 4: Design

This chapter presents the design of the primary display, which includes a configural decision support display called the Schedule Comparison Tool (SCT), developed for multi-UV schedule management in dynamic missions where replanning is essential for search and track mission success. Explanations of the interface display functionalities, appearances, and usages are outlined, and the rationale behind the SCT's configural design is discussed.

4.1 Primary Display

The primary display is shown in Figure 5. The main feature of the interface is a map area. Below the map area is a performance graph, timeline section, and a chat window. These components will be discussed in detail below.

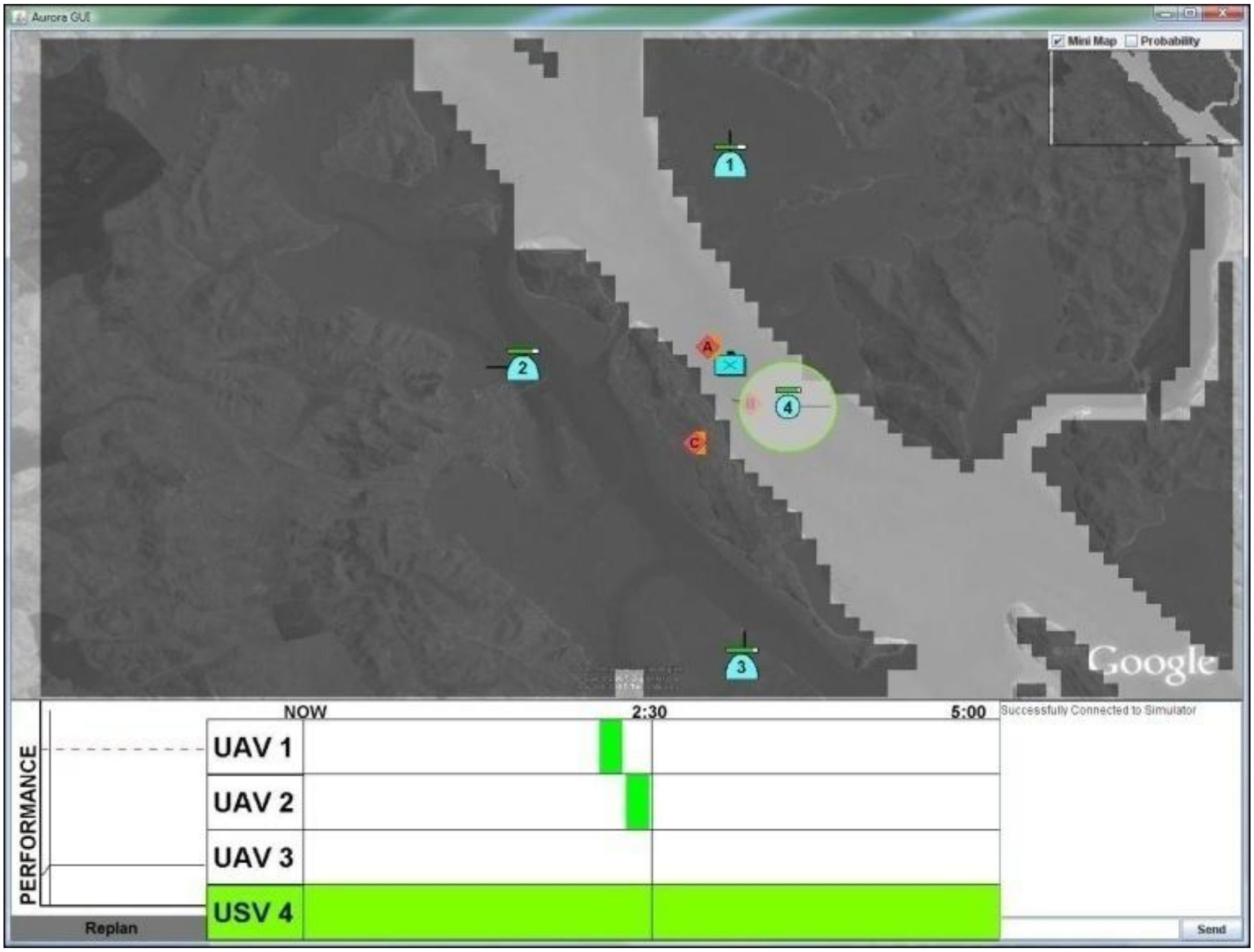
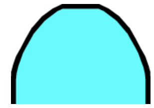
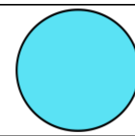
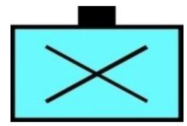
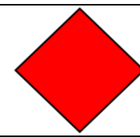
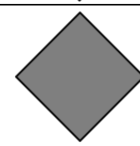
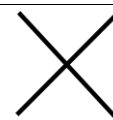


Figure 5: Primary Display

4.1.1 Main Map

The main portion of the primary display is comprised of the main map section. This area represents a bird's eye view of the AOI. The locations for the vehicles, targets, and tasks present in the AOI are represented by the various symbols shown in Table 4.

Table 4: Interface Symbology

Unmanned Aerial Vehicle	
Unmanned Surface Vehicle	
Military Base / Refuel Location	
Found Target	
Lost Target	
Task Location	

In order to promote overall geo-spatial awareness for multiple vehicle operations, the main map area supports the ability to zoom and pan. Because it is paramount to anchor views to prevent operators from becoming "lost" in a search task and to maintain high situation awareness, a mini map is shown in the upper right with a view of the entire map at all times. A rectangular box is shown in Figure 6 within the mini map to indicate where and how much of the entire map is seen through the main map area. This view can be toggled with a check box in the upper right corner of the map.

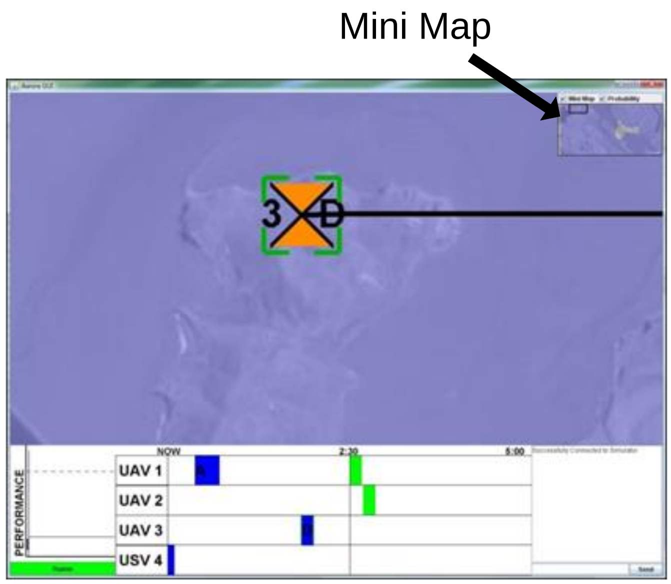
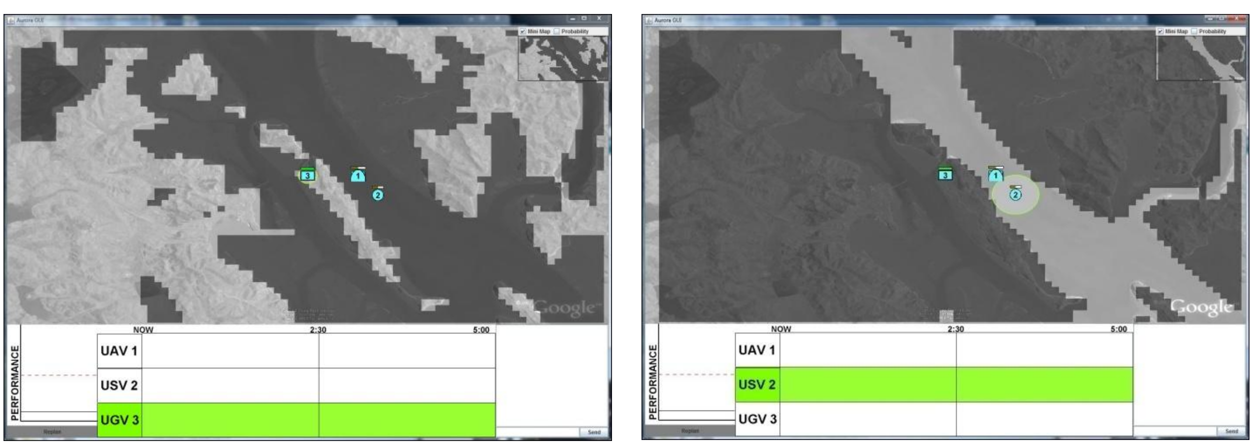


Figure 6: Zoomed in view of the upper left of the AOI showing Task D currently assigned to UV 3

In the map section, obstacles and impassable areas are represented as darkly shaded areas. These are shown in the map area per selected vehicle. For example, impassable areas for one type of UV may be very different from another, so these shaded areas will appear and disappear as the operator selects different vehicles. Thus, the dark gray areas give the operator a sense of where a given UV is allowed to go when managing tasks. In Figure 7(a), UV 3 is selected and, because it is a ground vehicle, the water areas within the AOI are grayed out. Similarly in Figure 7(b), UV 2, which is a ship, is selected and the land areas surrounding the central river are grayed out. It is critical that operators not confuse the constraints of the different vehicles so this display approach was chosen to avoid mode confusion. Mode confusion occurs when operators confuse the mode of operation they are in, which is a primary concern in multiple vehicle control (Cummings, Platts, & Sulmistras, 2006).



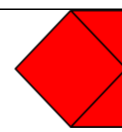
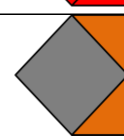
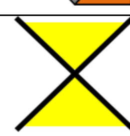
(a) Ground Vehicle Selected **(b) Water Vehicle Selected**

Figure 7: Obstacles per Selected Vehicle

UVs are displayed as the numbered blue symbols, representing that the vehicle is friendly. In general, the symbology conforms to MIL-STD-2525 (for instance the 'Military Base' symbol is used to represent the operators' base of operations) (DoD, 2006). The red color indicates that a vehicle is hostile. The red diamonds represent targets that need to be tracked. A black X symbol with colors on top and bottom represents a location that is scheduled to be searched. The targets and the Xs are designated as tasks and have their own identification alpha-numerics. All UVs are given a number and all tasks are given a letter. For example, Figure 5 shows four UVs with identifications 1 through 4 and three targets with the identifications A, B, and C. Tasks with both a number and a letter correspond to the identification of the UV scheduled to perform the respective task. Figure 6 shows a zoomed-in view of search task D with a number 3 included in its symbol, indicating UV 3 is currently assigned to perform task D.

All tasks and targets have an associated priority. As the AP calculates schedules to propose to the operator, these priorities are taken into consideration. The AP attempts to include higher priority tasks into the schedule before including lower priority tasks. The priority associated with a task or target is shown as a colored area connected to the symbol. Table 5 shows Red, Orange, and Yellow areas added to the task and target symbols to indicate a priority of high, medium, or low respectively.

Table 5: Colored areas added to symbols to indicate priority

High Priority Found Target	
Medium Priority Lost Target	
Low Priority Task	

4.1.2 Uncertainty Visualization

One key information requirement that was revealed in the CTA was the need for perception of likely target locations. Since dynamic targets (such as trucks, mobile surface-air missile sites, etc.) move, operators (and the AP) need an estimate of where a known target is likely to be given a particular time horizon. Thus, all dynamic targets with an initial known location have a probabilistic distribution associated with the location variable. These distributions enable the AP to keep track of both where a target could be, as well as where it most likely is.

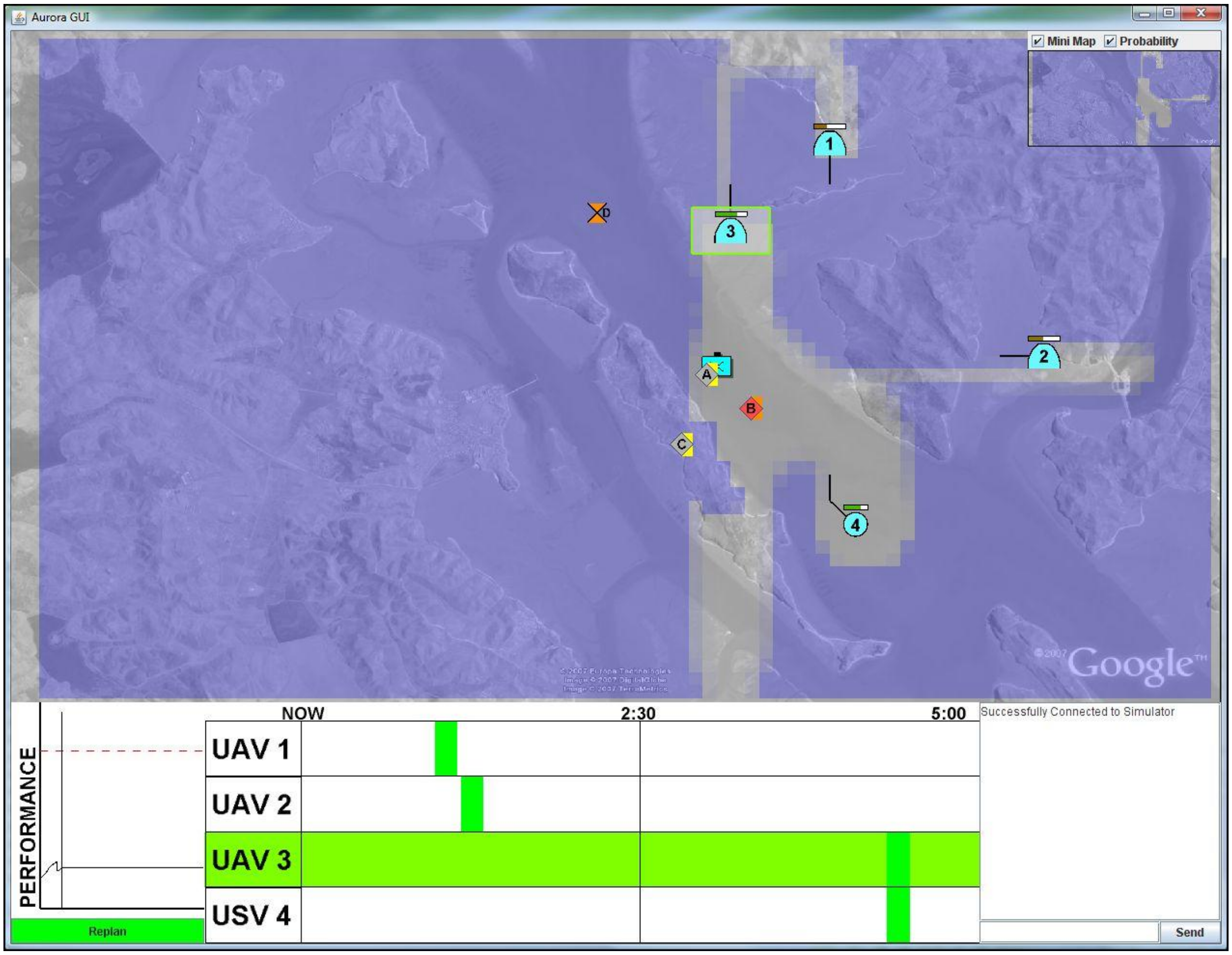
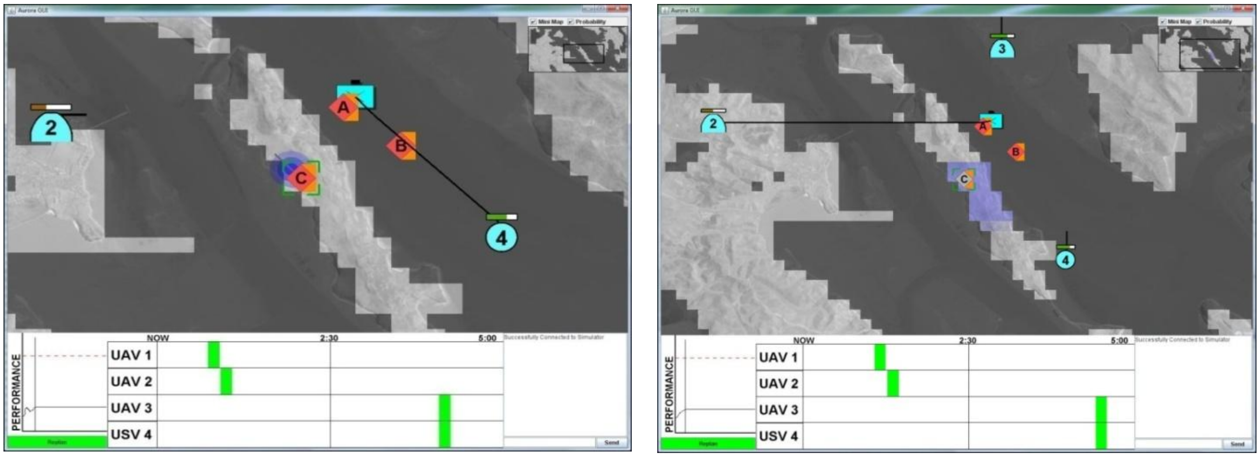


Figure 8: Primary Display Showing the Uncertainty Visualization

In Figure 8, target B is depicted in red, indicating that the AP estimates its locations with a high probability. During this time, the probability distribution (or the likelihood) associated with an individual target is a simple calculation based on its last known trajectory. The area covered by the uncertainty visualization follows the target trajectory, which grows over time to account for a growing uncertainty as to where the target is. Figure 9(a) shows this growing uncertainty for target C. If a UV travels to the position of highest probability for the target location within the distribution and does not find the target, or if a long enough time has transpired so that the distribution for the target is larger than a UV's sensor range, the target will be designated as lost and its probability distribution is then calculated throughout the entire map instead of along a single trajectory as shown in Figure 9(b). For both the probability distribution calculated based on the trajectory (Figure 9(a)) and calculated throughout the entire map area (Figure 9(b)), darker shades of blue indicate higher probabilities.

