Universal Ground Control Station (UGCS) Joystick Evaluation

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Abstract—**A goal of commonality and interoperability across U.S. Army and Joint Service unmanned aerial systems (UASs) was outlined by the Office of the Secretary of Defense. The Universal Ground Control Station (UGCS) is a U.S. Army initiative to meet this requirement. With an objective to control heterogeneous assets with expanded payloads, both displacement and force sensing hand-controllers have been reviewed against a baseline joystick and an alternative mouse-like device. This study compared operator performance in three mission environments, exercising critical payload operations tasks. Six combat-experienced UAS operators and six general aviation fixed wing pilots were tested. Performance data, subjective workload ratings, and comments were collected. Analyses revealed only small performance differences between displacement and force sensing joysticks in the UAS operators. Pilots showed better performance in a route reconnaissance task utilizing the familiar mouse-like controller. Individual preference, familiarity, and comfort influenced subjective views. Recommendations include additional testing in representative length missions and designing for sustained comfort.**

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1. INTRODUCTION

The Office of the Secretary of Defense's *Unmanned Systems Integrated Roadmap* (2009) outlined a goal to enhance commonality of command and control (C2) of various unmanned aerial systems (UAS) platforms. [1] The Universal Ground Control Station (UGCS) is intended to meet the U.S. Army and joint forces interoperability requirements. In order to support C2 of heterogeneous UAS platforms from a UGCS, the display, design, and function of the operator ground control station (GCS) must be examined. Following best practices in human-machine interaction, a universal design requires consideration and mapping of the functional requirements and critical operator tasks to the operator's displays and controls across designated UAS platforms. Critical task requirements [2, 3] to control multiple, complex payloads, and track/engage ground targets must be supported by the universal operator displays and hand-controller devices. Fielded hand-controller devices for UAS (i.e., joystick and trackball) were developed to support a single UAS with functionality limited to a unique platform and payload. To expand the joystick's functionality to control various platforms, an evaluation of hand-controllers by experienced operators in relevant mission scenarios is required. Initially, a review of joystick control and mechanics was conducted to understand benefits and tradeoffs of traditionally used displacement vs. force feedback in aviation applications.

2. JOYSTICK HISTORY AND TYPES

A joystick is an input device consisting of a stick that pivots on a base and reports its deflection to the system controlled (e.g., UAS). The joystick has been the principal method of control for the cockpit of many aircraft, particularly military jets (manned and unmanned), where either center stick or side-stick location may be employed. Applied to UAS flight control, joysticks are typically used to operate elevators by fore-and-aft longitudinal motion and ailerons by side-to-side lateral motion. In the current Shadow *RQ-7* UAS platform, a short-throw joystick (approx. 3") is used to manipulate pitch, pan, and zoom of the sensor payload. [4]

Joystick Use in Aviation History

It is believed that the first electrical joystick was invented in Germany in 1944 for remote (radio) glide bomb control. This joystick had discrete on-off switches rather than analogue sensors. During the 1960s, in addition to widespread use in manned aircraft, joystick control also became popular in radio-controlled, model airplane systems. Joystick control was also utilized during NASA's Apollo missions for the Lunar Lander test models. At present, joysticks are used in manned and unmanned systems and are much more sophisticated; from being a purely mechanical device to today's more advanced electro-mechanical devices that offer increased precision and support remote piloting when some sensory information is lost (i.e., UAS operations with a pilot separated from the cockpit due to remote piloting).

In order to evaluate the appropriate joystick for the UGCS, an understanding of the types of joysticks available should be reviewed. Further detail on the mechanics, applicability and use of displacement versus force sensing and force feedback joysticks follows.

Displacement Joystick

Displacement joysticks are the most common type of joystick used today and can be found in aviation, manufacturing, machinery, and home entertainment devices. Displacement joysticks function when force is applied to the joystick handle, which signals the controlled object (simulated or real) to move in a desired direction or stop in a desired location. Tilting the stick forward and backward pivots the Y-axis shaft from side to side. Tilting it left to right pivots the X-axis shaft (Figure 1). When the stick is moved diagonally, it pivots both shafts. Typically, mechanical springs are used to center the stick when the operator releases the joystick.

