Innovative Systems for Human Supervisory Control of Unmanned Vehicles

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The development of Unmanned Vehicles (UVs) with increasing autonomy has enabled a transition from teleoperation to Human Supervisory Control (HSC). In this demonstration, participants can test three innovative operator interfaces for HSC of UVs. The first system allows users to control a Micro Air Vehicle (MAV) via a hand-held device, such as an iPhone®, through high-level waypoint commands and fine-grained nudge controls. The second system enables a single operator to collaborate with an automated planner to control multiple heterogeneous UVs from a laptop-sized display for searching for, tracking and engaging moving ground targets. The third system is designed to aid in planning on naval aircraft carrier decks, serving as a decision support tool for a supervisor overseeing and scheduling the activity of people, vehicles and unmanned vehicles working in this complex and uncertain environment.

INTRODUCTION

Unmanned Vehicle (UV) operations have increased dramatically over the past decade (Haddal & Gertler, 2010; Naval Studies Board, 2005; U.S. Air Force., 2009). Specifically within the Unmanned Aerial Vehicle (UAV) domain, vehicles are controlled via teleoperation, with occasionally some low level autonomy, where a human operator can directly control the movement of the control surfaces of the aircraft via either a Ground Control Station (GCS) with a joystick and rudder pedals or via a manual hand-held flight controller. Even some newer point-and-click based interfaces still require the full attention of the operator, as the aircraft exhibit little "autonomy" in operations. These control systems require extensive training before an operator can safely and effectively operate the UV. More complex UVs often require more human operators than a comparable manned vehicle requires (Haddal & Gertler, 2010).

There is increasing pressure to reduce the training costs and manning requirements per vehicle (Haddal & Gertler, 2010) while expanding UV operations (U.S. Air Force., 2009). This can be achieved by leveraging advances in autonomy for both individual vehicle navigation (How et al., 2009) and multiple vehicle coordination (Choi, Whitten, & How, 2010). The United States Department of Defense envisions a future with single operator control of multiple heterogeneous (air, sea, land) UVs (Naval Studies Board, 2005).

In order to reduce the training requirements on UV operators or to enable operators to control multiple UVs, systems must be designed that enable Human Supervisory Control (HSC) as opposed to teleoperation. Current UV operations are best represented through the second system representation in Figure 1, where the human operator is directly controlling the actuators of the UV or possibly the third system, where the computer assists the operator by closing some of the control loops (such as automatic altitude holds). The fourth system illustrates true HSC, where the human operator provides high-level commands to the

