MULTI-SENSORY DISPLAYS AND VISUALIZATION TECHNIQUES SUPPORTING THE CONTROL OF UNMANNED AIR VEHICLES

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Abstract

Unmanned Air Vehicles (UAVs) have many potential benefits compared to manned systems. These advantages include increased loiter capability, less expensive airframes, and expendability without loss of human life. An example of this is the US Air Force Predator UAV. Although relatively new to the US Air Force inventory, the Predator has demonstrated its worth in performing various intelligence, surveillance, and reconnaissance (ISR) missions around the world. Although their potential benefits are many, current UAV control stations have several human factors deficiencies including issues of crew coordination, control/display design, and system time delays (Gawron, 1998). A research program is underway to explore how advanced multi-sensory interface technologies and visualization techniques might improve UAV operator performance and situation awareness while reducing workload. Advanced technologies under consideration include haptic feedback, head-mounted displays, spatialized audio, and virtual environments. The results of two studies are summarized and future research plans are described.

1 Introduction

Unmanned Air Vehicles (UAVs) have many potential benefits compared to using manned systems for similar missions. UAV platforms are generally smaller, lighter, and less expensive and have greater loiter capability. Additionally, they are expendable without loss of human life. These benefits allow UAVs to support a wide range of military and civilian missions (Gawron, 1998). Civilian uses include law enforcement surveillance, and relaying telecommunications information. Military utilization is currently centered on intelligence, reconnaissance, and surveillance (ISR) missions, with efforts to expand into combat operations (Worch, Borky, Gabriel, Heiser, Swalm, & Wong, 1996). Most existing UAVs are remotely operated as multiple task telerobotic control systems via "stick and throttle" manipulations. The majority of fielded UAVs carry a package of sensors to a desired location for the purpose of transmitting images back to a ground control station.

The physical separation of the crew from the aircraft has created problems for UAV system designers, however. Human factors issues such as system time delays, poor crew coordination, and reduced situational awareness (SA) have negatively affected mission performance (Gawron, 1998). When onboard aircraft, pilots and crew receive a rich supply of multi-sensory information regarding their surrounding environment. UAV operators, however, are currently limited to a reduced stream of sensory feedback delivered almost exclusively through the visual channel. As an example, UAV operators have identified the onset of sudden turbulence as being potentially detrimental to safe and effective UAV control. This is especially true for UAVs that require direct manual control in order to land. Turbulence is currently indicated solely by an unexpected perturbation of video images being transmitted from a UAV-mounted camera to the operator control station, appearing on a CRT with HUD symbology overlaid. Due to limitations inherent with reducing all environmental information to the visual channel, UAV operators may fail to perceive, or fail to correctly diagnose this video perturbation as sudden turbulence.

There is reason to believe that a UAV operator's SA and performance may be improved through increased multi-sensory stimulation akin to that experienced by an onboard pilot, at least for those UAVs that must be manually controlled. These improvements might result either from an increase in the operators 'presence' of the local environment (Sheridan, 1992), from increased information throughput afforded by effective use of multi-sensory stimulation per the multiple resource theory (Wickens, 1992), or a combination of the two.

This paper describes a research program that is investigating how advanced multi-sensory interface technologies and visualization techniques might improve UAV operator performance and situation awareness while reducing workload. This research focuses on the US Air Force Predator Medium Altitude Endurance (MAE) UAV. Although relatively new to the US Air Force inventory, the Predator has demonstrated its value in performing various intelligence, surveillance, and reconnaissance (ISR) missions around the world. The Predator UAV is described, including its ground control station configuration. Human factors issues inherent in existing UAVs are then summarized. This is followed by the current research agenda, which describes the simulation facility for interface evaluations, research completed to date, and planned efforts.

2 The Predator UAV

2.1 General Description

The USAF Predator UAV was developed as an Advanced Concept Technology Demonstration (ACTD) from 1994 to 1996. The aircraft is essentially a redesigned General Atomics Gnat 750. As illustrated in Figure 1, the Predator is a fixed wing aircraft with high aspect ratio wing and inverted-V tail.