Figure 1 – Example of Displacement Joystick Motion

Force Sensing Joystick

A force sensing joystick can be characterized as a zero deflection stick, showing no movement when operator force is applied. Instead, it responds to pressure applied to the shaft by the user. The applied force is translated to a system input correlated to the degree of pressure. It should be noted that some historic precedence exists for implementation of a force sensing joystick in military aircraft, as the AH-1F Gunner Sight Hand Control [5] utilized force sensing technology (Figure 2).

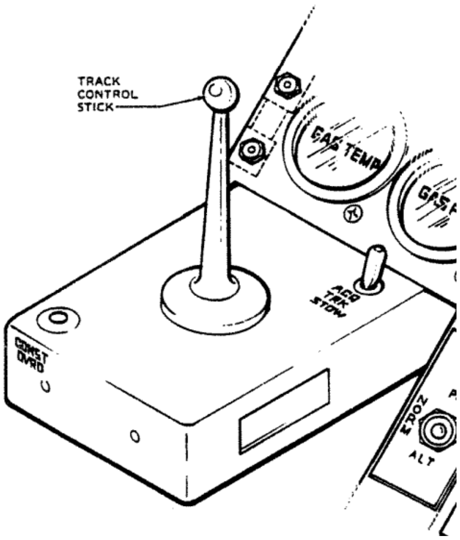

Figure 2 – AH-1F Gunner Sight Hand Control (SHC) - Force Sensing Joystick

Force Feedback Joystick

A force feedback joystick (or haptic feedback joystick) functions when the operator applies force to the joystick and likewise the joystick returns a force back to the operator. Haptic feedback is a tactile cueing method that provides somatosensory input through forces, vibrations, and/or motions directed on the user. For example, if a user were to attempt to crash an aircraft in a flight simulator, the stick would push back suddenly. A stick shaker is another example which can be found on many business jets, airliners, and military aircraft. It is a mechanical device that rapidly and noisily vibrates the control yoke (the "stick") of an aircraft to warn the pilot of an imminent stall. Force feedback joysticks have potential for UAS control application and could support successful mission performance just as displacement joysticks are currently utilized.

Advantages and Disadvantages of Displacement and Force Feedback Joysticks

Common use, lower cost, and availability are viewed as advantages in the Acquisition Life Cycle for the system maintainability and reliability required. Displacement joysticks are more common than force feedback joysticks, and therefore may have been the initial design preference for UAS ground control stations. In contrast, force feedback joysticks are, by nature of their functionality, more complex than displacement joysticks. Force feedback joysticks include electrical motors with position sensors, as well as a microprocessor and either a gear train or belt system. Increased complexity could result in an increased need for processing power in the operating system to which the joystick is interfaced. This requirement for additional power is a disadvantage to a force feedback joystick design implementation. In addition, more difficult and expensive maintenance and equipment availability can be a concern in fielded systems. In exchange for increased complexity and cost, force feedback joysticks can offer increased situation awareness and control, such as warning an operator of turbulence or an imminent stall; an ability not offered by displacement joysticks.

Remote vs. Cockpit Joystick Control and the Argument for Force Feedback

One of the primary consequences of the physical separation between aircraft and operator (remote operation) is that the operator is deprived of a range of sensory cues that are normally available to the pilot of a manned aircraft. Rather than receiving direct sensory input from the environment in which the vehicle is operating, a UAS operator receives only that sensory information provided by onboard sensors via datalink. Currently, this information consists primarily of visual imagery covering a restricted field-of-view. Therefore, sensory cues that are lost include ambient visual information, kinesthetic/vestibular input, and sound. As compared to the pilot of a manned aircraft, a UAS operator can be said to perform in relative “sensory isolation” from the asset under his/her control. [6]