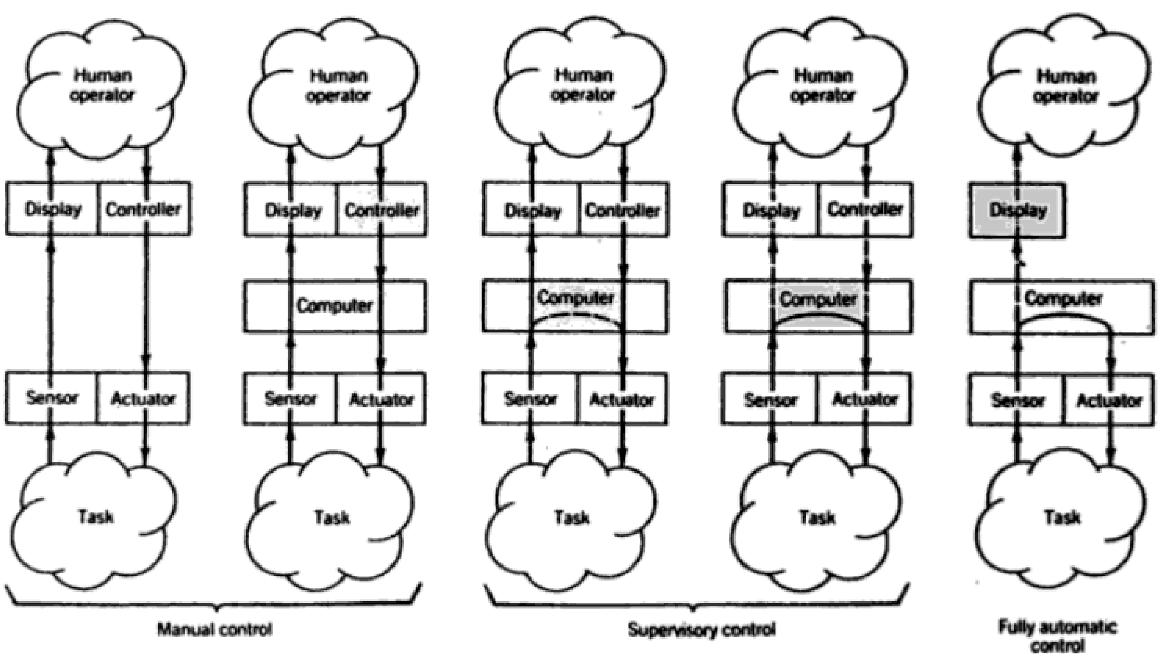

Figure 1. Spectrum of Control Modes (Sheridan, 1992)

computer, which interprets those commands and implements the low-level control loops necessary to operate the UV in the desired manner.

Three innovative systems have been designed, implemented and tested extensively to enable this higher level of HSC for controlling UVs. The first system allows users to control a Micro Air Vehicle (MAV) via a hand-held device, such as an iPhone®, through high-level waypoint commands and fine-grained nudge controls. The second system enables a single operator to collaborate with an automated planner in a laptop-based system to control multiple heterogeneous UVs in order to search for, track and engage moving ground targets. The third system is designed to aid in planning on naval aircraft carrier flight decks, serving as a decision support tool for a supervisor overseeing people, vehicles and unmanned vehicles working in this complex and uncertain environment. All of these systems leverage advanced autonomy to aid the operator with controlling UVs and making high-level scheduling decisions, enabling effective HSC with minimal training requirements.

In this demonstration, participants will be able to test all three systems by controlling simulated UVs on either a mobile handheld device or a laptop computer. The following sections describe each of the three systems, including their potential applications. The proposal concludes with a description of the logistics of the demonstrations.

MICRO AERIAL VEHICLE VISUALIZATION OF UNEXPLORED ENVIRONMENTS (MAV-VUE)

Although Unmanned Aerial Vehicles are becoming increasingly common in both military and civilian domains, most of the systems in use are large, expensive and require many hours of training for operator certification. Additionally, most of these systems lack the capability to quickly deliver real-time surveillance information to the persons on the ground who need it most. To address this need, the Micro Air Vehicle Visualization of Unexplored Environments (MAV-VUE) platform was developed. The MAV-VUE interface gives a single operator with minimal training the ability to control a MAV using a mobile device to obtain immediate information about their surroundings.

The design of the MAV-VUE system moves away from direct teleoperation and leverages automation to create a system that is more robust, easier to learn and easier to control. This is achieved using two modes of control: a high-level waypoint mode and a lower-level nudge control mode.

The waypoint control interface, shown in Figure 2, allows for high-level control of the vehicle. The position of the MAV is shown in real-time on a map display. An operator can place a waypoint on the map by tapping on the screen on the desired location. The MAV will autonomously traverse to each waypoint where it will then hover and wait for the next command. The waypoint mode incorporates autonomous obstacle avoidance and commands the MAV to a constant altitude above ground level. This mode's high level of automation requires minimum attention and interaction on the part of the pilot, freeing him or her to attend to other tasks as necessary.