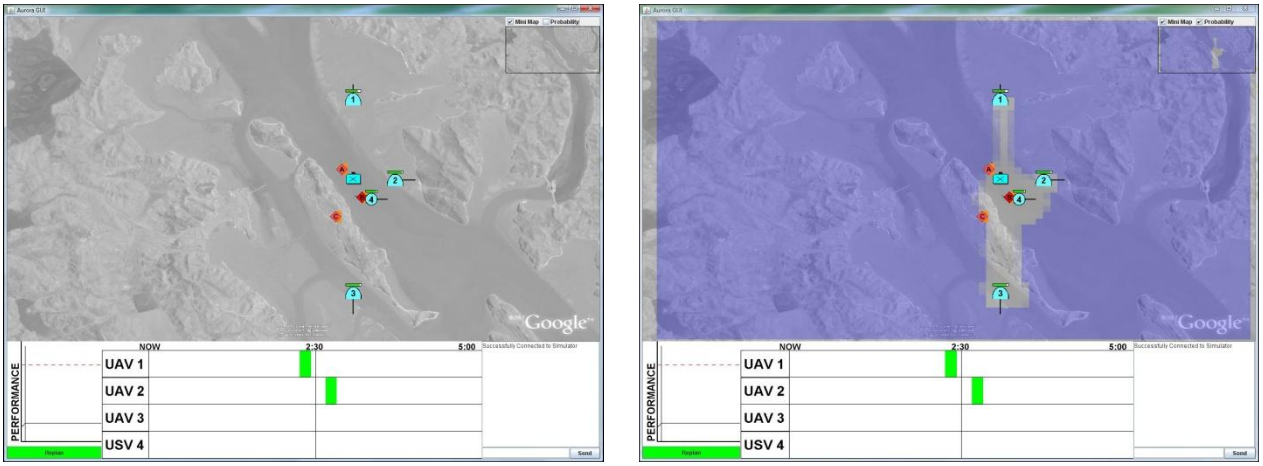


(a) Calculated based on last known trajectory **(b) Calculated throughout the map area**

Figure 9: Uncertainty Visualizations for Target C

Due to the potential clutter introduced by the uncertainty visualizations, a target's unique probabilistic distribution will only be visible by a mouse over effect or when that target is selected. This context-sensitive approach operates on a per-task basis in an effort to improve situation awareness, and reduce display clutter.

In addition to searching for last known trajectories of targets, the AP also calculates a probabilistic distribution over the entire map area for an "unknown" target. This distribution, seen in Figure 8, is known as the global uncertainty visualization. If a UV has no tasks scheduled, the UV will search for an "unknown" target, which represents a target of opportunity. Also, as a UV travels between tasks, the UV will pick a route so as best to search for an "unknown" target and still arrive to the task on time. The UVs are always searching as they travel; so if a target is opportunistically found, it is presented to the operator as a new target that needs to be tracked. In the map area in Figure 8, the UVs have no assigned tasks, so they are scheduled to search the darker blue areas. The uncertainty visualization (labeled Probability) can be toggled, as seen in Figure 10, by one of the check boxes in the upper right corner of the map.



(a) Turned Off (b) Turned On

Figure 10: Primary Display with Global Uncertainty Visualization Turned Off (a) and Turned On (b)

4.1.3 Direct Manipulation

Direct manipulation is an important part of this interface's design. Direct manipulation is the ability for users to directly interact with screen elements to execute some action, as opposed to having to navigate unwieldy and time consuming embedded windows (Shneiderman, 2005). One example of how this interface incorporates this functionality is if the operator wishes to specify a task. Clicking in the main map area at the desired location will bring up the window shown in Figure 11 allowing the operator to specify a task.

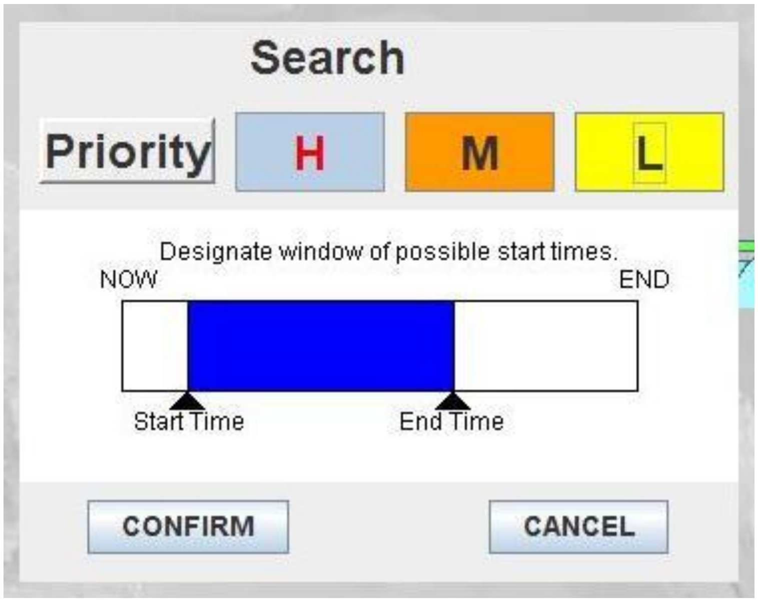


Figure 11: Task Specification Window

In terms of task specification, there are two main attributes of a task that the user can specify, as seen in Figure 11. These attributes are "priority" and "timeline" information. "Priority" is a three mode value: Low, Medium, and High (yellow, orange, and red respectively). "Timeline" information consists of a start time and an end time. The operator can directly manipulate the picture of the timeline by dragging the mouse through this area to select a block of time. The optimization algorithm uses these two pieces of information to determine optimal schedules for all the UAVs.

4.1.4 Timeline

The bottom center of the interface contains a set of time lines that allow the operator the ability to track the temporal progress of the mission, as well as determine when vehicles are in a refueling status. A blue bar in the timeline indicates a task is being performed or scheduled to be performed in the future. Each task's blue bar also has its identifying letter visible over the blue bar in the timeline. White indicates when the UV is idle or en route to another task. Green indicates refueling and red would indicate an out-of-fuel event. A selected UV's timeline is highlighted in a bright green. The bright green is easily differentiable from the green indicating refuel events, and allows for quick perception of the selected UV's time line. As the allotted time for the mission comes to an end, a semi-transparent gray overlay appears over the timeline area. Clicking on a UV's timeline effectively selects that UV. Figure 12 shows with four UVs' timelines with green refuel times, blue task times, and the gray end of mission time visible.

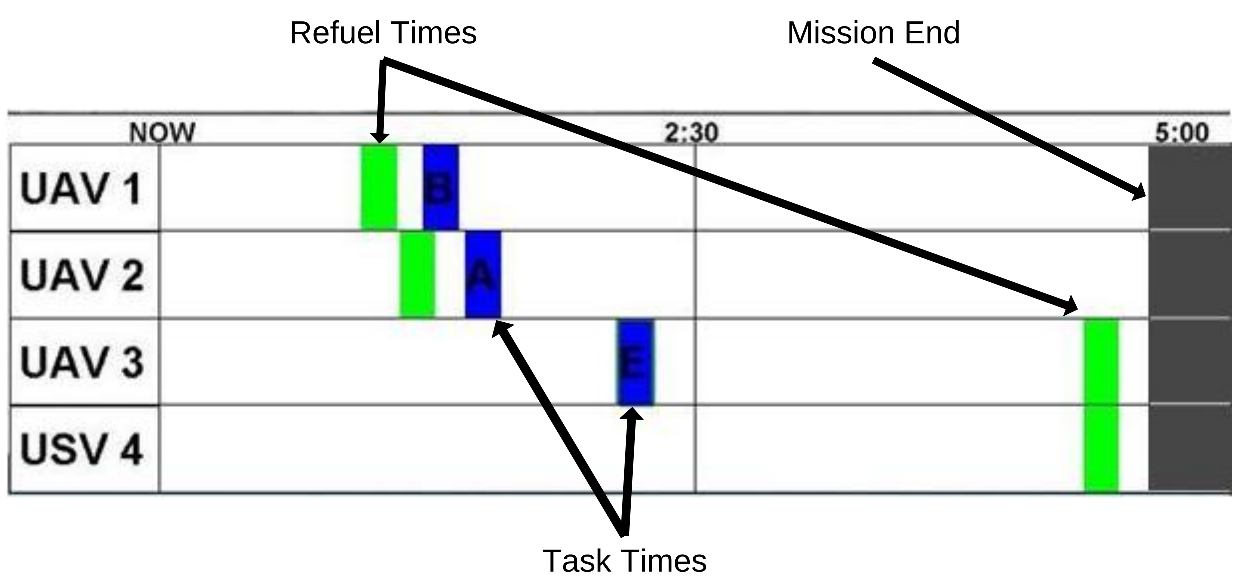


Figure 12: Timeline highlighting task times, refuel times, and the end of mission time

4.1.5 Mission Performance Indicator

The bottom left of the interface contains a graph of performance over time above a "Replan" button. The AP analyzes the current state of the mission and calculates a score based on the amount of area scheduled to be surveyed and the amount of targets scheduled to be tracked. The current performance is then plotted against the predicted performance, which allows the operator to gain situation awareness over the planning accuracy of the AP, and whether intervention may be required.

This intervention can be motivated in one of two ways. The AP is constantly replanning and the interface analyzes each schedule received from the AP. The analysis results in a basic comparison between the most recently proposed schedule and the current schedule. The CTA indicated that when this basic comparison finds the new schedule to be *appreciably* better than the current schedule (given some a priori user-determined weights), the operator should be notified. To perform this comparison, the interface currently calculates the projected percentage of AOI coverage and the percentage of targets schedule to be tracked. These percentages are combined to form a score for each schedule. If the comparison results with the proposed schedule's score greater than the current schedule's score, the operator is notified by the "Replan" button turning green. The operator can then select the "Replan" button, which allows the operator to explore solution alternatives through the Schedule Comparison Tool, discussed below.

Intervention can also occur because the operator determines, through comparison of the two performance graph curves, that the automation is not performing as expected. Thus, the operator does not have to wait for the automation to suggest a new, better plan. At any time, the operator can initiate a replan.

4.1.6 Chat

The bottom right of Figure 8 is a chat box, representative of commonly used programs in the military today. This chat box allows archival communications in real-time with various entities, as well as a location for mission specific message updates.

4.2 Schedule Comparison Tool

The Schedule Comparison Tool (SCT) was developed to address the challenges and design requirements revealed through the hybrid cognitive task analysis discussed in Chapter 3. The purpose of the SCT is to help minimize the intermediary cognitive processes in determining effective schedules that are currently required to get from perception to comprehension and projection, via the levels of situation awareness.

The CTA showed that covering the AOI in an effort to find targets and scheduling already-found targets to be tracked are critical for mission success. The SCT minimizes the cognition required because it directly shows the projected AOI coverage, percentage of task and target completion, and the specific unassigned tasks and targets.

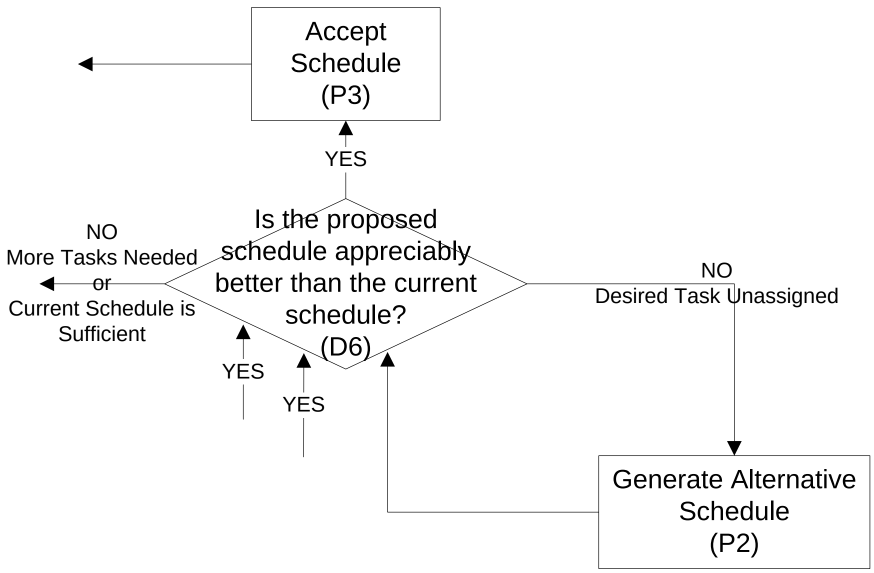


Figure 13: Portion of the CTA's Event Flow Diagram which led to the development of the SCT

The SCT was designed to leverage the configural form because of the need for rapid schedule comparisons as outlined the CTA requirements. Figure 13 shows the portion of the event flow diagram, shown in its entirety in Appendix A, which outlines the process of collaborating with the AP which, in turn, surrounds a critical decision requiring the comparison of multiple schedules. The SCT (Figure 14) integrates several instances of a configural display and is intended to be used as a quick way to elicit an effective comparison between the possible schedules and allow a human operator to make an informed decision under time pressure.

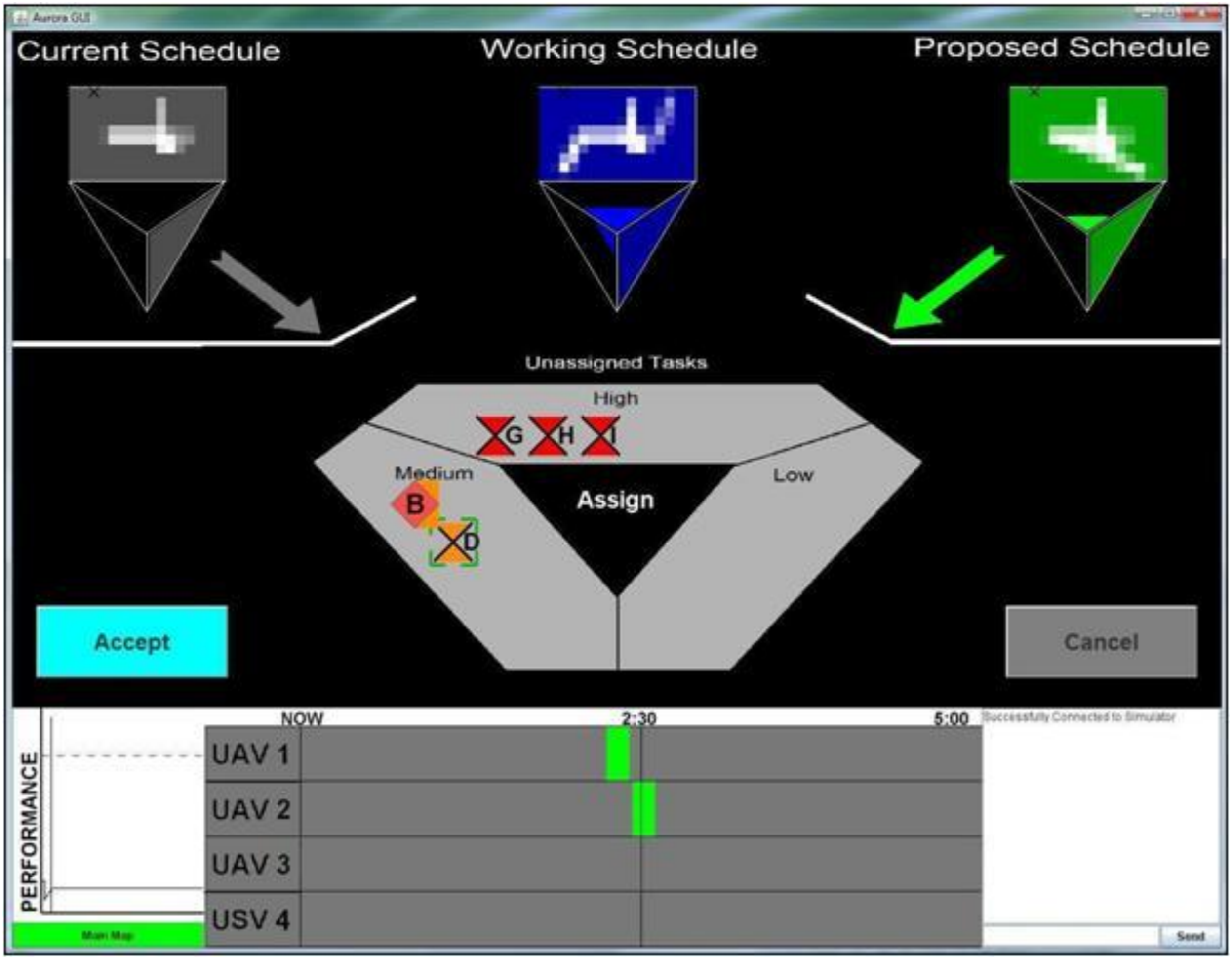


Figure 14: Schedule Comparison Tool (SCT)

The SCT presents three different schedules for the operator to compare. The three schedules are the current schedule, the working schedule, and the proposed schedule. The current schedule corresponds to the schedule currently being performed by the vehicles to complete the mission. The proposed schedule corresponds to the most recently received schedule generated by the AP. The working schedule corresponds to the schedule generated by the human operator "working" with the AP. The process by which the working schedule is generated is further described below.

4.2.1 Configural Displays for Schedule Comparison

The Schedule Comparison Tool (SCT) (Figure 14) leverages the idea of direct perception-interaction in the form of a configural display. A configural display integrates several pieces of information and displays them in a single geometrical form that maps multiple variables. Changes in the individual variables cause the form to vary (Bennet, 1992). Configural displays enable faster reasoning about complex, multivariate problems by reducing a cognitively complex problem to one that is supported by less demanding perceptual reasoning (Gibson, 1979).

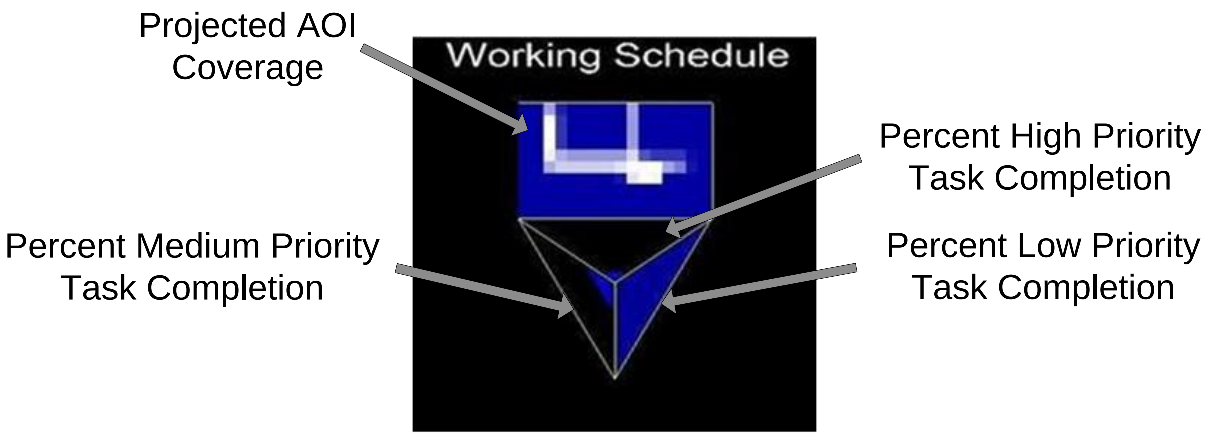


Figure 15: Configural Display Representation Found in the SCT

The three different figures across the top of the SCT represent integrated configural displays that allow operators the ability to almost immediately compare solution quality. Figure 15 shows a single instance of the configural display that corresponds to the working schedule. The rectangle on top of the triangle represents coverage area, which, as shown by the CTA, is a critical concern in a search and track mission. The level of shading depicts how much of the area has been and is scheduled to be covered by all the vehicles. The triangles represent how many high, medium, and low priority tasks will be covered by the associated schedule. The more the triangle is filled in, the more tasks that are scheduled to be completed. While the actual numbers will be able to be seen through a scroll over feature, representing both the tasks and the coverage area through gradient shapes allows operators to perform satisfying comparisons very quickly, which is especially critical in this dynamic domain where solutions are valid for short periods of time.