Figure 1. The USAF Predator MAE UAV

The Predator can carry an electro-optic/infrared (EO/IR) gimbaled sensor with zoom and spotter lenses. In addition, the Predator can support an all-weather synthetic aperture radar (SAR).

This aircraft was built for endurance rather then speed. It can loiter for up to 24 hours on station at 400-500 nautical miles. Its cruising speed is a modest 70-90 kts, however. The Predator is a medium altitude vehicle, operating up to 26,000 feet (UAV Annual Report, 1996).

The Predator is controlled from a ground control station (GCS). Communications between the GCS and aircraft can either be line-of-sight, or via satellite link. If the connection is via satellite, the transport delay between command and response can be on the order of several seconds (UAV Annual Report, 1996).

2.2 Missions

The Predator, although new to the US Air Force inventory, has seen action in several operational exercises and deployments. It initially proved its value at Roving Sands '95, an annual air defense exercise held in the southwestern United States. It has since successfully performed ISR missions in deployments to Southwest Asia, Bosnia, and Kosovo (Garamone, 1999).

2.3 Operator Control Station

The operator control station is contained within a mobile GCS. The GCS consists of pilot and sensor operator workstations, a data exploitation, mission planning, communication workstation (DEMPC), and SAR workstations.

The main operator console (Figure 2) includes workstations for a sensor operator (SO) and an air vehicle operator (AVO) and as such provides the primary means for controlling the aircraft and sensors. The AVO, sitting to the left, controls UAV flight (via stick, throttle, and rudder controls, as well as through autopilot commands), manages subsystems, and handles external GCS communications. From the right workstation, the SO is responsible for locating and identifying targets by controlling a gimbaled camera mounted on the UAV. The focus of this research effort is to evaluate operator interface improvements to this console.

Figure 2: Predator PPO (AVO station on the left, SO station on the right)

Each station has an upper and a head-level 17" color CRT display, as well as two 10" lower displays. The upper CRT of both stations displays a 'God's Eye' area map (north-up) with overlaid symbology identifying current UAV location and sensor footprint. The head-level CRT displays video imagery and overlaid symbology. The AVO often views video imagery from a camera mounted on the nose of the Predator, while the SO views imagery generated from the gimbal-mounted sensor. However, the AVO may choose to also view imagery from the gimbal-mounted camera if conditions warrant. HUD symbology is overlaid on the AVO's camera display while sensor specific data is overlaid on the SO's camera display.

3 Current Human Factors Issues

Human factors issues with current UAV systems have been well documented (Gawron, 1998). These issues include system time delays, poor crew coordination, suboptimal controllers, limited field-of-view (FOV), high workload and low situational awareness (SA). As an example, a recent Predator mishap was attributed in part to 'human factors'

(Rogers, 1999). Given that an identified benefit of UAVs is the potential to control more then one from a single GCS, the effects of lingering human factors issues will be magnified.

4 Research Agenda

As stated earlier, this research effort investigates how advanced multi-sensory interface technologies and visualization techniques might improve UAV operator performance and situation awareness while reducing workload. Separating the crew from the aircraft has eliminated many rich and intuitive sources of information on the aircraft and the surrounding environment. Multi-sensory interfaces that surround the user in the information space directly affect the primary cause of limited SA in UAV operations. Advanced interface technology, if applied appropriately, can provide a rapid, intuitive means to obtain local situation awareness. In addition, multi-sensory interface technology will increase information throughput via coordinated use of multiple sensory channels, rather then relying on the near exclusive use of the visual channel, as current UAV control stations do. This research does not focus exclusively on multi-sensory solutions, however. Potentially lower cost visualization solutions are evaluated as well in order to empirically determine the relative value of multi-sensory versus conventional solutions to improve SA and mission performance in the context of current and planned UAV operations.

5 Simulation Facility

A UAV ground control station (GCS) simulation capability has been fabricated within the Air Force Research Laboratory's Synthetic Interface Research for UAV Systems (SIRUS) facility at Wright-Patterson Air Force Base, Ohio. As illustrated in Figure 3, this simulator is patterned after the main operator console for the USAF Predator UAV.

