Advancement and Application of Unmanned Aerial System Human-Machine-Interface (HMI) Technology

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Abstract. Interface designs native to handheld control and feedback devices (e.g., smartphones and tablets) are becoming more accessible within the small unmanned aerial system (sUAS) community due to increased usage in remote control (R/C) model aircraft platforms [33], improved processing to cost [4], and increased interoperability supporting custom development and programming [2], [33]. These smaller, power efficient control systems have the potential to change the paradigm of sUAS control to be more aligned with semi-autonomous operations based on their innate ability to provide intuitive user interactions [44], low cost, reduction of latency effects on control, and improved real-time configuration and data measurement [33]. The objective of this study is to identify common themes in the advancement and application of human-machine-interface technologies in UAS control. This paper proposes to review available literature, associated technology designs, and identify how the UAS community can best leverage this technology and interaction concepts to support safe and efficient operations of UAS.

Keywords: Human-Machine Interface, HMI, Unmanned Aerial System, UAS, sUAS, UAV, Intelligent, Intuitive, and Innovative (I^3) design.

1 Introduction

1.1 Current State of UAS HMI

The unmanned systems industry, specifically the UAS market, has been experiencing significant growth in the last three years due to maturation and advances in related technology, increased application opportunities, and availability of key components and materials [18], [48], [49]. Historically, this market has been supported by military/DoD needs [1], [6], [48]. However, with the Congressional mandates identified in the *FAA Modernization and Reform Act of 2012,* opportunities for civil and commercial use have begun to increase [6], [14], [48]. The domestic economic impact of integration of UAS into the National Airspace System (NAS), as mandated by Congress, is expected to exceed $13.6B between 2015 to 2017, reaching more than $82.1B by 2025 [5]. While government customers are anticipated to continue providing the largest source of economic support and growth in the near term, the

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commercial applications are expected to support the continued growth of this industry and market [5], [48].

The majority of commercial applications are projected to use micro to small UAS (sUAS), featuring low-cost designs that will be dedicated to specific uses [1], [48]. The designs and technology for these smaller systems are expected to initially come from the remote control or model aviation market [48]. This market already exhibits equipment featuring a high degree of complexity, capability, and support at a low price point [23], [26], [36]. Achieving the projected industry growth will require the confluence of three critical factors, the availability of enabling technologies, a need for use, and a viable economic climate [48]. While the current economic market appears ready for the availability of commercial sUAS, the regulatory framework is not. The FAA is not currently allowing commercial UAS operations in the NAS, but they are working to address this limitation for sUAS in the near term [15].

Unlike existing GCS interfaces, current interface technology has the potential to integrate a number of innovative developments in interface design, thus creating the potential to alleviate many of the existing interface issues currently of concern. Interfaces integrating intuitive design, touch screen capability and other innovative technologies currently existing in smartphones and tablets today (e.g., global positioning system [GPS], accelerometers, and gyroscopes) can be designed to feed the interface and control the sUAS in a much more intuitive manner than before. Dependency on legacy controls and software interfaces, lack of intuitive interfaces and sensory cues, low resolution interface fidelity, and high latency due to poor data link capabilities all contribute to poor information transfer, resulting in poor performance and reduced situational awareness.

1.2 UAS HMI Issues

Despite the great potential UASs provide, there are still a number of challenges facing the UAS community. For the past decade, much effort has been focused on developing new automation technology and interoperability, however, there has not been much investment focusing on the HMI for UAS systems. Despite the name given to these "unmanned" systems implying that the human is not involved, it is essential to remember that human operators are still involved in the control loop and operation of the vehicle, as well as interpretation of video and sensor data being collected and transmitted by the vehicle. It is not uncommon to find a single UAS to be monitored and controlled by a number of human operators. A well designed HMI is indeed critical for coordinating among UASs and multiple human operators.

The current state of HMI technology and design in UASs in use today contain many issues and challenges. Four major issues and challenges related to HMI deficiencies and design inadequacies are as follows:

1. There is no well-established standard for UAS HMI. The HMI among different UAS designers and manufacturers varies a great deal in terms of the information presentation and layout. Due to the high level of complexity involved in UAS HMI functionality, this often requires extensive amount of time for training to be able to use the HMI, and this lack of standardization leads to poor transfer of training between different systems.