4.2.2 Configural Display for the "What-If" Section

The lower half of the SCT shown in Figure 16 represents the "what-if" section of the SCT, which allows operators to explore the solution space, giving them greater flexibility in solution generation as well as a way to understand the automation's solution. Mapping the same high, medium, and low relationships as above, this representation gives operators more details about which specific tasks are unassigned. All the symbols in Figure 16 represent tasks that are not yet assigned, so there are 3 high, 2 medium, and 0 low priority tasks unassigned. Using direct manipulation, operators drag the icon of the task they want to include in the schedule into the "Assign" triangle, and the resulting schedule is then seen in the upper blue working schedule configural display.

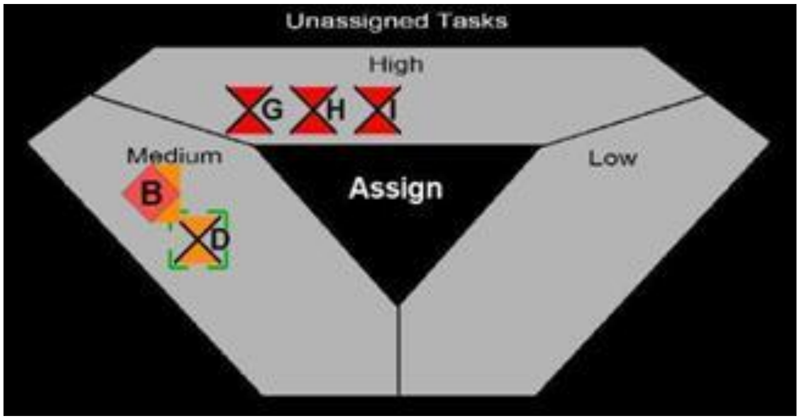


Figure 16: SCT "what-if" section

While the unassigned tasks visible in the region depicted in Figure 16 always correspond to the working schedule, it is possible to view the unassigned tasks for both the current schedule and the proposed schedule. Clicking on either schedule's configural display will load that schedule into the working schedule. The selected schedule's and the working schedule's configural displays will be identical, and the unassigned tasks for the selected schedule will be visible.

4.2.3 Collaborating with the Automated Planner

Figure 17 shows the SCT after transitioning from the primary display. The working and proposed schedules are identical as the operator has not yet queried the AP. The green "Replan" button indicates the proposed schedule is *appreciably* better than the current schedule, and this comparison is seen in the configural displays. The proposed schedule both searches the AOI and performs medium and high priority tasks better than the current schedule.

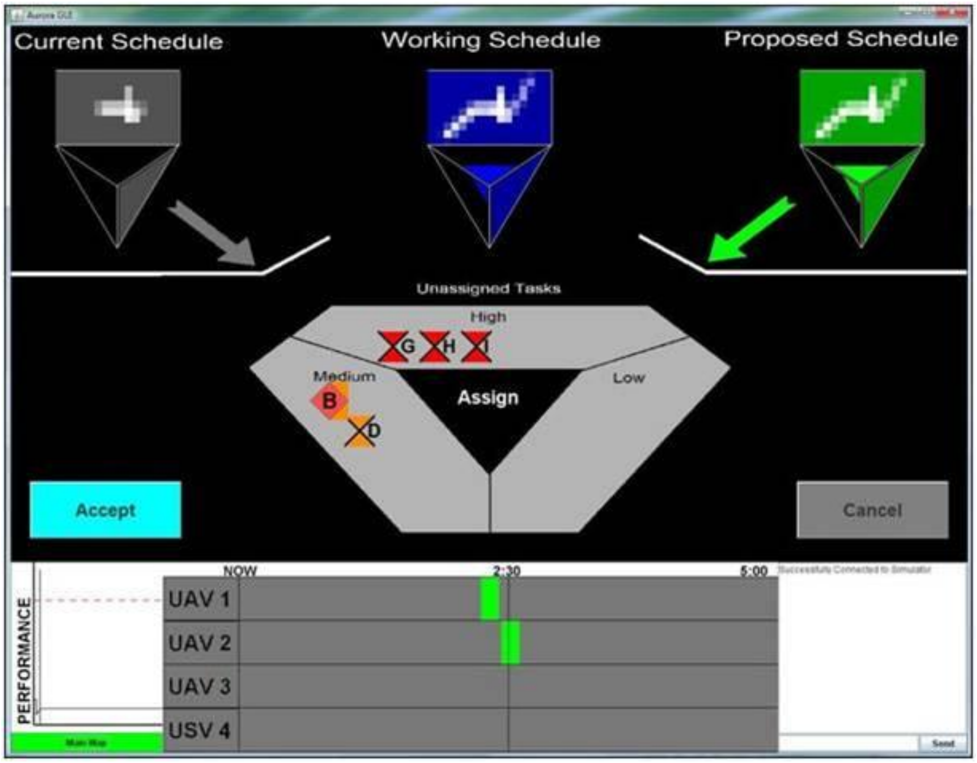


Figure 17: Schedule Comparison Tool before Querying Task D

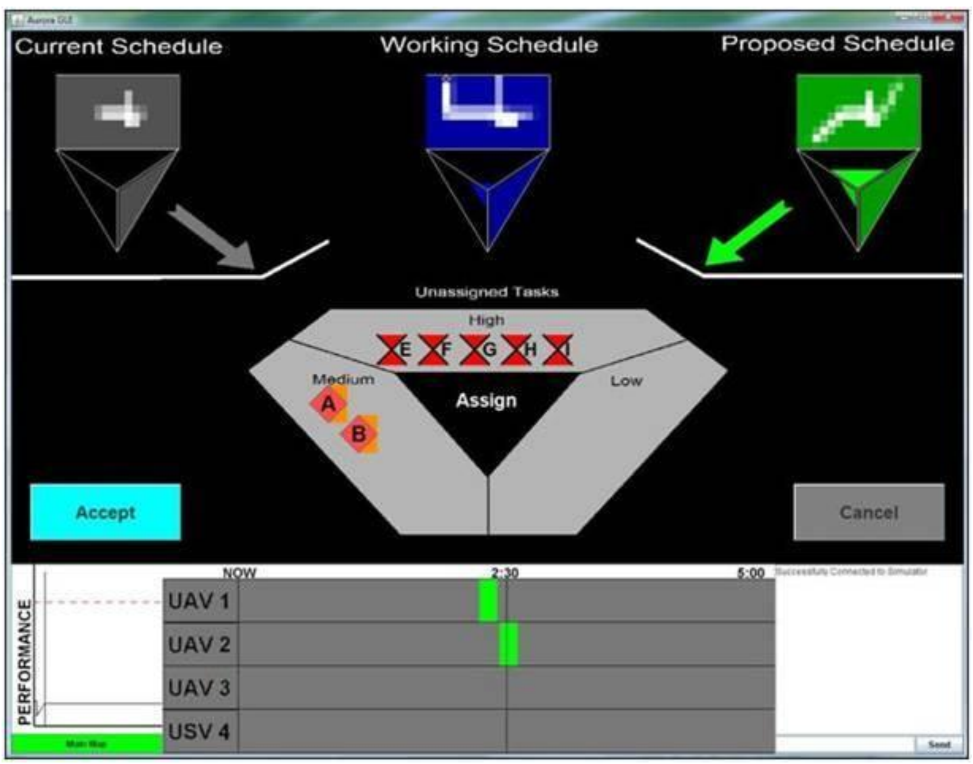


Figure 18: Schedule Comparison Tool after Querying Task D

Figure 18 shows the result of dragging task D into the "Assign" area and querying the AP if it is possible to include task D into a schedule. The current and proposed schedules remain the same, while the working schedule's configural display changes to present the critical information for the new schedule.

An interesting aspect of the central area is its ability to answer the "what if" question by showing the trade-offs between the previous schedule (Figure 17) and the new schedule (Figure 18). The SCT includes animated transitions to allow the operator to visually follow the various aspects of the original schedule that change to result in the new schedule. Specifically, after task D is incorporated into the schedule, tasks E, F, and A can no longer be included in the schedule.

The operator may perform queries until a desirable schedule is generated. During this time, the proposed schedule's green configural display is updated with the AP's latest schedule which is not affected by the operator's queries. Similarly, the current schedule's gray configural display is updated as occasional changes do occur. Thus, as the operator collaborates with the AP, sufficient situation awareness of the two other possible schedules can be maintained.

4.3 Summary

As motivated by the CTA in Chapter 3, a schedule management decision support tool is needed that allows a single-operator to control multiple heterogeneous UVs performing a search and track mission. In particular, this tool must allow for the operator to both compare schedules generated by an automated planner and collaborate with the automation such that human input can be provided. Given the functional and information requirements, a primary display was designed to allow for detailed geo-spatial situation awareness of the mission search and track progress. Direct perception interaction was leveraged to allow the operator to intuitively and efficiently create tasks, select vehicles, and view context sensitive information.

In conjunction with the primary map display, a schedule comparison tool (SCT) was developed to provide high level global awareness as to how AP solutions compare to one another in a quick, cognitively effortless fashion. However, the SCT also allows operators the ability to explore the local solution space and determining at a lower level, which tasks are left unassigned. This is critical because automated algorithms can never know a priori all the variables and constraints that are important in dynamic command and control environments. This kind of what-if tool allows operators the ability to ensure that their intentions are explicitly addressed, while also allowing them the ability to see how their proposed schedule compares to the automation's as well as the current schedule.

The next chapter presents a cognitive walkthrough experiment conducted to determine how intuitive human subjects found the new interface to be.

Chapter 5: Cognitive Walkthrough

Given the interface described in the previous chapter, it is of primary interest to understand how operators use the interface to search the solution space to ensure the interface actually provides decision support. Primary concerns include how intuitive operators find the interface to be, and how effective their combined performance with the computer is for overall mission success. To this end, five subjects participated in a cognitive walkthrough of the decision support tool outlined in Chapter 4.

5.1 Cognitive Walkthrough

A cognitive walkthrough is an implementation of user-centered design, and is a process by which the design is significantly influenced by inputs from end-users and field experts (Abras, Maloney-Krichmar, & Preece, 2004). The cognitive walkthrough process focuses on how well an experienced user can perform the various tasks required by the interface for mission success. Through this process, ease of learning, ease of use, memorability, effectiveness and utility, among others, are investigated through exploration of the system (Polson & Smith, 1999). To investigate these various interactions, specific questions will be answered by the cognitive walkthrough (Wharton, Rieman, Lewis, & Polson, 1994):

1) Will the user try to achieve the right effect?
2) Will the user notice that the correct action is available?
3) Will the user associate the correct action with the effect that the user is trying to achieve?
4) If the correct action is performed, will the user see that progress is being made toward the solution of the task?

5.2 Experiment

Participants in the cognitive walkthrough included two graduate students with extensive backgrounds in UAV operations and human-computer interaction, two undergraduate students with extensive video-gaming experience, and one USAF 2nd Lieutenant .

Subjects were first presented with the PowerPoint tutorial found in Appendix C which explains the basic features of the interface. The symbology and the meaning of the configural displays in the Schedule Comparison Tool (SCT) were explained, and the processes for creating tasks and querying the Automated Planner (AP) with a task via the SCT were described in detail.

After going through the tutorial, subjects performed a single 15 minute mission. During the mission, the subjects utilized four heterogeneous unmanned vehicles (UV) in order to search the area of interest (AOI) for targets. Once targets were found, they needed to be monitored for possible movement. To perform the mission, subjects were expected to create search tasks at various locations in the AOI and use the SCT to assign the tasks to UVs. As targets were found, subjects were forced to choose between allocating UVs to track the targets or to continue searching the AOI.

While the subjects performed the mission, they were engaged in an informal discussion. During this discussion, subjects were encouraged to voice their thought processes for carrying out the mission and to specifically mention anything they found not very intuitive or confusing. They were also asked throughout the mission on the specific meanings of various aspects of the primary display and the SCT.

5.3 Results and Discussion

During each subject's session, an informal discussion was held to investigate the subject's reactions to the various aspects of the interface. Upon completion of the mission and the informal discussion, the subjects were asked to answer a series of usability questions, which will be discussed below. The section on user feedback focuses on some positive and negative aspects of the interface that were mentioned frequently.

5.3.1 Usability Questions

Seven usability questions, partially based on the NASA-TLX questionnaire (Hart & Staveland, 1988) (Rubio & Diaz, 2004) (Selcon & Taylor, 1991), were used to rate the interface on a Likert scale from 1 to 5 which will be discussed in detail below:

1) How much perceptual effort is required to understand and use the interface?
2) How much mental processing is required to understand and use the interface?
3) How well would an operator perform with this interface?
4) How confused would an operator be using this interface?
5) How well does the interface give feedback to the user?
6) How much in control is the operator using the interface?
7) How satisfied vs. frustrated an operator would feel using the interface?

The five subjects' answers to these questions are shown in Appendix D, and the averages are presented in Figure 19. The averages, modes, and standard deviations for each question are presented numerically in Table 6.

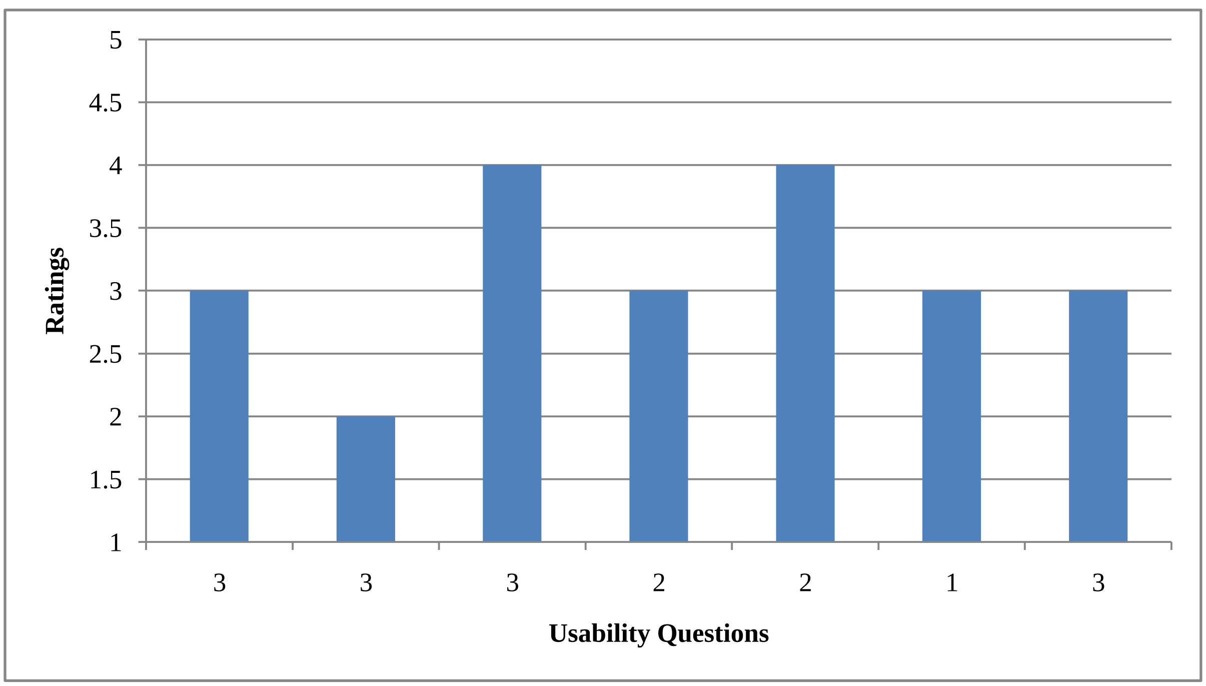


Figure 19: Usability Ratings

Table 6: Usability Ratings: Average, Mode, Standard Deviation

	Average	Mode	Standard Deviation
Perceptual Activity	2.9	3	1.14
Mental Activity	2.6	2	.89
Projected Performance	3.6	4	.54
Confusion	2.4	1	1.67
Feedback to User	3.2	3,4	.83
Control	2.2	2,3	.83
Satisfaction	3.4	3	.54

1) *Perceptual Activity*. The scale ranged from 1 (little perceptual activity required) and 5 (much perceptual activity required). The interface produced mixed responses about the perceptual effort required to view the many pieces of the mission. The two subjects that rated the perceptual effort as high commented on the fact that there were numerous tasks and various other pieces of information to monitor. Conversely, the three subjects that indicated they used less perceptual effort commented on the simplicity of the design and lack of clutter in the interface. These results reinforce the design decision to consolidate information into the configural displays to simplify the mission. However, these results also allude to the fact that the mission is still complicated and requires the integration of many pieces of information.

2) *Mental Activity*. The scale ranged between 1 (little mental activity required) and 5 (much mental activity required). All but one subject gave lower scores indicating that the interface does not require much mental activity to understand the mission and compare schedules using the SCT. Three subjects praised the configural displays as a quick and efficient way to compare schedules and as an effective tool at predicting the performance of the mission with each schedule. The one subject that selected a four for mental activity also praised the interface for its clarity, but commented that there was a learning curve to become proficient. This may speak more to the disparity between the tutorial and the real interface than any inherent problem with the interface itself. The animation and fluid transitions present in the real interface are not captured by the PowerPoint tutorial, and all subjects commented on the animation upon transitioning to the SCT for the first time. An interactive tutorial may be a more prudent choice for a training platform.

3) *Projected Operator Performance*. The scale ranged between 1 (poor performance) and 5 (excellent performance). The scores the subjects gave the interface on projected operator performance averaged out to 3.6. This score indicates that the interface will help operators perform just slightly above average and speaks of the occasional issue with the AP's schedules which all subjects experienced. These issues will be discussed in more detail below. Most of the time, however, subjects were able to produce a desirable schedule with the SCT, and subjects commented that "the interface is easy to use"

and that it "does most of the work for you." One subject felt creating a good schedule with the SCT, reduced his workload, such that he could attend to other tasks.