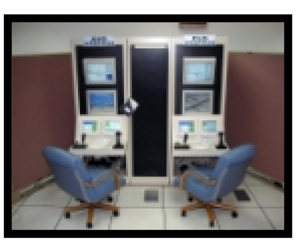

Figure 3. UAV Simulation Facility in SIRUS

The simulation is constructed by connecting four dual-Pentium PCs under the Windows NT operating system. The simulation software, the UAV Simulation Environment (USE), was obtained by leveraging ongoing USAF efforts to fabricate Predator training simulators. The control sticks are from Measurement Systems Incorporated and the throttle assemblies were manufactured in-house to resemble those in the Predator GCS.

6 Empirical Studies

Two completed research studies are summarized. The first study focused on visualization concepts to improve the communication of target location between crewmembers. The second study evaluated the usefulness of haptic feedback technology to enhance AVO detection of unexpected turbulence.

6.1 Target Localization Research

Current UAV ISR missions require a high degree of crew coordination to successfully locate and identify ground targets (Gugerty, DeBloom, Walker, & Burns, 1998). Overall mission success is often determined by crewmembers' efficiency in communicating target location. However, communication is hampered by the separation of the crew from the UAV's physical location, the separation of crewmembers within the GCS, and frame-of-reference taxonomy differences between earth-referenced locations and sensor-referenced locations.

Often, the AVO acts as an "extra set of eyes" to assist the SO in locating and identifying targets. The AVO's head-level display can be configured to view a large field-of-view (FOV) image from the camera that the SO controls while the SO views a higher resolution (smaller FOV) image to facilitate individual target identification and classification (Figure 4). Therefore, while the SO is zoomed in on a particular area, the AVO can spot points-of-interest (POI) which lie outside the SO's instantaneous FOV. The current method of communicating target location between crewmembers in this scenario is through verbal instructions. This study evaluated additional information conveyance display concepts designed to expedite transfer of target location between the AVO and SO.

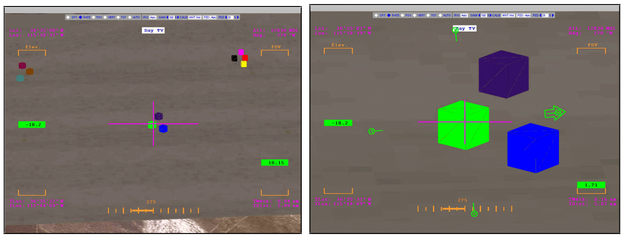

Figure 4. Camera Displays. AVO's (left), SO's (right).

One display concept candidate was a compass rose overlay on the SO's camera display (Figure 5). The floating compass rose (an indication of magnetic North, South, East and West) was designed to provide a constant reference to real-world cardinal headings on the SO's camera display regardless of air vehicle or camera orientation. Adding a floating compass rose to the SO display provides a direct indication of the world-referenced coordinate frame thus potentially reducing the time and effort otherwise required for the SO to perform reference frame translations and rotations.

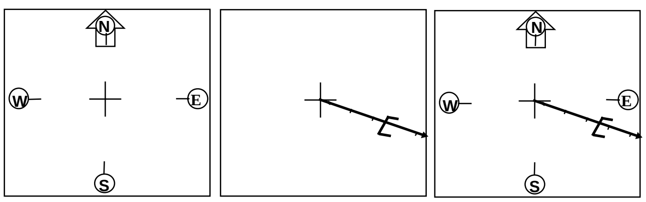

Figure 5. Display Concepts (left: Compass Rose, center: Telestrator, right: Combined)

Another candidate display concept included the use of point designation and locator line vector symbology overlaid on the SO's camera display (Figure 5). Termed the 'telestrator' concept, this approach was designed to provide graphically represented target location communication directly between the AVO and SO. Via a cursor, the AVO designates a POI location on the AVO display to which the SO is supposed to direct the narrow FOV camera line-of-sight (LOS). When a POI is designated, a locator line is presented on the SO display. The locator line is a vector that indicates the direction and angular distance the camera LOS should traverse in order to overlay the camera LOS on the POI location. This concept was based on the effective use of locator line symbology on aircraft head-up and helmet-mounted displays (Geiselman and Tsou, 1996).