2. The information presented in the HMI is often not optimized. There are large amounts of information involved in UAS operations, especially for multi-mission systems, where there are multiple teams of UASs and human operators are involved. When handling high stake, time pressured tasks under environmental uncertainty, it is essential that the HMI be intelligent enough to aid the human decision-making process in order to perform the tasks with accuracy and efficiency. The current HMIs lack this capability and level of functionality.
3. Related to HMI Issue 2, adaptability and flexibility are essential for effective HMI design. HMIs need to be adaptive to be able to adjust the level of automation to suit human operators' workload and increase their situational awareness, to minimize automation bias and build trust between human operators and UASs.
4. Finally, an examination of UAS literature reveals that one of the most prominent HMI issues is that of the sensory isolation of the operators (and other crew) due to their physical separation from the aircraft. Pilots and crew in manned aircraft have access to an abundance of multisensory information, aiding their understanding of the status of their aircraft in the environment [12]. Such information includes ambient visual input, and kinesthetic, vestibular, and auditory information, which can provide pilots with cues to the speed of travel, orientation, other elements in the vicinity, weather conditions, and aircraft health and status [22]. Currently, no such HMI exists that incorporates this type of information.

With the major sensory disconnects and lack of environmental cues found in UAS today, it is more important than ever to design control interfaces that project to the operator information that is necessary and vital to produce superior situational awareness outside the cockpit and away from the vehicle itself. With the new capabilities present in current interface technology and software, it is now possible to design functional, intuitive interfaces that take advantage of the available cues and impart the necessary information to maintain high levels of situational awareness needed for safe, efficient, and effective control of unmanned vehicles.

2 Regulation and Certification

Although there are few regulatory measures in place governing the development and certification of unmanned systems and their control systems, with the recent release of the FAA's UAS Roadmap document, some insight into what may be forthcoming has come to light. Currently, the primary regulatory guidance stems from FAA Order 8130.34 Airworthiness Certification of Unmanned Aircraft Systems and Optionally Piloted Aircraft. This guides users to 14 CFR Part 21 certification procedures for products and parts which allows for certification procedures similar to those for restricted category manned aircraft [16]. Other evidence appears that the FAA will use manned standards to guide the UAS certification process while at the same time trying to flexible with the unique needs for unmanned systems [46]. The FAA has also stated that UAS manufacturers should follow RTCA Operational and Functional Requirements and Safety Objectives (OFRSO) for UAS, Volume 1 which provides recommendations for UAS system level operational and functional requirements and safety objectives for UAS flown in the United States NAS under the rules and guidelines for civil aviation. This document provides a framework to support the development of future UAS performance standards and will prove useful to designers, manufacturers, installers, service providers and users in the development of future standards [17].

Various manned standards are likely to apply for UAS interfaces. These will likely include 14 CFR Part 23.1311 which lays forth requirements for electronic display systems providing for standardized information display and color codings. The FAA has also shown an affinity for applying existing software and hardware standards across airborne platforms. Thus applying standards outlined in DO-178B and ARINC 653, both of which govern the design and standards for complex avionics systems for use in airborne systems, is likely to be part of the future adoption of certification requirements for UASs. These dictate that systems operate at an acceptable level of safety through the design and verification of the viability and durability of both hardware and software and have been the accepted norms in manned aircraft for quite some time. Considering the concerns that the FAA has voiced over command, control, and communication, as well as sense and avoid, processes outlined by RTCA are the most relevant for moving forward with any UAS interface systems in development [19]. Moreover, the support of cross-application of hardware and software among numerous types of flight platforms through the standards of the Future Airborne Capability Environment (FACE) by the Department of Defense is likely to influence the potential adoption of tested and validated hardware and software protocols when using manned aircraft components in unmanned systems [11].

3 Applicable Technology

3.1 UAS Specific

The HMI for manned aircraft has been evolving with the incorporation of touch sensitive components, simultaneously able to depict information and accept user input, and voice recognition (e.g., multifunction displays for Lockheed Martin F-35 Joint Strike Fighter, Beechcraft King Air, custom General Aviation cockpits) [28], [38]. The use of such intuitive user interfaces provides the user with a wider variety of options for interacting with the system, while retaining situational awareness of the state and orientation of the aircraft given sufficient sizing of the display [28], [42]. For this research, applicable technology and associated research relating to HMI and user interfaces were examined and categorized as they relate to handheld controls, touch sensitive portable devices, autonomous control, commercially available user interface solutions, and customizable open source and proprietary user interfaces. Each of these categories is presented in the following subsections.

Handheld Controls. A common control configuration for sUAS requires the coordination of two-operators using a handheld input device and a laptop to affect aircraft control and obtain feedback in manual and autonomous/semi-autonomous operational modes [41]. In this arrangement, the first operator provides manual control of the aircraft using the handheld input device and live video from the aircraft, while the second monitors the position and inputs appropriate autonomous control parameters [41]. While singular operator control is possible with such a configuration there are several disadvantages, including reduced situational awareness, hardware limitations, and poor UI design [41]. Researchers at the Space and Naval Warfare Systems Center Pacific (SSCPAC) are performing research and development for a unified system, the Multi-robot Operator Control Unit (MOCU), to address improved usability, limitations of existing control systems, and increased interoperability to support control of a larger range of unmanned or robotic systems across multiple domains (e.g., land, air, sea, and underwater) [39], [41]. The design of the MOCU was made to be modular, flexible, and intuitive to support future expansion and development [41]. Researchers Stroumtsos et al [41] used the MOCO framework to develop a control and display interface to improve usability and system safety for a single sUAS operator [41]. Their custom configuration of the MOCO featured a simplified control interface (i.e., X-box controller), smaller hardware footprint (single laptop and radio), and a unified graphics-based user interface to improve situational awareness [41].