4) *Confusion*. The scale ranged from 1 (not at all confusing) and 5 (very confusing). Subject interviews revealed there were two primary areas where confusion could be an issue, 1) Configural display interpretation, and 2) AP behavior. The responses from this question mirrored this bimodal distribution with the three subjects selecting a lower level of confusion focused on the configural display (as reflected by the mode of 1), while the other two subjects selecting high levels of confusion were focused on the AP. Those subjects that focused on the configural display commented on how well the design simplifies the large amounts of information. For the subjects who selected a higher level of confusion, they generally commented on behavioral aspects of the AP that produced some opacity about what the algorithm was doing. These aspects of the AP will be further discussed in the next section on feedback.

5) *Feedback to User*. The scale ranged between 1 (poor feedback) and 5 (excellent feedback). The system's communication of its intent and actions is a critical assessment of an interface (Nielsen, 1993). Moreover, the operator needs to know that his or her commanded action was actually performed. Although all subjects rated the interface as having slightly above average feedback, the subjects gave very clear reasons why they did not rate the interface as having excellent feedback. As will be explained in more detail below, there were times when a better schedule that intuitively looked feasible could not be produced with the SCT. Subjects commented that the interface gave no indication as to why, after querying a particular task, that task could not be assigned. This lack of feedback led to subjects desiring ways to micromanage various aspects of the mission and also led to the states of confusion discussed previously.

6) *Control*. The scale ranged between 1 (lack of control) and 5 (completely in control), in terms of human operator control. Three subjects did not consider themselves to have much control over the mission. One subject commented that "the automation pretty much handles everything" and another said "the operator only seems to be providing hints to the algorithm". It is interesting to note the emphasis the subjects gave to their interaction with the algorithm. In order to perform the mission, subjects created, edited, and deleted tasks, accepted, compared, and rejected schedules, and interacted with the SCT to work with the opaque algorithm to produce new schedules. The subjects performed these various tasks with little trouble. However, because the AP occasionally could not produce desirable schedules, all subjects expressed a lack of control while interacting with the interface.

7) *Satisfaction vs. Frustration*. The interface was rated between a score of 1 (very frustrated) and 5 (very satisfied). Although all the subjects were frustrated with the AP on occasion, there was a general feeling of satisfaction with the interface. None of the subjects were very satisfied with the interface because of the feeling of a lack of control over the mission, but no one actually identified themselves as frustrated. Three subjects' comments focused on how easy it was to perform the mission. One subject said "it is easy to achieve good performance and actually perform the tasks".

5.3.2 Usability Correlations

In addition to the subjects rating these seven aspects of their experiences, they were rated by an expert external observer on the extent to which they interacted with the AP on a similar 5 point scale. Expert subjective assessment of operator performance has been shown to be a reliable indicator of performance (Bell & Lyon, 2000). The scale ranged between 1 (low activity, interacting with the interface less than once every 45 seconds) to 5 (high activity, interacting with the interface more than once every 10 seconds). Using this rating, correlations between activity and the various usability questions were calculated.

Strong correlations ($p = .629$) were found between both the "feedback" and "control" questions and the interactivity of each subject with the AP. This correlation indicates that subjects who interacted more with the AP tended to think they had more control and that the feedback was better. This result makes sense because as all subjects experienced at least one poor schedule, the subjects who interacted more with the AP experienced many more good schedules. Additionally, when the subjects who interacted more with the AP experienced poor schedules, they were more willing to continue working with the interface at trying different strategies to solve the problem. This result suggests that more familiarity with the interface could improve user experience, and moreover people who take the initiative to interact more with the AP are more comfortable with automated solution generation.

An interesting, but weak correlation ($p = -.19$) was found between "mental activity" and the interactivity of each subject with the AP. This correlation means that subjects who interacted more with the AP tended to think they had less mental workload. The implications of this trend are important, and because this trend was existent, although weak, validating this trend should be an area of future research. More interaction, on the surface, would suggest higher mental workload, but these subjects did not perceive it that way. This could be an area that has significant trust implications, i.e., more interaction promotes less mental workload and higher acceptance of the AP.

5.3.3 User Feedback

The command and control resource allocation problems inherent in this search and track mission utilizing four UVs is too large in terms of the number of possible schedules for a human to explore individually via a manual process. However, because of the dynamic aspects of the mission which often result in shifting priorities, the AP can benefit from the intelligent inputs of a human operator. This preliminary data supports the notion that collaboration between an operator and an automated algorithm for mission planning and replanning to potentially generate better schedules is possible. In general, these results demonstrate that high-level graphical interfaces can be designed to promote human-AP collaboration that reduce mental effort, however, adequate feedback and controllability is critical to promote high usability.

More specifically, the cognitive walkthrough demonstrated that while the interface efficiently presents sufficient information to quickly and efficiently compare schedules, it still does not promote adequate collaboration. The interface succeeds at allowing an operator to quickly explore the solution space while taking into account the various tasks, targets, and AOI search requirements; however, exploring the solution space occasionally results in non-intuitive limits on the solution space. There were times where a subject thought a particular task could be assigned, but the AP was incapable of assigning it, and it did not provide adequate feedback as to why. Limitations in the AP algorithm occasionally resulted in tasks sometimes not being assigned. Some of the infeasible tasking resulted from a lack of information presented to the user about the fuel and speed limitations of the different UVs used in the mission. When subjects tried to assign tasks beyond the range of the UVs, the interface failed to show the user why the AP could not assign the task.

While the limitations in the AP could be resolved, no AP will always be correct, so it is critical that some transparency exist into the AP such that operators can determine why certain solutions were generated, and how they could possibly be resolved. With a more transparent AP, users will better understand why individual tasks cannot be assigned, leading to less frustration. With a better understanding of how the AP operates, users should be more trusting of the automation and may be less inclined to micromanage the mission. In addition, more information about UV limitations should be presented in the interface, so users feel less frustrated collaborating with the AP. More ways to improve the interface will be discussed in Chapter 7.

The subjects generally felt that the schedules generated by the AP usually did a good job of intuitively assigning tasks to UVs and searching the AOI for targets. Without the aid of the SCT, the amount of information involved in managing the AP and performing the mission might overload the operator. The scalability of the SCT was also noted. In the current experiment, only four UVs were used.

However, the subjects felt that many more UVs could have been used with more tasks in the AOI without introducing any more work load to the operator. This benefit was due to the SCT providing a layer of abstraction between the user and task assignment. If the SCT is used with more UVs and more tasks, as long as only a few tasks are left unassigned by the AP, there is not necessarily a limit to the number of UVs or tasks this interface can handle. The SCT provides an easy method for querying the AP given a few unassigned tasks, and the configural displays give a view of AOI coverage unaffected by potential clutter from numerous UVs and tasks in the main map display.

On the other hand, the layer of abstraction provided by the SCT was also a cause for concern. Although the AP usually did a good job, all subjects experienced schedules with which they disagreed. This disagreement led to frustration when they could not get the AP to generate a desirable schedule. The primary cause for this frustration was that some particular task could not be assigned by querying the AP. Each time this happened, subjects were able to describe why they thought the AP should be able to assign the task. Figure 20 shows a scenario where two targets are present in the AOI and clearly within the UV's range from base, but the AP could not assign either target.

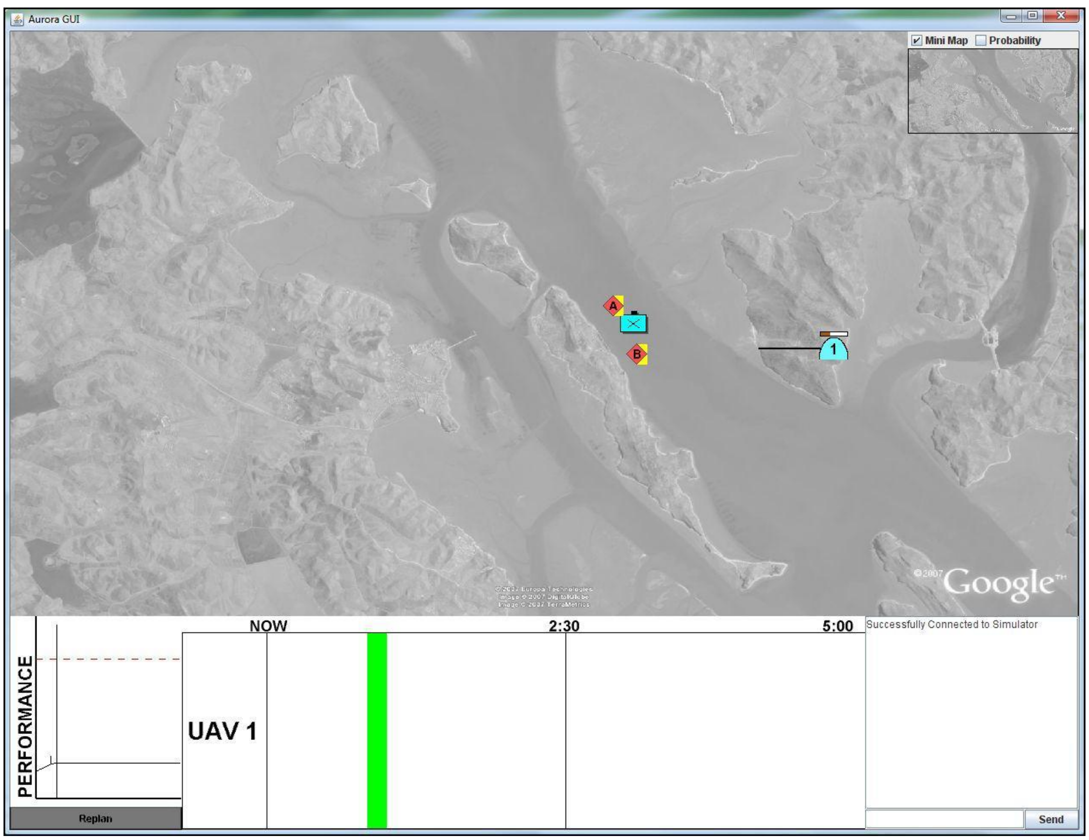


Figure 20: Mission Scenario showing two targets which the AP cannot assign due to an error in the AP

Figure 20 shows an example scenario very similar to those experienced by the subjects that caused some frustration at the lack of feedback. In this figure, a single UV without much fuel is shown heading back to the base to refuel. There are two targets in the AOI that need to be scheduled to be revisited by the UV, but as the grey "Replan" button indicates, the proposed schedule cannot assign either task. In similar scenarios, subjects entered the SCT and queried unassigned tasks, but the AP was not capable of assigning them. The AP could not take into account the future refueling, thus no tasks could be scheduled until after the refueling was complete. An error in the AP caused these limits as to which tasks could be assigned.

Subjects also experienced scenarios where the AP switched assignments at seemingly inopportune times. For example, UV 1 is assigned to task A, and UV 2 is assigned to task B. Task C was created after the last schedule was accepted. Task C is closest to UV 2 and is currently unassigned. When UV 1 and UV 2 approach tasks A and B, a new schedule is proposed that can perform all three tasks. However, upon accepting the new schedule, UV 1 is routed back to base to refuel before going to C. After completing task C, UV 1 is scheduled to refuel again before going back to task A. If UV 1 was very close to task A's location when the new schedule was accepted, upon re-attempting task A, UV 1 must fly over the already surveyed portion of the AOI. If UV 1 had been scheduled to complete task A first, there would have been less inefficient overlap in surveyed areas, and each UV could spend more time searching uncovered areas.

Because of these problems the subjects experienced while collaborating with the AP, there was general agreement that the operator should have more power to override the AP's schedules. Some desired features were the ability to add tasks to which the AP could only assign a single UV. In the previous example, a subject may have wished to constrain the AP to only allowing UV 2 to perform task C.

Another functionality subjects desired was the ability to very quickly be able to edit a particular UV's waypoints en route to a destination. The current system does not provide any functionality to specify a UV's waypoints; so when a UV's waypoints seemed sub-optimal, subjects desired to reroute the UV. These desired abilities to micromanage speak not only of the sub-optimal qualities of the AP's schedules, but of a potential need for more ways for the operator to collaborate with the AP so that the operator's goals are accomplished.

5.4 Conclusion

The cognitive walkthrough is a usability test designed to gather subjective feedback on the interface's design, and it provided key insight into how operators would actually interact with the interface. The cognitive walkthrough shows that the interface is both relatively "easy" to use and intuitive. However, the quality of collaboration with the AP provided by the interface needs to be improved. Even with the occasional AP problem, the interface is simple enough, in terms of perceptual and mental activity, confusion, and interactivity, that all users understood what needed to be done to successfully perform the mission.

The next chapter will compare the new interface against a previous interface in terms of efficiency and effectiveness for the previously described mission functions.

Chapter 6: Functional Comparison and Analysis

This chapter presents a functional comparison between a previously existing interface and the newly designed interface presented in Chapter 5. The previous interface is introduced, including the processes required to perform the various functions for mission completion. How each interface allows an operator to create tasks and manage the mission schedule is compared, and the efficiency of both interfaces is discussed.

6.1 Original Interface

The original interface created by engineers to manage the multiple UVs is shown in Figure 21, and will be referenced as the ENGR-INT, as compared to the interface described in Chapter 4, referenced as HF-INT (human factors interface). The main feature of the interface is the map area. To the left of the map area is a column containing an area for status messages and an area for schedule management. The bottom section of the interface contains an area to specify information for creating tasks.

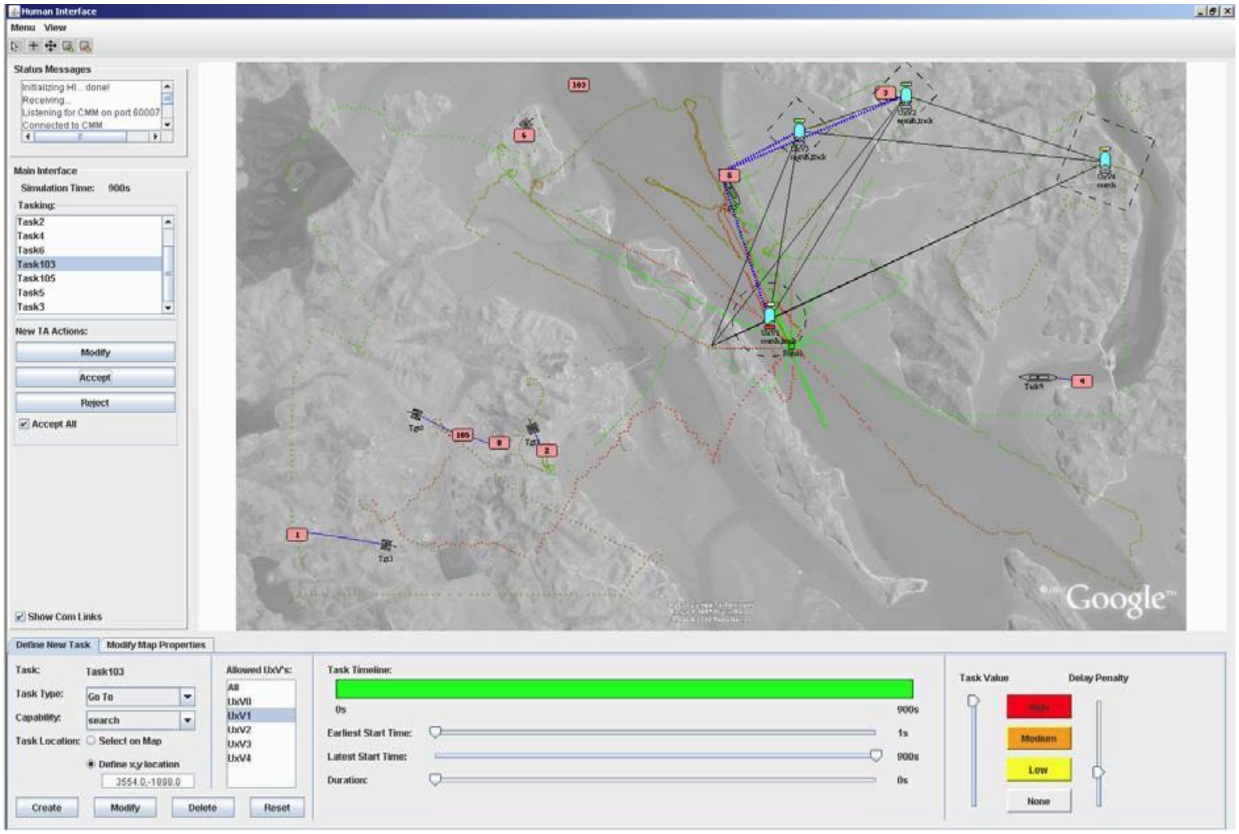


Figure 21: Aurora Flight Sciences' Original Interface (ENGR-INT)

6.1.1 Main Map

The main map area of this interface is very similar in appearance to the HF-INT main map (Figure 5). The same bird's eye perspective of the area of interest (AOI) is presented to the operator with the various vehicles, targets, and tasks represented by symbols. The symbology used by this interface is very similar to the symbology present in the HF-INT found in Table 4, which is expected since both attempted to adhere to proscribed military standards (DoD, 2006) to the greatest degree possible.

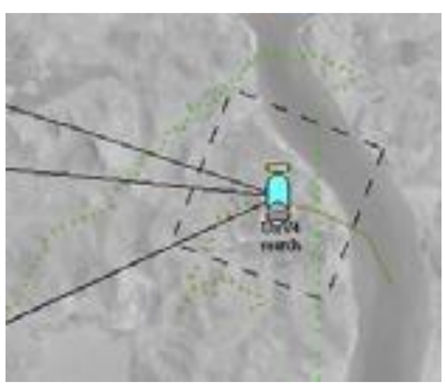


Figure 22: ENGR-INT Representation of UV with Peripheral Information

In addition to showing geo-spatial information about each vehicle, the ENGR-INT's main map also contains peripheral information such as communication status links as well as past locations. Each UV has numerous black lines connecting that particular UV to every other UV in the AOI and to the base. These lines represent the status of communication for each UV with every other UV in the AOI. Figure 22 shows three lines of communication indicating that the UV shown is connected to three other UVs. In addition, throughout the main map area in Figure 21 and Figure 22 there are numerous green, brown, and red dots forming lines that gradually change color. These dots represent past locations for each UV and the color of the dot indicates the fuel level of the UV at that time. The brighter green colored dots indicate higher fuel levels.