Various studies and articles in the area of haptics from both aviation and gaming tend to lean toward force feedback joysticks or controls as the preferred choice of control compared with simple displacement controllers. Force feedback relies on haptic technology, or haptics, which is a tactile feedback technology that takes advantage of a user's sense of touch by applying forces, vibrations, and motions to the user. [7] Haptic feedback is often suggested to complement visual information through the sense of touch to improve efficiency and safety in the teleoperation of unmanned aerial systems. [8] Flight feedback sensation to the pilot of an aircraft has been a part of aviation since its inception; although perhaps not by design. Early aircraft utilized mechanical means of control from the pilot. With purely mechanical flight control systems, the aerodynamic forces on the control surfaces are transmitted through the mechanisms and are felt directly by the pilot. Operators of remote aircraft do not have this same cueing unless it is presented artificially (e.g., through haptics). Both natural (local) and artificial (remote) feedback can be used to indicate to a pilot that the aircraft flight control surfaces are being overstressed and/or indicate the potential for aircraft stall, existing turbulence, and obstacles.

Force Feedback has been successfully used in alternate domains including robotics (medical and flight simulators), underwater vehicles, land vehicles, and computer/video games. In a broad application of haptic technology, Hill and Salisbury (1977) found in their experiments that with force feedback, task completion times were significantly shorter than without force feedback for peg-in-hole tasks. [9] Further, Hill (1979) concluded that difficult tasks such as crank-and-turn operations were done twice as fast when force feedback was present. [10] Historically, force cues have also been shown to improve the accuracy of positioning a control stick or manipulator arm. [11]

UAS domain-related research has indicated that a haptic interface using force feedback via a haptic control device can be used to complement the visual interface by providing situational information through the sense of touch. [12, 13] In a study by Lam et al, the multi-sensory interface improved operator performance and decreased the number of collisions, hence, increasing the level of safety. [12] Further recommending the use of a haptics, a study by Ruff et al, found that haptic information conveyed via the joystick control improved operator’s self-rated Situational Awareness (SA) in a simulated UAS approach and landing task. [14]

In the "Haptic Feedback for UAV Tele-Operation - Force Offset and Spring Load Modification" study [8], an experiment was conducted with eight subjects with no flight experience. The main task was to fly from waypoint to waypoint as accurately as possible in an obstacle-laden environment, simulating a reconnaissance mission. The waypoint was represented by smoke, located in the vicinity of an obstacle. The results of this experiment showed that the total amount of collisions was highest when flying without haptic feedback, which was expected. No haptic feedback led to a certain lack of SA, especially when the visual information was reduced due to the smoke.

One of the drawbacks of force feedback is that the order of magnitude between haptics and vision bank widths require that haptic interfaces incorporate a dedicated controller. The human sensorial characteristics impose much faster refresh rates for haptic feedback than for visual feedback. [15] Tactile sensors in the skin best respond to vibrations higher than 300 Hz for instance. [14]

Additionally, while 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, the results of the Ruff et al study (2000) indicate otherwise. The relatively high-gain stick movement generated by the haptic feedback used in this study required more mediating effort on the part of the pilot. Participant comments confirmed that while haptic feedback was a useful tool for each task, the magnitude of the control stick deflections was judged to be far too severe for actual use. [16]

Still, other studies in which multiple obstacles are presented to UAS operators finds that while force feedback can successfully help avoid collisions with one obstacle by deflecting the control device away from the direction of the obstacle, it may direct the UAS toward another obstacle located in the opposite direction. This incompatibility is expressed by the fact that the haptic interface does not know about the other closely located obstacle and the force feedback would not generate an escape maneuver until the UAS is closely approaching the other obstacle. [17]

Recommendation for Testing

After a literature review of displacement versus force sensing and force feedback hand-controllers, representative joysticks from displacement and force sensing categories were selected from commercial-off-the-shelf (COTS) inventory for comparison. Benefits and performance tradeoffs related to joystick type supported inclusion of both types of joysticks in the evaluation. Due to the increased complexity, processing demand, and additional cost of force feedback joysticks, none were selected for evaluation. COTS joysticks were intentionally selected that featured a majority of buttons/switches either on the joystick itself or on the joystick's base. As a cost-saving acquisition strategy, no input gaming devices were selected that might result in expensive design retrofits to existing UGCS shelters.