Touch Sensitive Portable Devices. One of the most critical considerations of implementing user interfaces for touch sensitive portable devices such as phones or tablets is determining how to present the data in the limited visible space (i.e. footprint), while retaining the ability to interact [3]. Arhippainen et al [3] hypothesized that three dimensional (3D) user interfaces could provide benefit given the ability to enhance a user's task. In support of their research, they developed a series of conceptual 3D UIs to perform iterative design and evaluation to gain a better understanding of user experience [3]. Their findings indicated that providing context-aware service multitasking provides positive results for users by simplifying and reducing the speed for interaction [3]. Such findings have merit in relation to the user interface needs of sUAS controls, such as reduced reaction timing and ability to obtain and maintain situational awareness through monitoring of map location and telemetry data in addition to the real-time video visualization.

Autonomous Control. Implementing autonomous control for sUAS requires incorporation of an autopilot with trajectory planning and path following (i.e., waypoint tracking) capabilities [8], [9]. Achieving trajectory planning and path following requires a user to input operational parameters (i.e., predefined constraints), such as waypoint locations, minimum and maximum airspeed, minimum and maximum altitude, and identification of specific areas to avoid [43]. The control parameters are entered using a graphical user interface (GUI), which also depicts the state of the aircraft using telemetry (i.e., state observations) during live flight [8], [43]. Researchers Tozicka et al [43], have identified an issue inherent to autonomous planning systems where the system is unable to account for conditions outside the predefined parameters (i.e., system is unaware of specific conditions). Such an issue can lead to scenarios where the calculated trajectory does not align with the needs or requirements of the operator [43], reducing the end usability of the system. Tozicka et al [43] developed a planning system that features improved conveyance of the planning processes to the user and inclusion of human-in-the-loop control to present multiple trajectory path options (i.e., diverse planning), which are used to select the final trajectory of the aircraft. This improved user interface incorporates touch control to reduce the reaction time and present alternative options (diversity) to increase system effectiveness and user trust in system autonomy [43].

Commercially Available User Interface Solutions. Several companies have begun to release small, portable, handheld control systems and associated software packages to address the growing need for a unified, intuitive, solution that support singular operator control of a variety of unmanned systems [7], [24], [25], [27], [32], [45], [47]. These handheld controls provide a myriad of features and capabilities, including intuitive interfaces, full motion video (live and playback), touchscreens, multiple-views, color-coded warning, caution, and advisory, real-time information display, vehicle state (e.g., fuel and battery remaining), and video overlays (text and graphics) [7], [24], [25], [27], [32], [45], [47]. The common feature of note among the various options is the ability to be customized for a specific platform and application, while retaining interoperability for use with multiple systems [21], [24], [25], [27], [32], [45], [47]. The U.S. DoD has identified a requirement for interoperability in future systems and that those companies with products featuring closed-architecture will need to adjust their strategies or lose market share [49]. The incorporation of interoperability in unmanned systems is anticipated to provide the DoD with up to $86 million in savings [21].

Customizable Open Source and Proprietary User Interfaces. The ability to improved interoperability and customization of interfaces has also been a core feature of open source projects for COTS autopilot systems (e.g., ArduPilot) and customizable propriety systems (e.g., WiRC) using software development kits (SDKs) [2], [50]. The PixHawk GCS, an open source software package developed for the PixHawk micro air vehicle (MAV) platform, features support for multiple aircraft (rotary and fixed-wing), deployment on multiple OS (Windows, Linux, MacOs, and Maemo) and hardware (PC, Mac, iPad, iPhone, and Nokia N900), and customization of the GUI [2], [35]. The user interface for PixHawk GCS provides the user with several views, including an engineer view, a parameters/setting/MAVLink view, and a pilot view [2]. The PixHawk design was recently updated to serve as an open-hardware autopilot solution for the open-source autopilot domain, providing new features such a direct programming scripting of autopilot operations, incorporation of peripheral sensors (digital airspeed and magnetometer), and data logging [34].