The HF-INT does not present visualizations for these pieces of information in order to reduce unnecessary clutter in the main map area. One assumption, as mentioned in Chapter 3, is that a primary assumption is that communication links between all vehicles will always be valid. Therefore, communication links are assumed and no visualization is necessary. Moreover, in an interface that required such information, such a link should only be shown when there is a problem, which could be shown in a health and status monitoring display instead of directly on the map which could cause confusion with vehicle routing.

The HF-INT does not show past locations in the same way as the ENGR-INT. Past locations have been replaced by the global uncertainty visualization (Figure 8). The underlying probability distribution takes into account both UV past locations and each UV's sensor range to give a much more accurate depiction of where in the AOI has been visited. Fuel values corresponding to previous UV locations do not represent pertinent information to complete the mission and this information is not presented in the HF-INT.

Figure 23: ENGR-INT Buttons for switching modes

The main map area of the ENGR-INT has none of the direct manipulation capabilities as the HF-INT. The HF-INT uses direct manipulation to allow the user to select units, specify task locations, pan around the AOI and zoom in the AOI. The operator can perform any of these actions at will by clicking directly in the map area with the different mouse buttons. The ENGR-INT makes use of only the primary mouse button and each action requires the operator to be in a different mode, which increases the likelihood of mode confusion. The ENGR-INT allows the operator to switch between modes via the various buttons in the upper left corner of the interface and shown in Figure 23. While in each mode, the cursor changes to the image seen in each button in Figure 23 while over the main map area. While the mouse is not over the main map area, the operator has no way of knowing which mode is currently selected, producing mode confusion. To verify which mode is currently selected, the operator can move the mouse over the map area to view the cursor image or simply click the desired mode button each time a mode is needed.

6.1.2 Task Specification

The bottom portion of the interface contains areas to specify information for each task such as task type, allowed UVs, timeline information, and priority information. The bottom left, shown in Figure 24, contains areas to specify the type of task (search or track) and which UVs are allowed to perform the task.

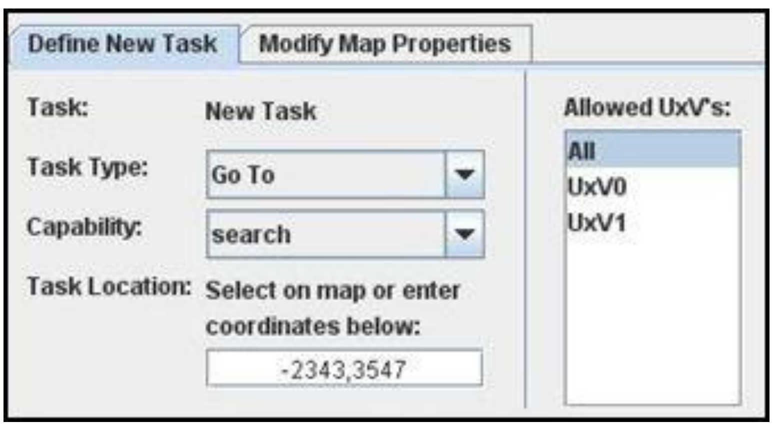


Figure 24: Task Specification Portion of the ENGR-INT showing Location, Task Type, Capability, and Allowed UVs

The ENGR-INT also includes timeline information about the task, but this should not be confused with the aggregate timeline of the HF-INT. As seen in Figure 25 the operator can configure three sliders to indicate the window of start times and the task's duration. Duration for a search task indicates how long the UV should loiter at the location upon arriving, and duration for a track task indicates how long a UV should track a target before moving on. All track tasks corresponding to specific targets that are created by the automated planner (AP) have their window of start times and duration set by the AP.

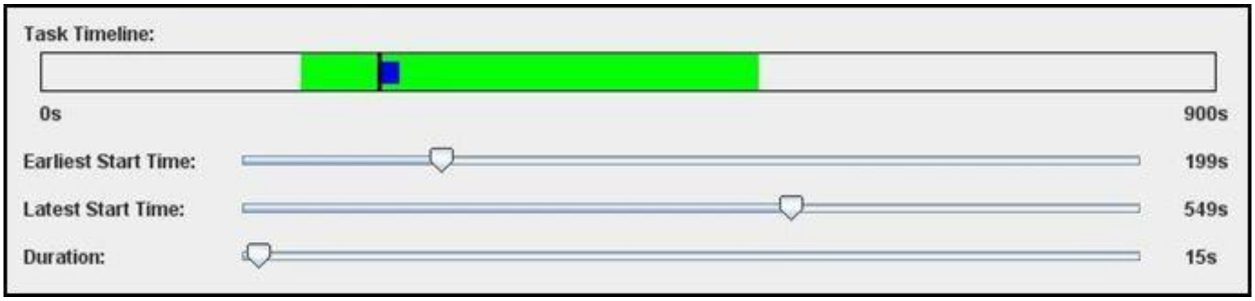


Figure 25: ENGR-INT Task Specification Timeline

The area to the bottom right of the interface, shown in Figure 26, contains priority information. The two sliders indicate the task value and the delay penalty. Task value is what the AP uses to prioritize tasks when creating a schedule. Delay penalty refers to how important it is to arrive at a certain task on time. Delay penalty can also be thought of as a type of priority because the higher the penalty, the earlier the AP attempts to perform the task. Problems with this representation will be discussed in the next section.

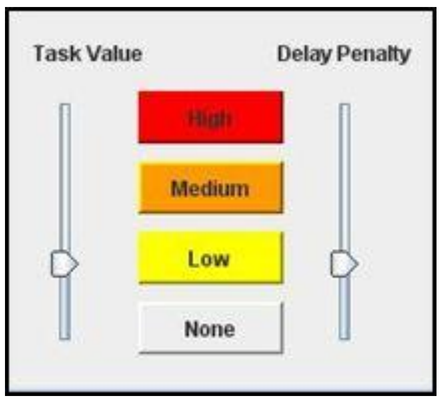


Figure 26: Task Specification Priority - Task Value and Delay Penalty

6.1.3 Schedule Management

The left side of the interface allows the operator to view the various tasks and manage the mission schedule. The list shown in Figure 27 shows all tasks present in the AOI. Selecting a task in this list will highlight the task in the map area and configure the bottom task specification area to show the task's specific information.

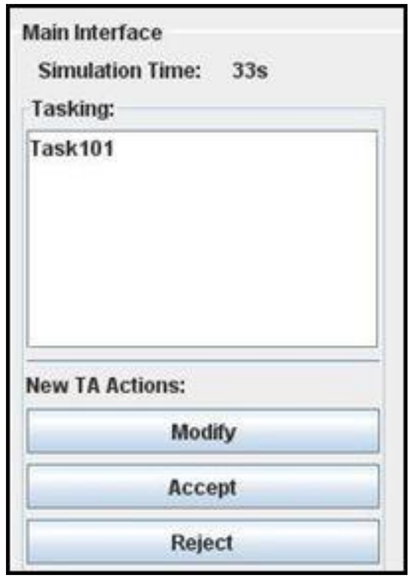


Figure 27: ENGR-INT's List of Tasks in the AOI

Included in the left side of the interface and shown in Figure 27 is an "Accept" button. When a new schedule is proposed that improves mission performance, the operator can accept the proposed schedule by clicking the "Accept" button.

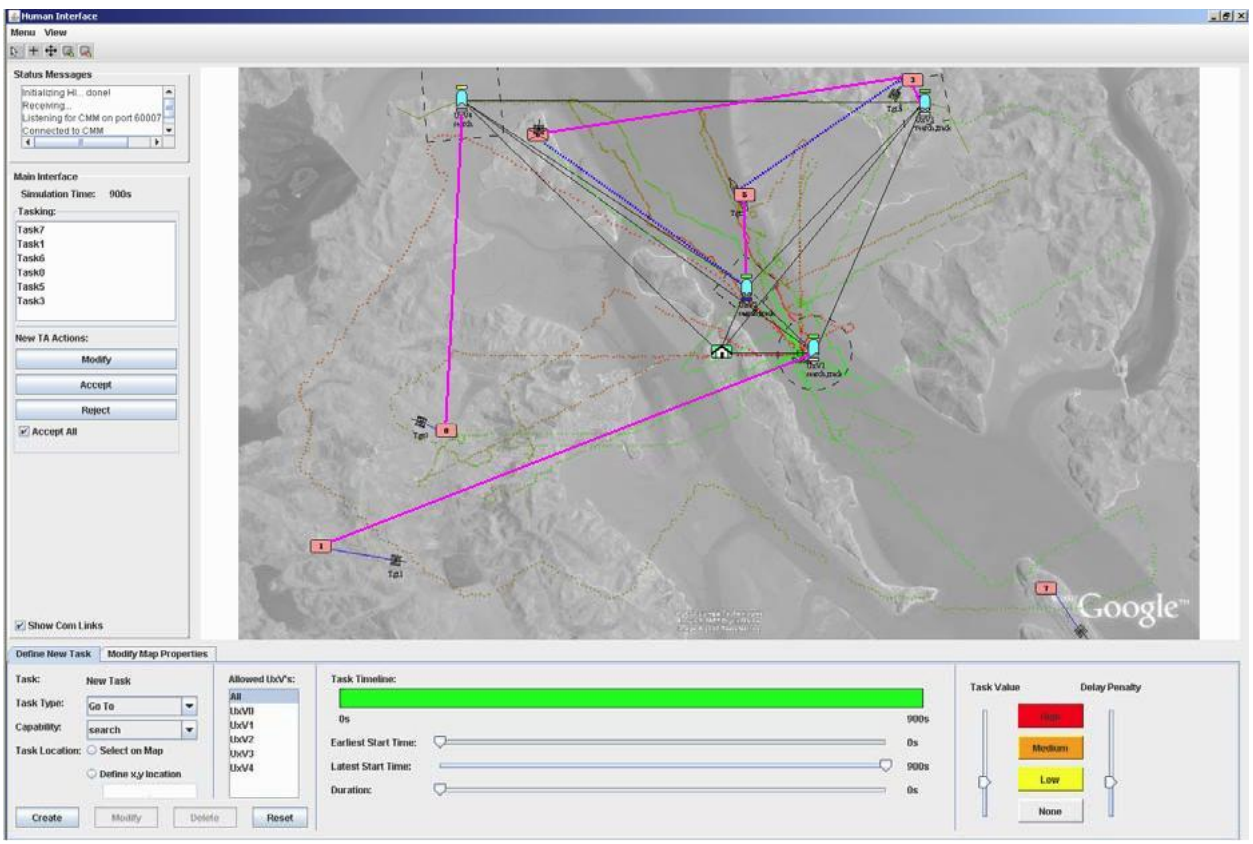


Figure 28: ENGR-INT showing the current schedule and the proposed schedule

In order to analyze the proposed schedules, the ENGR-INT presents the schedules to the operator using different colored waypoints for each UV. The current schedule is shown for each UV as blue paths. As proposed schedules are received by the interface, they appear for each UV as purple paths. Figure 28 shows both blue and purple paths for each UV.

6.2 Functional Comparison

Table 7 presents the various functions and sub-functions supported by each interface. The three primary functions supported by both interfaces are: Search, Track, and Schedule Management. These functions are then further broken down into corresponding sub-functions.

In order to successfully search the AOI, both interfaces allow the operator to add, edit, and delete search tasks. The specific steps required to add and edit tasks are different for each interface and these differences, seen in Table 7, will be explained in the ensuing analysis. One difference is in the operator's ability to create track tasks. To track the targets that have been found in the AOI, the ENGR-INT allows the operator the ability to create track tasks. Since the AP automatically creates track tasks for targets as they are found, the ability for the operator to create additional track tasks that do not belong to a found target was excluded from the design of the HF-INT. This functionality stemmed from the need for engineers to test the algorithm.

The processes required to create and edit tasks are similar within both interfaces, so there is only a detailed comparison for both creating and editing both search and track task functions. As will be explained later, other functionalities such as schedule comparison are so different between the interfaces that a balanced comparison cannot be made. This analysis covers the steps required to create a search task. The steps required to edit search tasks, add track tasks (for the ENGR-INT only), and edit search tasks are contained wholly within the steps for creating a search task. Additionally, the resulting discussion on efficiency applies to all of these areas as well.

As mentioned previously, schedule management is an essential component to performing the mission. In order for any task to be performed, a schedule needs to be accepted by the operator and enacted by the UVs. Throughout the mission, the AP calculates schedules which are then proposed to the operator as alternatives to the current schedule. The operator must accept a proposed schedule for it to become the mission schedule, but before accepting each schedule, the operator needs to verify that the proposed schedule is in fact better than the current schedule. The two interfaces will be compared on the process the operator must take to accept a schedule concentrating specifically on how the operator performs the comparison between the proposed schedule and the current schedule.

As shown in Table 7, the HF-INT allows the operator to query the AP for schedules assigning an individual task. This feature was added to the AP during the development of the HF-INT and is not supported by the ENGR-INT. The schedule returned by AP presents a third schedule needed to be compared in the HF-INT. In the comparison of the two interfaces on the schedule management function, the ability to query the AP will not be explored since it represents added functionality.

Table 7: Supported Functions for each Interface with supported sub-functions

<table>
<tr><th colspan="2">Supported Functions</th></tr>
<tr><th>ENGR-INT</th><th>HF-INT</th></tr>
<tr><td colspan="2">SEARCH</td></tr>
<tr><td colspan="2">Add/Edit Individual Tasks</td></tr>
<tr><td colspan="2">Specify Task Location
Specify Window of Opportunity</td></tr>
<tr><td>Specify Task Value
Specify Delay Penalty
Specify Task Duration
Specify UxVs allowed to perform task</td><td>Specify Task Priority</td></tr>
<tr><td colspan="2">Delete Task</td></tr>
<tr><td colspan="2">TRACK</td></tr>
<tr><td>Add/Edit</td><td>Edit</td></tr>
<tr><td colspan="2">Specify Window of Opportunity</td></tr>
<tr><td>Specify Task Location
Specify Task Value
Specify Delay Penalty
Specify UxVs allowed to perform task</td><td>Specify Task Priority</td></tr>
<tr><td colspan="2">SCHEDULE MANAGEMENT</td></tr>
<tr><td colspan="2">Accept Schedule</td></tr>
<tr><td>N/A</td><td>Query Individual Task</td></tr>
</table>

6.2.1 Task Creation

This section documents the steps required to add a search task to the mission and compares the two processes on efficiency. Table 8 presents the steps required by each interface to create the task.

Table 8: Steps Required by each Interface to Create a Task

ENGR-INT	HF-INT
Select task location button, entering set task location mode.	Right click in map area at desired location.
Click in the map area to specify location.	Specify Priority.
Specify task type: Search or Track	Specify the start and end time for the window of start times.
Specify UVs allowed to perform the task.	Click on the “CONFIRM” button.
Move the three timeline sliders to specify the window of start times and the duration.	
Specify the task value.	
Specify the delay penalty.	
Click on the “Create” button.	

The ENGR-INT requires twice as many steps to add a task as compared with the HF-INT, although both interfaces allow the operator to specify a similar quantity of information for each task. Specifically, the ENGR-INT allows the user to specify task duration, allowing the operator to designate a loiter time or a time to track the target upon arriving at the task location. The ENGR-INT also allows a delay penalty and task value to be set instead of a single priority value allowed by the HF-INT.

The ability to designate a length of time to perform a loiter task, given the CTA analysis, was not included in the HF-INT since loitering was not part of the search and track mission goals, which were to search as much of the AOI as possible and to track as many found targets as possible. If this functionality were needed for a future mission, it could be added to the task specification window as seen in Figure 11. Since the interface allows for task duration, this could easily be modified to include a loiter function.

To streamline the specification of task priority, the HF-INT presents three priority options to the user: low, medium, and high. The HF-INT uses this priority to specify both the task value and the delay penalty seen in the ENGR-INT and required by the AP. The specification of the task value and the delay penalty is presented in the ENGR-INT similarly to the HF-INT’s presentation of priority with the high, medium, and low values. However, the ENGR-INT’s use of both of these values was confounding for the user, making it difficult to extract a meaningful understanding of the task’s overall priority. If a user assigned a task with a high task value and low delay penalty and another task with a low task value and high delay penalty, it is not clear which task the AP will prioritize. Moreover, it’s not clear what the operational implications of such a priority scheme would be. Under the new simplified presentation of the priority, proposed schedules behave much more intuitively, generally assigning higher priority tasks before lower priority tasks.

In the process of streamlining, however, a feature was removed that, as the cognitive walkthrough indicated, should have been kept. The ability to limit the UVs allowed to perform a particular task is not supported by the HF-INT. The initial reasoning for the removal was that if the AP truly gives an optimal plan for performing the tasks, the operator should not have to worry about which UV gets assigned to each task. The cognitive walkthrough showed, however, that without a near-perfect AP, users desire the ability to specify a particular UV for a particular task.

Another difference between the two interfaces is in the distance the mouse is required to move in order to create the search task. The ENGR-INT requires the operator to click in the upper left corner, in the map area, and along the bottom of the interface. The HF-INT minimizes the amount the operator must move the mouse across the screen, displaying related information together and taking advantage of the proximity compatibility principle (Wickens & Carswell, 1995). In addition, the HF-INT utilizes direct manipulation by requiring the operator to simply move the mouse to the desired location and click (Shneiderman, 2005). The window then appears at that location.

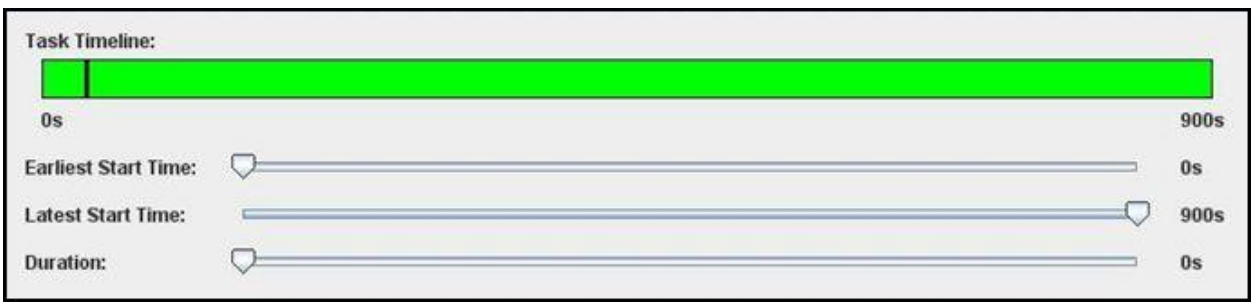


Figure 29: ENGR-INT Timeline with Default Values

To specify the earliest possible start time and the latest possible start time for a specific task, the ENGR-INT requires the operator to move two sliders. The green bar seen in Figure 29 indicates the window of possible start times. As the operator moves the two sliders, the green bar will change length and position. One drawback to this approach is that, by moving the sliders, the operator can configure an illegal window if the latest possible start time is set earlier than the current mission time (shown as the vertical black line toward the beginning of the green bar in Figure 29). The HF-INT presents the operator with a similar timeline where the blue bar is analogous to the green bar in the ENGR-INT. Because the entire timeline represents only the time remaining, the operator cannot specify an illegal window, thus providing a forcing function which prevents errors that could propagate through the system. The timeline in the HF-INT also makes use of direct manipulation by allowing the operator to directly click on and drag each end of the blue bar. Moreover, the HF-INT's shorter bar provides a more efficient method of specifying the window of possible start times.