This study evaluated the relative benefits of the compass rose, telestrator, and the combined use of these concepts in improving UAV crew coordination in the locating of ground targets over a baseline condition (Draper et al., 2000).

A 4x2x2 within-subjects design was employed. Four levels of DISPLAY (Baseline, Compass Rose, Telestrator, Combined) combined with two levels of LOCATION (Near: 5° radial distance from initial sensor position, Far: 20° radial distance) and 2 REPETITIONS. The LOCATION factor determined whether the POI initially appeared within the AVO head-level display (Near condition) or outside of it (Far condition). The Far condition required the AVO to first utilize the upper (map) display to instruct the SO. Each SO completed a total of 64 trials.

The results of this study indicate that trials utilizing the telestrator concept resulted in significantly improved crew performance. Time to designate targets was reduced an average of almost 50% using the telestrator, while path efficiency improved by an average of approximately 40% for near targets (Figures 6 and 7). Mental workload metrics also indicated significantly less mental workload in the telestrator conditions. Additionally, the data suggests that crew verbal communication was reduced when using the telestrator. This reduction of crew 'chatter' potentially frees the audio channel to more efficiently receive other types of information and alerts.

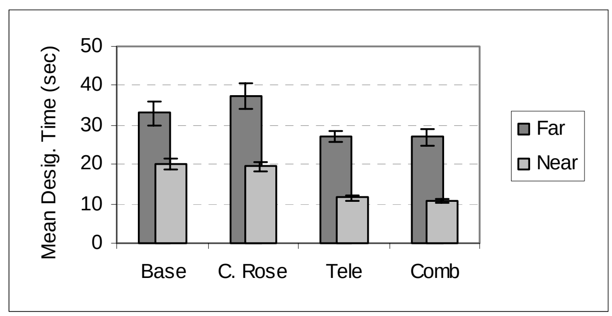

Figure 6. Total time to designate target by DISPLAY and LOCATION. (Error bars = ± SEM)

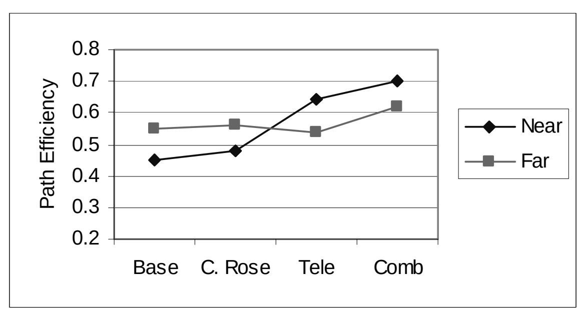

Figure 7. DISPLAY x LOCATION interaction (path efficiency data). Near targets adversely effected efficiency for the non-telestrator conditions but improved efficiency for the telestrator conditions.

The potential exists for this telestrator concept to be expanded beyond use within UAV crews. For example, a UAV crew is often tasked via an external, geographically separated agency to view a particular POI. This communication of target location is also currently accomplished strictly via verbal instruction. Assuming that point designation can be accomplished by the external agency, the results of this study suggest that the telestrator may be a more efficient solution.

6.2 Turbulence Detection Research

As mentioned earlier, UAV operators have identified the onset of sudden turbulence as being potentially detrimental to safe and control of existing UAVs. Turbulence is currently indicated solely by an unexpected perturbation of video images being transmitted from a UAV-mounted camera to the operator control station. Due to limitations inherent with reducing all environmental information to the visual channel, UAV operators may fail to perceive, or fail to correctly diagnose this video perturbation as sudden turbulence.

This study explored the utility of haptic feedback technology for providing the UAV operator with an enhanced indication of the sudden onset of wind turbulence (Ruff, et al., 2000). Visual feedback was supplemented by haptic feedback applied directly to the pilot's control stick, providing a redundant, kinesthetic alert as a force reflection in the axis-direction and scaled-ratio magnitude of the turbulence event. Rather then attempt to exactly replicate haptic sensations that pilots may feel in an actual cockpit, the goal of this initial study was simply to provide a supplemental and intuitive means of displaying the onset of turbulence in order to evaluate its effects on UAV operator SA and performance.