3.2 Non UAS User Interfaces

The non-UAS, aviation user interface has undergone a significant transformation since the World War II era. Allied and Axis aircraft laid the foundation for civilian aviation with the primary interfaces being based on analog gauges, switches, dials, buttons, and levers [40]. As jet aircraft were introduced, it became readily apparent that pilots and other crewmembers were being saturated with instruments as noted by the fact that the average 1970's era airline cockpit had more than 100 instruments to monitor and even more interfaces with aircraft systems and avionics [30]. A shift to simpler displays and interfaces occurred gradually with the introduction of glass cockpits, first with military aircraft, then migrating into civilian use. Originally only a repetition of common flight instruments on cathode ray tube (CRT) displays, glass cockpits have morphed into intelligent systems providing pilots with critical data and suppressing less necessary data. These "new multi-function interfaces [present] designers with the challenge to optimize the pilot's interaction with controls and tasks whilst maintaining the familiarity and functionality of the existing system" [30], thus a variety of novel human interfaces have surfaced.

The primary type of output interface has remained fairly constant, typically a CRT or liquid crystal display (LCD) screen showing intuitive instruments, colors, or symbols, to convey flight critical data. Other outputs include warning lights and other captions to draw attention to system status. Additionally, head's up displays (HUDs) have become relatively common in civilian aircraft so that pilots can monitor flight instruments and condition without having to look down at more conventional displays. More variety in input interfaces have surfaced with the growing complexity of output presentations. Two primary types of input interfaces exist: indirect and direct. Indirect (relative) require hand movements or other interactions to bring forth actions. Examples include QWERT or unconventional keyboards, rotary, trackball, and touchpad interfaces. Direct (absolute) types allow the user to directly access input features through touching desired outcomes, the most typical being a touchscreen [37]. Generally, indirect interfaces require a higher cognitive loading of the user whilst they were found better for repetitive and precision tasks [20]. Direct controls were found to be superior for selection actions and menu driven systems [37].

Stanton et al. [40] compared performance in two menu selection tasks among trackball, rotary controller, touch pad, and touch screen interfaces. They found that the touch screen performed best in drop down menu tasks as well as in action based menu tasks in terms of response times. In terms of performance of errors, touch screens showed only a slight advantage over other interfaces in drop down tasks while the rotary controller surpassed touch options for action based tasks. The highest level of interface usability was determined to be the touch screen, with the trackball being found to be second best. Touch screens provided the least amount of hand discomfort but had the highest level of body discomfort [37].

3.3 New HMI Technology

Little research has been performed toward collection of data to support the needs of the UAS community to determine requirements for new and innovative HMIs for UAS. The DoD has published "roadmaps" on a regular basis that provide high level overviews of desired technological functionality, but very little specific information about what that technology should include. As mentioned previously, the U.S. DoD has identified a requirement for interoperability in future systems and that those companies with products featuring closed-architecture will need to adjust their strategies or lose market share [49]. They also include verbiage that outlines the need for greater use of analytical automation that will enhance the UASs "cognitive behavior" but these documents say nothing about designing an interface that enhances the human operator's capability to operate these units efficiently and safely [49].

Consideration must be provided to the design and implementation of highly intelligent and intuitive interfaces if UASs are to be accepted by the public and safely operated over civilian airspace. These technologies should be designed to provide information to the human operator that compliments and enhances their abilities to operate the UAS. Recent research has identified six design improvements based on a cognitive work analysis performed using a limited pool of UAS operators and subject matter experts (SMEs). The six HMI design improvement needs identified were the need for: 1) better communication of system status and environment, 2) reduced demand on memory, 3) support for attention management, 4) more robust feedback-control loop, 5) improved error avoidance, detection, and recovery, and 6) support for information synthesis [31].

New HMIs must provide the human operator with the information needed to safely and efficiently operate the UAS while maintaining a delicate balance to ensure the human operator is not inundated with non-essential information. New interfaces should optimize the use of all sensory modalities and information processing channels available to the operator including visual, auditory, and tactile modalities. Interfaces that are innovative, intelligent, and intuitive (I^3) must dominate the market is humans are to remain an effective component of the UAS.

4 Conclusions

When new technologies are designed and developed, the HMI design needs listed must be recognized and addressed. The existing DoD roadmaps seem to address only the support for information synthesis aspect, but all of the needs identified are important from a human factors design perspective. With the obvious desire on the part of the military to develop more advanced and sophisticated automation for incorporation into UAS platforms, it is reasonable to assume that the same issues that plague manned aviation platforms will also manifest themselves in unmanned platforms (i.e. more automation, increased workload, increased potential for human error, decreased situational awareness, etc.) Using interface design principles and innovations from other domains may be helpful (i.e. intuitive design, touch screens, mobile device innovations, solid human factors information processing principles and guidelines), but real advances will only appear when new innovations designed to complement and enhance human capabilities are introduced and implemented.

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