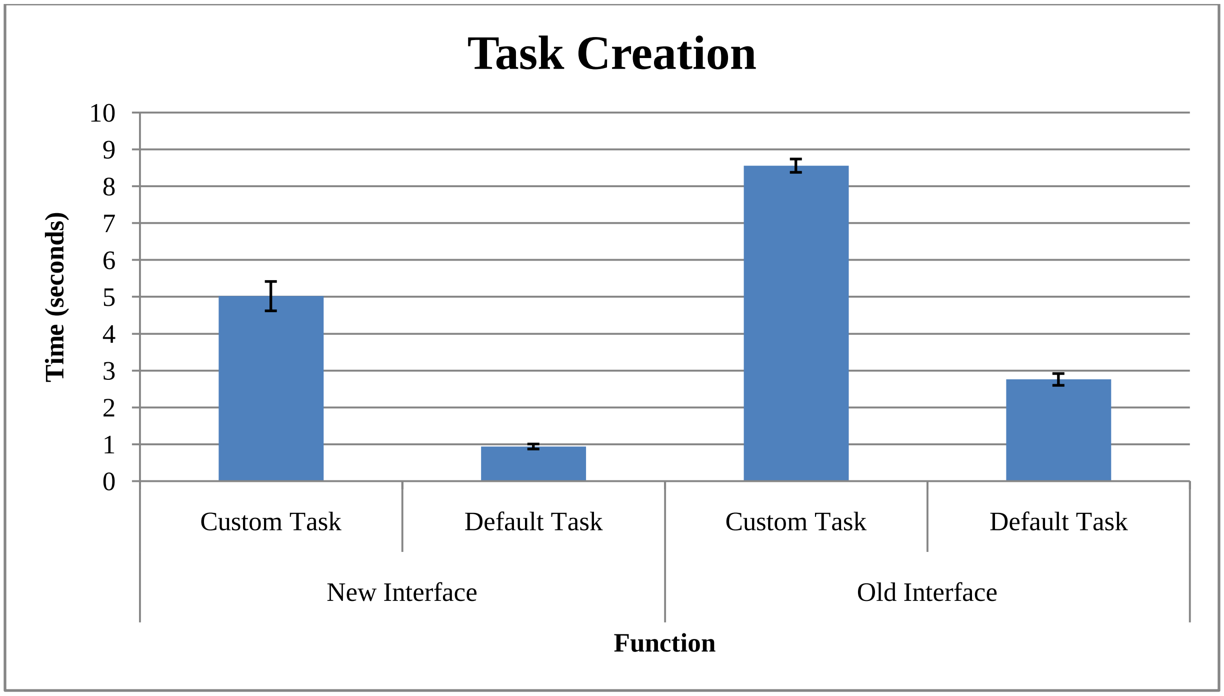


Figure 30: Time required to create both a custom task and a default task across the two interfaces.

To illustrate the differences between the two interfaces in terms of required user inputs, an expert user was directed to create tasks using both interfaces, and the time required to create a task was recorded and averaged over five trials. The results are shown in Figure 30. The expert user was asked to create custom tasks in both interfaces where many parameters were changed from their default values. Because both interfaces differ in the parameters the user may specify, the user was asked to create custom tasks for both interfaces, limited to only the parameters present in the HF-INT. The user was also asked to create tasks where as many parameters as possible were left at their default values. For the default tasks, only the location was specified in each interface before creating the task. These two tasks, custom and default, represent the extreme ends of complexity for task specification, from the most difficult to the easiest.

The results show a trend of decreasing task creation time in going from the ENGR-INT to the HF-INT. These results can be attributed to the use of direct manipulation, the interactive timeline, and priority buttons replacing the more cumbersome sliders in the old interface. To create the same type of task, either custom or default, the HF-INT is on average 3 seconds quicker than the ENGR-INT. Although a difference of 3 seconds is small compared to a mission time of 15 minutes, multiple task creations can create accumulated time which will have an impact in the long run, especially for novice users. Furthermore, seconds can be critical in high-risk command and control settings. As the operator creates tasks, less time spent on actually creating tasks allows for more time to be spent on managing the mission and getting the tasks assigned.

6.2.2 Schedule Management

This section documents the steps for each interface required to compare a proposed schedule against the current schedule and ultimately accept it if it is deemed better. For this search and track mission, the operator is given the ability to create various tasks requiring visitation by one of the UVs. In order to assign these tasks, the AP generates schedules which, if accepted, assign a number of the existing tasks to be performed by the UVs. The AP constantly generates these schedules in an effort to improve on the existing schedule as more tasks are created and targets are found. When these schedules are proposed to the operator, the operator needs to compare the proposed schedule against the current schedule to see if it will better perform the mission. Table 9 presents the steps required to accept a schedule, and these two processes are subsequently compared on efficiency.

Table 9: Steps Required by each Interface to Accept a Proposed Schedule

ENGR-INT	HF-INT
Compare schedules by comparing blue and purple schedules for each UV.	Click on the "Replan" button to view the Schedule Comparison Tool (SCT).
Click on the "Accept" button.	Compare schedules by comparing configural displays.
	Click on the "Accept" button.

The two interfaces require similar steps of comparing schedules and then accepting the proposed schedule if it is appreciably better. The significant difference between these interfaces is in how the operator carries out comparisons and arrives at a meaningful conclusion.

To allow the operator to compare schedules, the ENGR-INT presents the current schedule as a set of blue paths for each UV and the proposed schedule as a set of purple paths for each UV. The purple paths appear whenever the ENGR-INT receives a proposed schedule which generally happens every 4 to 20 seconds. The purple paths will disappear upon accepting the new schedule, and they will re-appear upon receiving the next proposed schedule. Figure 31 shows the ENGR-INT with both the current schedule and the proposed schedule.

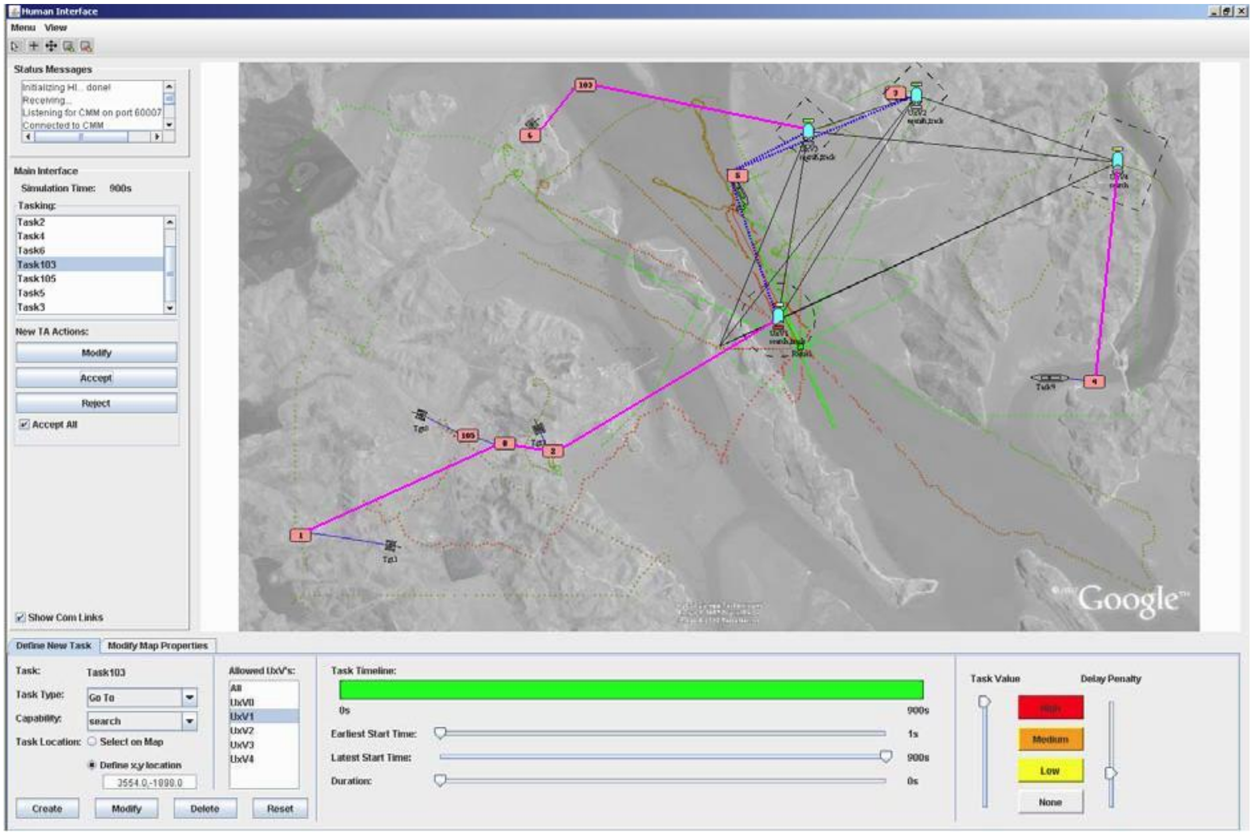


Figure 31: ENGR-INT showing the current schedule and the proposed schedule

A drawback to this method of presenting the two schedules is that the two colored paths may overlap for identical portions of the schedules and create clutter. If one color obstructs the other, the operator may not see the full effect of one schedule and will not have a complete understanding of the schedule. In addition to the possibility of the two schedules overlapping, the communication links and previous locations also add sources of clutter. Another drawback to this method is known as change blindness. When viewing the proposed schedule, a new, more recent proposed schedule may arrive. While analyzing the proposed schedule, the operator may not notice that there has been a change in proposed schedule. If the operator does not realize the schedule has changed, the operator will not have a complete understanding of the schedule on which to make an informed decision. The operator can determine which tasks are included in each schedule by viewing each task's symbol. A task with only a blue path leading towards it will no longer be assigned in the schedule, but a task with only a purple path leading towards it is a currently unassigned task which will be assigned in the new schedule. Tasks with both colors of paths or no paths leading towards them will be unaffected by the new schedule. Even with these potential problems, the ENGR-INT does present the complete schedule to the operator. The operator can see specifically where each UV will go under the new schedule, but an extensive serial search must be conducted to ensure task completion.

Unlike the ENGR-INT, the HF-INT requires the operator to click the "Replan" button in order to begin comparing schedules. This process takes time and potentially breaks the operator's concentration. However, it offers the operator a significant reduction in cognitive load and allows the operator to more effectively manage mission time. The rationale behind the "Replan" button is that no matter how often schedules are sent to the operator, the operator should not have to compare the proposed schedule against the current schedule, a process requiring significant cognitive resources, unless the proposed schedule has a chance of improving mission performance in some significant way. The operator need only spend the time and effort to compare schedules when the proposed schedule is likely to be better than the current schedule as indicated by a green "Replan" button.

Upon entering the SCT, the operator is presented with configural displays which represent the current and proposed schedules' estimated mission performance. The top of each configural display shows the estimated AOI coverage. The top of the configural display presents a smaller rectangular representation of the AOI allowing for a direct mapping to the real AOI. Instead of having to follow purple and blue paths throughout the map area, this configural display allows the operator to quickly see the differences in AOI coverage. The smaller overall area required to view all pertinent information about each schedule and the animated transition as proposed schedules are received reduce the likelihood of change blindness occurring.

The SCT also allows the operator to compare how well each schedule performs the various high, medium, and low priority tasks. The configural display presents the percentages of high, medium, and low priority tasks assigned by each schedule. Because the configural display presents these percentages via three triangles arranged in an ecologic fashion (the biggest overall triangle is the best solution), the operator can quickly compare each schedule's task completion. The ENGR-INT does not provide this information to the user for the quick comparison.

In addition to the various percentages, the tasks left unassigned by the proposed schedule are visible in the SCT. The operator can not only clearly see which tasks will still be unassigned with the proposed schedule, but the operator can also see specific tradeoffs between the two schedules as currently assigned tasks will have the number of the UV assigned to them visible in their symbols. The only way for operators to perceive these types of tradeoffs in the ENGR-INT is by viewing individual tasks with only a single blue or purple path leading to it.

6.3 Conclusion

This functional comparison and analysis shows how the HF-INT simplifies the processes required to perform the primary functions in the mission: creating and editing tasks and managing the schedule. In the case of creating a task, the HF-INT reduces the amount of steps by approximately half, simplifies the task parameters, and reduces the area the mouse must travel to specify the parameters. The HF-INT also provides a more efficient method for creating tasks as shown by the results in Figure 30.

In the case of comparing schedules, the new interface adds a step to the process, but in doing so, produces a more efficient process. By allowing the automation to calculate a quick comparison to determine if a new schedule is worth analyzing, the operator's cognitive workload is significantly reduced by not having to analyze every proposed schedule against the current schedule. Moreover, the configural displays provide an efficient and rapid way of comparing the proposed schedule with the current schedule. The pertinent information which the operator must know about each schedule to make an informed decision is presented in an ecological fashion in the configural display. In contrast, the ENGR-INT forces the operator to perceive the various paths and extrapolate the pertinent information, which is very cognitively cumbersome.

It should be noted that the ENGR-INT was designed by engineers without the benefit of a CTA and understanding the need to support cognitive reasoning processes. Thus the ENGR-INT met the engineers' cognitive needs, but not necessarily a user's. Thus what is functional from an engineering perspective is not always the best interface from an operational user's perspective.

Chapter 7: Conclusion

This chapter summarizes the motivation and objectives for this research, presents the key findings, and makes recommendations for future work in multi-UV mission replanning research.

7.1 Study Motivation and Research Objectives

As UVs become more common in civilian and military applications, increasing levels of autonomy will lead to one or more operators supervising multiple UVs. Under this operational scheme, critical human factors issues of performance, mental workload, and situation awareness are of concern. Dynamic time-critical multi-UV missions involving potential emergent events will likely require significant operator higher level reasoning to manage complex missions. Multi-UV operators will need to manage the mission schedule in real time, and as scenarios change, replan the mission schedule to ensure mission success. In order to effectively manage the mission schedule, operators need to understand beforehand the effects of their potential actions on the schedule and the potential benefits of performing alternative actions. Operators will need to quickly compare schedules to determine the best course of action, which will be particularly difficult in the multi-UV management concept of operations due to the potential for information overload. A decision support tool for schedule management and comparison is needed in order to reduce the complexity of the incoming information such that rapid but informed decisions can be made in determining best possible schedule.

In order to address these needs, this thesis developed cognitive requirements and a conceptual design of such a scheduling decision support tool that reduces operator workload by leveraging direct manipulation and direct-perception interaction. The cognitive requirements clearly showed the need for a decision support tool for schedule management. A configural display, the Schedule Comparison Tool (SCT), was designed to provide pertinent information on three distinct schedules generated by an automated planner (AP) to be compared by the human operator. The requirements also led to the development of an indicator to notify the operator of potentially better schedules. This notification significantly reduced cognitive workload, no longer requiring operators to analyze every scheduled received from the AP.

7.2 Findings

Two evaluation tools were used to determine the effectiveness of the proposed interface and decision support tool. First, human-in-the-loop usability trials were conducted in a simulated search and track mission. In addition, a functional analysis was conducted to determine how this new interface compared to a previous engineering interface.

In the usability evaluation, a cognitive walkthrough was conducted to determine how well the new interface presents intuitive ways for operators to engage and successfully perform the search and track mission. The cognitive walkthrough showed that the new interface provides a concise display for interpreting the large amounts of data required for effective schedule comparison. The cognitive walkthrough also indicated that the configural displays in the SCT were successful at simplifying an otherwise complicated mission that would have overloaded the operator. Subjects noted that the SCT would allow for the same effective schedule management for a mission with many more UVs and many more tasks than would be possible with the older interface. Also revealed by the cognitive walkthrough were various areas of the interface that could be improved, which will be discussed in detail in the next section.

During the evaluation of the interface, results showed that with increased use of the interface, subjects felt more comfortable collaborating with the AP. Also noted with increased use of the interface was an interesting, although weak trend of overall less mental workload required to perform the mission. This trend supports the notion that well designed interfaces can greatly facilitate human-automation interaction and should be an area for future study.

A functional analysis across the proposed interface and a predecessor interface designed for engineering evaluations was conducted. This comparison showed that the new interface was able to increase the functionality for an operator while reducing the total possible interactions with the interface. The new interface was successful at consolidating the necessary functions, providing not only more efficient mission management, but individual functions were streamlined as well. The new interface required on average only half the time for inputs, compared with the engineering interface, to perform the same functions, which is critical for time-pressured environments.

7.3 Recommendations

7.3.1 Design Recommendations

Based on comments derived from the human subjects during the cognitive walkthrough, the following design recommendations should be considered for the next generation of this interface and the SCT.

- Track tasks associated with specific targets need to be treated separately from search tasks in the SCT display. Currently all tasks are grouped together, differentiated only by their priority. Track tasks have a direct impact on performance, maintaining coverage of known targets; search tasks have only an indirect impact on performance as potential ways to find the target of opportunity.
- The interface and the AP need to provide more feedback about how schedules are generated. An operator needs to know, after unsuccessfully trying to assign a particular task, why the AP cannot generate a schedule with that particular task.
- The interface should provide the capability for operators to limit the UVs the AP can assign to a particular task. The cognitive walkthrough indicated that this capability could reduce the frustration operators might experience when collaborating with the automation. The interface might also discourage use of this capability in an effort to build trust in the automation's ability to produce acceptable schedules.
- Individual UV range limitations should be made visible on demand. Viewing both the UV's maximum range and the UV's current range given its current amount of fuel would give the operator better situation awareness.
- The colors used for the configural displays in the SCT need to be more consistent. Specifically, in the triangular areas in each configural display, the goal is to fill each area with the configural display's unique color. Conversely, in the rectangular portion of each configural display, the goal is to remove as much of the configural display's unique color as possible.
- The timeline allowing operators to specify a window of possible start times for each task should be integrated better with the timeline at the bottom of the screen. Currently, the disconnect between the two views is too great to effectively specify a task's window of possible start times.
- The use of the triangles to convey priority may not be the most intuitive display for hierarchical information. Another more vertical representation, such as a ladder, should be investigated.