The current study conducted by U.S. Army Aeroflightdynamics Directorate (AMRDEC/RDECOM) sought to compare operator performance in payload manipulation, tracking accuracy, and weapons engagement precision while utilizing the current Shadow joystick versus four COTS joysticks. In addition, an alternative sensor control device (3D SpaceExplorer) was included for comparison because previous work by Shively, Brasil, & Flaherty (2007) had shown performance benefits when participants with gaming skills used this device. [18] A Shadow UAS joystick was used as the baseline comparison joystick. It was hypothesized that previous exposure to a joystick could yield subjective biases, therefore a balanced review of mission performance and subjective preferences were considered. Results from this study are intended to guide design recommendations for the selection of the UGCS joystick.

3. METHOD

Study Participants

Due to the limited availability of returning warfighters with UAS flight experience, an alternate population of general aviation private pilots was identified for testing in this study. This population has been previously tested in UAS studies [18, 19] and was hypothesized to possess similar skill sets to the incoming Army 15W UAS operator. Specifically, pilots had knowledge of aircraft control, airspace, and were screened for frequent video game usage. Age limits on the pilot population was restricted to 18-35yrs. in order to more closely align with the Army UAS operator population.

UAS Warfighters— Six combat-experienced UAS operators from B Company, 2nd Battalion, 13th Aviation Regiment participated in the study at Ft. Huachuca, AZ. Five male operators and one female operator ranging in age from 24-30 years (*M* = 27; *SD* = 2.28) were tested. On average, operators completed their Advanced Individual Training in approx. 2005. Average combat flight hours serving as an Aircraft Operator (AO) and Payload Operator (PO) were *M* = 661.67 hrs. and *M* = 587.50 hrs., respectively (Figure 3). Combat experience amongst the warfighters included tours of duty served in Iraq and Afghanistan, including both dense, urban and sprawling mountain terrain. More than half of the operators had experience with firing a laser and/or target illumination. All operators had experience with the Shadow *RQ-7* aerial platform, while two operators also had Pioneer and Hunter UAS flight experience. Additional duties completed by operators included mission commander, Non-Commissioned Officer-in-Charge (NCOIC), Emplace/Displace, and UAS maintenance. Operators interviewed now serve as instructors at the UAS Training Battalion. All six operators were right-handed with normal or corrected-to-normal vision.

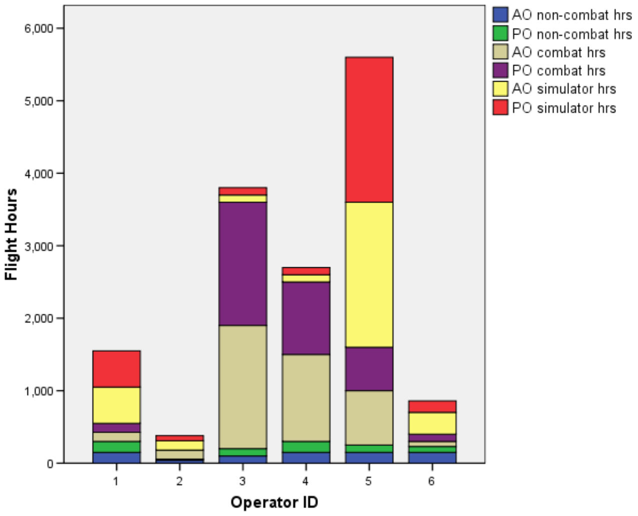

Figure 3 – Flight Hours for Warfighters Tested

Private Pilots— Six volunteer pilots were recruited to participate in this study. All six participants were male, with an age range of 24-30 years (*M* = 29; *SD* = 2.30). Participants were required to play video games at least once a month, and to hold, at minimum, an active Private Pilot License. Total flight hours ranged from 150 to 4500 hours (*M* = 1904.17; *SD* = 833.60). All six pilots held both IFR and VFR ratings. None of the pilots had any military flight experience or UAS payload or aerial vehicle (AV) control experience.

Multiple UAS Simulator (MUSIM)

Ground Control Station Hardware—The simulation was generated with a quad-core CPU, 2GB system RAM, and an NVidia GeForce Go 7950 GTX video card with 512MB video RAM. The display provided 1920x1200 resolution with 24-bit color.