The nudge control interface, shown in Figure 3, allows for more fine-tuned control. Once the vehicle reaches an area of interest, the operator can explore a possibly unknown area, relying on solely on feedback from the device, primarily through visual information from the onboard camera. The operator interacts with the system and gives flight controls through natural gestural inputs. The system aims to transfer controls or interactions from typical smart phone interactions and map them intuitively on to control inputs for the vehicle. Translational commands are given by tilting the device in the desired direction of motion, with the degree of tilt representing the magnitude of the input. Rotational commands require a swiping motion around the circle in the center of the display. Altitude commands involve a pinching motion, with the size of the input corresponding to the magnitude of the resulting command. Beneath this control interface is a framework called Perceived First Order Control (Pitman, 2010). The operator has the benefit of a joystick-like, velocity-based (first-order) control, but the underlying system is actually sending waypoint commands, (zero-order control) which results in increased robustness in situations with high system lag or loss of communication.

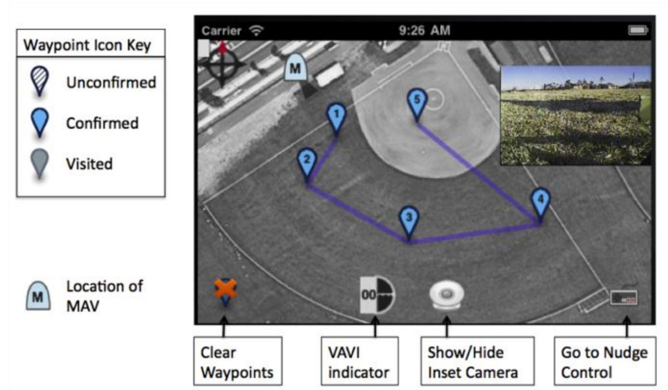

Figure 2. MAV-VUE Waypoint Control Interface

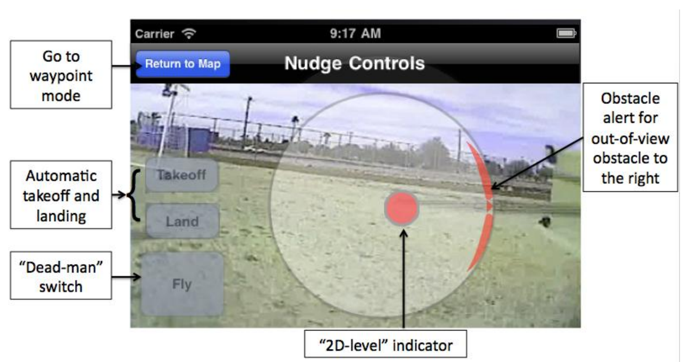

Figure 3. MAV-VUE Nudge Control Interface

The nudge control interface also incorporates an obstacle alerting display to notify operators of potential collisions. Operators working in a field environment cannot expect to have detailed information of the environment in advance, so the operator needs to be aware of potential obstacles in order to make appropriate flight decisions. The overlaid indicators (see Figure 3) provide simplified information about proximity and location of obstacles in the environment.

The current interface is implemented on an iPhone®, although it could be adapted to nearly any smartphone or tablet platform. Figure 4 outlines the full system architecture. The system is modular and can currently interface with the Ascending Technologies Hummingbird and Pelican quadrotor helicopters as well as a simulation environment and it could be extended to interface with other systems as necessary.

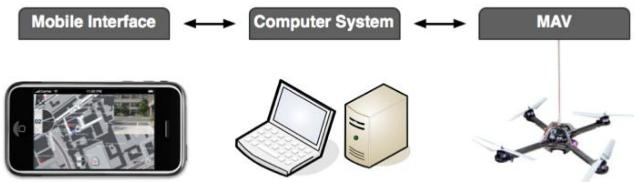

Figure 4. MAV-VUE System Architecture

Usability studies in an indoor motion capture environment and in an outdoor field environment have demonstrated that operators with only three minutes of training can successfully operate the system to perform navigation and surveillance tasks. Full results from these studies are available in Pitman (2010) and Jackson, Quimby, and Cummings (2011).

Initial work focused on military applications, where soldiers need immediate, accurate information about their surroundings. Additionally, as these systems start to become more available, new applications will continue to emerge. Examples include police surveillance, traffic monitoring, wildfire monitoring and aerial photography, and the list is quickly growing. However, as these MAVs become more common in the civilian sector, having an intuitive interface and robust system becomes even more crucial, given lower operator experience and fewer organizational resources.