7.3.2 Future Experiment Recommendations

The newly designed interface imbedded in a search and track mission simulator provides a robust platform on which to conduct further research in multi-UV mission management and, in particular, mission replanning. Using this system, future experiments could focus on the details of human-automation collaboration and the performance ramifications of such collaboration.

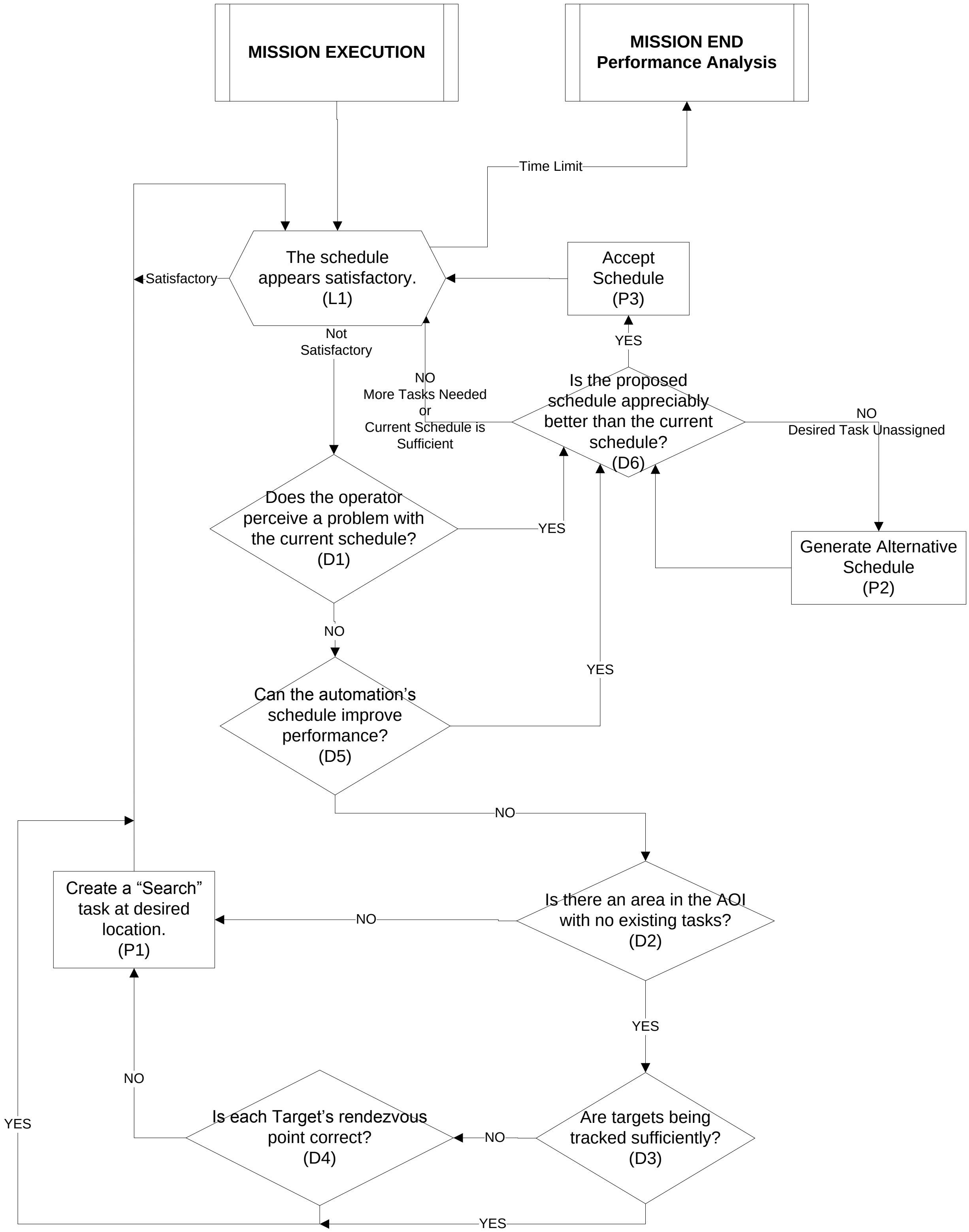
The human-automation collaboration presented in the new interface with the SCT display makes use of direct manipulation techniques by requiring the user to drag and drop task icons into an “Assign” region. Using the existing software, alternative techniques requiring the operator to perform different actions could be investigated.

Alternative approaches to allowing the operator to interact with the automation could also be an area for future research. The current method using the SCT allows the operator to present a single task to the AP to be included in the mission schedule. Providing more ways to interact with the AP could lead to improved schedules and, as indicated by the cognitive walkthrough, improved trust of automation. Additional ways of collaborating with the AP could include allowing operators to attempt to assign more than one task at a time.

Given the need for human-automation collaboration using the current system, one important question that needs to be addressed is how often the operator should collaborate with the automation. Since automated planners can often generate new plans faster than humans can understand them, how often new plans should be generated and under what levels of uncertainty and degrees of mission performance improvement are open questions with important, operator workload implications. Thus, further research could examine at what rate the AP and the role that visualizations play in developing better schedule management strategies.

Appendix A

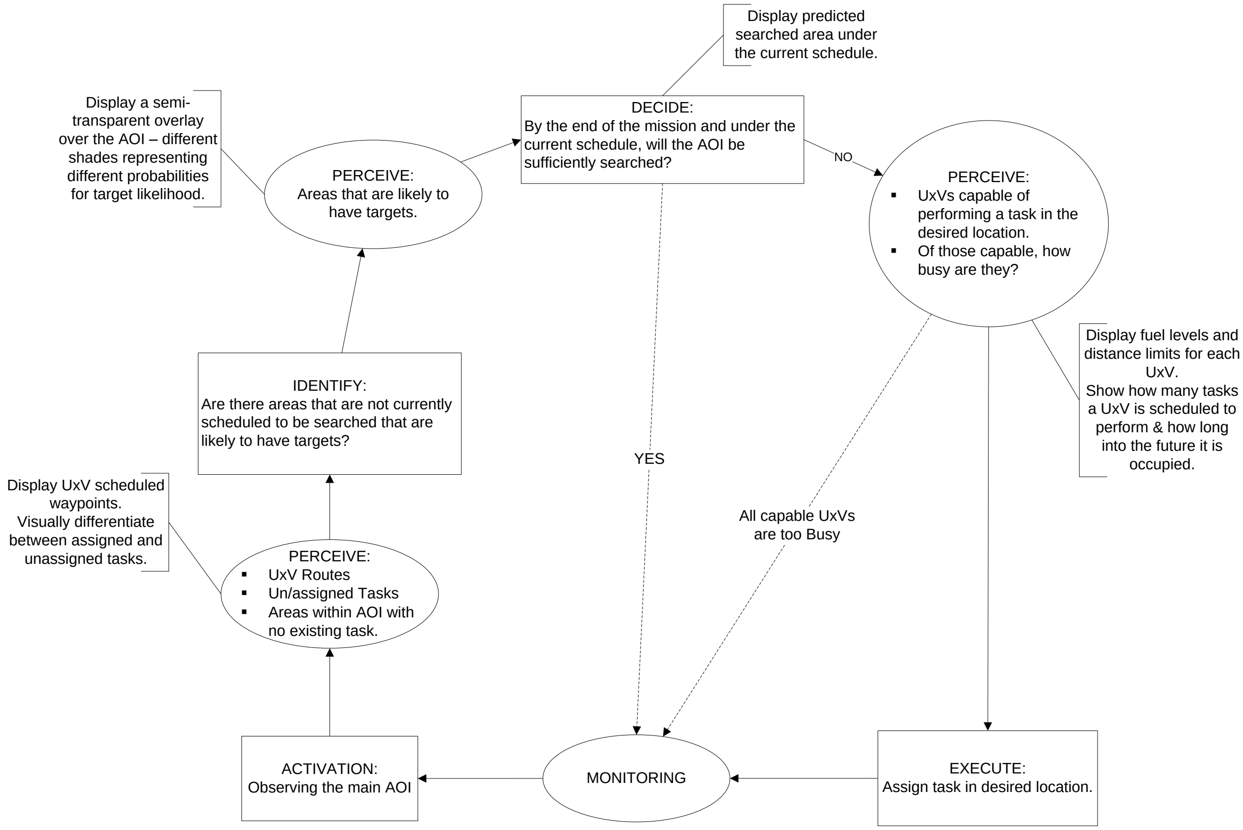
Event Flow Diagram



Appendix B.1

Decision Ladder with corresponding display requirements:

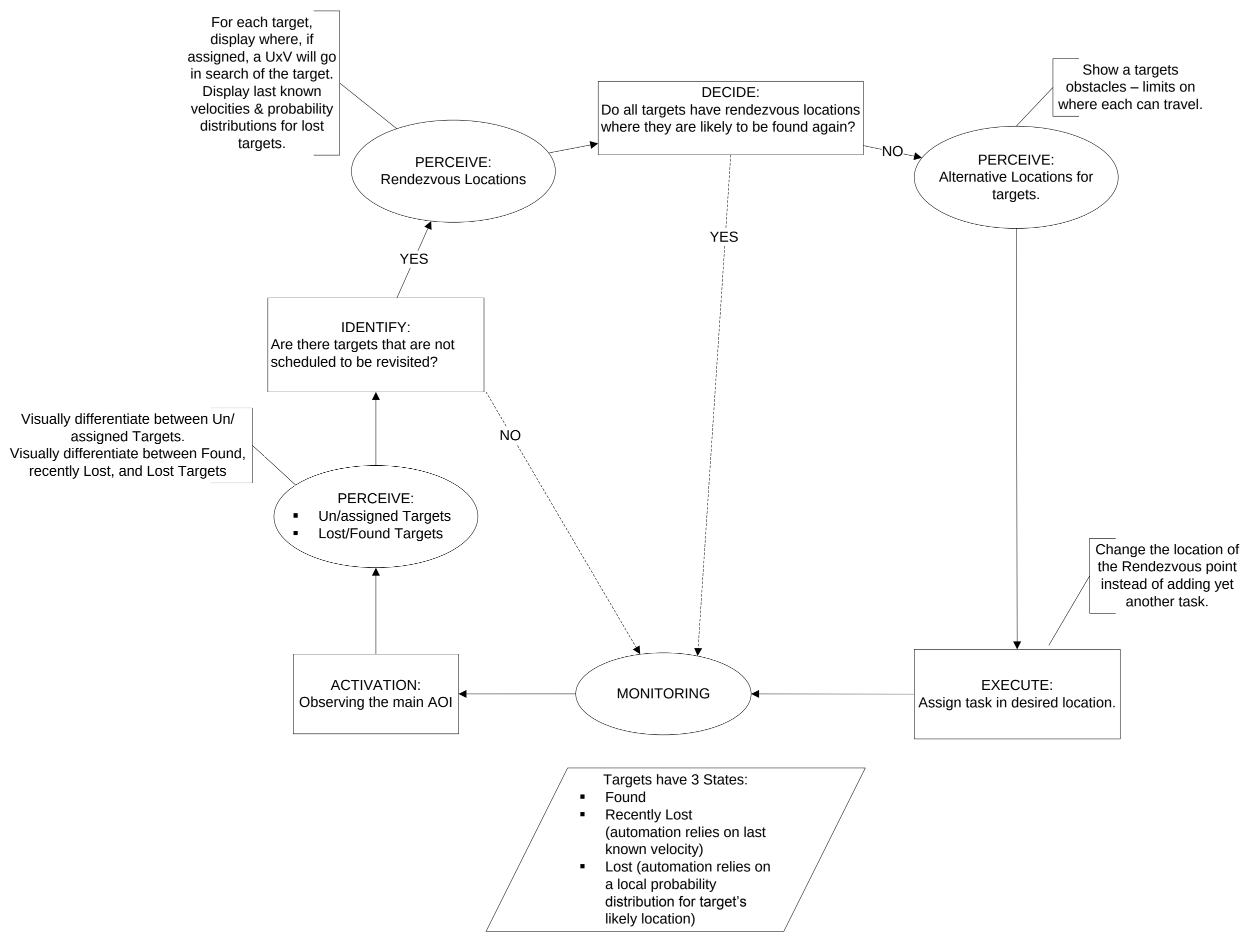
Is there an area in the AOI with no existing tasks? (D2)



Appendix B.2

Decision Ladder with corresponding display requirements:

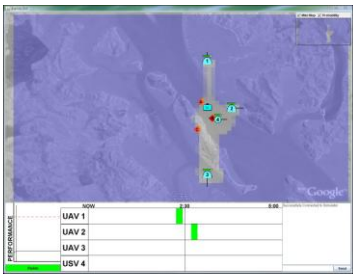
Are targets being tracked sufficiently? (D3)



Appendix C

Power Point Tutorial

Aurora Flight Sciences
Human Interface



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Massachusetts Institute of Technology

Your Mission

- You are a mission operator in charge of commanding multiple unmanned vehicles (UxVs).
- Your mission is to search the designated area for targets.
- Once a target is found, it is to be revisited as often as possible, tracking its movement.

Mission How-To

- Found Targets will always be associated with a task (explained in next slide).
- "Search" tasks can be added to the mission. A "Search" task designates a location for a UxV to go to in search of a target.
- An algorithm will generate schedules for each UxV to complete the existing tasks. If tasks are unassigned in a given schedule, the algorithm can be queried whether it can do one of the unassigned tasks.
- These schedules must be "Accepted."

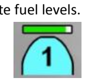
Revisiting Targets

- Once targets are found, they have a track task associated with them. An algorithm calculates where the target is most likely to be in the future based on the target's last known velocity. (tracking targets will be explained in more detail in the section on selecting targets)
- If assigned, a UxV will arrive at the specified location in search of the target. If found, the algorithm will calculate a new position for a track task based on the new position and velocity.
- If the UxV does not find the target, the target will be designated as lost (symbol will turn gray & shown in next slide). A probability distribution for where the target is likely to be will be calculated and a track task will still be associated with the target.

Symbols

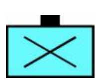
UxVs (your units) are identified with numbers.
The green bars above each UxV indicate fuel levels.

- Unmanned Aerial Vehicle (UAV)



- Unmanned Surface Vehicle (USV)

- Base – Refuel Location



Symbols

Tasks are designated with letters. A number appearing on a task represents the ID of the UxV assigned to that task.

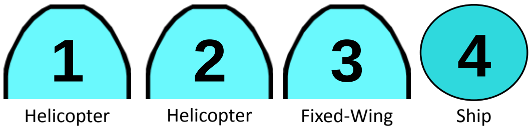
- "Search" Tasks with High, Medium, & Low priority respectively

- Found (C) & Lost (B) Targets with Medium Priority

- UxV 3 Assigned to Task D

- UxV 2 Assigned to Target C

Symbols



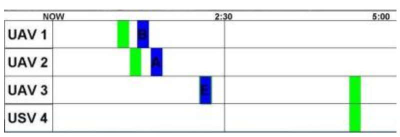
For all the simulations, UAVs 1 and 2 are helicopters and UAV 3 is a fixed-wing plane. Helicopters travel slower than the fixed-wing and have a smaller field of view. Helicopters also have less fuel than the fixed-wing so they have a shorter range. UAVs have rectangular search areas because they have bottom-mounted cameras. The ship uses a radar sensor so it's search area is circular.

Timelines

The bottom center of the interface contains a timeline for each vehicle.

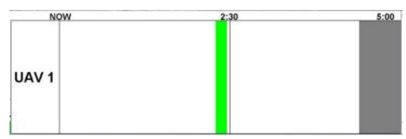
Timelines

The timeline gives temporal information for each UxV for the next five minutes into the future. Green bars in the interface indicate times of refueling and blue bars indicate times performing a task. The letter of the task appears in the blue bar. White indicates idle time or time traveling between tasks.



Timelines

Towards the end of the mission time, a semi-transparent gray overlay will appear over the timeline. The timeline below indicates that the mission will end in just under 5 minutes.

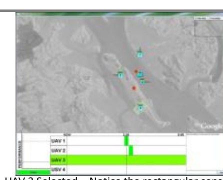


Selecting Units

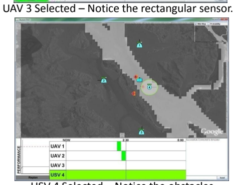
- UxVs, Tasks, and Targets can all be selected by clicking on each one's symbol.
- The following slides describe visual changes from selecting each type of unit.

Selecting Units

- Selecting a UxV
  - UxV's Sensor Range Appears
  - UxV's obstacles appear
  - UxV's Timeline is highlighted



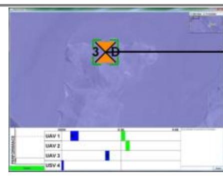
UAV 3 Selected – Notice the rectangular sensor.



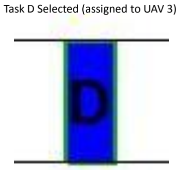
USV 4 Selected – Notice the obstacles and circular sensor.

Selecting Units

- Selecting a Task
  - Outlined in Green
  - Task highlighted in the timeline of the UxV it is assigned to. (if assigned)



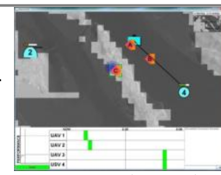
Task D Selected (assigned to UAV 3)



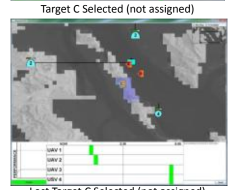
Task D in UAV 3's Timeline

Selecting Units

- Selecting a Target
  - Target's obstacles appear
  - Target's likely position highlighted (blue).
  - Target highlighted in the timeline of the UxV it is assigned to. (if assigned)



Target C Selected (not assigned)



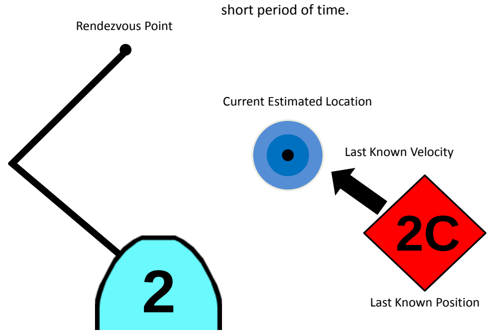
Lost Target C Selected (not assigned)

Tracking a Target

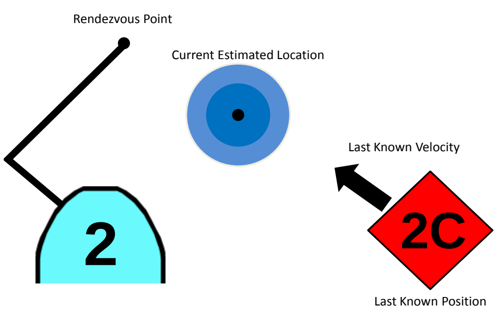
- The concept of tracking a target is further explained in the next slides.
- For the next two slides:
  - The target was last seen in the bottom right of the screen.
  - The target was last seen traveling toward the upper left of the screen.
  - Over time, the target's position is currently estimated by a blue circle. The circle gets bigger over time to indicate a growing uncertainty of where the target is.