Terrain Database—A visual database was created using Creator Terrain Studio 2.0.2 and Creator 2.5.1. Terrain imagery was obtained from U.S. Geological Survey satellite photography. The simulation utilized 30-meter elevation data with 45-meter texture data in the lower resolution areas and 0.7-meter texture data in the high resolution areas. Three designated areas within the database were utilized for this experiment. These areas can be characterized as dense, urban terrain, or medium density, industrial terrain.

UAS Flight Model—A generic flight control model emulated a medium-sized, tactical fixed-wing UAS for this simulation. Airspeed and altitude were fixed for the UAS in all missions.

Figure 4 – MUSIM Operator Interface

Operator Interface—The simulation utilized a 1:1 operator/vehicle ratio user interface, consisting of a sensor payload view, a 2D top-down map view, and an AV control panel (Figure 4). An optical mouse was used for navigation of operator control panels in the operator interface.

Cursor Controller— An optical mouse was used for navigation of operator control panels in the operator interface.

Payload Control Devices

Most of the following devices are traditional joysticks based on a 2-axis analog joystick with some buttons on the base and/or stick. The main exception is the 3D Connexion SpaceExplorer, which is a six degrees of freedom (6-DOF) analog puck mounted on a base with buttons. Also an exception, the UGCS joystick is a simple stick with no buttons and paired with a separate keypad. Unless otherwise indicated below, all digital actions were performed with standard buttons. Functional assignments to buttons were vetted against aviation standards and assigned by the researchers, maintaining consistent placement across comparable devices. Devices were matched in gain settings and maintained the same pan speed throughout all levels of zoom.

3D Connexion SpaceExplorer—The SpaceExplorer utilizes 6-DOF sensing technology (translation: x-axis, y-axis, z-axis; angular deflection: pitch, heading, and roll) in a pressure sensitive puck. Three of the six degrees of freedom were used: left/right twisting motions to control the pan of the payload, downward/upward tilting for payload elevation changes, and a forward/backward translation motion to control the zoom level (Figure 5).

Universal Ground Control Stations Joystick and *P.I. Engineering X-keys MWII*—The baseline joystick was a simple, short-throw cylindrical joystick containing no buttons and controlling sensor pitch and pan movement only. It was paired with the X-keys keypad for additional required functions (e.g., zoom, mark target) (Figure 6). Button assignments on the keypad were intended to be consistent with current placement and functionality in the UGCS. It can be characterized as a displacement joystick.

Logitech Force 3D Pro—This joystick operated as a standard COTS displacement joystick in sensor pitch and pan inputs, requiring operator forward/back and left/right inputs, respectively. The device utilized 2 inputs of a 4-way digital hat for zoom, initiated with a forward and back thumb motion (Figure 7). Some functions were assigned to buttons located on the base of the joystick (e.g., auto-track, weapons fire).

Thrustmaster Hotas Warthog—Another standard displacement joystick was selected for evaluation due to its larger size and presence of all switches on the joystick. This device used two inputs of a 4-way digital hat for zoom, two inputs of a 4-way digital hat for electro-optical/infrared (ER/IR) camera mode changes, one input of a 5-way digital hat for initiating Point @ Coordinate, and a “pinky” paddle for firing weapons (Figure 8).

Saitek X65F Combat Control System—This joystick was selected for evaluation due to its unique force sensing technologies. The joystick did not displace in response to operator inputs on the pan and pitch axes. Instead, operator pressure applied to the stick actuated movement in these axes with visual feedback given in the updated payload position. Two inputs of a 4-way digital hat were used to alter zoom levels with a forward and back thumb motion, similar to the Thrustmaster Hotas Warthog. Two inputs of a different 4-way digital hat were assigned for ER/IR mode changes; one input of a 4-way digital hat was assigned to initiate Point @ Coordinate mode; and a “pinky” paddle was used for weapons firing (Figure 9). Button assignments on this joystick mirrored the Thrustmaster Hotas Warthog, with the significant difference of the presence of force sensing technology and lack of joystick displacement.