ONBOARD PLANNING SYSTEM FOR UVS SUPPORTING EXPEDITIONARY RECONNAISSANCE AND SURVEILLANCE (OPS-USERS)

The Onboard Planning System for UVs Supporting Expeditionary Reconnaissance and Surveillance (OPS-USERS) enables a single operator to collaborate with an automated planner to control multiple heterogeneous UVs from a laptop-sized display. The system leverages decentralized algorithms for vehicle routing and task allocation. Operators utilize the UVs for the purpose of searching the area of interest for new targets, tracking targets and approving weapons launch. The system has been used in simulation-based experiments, indoor flight tests and outdoor flight tests.

All targets are initially hidden, but once a target is found, it is designated as hostile, unknown or friendly and given a priority level by the user. Hostile targets are tracked by one or more of the vehicles until they are destroyed by a Weaponized Unmanned Aerial Vehicle (WUAV). Operators are presented with imagery of the target to allow them to verify the classification of the target as hostile, after which they have the final decision to approve all weapon launches. Unknown targets are revisited as often as possible, tracking target movement. A primary assumption is that operators have minimal time to interact with the displays due to other mission-related tasks.

The main interface used by the operator is a Map Display, shown in Figure 5. The operator commands the UVs in collaboration with the automation by creating search tasks in the Map Display, then choosing a schedule generated by the automation that assigns vehicles to tasks. Operators have two exclusive tasks that cannot be performed by automation: target identification and approval of all WUAV weapon launches. The operator compares and selects task schedules through a second display called the Schedule Comparison Tool (SCT), shown in Figure 6.

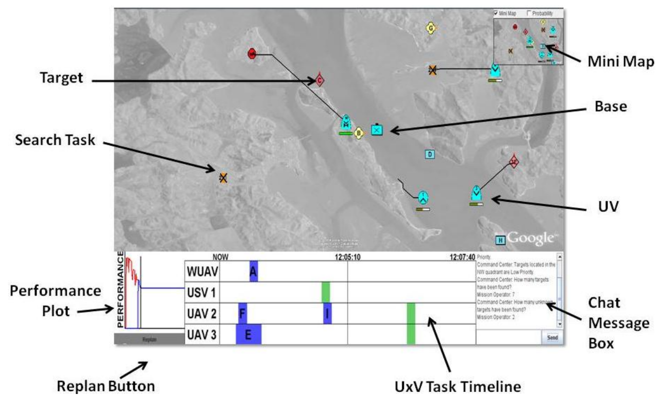

Figure 5. OPS-USERS Map Display

A task-based, decentralized implementation was chosen for the automated planner to allow rapid reaction to changes in the environment. The task planner used in OPS-USERS is the Consensus Based Bundle Algorithm (CBBA), a decentralized, polynomial-time, market-based protocol that can generate new schedules on the order of seconds (Choi, Brunet, & How, 2009). The human operator provides high-level task-based control, as opposed to more low-level vehicle-based control, by approving which tasks should be completed by the vehicles. The vehicles then utilize CBBA to allocate tasks amongst themselves in a decentralized manner.

In such architectures, operators do not directly individually task a single vehicle. When appropriate, the decentralized task planner can modify the tactical-level plan (at the vehicle level) without human intervention, which includes changing the task assignment without affecting the overall plan quality (i.e., agents switch tasks). The CBBA algorithm is able to make these local repairs faster through inter-agent communication than it could if it had to wait for the next update from the human operator. Plans can be carried out even if the communication link with the ground control station is intermittent or lost. The architecture is scalable, since adding additional agents also adds computational capability and the decentralized framework is robust to a single point of failure, since no single agent is globally planning for the fleet (Choi, et al., 2009).