This experiment was conducted as a 2x2x2x2 within subjects design. The independent variables included level of HAPTIC feedback (Off, On), turbulence onset STRENGTH (Mild, Severe), primary turbulence AXIS perturbation (Horizontal, Vertical), and PROXIMITY to the runway when the turbulence onset occurred (Near, Far). Each subject participated in 16 trials.

The results indicate that the addition of haptic feedback improved operator SA of turbulence events. However, this improvement was reduced for mild turbulence occurring when the UAV was near the runway (Figure 8). The operator's heightened state of alertness associated with the anticipated contact of the aircraft with the runway surface may have been a contributing factor in detecting mild turbulence events. This situation-based increase in SA likely served to diminish the increases in SA due to the supplemental haptic feedback.

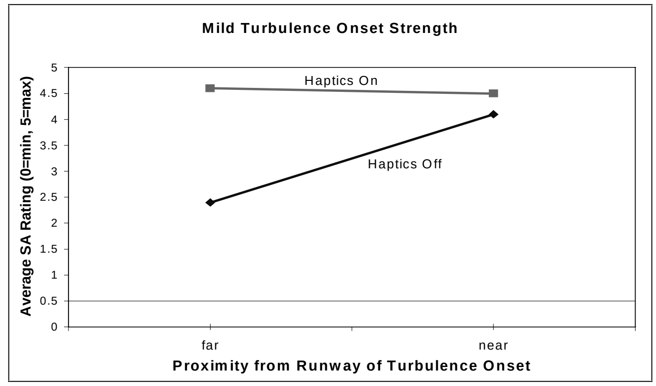

Figure 8. Interaction of HAPTICS x PROXIMITY for Mild turbulence STRENGTH.

One might expect the addition of haptic feedback in landing tasks to decrease ratings of landing difficulty due to its ability to significantly increase SA. However, results of this study indicate otherwise (Figure 9). The relatively high-gain stick movement generated by the haptic feedback required more mediating effort on the part of the pilot. Indeed, while participant comments confirm that haptic feedback was a useful tool for the task, the magnitude of the control stick deflections was judged to be far too severe for actual use.

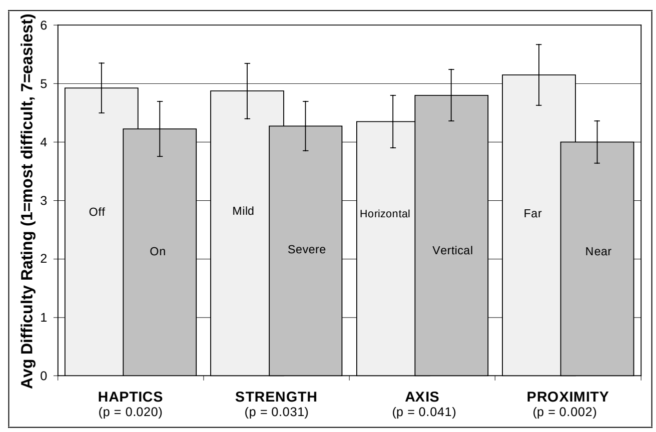

Figure 9. Average difficulty ratings. (Error bars = ± SEM)

Because haptic feedback was confounded with alert redundancy, it is not possible to ascertain if the increases in SA encountered in this study were due to haptic technology in particular or due simply to the addition of a redundant turbulence alert cue. A follow-on investigation is being conducted to tease-out the redundancy effect through the addition of a non-haptic redundant cue. This follow-on experiment also increases landing task difficulty by requiring more stick inputs and by challenging the visual channel feedback by providing turbulence onset in degraded visual conditions.

7 Future Plans

As mentioned above, additional research is being conducted to further explore the operational benefits associated with using haptic feedback to alert the operator to sudden turbulence. Additionally, head-mounted display and 3-D spatialized audio technology is being considered to improve operations and crew situation awareness. Specifically, head-coupled HMD applications include support for emergency landing tasks, avoidance of other aircraft, and target localization tasks. 3-D audio is primarily being applied to improve target localization tasks, spatialized alerts, and spatial separation of multiple sources of verbal communication.

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