Figure 5 – 3D Connexion SpaceExplorer input device

Figure 6 – Universal Ground Control Stations Joystick and P.I. Engineering X-keys MWII input devices

Figure 7 – Logitech Force 3D Pro input device

Figure 8 – Thrustmaster Hotas Warthog input device

Figure 9 – Saitek X65F Combat Control System input device

Joystick Evaluation Tactical Scenarios

The tactical scenarios developed to support the joystick evaluation were carefully selected in an effort to present an appropriate and relevant test environment that matched core UAS mission tasks published in Army UAS Operations Doctrine. [2] Creating realistic evaluation scenarios was especially important since half of the test subjects were military trained, combat-experienced UAS operators. Additionally, there was a conscious effort to ensure that each scenario required the operator to use various joystick input techniques to complete the mission tasks in order to fully explore the functionality of each control device being tested.

Three tactical missions were designed and programmed into MUSIM to support the joystick evaluation. They were: 1) route reconnaissance, 2) manned/unmanned teaming engagement, and 3) autonomous weapons engagement. Each of the three scenarios lasted between 4-5 minutes as described below.

Route Reconnaissance—Operator Task: While on a route reconnaissance of a several block-long road network in an urban environment, the operator's mission was to positively identify and mark tactical vehicles that were parked alongside the road (Figure 10, 11). Tactical vehicles were located in proximity to distractor civilian vehicles, however only military vehicles could be marked successfully. The UAS initially loitered over the downtown target area in a point-at-coordinate sensor mode. The mission began when point-at-coordinates was disengaged, the sensor zoom was adjusted, and the sensor crosshairs were slewed to a parked military vehicle. The operator pressed the mark target button, which resulted in a superimposed red dot appearing over the target vehicle. The red dot indicated a successful mark. The operator continued to mark targets until all 80 available target vehicles were marked or the four minute scenario time expired, whichever occurred first.

The joystick functions that were required for this mission scenario included: disengaging POINT at COORDINATE, SLEWing the sensor crosshairs over each target, ZOOMing to positively identify the target, and MARKing each target.

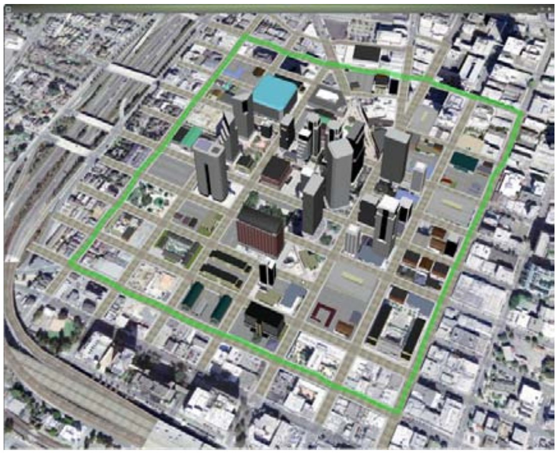

Figure 10 – Reconnaissance Route

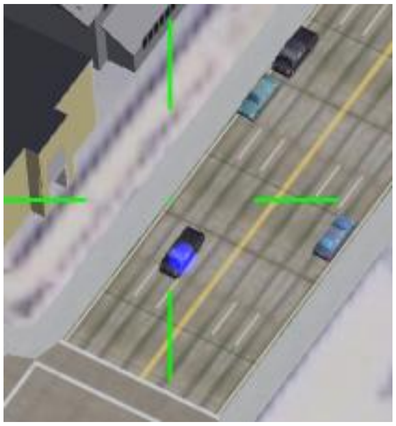

Figure 11– Crosshair Symbology and Marked Target

Manned/Unmanned (MUM) Teaming Engagement— Operator Task: The MUM mission scenario was a cooperative target engagement of a moving high value target (HVT) vehicle traveling through a major city. The payload operator's mission was to remotely lase the target for a notional Apache Hellfire missile engagement. The mission began with the UAS positioned in a stationary orbit in the point-at-coordinates sensor mode, observing a building that concealed the HVT vehicle. As the vehicle departed the building, the operator manually tracked the target. With the sensor crosshairs centered over the vehicle, the operator engaged auto-track. The operator was directed by digital message to switch sensor modes from EO to IR. The operator was then given permission by message to lase the target. The operator activated the laser by accessing the weapons multi-function display (MFD) page, manually tracking the maneuvering target vehicle, and firing the laser. Manual HVT tracking continued for over 2 minutes while awaiting the arrival and weapons delivery from the Apache helicopter. The 5-minute mission terminated after the target vehicle was destroyed by the Hellfire missile (Figure 12).