Operators are shown the results of the scheduling algorithm through the SCT, a decision support interface, shown in Figure 6. Configural displays show the high-level performance metrics of each schedule, as well as unassigned high, medium and low priority tasks that could not be completed by one or more of the vehicles due to constraints on vehicle resources. If the operator is unhappy with the automation-generated schedule, he or she can create new tasks or conduct a "what-if" query process by dragging the desired unassigned task into the large center triangle. This query forces the automation to generate a new plan if possible that prioritizes a particular task, in effect forcing the decentralized algorithms to re-allocate the tasks across the UVs. Operators can leverage direct-perception interaction (Gibson, 1979) to quickly compare schedules. Details of the interface design and usability testing are provided in previous research (Cummings, Clare, & Hart, 2010; Fisher, 2008)

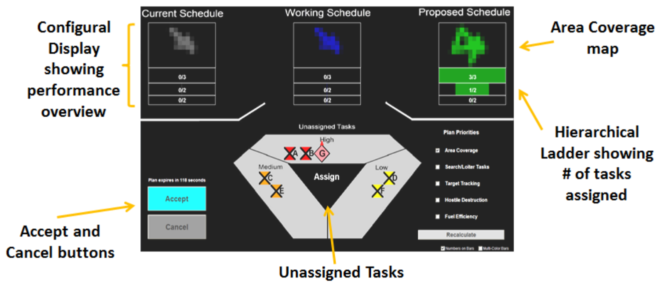

Figure 6. The Schedule Comparison Tool (SCT)

The system was designed to aid an expeditionary controller, i.e., a human moving through the environment with only a laptop to control a team of UVs for an Intelligence, Surveillance and Reconnaissance (ISR) mission. Potential applications of this system include any ISR mission in a dynamic and uncertain environment, such as military operations, border patrol, forest firefighting, emergency first responder operations and search and rescue.

DECK OPERATIONS COURSE OF ACTION PLANNER (DCAP)

Certain environments, however, require the coordination of both manned and unmanned systems. In these domains, the focus of supervisory control must shift from managing the activity of individual vehicles to managing the allocation of resources throughout the system. The supervisory controller cannot take control of a manually piloted vehicle or a single crewmember, as they would a teleoperated UAV. However, the goal of operating any vehicle system is not to accomplish the physical feat of operation, but instead to meet some task goal – to reach a certain area by a certain time. To do so requires the leveraging of resources within the system to accomplish tasks. As such, the supervisory control of the system becomes that of managing resource allocation with time windows.

A example of this domain is the aircraft carrier flight deck, where upwards of 40 aircraft may be operating at a given time, serviced by over 100 human crew working in close proximity. Operations happen in parallel across the deck and replanning must take into account not only interactions required to perform tasks (such as crew being present to operate machinery) but also traffic management as vehicles navigate around the deck. Complicating this environment is the high frequency of failures on the deck. Operations must continually be adjusted due to the accumulation of failures and delays in tasks. In the current operating paradigm, operations are managed by a network of controllers, termed Aircraft Directors, supervised by the Deck Handler, who issue instructions to pilots in real time via hand gestures. While this system works at a high proficiency and shows surprising robustness (Rochlin, La Porte, & Roberts, 1987), the gestural actions used in communication will not possible with UAVs like the X-47B Pegasus (Ackerman, 2011; McKinney, 2011). A new form of coordination and management is required.

The Deck operations Course of Action Planner (DCAP) was developed to facilitate the supervision and replanning of schedules in these environments, moving from a decentralized supervisory architecture to a centralized one. Because of the heterogeneous nature of operations, DCAP focuses on the allocation of resources to vehicles in the environment. DCAP provides four main elements to the operator (Ryan, Cummings, Roy, Banerjee, & Schulte, 2011). First, a "birds-eye view" of live operations on the deck is presented (the Carrier Display, Figure 7), providing the operator with information on the geospatial location and movement of every aircraft and crewmember on the flight deck. The second and third elements concern the current schedule of operations. Timelines are generated for the predicted resource allocations and the predicted execution of individual aircraft tasks. The former is termed the Resource Allocation Timeline and appears at the bottom of the interface; the latter is the Aircraft Scheduling Panel and appears on the right. The fourth and final element of DCAP is a collaborative scheduling system that is integrated into the other major components. This scheduling system requires input from the human operator, which is then used to guide the solution of an integer linear program (ILP) planner (Banerjee, Ono, Roy, & Williams, 2011; Ryan, Banerjee, Cummings, & Roy, 2011).