Tracking a Target

The next slide shows how these symbols change after a short period of time.

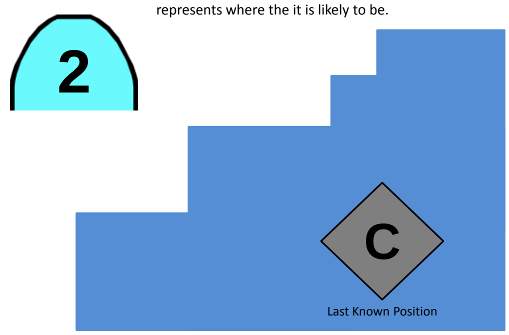


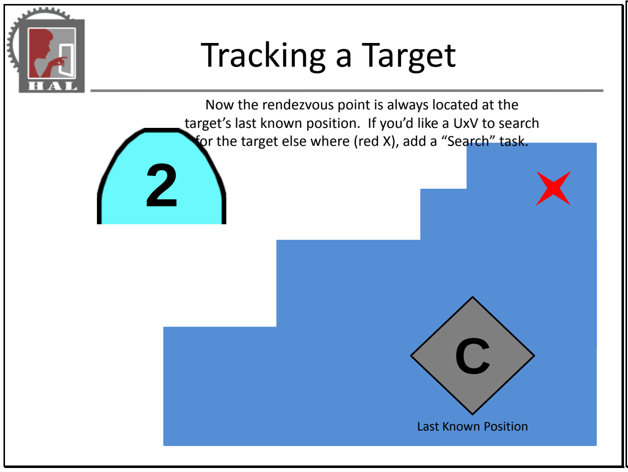
Tracking a Target

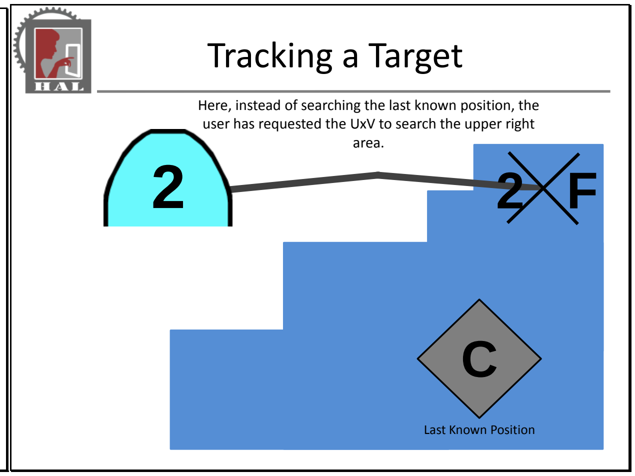


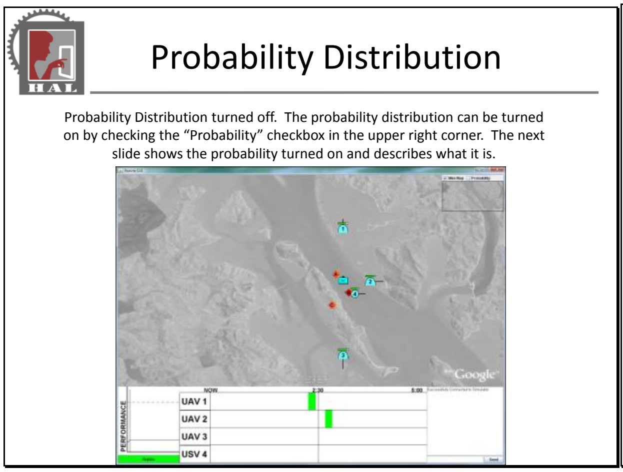
Tracking a Target

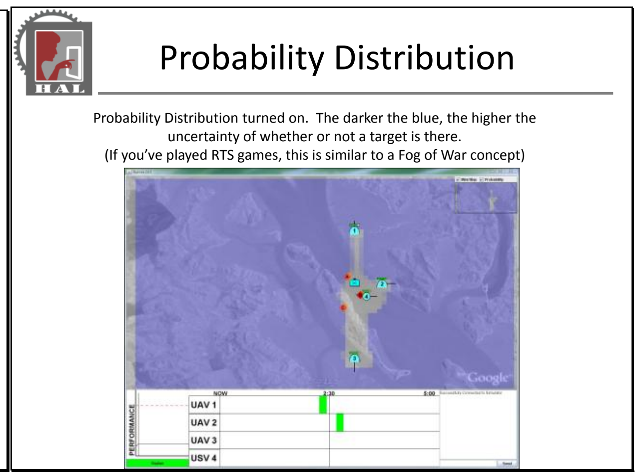
The target is lost, so it is designated as lost. The blue represents where the it is likely to be.

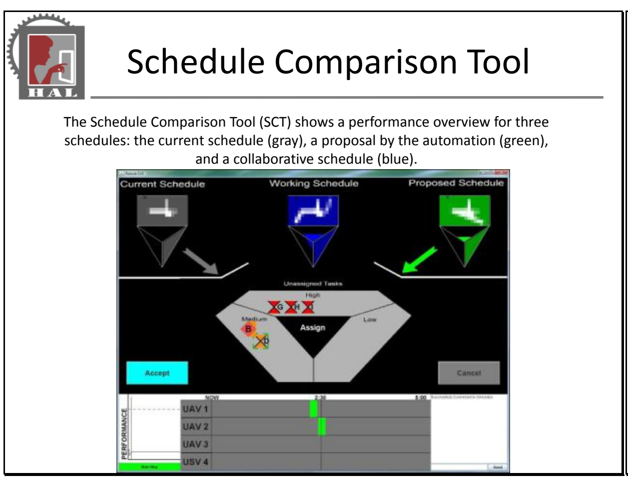


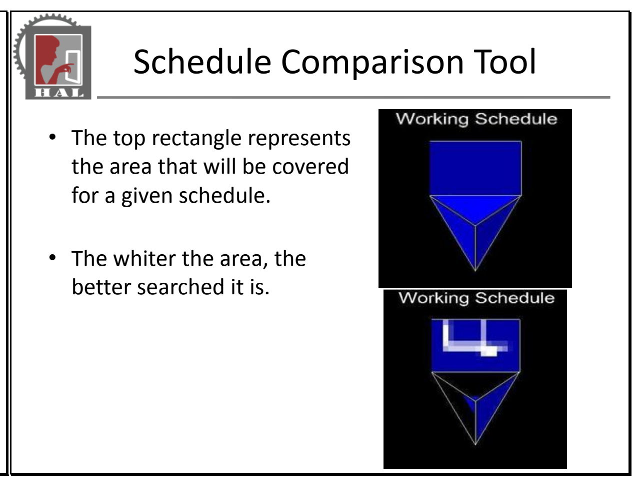

Tracking a Target
Now the rendezvous point is always located at the target's last known position. If you'd like a UxV to search for the target else where (red X), add a "Search" task.
2
C
Last Known Position


Tracking a Target
Here, instead of searching the last known position, the user has requested the UxV to search the upper right area.
2
2
F
C
Last Known Position


Probability Distribution
Probability Distribution turned off. The probability distribution can be turned on by checking the "Probability" checkbox in the upper right corner. The next slide shows the probability turned on and describes what it is.
UAV 1
UAV 2
UAV 3
USV 4

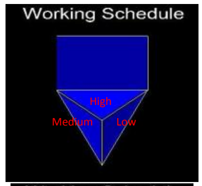

Probability Distribution
Probability Distribution turned on. The darker the blue, the higher the uncertainty of whether or not a target is there.
(If you've played RTS games, this is similar to a Fog of War concept)
UAV 1
UAV 2
UAV 3
USV 4


Schedule Comparison Tool
The Schedule Comparison Tool (SCT) shows a performance overview for three schedules: the current schedule (gray), a proposal by the automation (green), and a collaborative schedule (blue).
Current Schedule
Working Schedule
Proposed Schedule
Assign
Accept
Cancel
UAV 1
UAV 2
UAV 3
USV 4


Schedule Comparison Tool
• The top rectangle represents the area that will be covered for a given schedule.
• The whiter the area, the better searched it is.
Working Schedule
Working Schedule

Schedule Comparison Tool

- The bottom three triangles show percentages of high, medium, and low priority tasks to be completed for a given schedule.
- The more filled in the triangle is, the more of that priority task is being done.

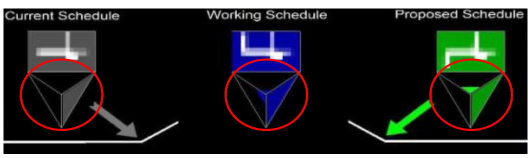


Schedule Comparison Tool

Area Covered

Comparing these three schedules: both "Working" and "Proposed" cover more area than "Current". "Working" covers the top left corner while the "Proposed" covers the bottom left corner.

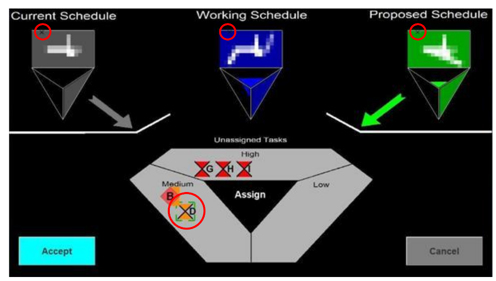
Schedule Comparison Tool



Tasks Completed

Comparing these three schedules: both "Working" and "Proposed" perform more tasks than "Current". "Working" performs more medium priority tasks, but "Proposed" covers more high priority tasks.

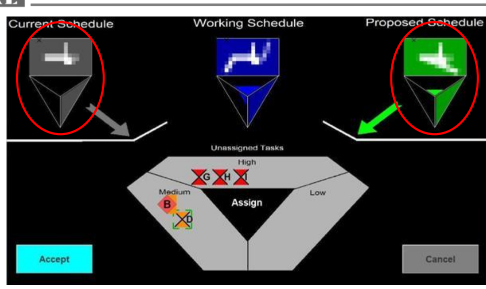
Schedule Comparison Tool



Task Location

The **X** appearing in each configural display toward the top left corner of the rectangular area corresponds to the location of the currently selected task.

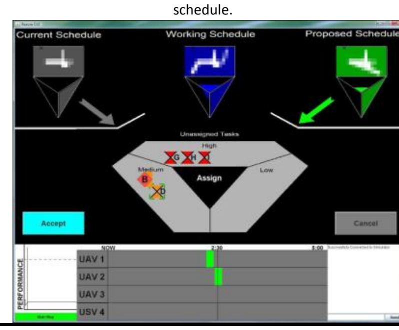
Schedule Comparison Tool



Tasks viewed in the central area always correspond to the "Working" schedule. To view unassigned tasks for either the "Current" or "Proposed" schedules, clicking on each one's configural display will set the "Working" schedule as equivalent to the selected schedule.

SCT Timeline

In the SCT interface, the timeline has been grayed out to indicate that it is the timeline for the Current schedule and will only correspond to the Current schedule.



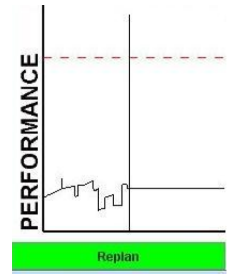
Monitoring Performance

Performance will be calculated based on:

- The percentage of the area searched.
- The number of targets found.
- The percentage of the time the targets' locations were known / the percentage of time the targets were successfully tracked.

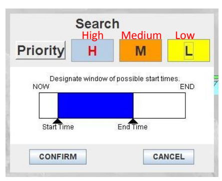
Monitoring Performance

- The bottom left portion of the interface gives an overall performance value for the current schedule.
- The "Replan" button, which is gray by default, will turn green if the automation's proposed schedule will yield a better performance.



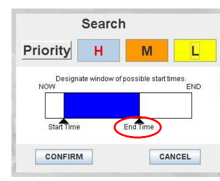
Task Assignment

- To add a Search task, right click anywhere in the main map area to bring up the following menu.
- Select the priority and window of start times for the task. The priority is used by the algorithm to add the task to the schedule. The window specifies when the task is allowed to be done.



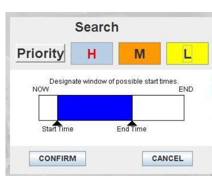
Task Assignment

- A Note on setting the Window of Start Times
  - If the time set for the latest possible "End Time" is passed before the task is completed, the task will be deleted.



Task Editing

- Right clicking on a task or target in both the Main interface and the SCT will bring up this interface, allowing you to change the priority and window of start times for the task.



Target Identification

- In real search & track missions, when a target is found, an operator must identify what type of target has been found.
- To simulate this process, the following mini-game has been included.

Target Identification

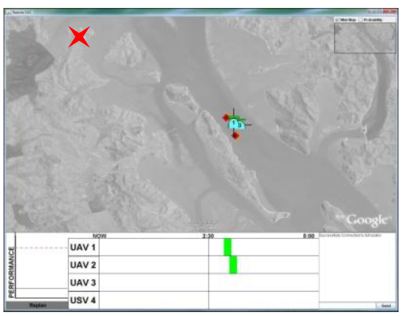
- When a target is found the following interface pops up, blocking the rest of the interface.
- Initially the colored square is not in view. Dragging the main image around will bring the square into view. Click the bottom button which corresponds to the squares color.
- In the example shown, the bottom button "Team 2" should be clicked.

Add & Assign a Task

- The following slides will walk you through the process of adding a task and getting it assigned to a UxV.
- In the following slides, the user thinks there might be a target in the upper left corner of the screen.

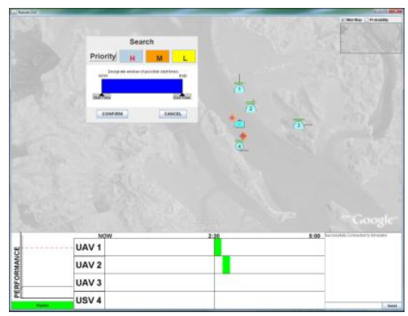
Add & Assign a Task

To add a "Search" Task, Right Click at the desired location. (Red X)



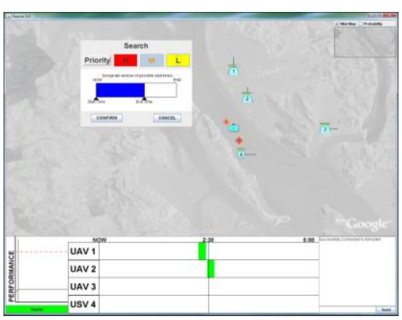
Add & Assign a Task

Edit the Priority & Window Of Start Times as desired.



Add & Assign a Task

Once finished, click CONFIRM to add the task, or CANCEL to exit.

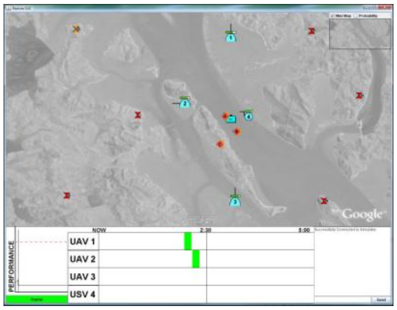


Add & Assign a Task

The Task has been added with ID "D".

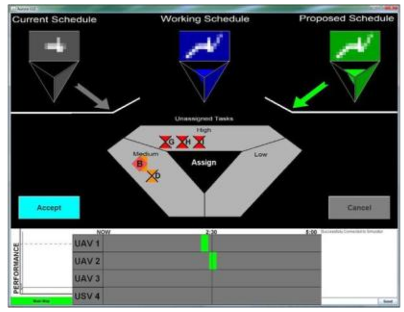
Add & Assign a Task

More tasks have been added. Notice the Green "Replan" button, indicating that the automation has a better plan than the current one.



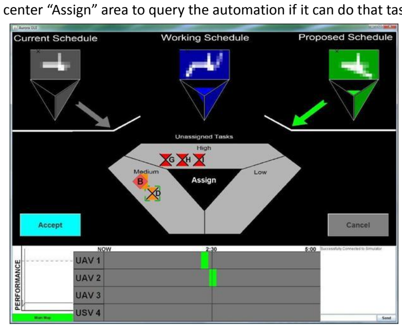
Add & Assign a Task

Clicking on "Replan" brings you to this screen. Notice, the "Working" and "Proposed" Schedules are identical.



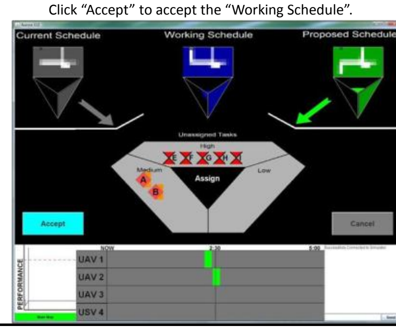
Add & Assign a Task

Clicking on a task will bring up its location in the configural display. Drag it into the center "Assign" area to query the automation if it can do that task.



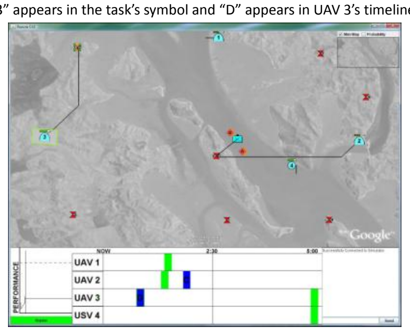
Add & Assign a Task

The automation can do task "D"; it is no longer visible in the "Unassigned" area. Notice in the configural display a path leading toward the upper left. Click "Accept" to accept the "Working Schedule".



Add & Assign a Task

Task "D" is now assigned to UAV 3. UAV 3's path heads straight for task "D". A "3" appears in the task's symbol and "D" appears in UAV 3's timeline.



Performance Reviewed

Performance will be calculated based on:

- The percentage of the area searched.
- The number of targets found.
- The percentage of the time the targets' locations were known / the percentage of time the targets were successfully tracked.

Appendix D

Usability Ratings per Subject

Questions:	Perceptual Activity	Mental Activity	Projected Performance	Confusion	Feedback to User	Control	Satisfaction vs. Frustration
Subject 1	4	2	4	1	3	2	3
Subject 2	1	2	4	1	4	3	4
Subject 3	3.5	4	3	5	3	2	4
Subject 4	3	3	3	2	2	1	3
Subject 5	3	2	4	3	4	3	3

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