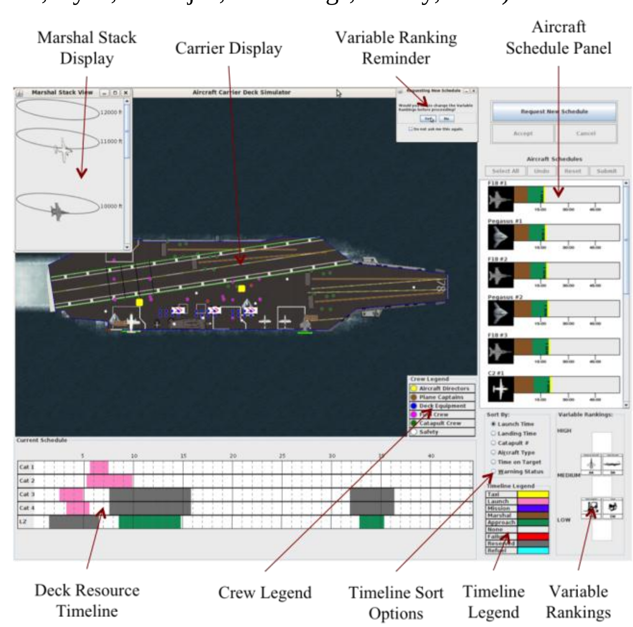

Figure 7. DCAP Interface

Expert users in these environments have developed sets of heuristics that help them quickly replan within the environment through accumulated experience with the environment. Planners have goals of operations and understand what a good schedule should be, even if they cannot create it very quickly. Additionally, the expert users are better able to understand the changing priorities within the environment than the algorithm. The algorithm, however, can more quickly develop a schedule that adheres to these principles than the human operator. The collaborative planning step leverages the combined strengths of the human and the algorithm: the user sets priorities and constraints for the algorithm (in terms of a drag-and-drop ranking system and scheduling timelines, respectively) and the algorithm returns to the operator a new schedule for review. This new schedule is feasible and adheres to operator specifications as best as possible, given the current state of the system and current set of feasible actions.

Although DCAP is currently built to replan for aircraft carrier flight decks, the general properties of this environment are not unique. Similar environments include airport traffic management, rail or shipping scheduling or even hospital room or surgical bed allocation. In every case, the system functions by allocating the uses of a single resource (e.g., a surgical bed) to an active agent (a patient) for a limited period of time (the surgery). Once the task is completed, the agent then leaves the resource, which is then free to execute the next task. Thus, the general design of DCAP is adaptable to any type of system that can be classified as resource allocation with time windows.

DEMONSTRATION SETUP

For the MAV-VUE demonstration, we will bring one laptop, one desktop, and one monitor. The demonstration will allow users to control a simulated MAV using an iPhone® that we will provide. Imagery on the iPhone will be generated using USARSim, a high-fidelity simulation based on the Unreal Tournament game engine (Lewis, Wang, & Hughes, 2007). We will bring one laptop dedicated for the OPS-USERS demonstration, so that operators can command four simulated unmanned vehicles via a point-and-click interface. Finally, we will bring one laptop and one 21” touchscreen monitor for the DCAP demonstration, which enables the use of a stylus for supervising simulated carrier desk operations.

We will require 6 power outlets (or one power strip with 6 outlets) to power all of the equipment. We will require two standard six-foot tables to hold the computer equipment.

Once again, all demonstrations will be of simulated Unmanned Vehicle control and there will be no actual flying vehicles in motion at the demonstration. Each demonstration is independent of the others, allowing us to demonstrate for three groups of visitors at a time. We were advised by the HFES Technical Program Committee Chair to submit a single proposal because of the related nature of the three systems, but they are essentially three separate demonstrations, but all occurring in the same laboratory.

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