Figure 12 – Cooperative Weapons Engagement Target Destroyed

The joystick functions that were required for this mission scenario included: disengaging POINT at COORDINATE, SLEWing the sensor to acquire the target, ZOOMing to identify the target, engaging AUTO-TRACK, switching sensor modes from electro optical (EO) to infrared (IR), and activating the LASER.

Autonomous Weapons Engagement— Operator Task: The weapons engagement scenario required the operator to search for, track, and engage a HVT vehicle traveling through an urban environment using the on-board laser and notional Hellfire Missile weapons systems. The initial condition was a stationary orbit over a building that was believed to conceal a HVT vehicle. When no vehicle appeared, the operator was directed by digital message to observe a second building. As a result, the operator slewed the sensor to the second building and engaged point-at-coordinates. Once again, no vehicle appeared and the operator was directed by message to a third building. The sensor was slewed to the third building where the HVT vehicle emerged (Figure 13). The operator acquired the vehicle and subsequently engaged auto-track. The operator then received a message granting authority to engage and destroy the HVT vehicle. By accessing the weapons MFD page, the operator armed the laser and Hellfire missile. The operator then manually tracked the vehicle, lased it, and fired the missile. The operator continued to manually track the maneuvering vehicle throughout missile fly-out and impact. The mission ended when the target vehicle was destroyed after approximately 5 minutes total mission time.

The joystick functions that were required for this mission scenario included: engaging and disengaging POINT at

COORDINATE after SLEWing to each building location, ZOOMing to identify the target, initiating AUTO-TRACK to follow the HVT vehicle, accessing the weapons page to ARM the laser, FIRE the Laser and FIRE the HELLFIRE missile to destroy the target.

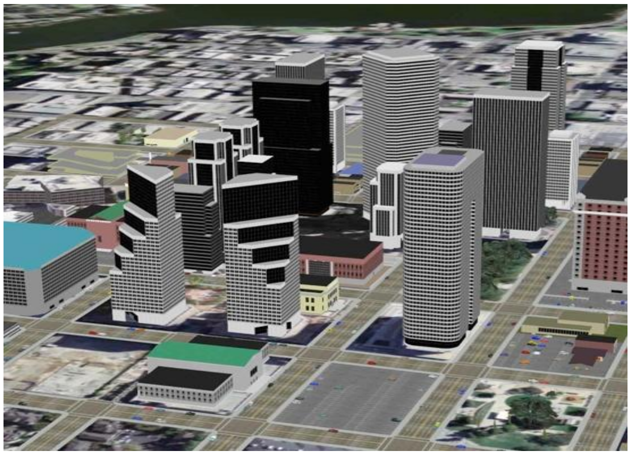

Figure 13 – Building Location of HVT Vehicle

4. EXPERIMENTAL DESIGN

A single factor of joystick type was manipulated across five levels (4 COTS joysticks tested; 1 baseline UGCS joystick) in three evaluation missions. Participants from both UAS Warfighter and Pilot test groups used each of the five control devices in blocked presentation order. A total of 15 evaluation missions were flown by each participant. Experimental session details for each test group are outlined below.

UAS Warfighter Testing—Joystick testing was conducted in two 2-hr. experimental sessions across two days. The presentation of devices was randomized for the warfighter test group with the exception of the SpaceExplorer device. For this device, the SpaceExplorer was the final test condition. This restriction was emplaced because the SpaceExplorer device was deemed most experimental and therefore least likely for user community and acquisition corps acceptance. With limited time allotted for each operator, it was viewed that the SpaceExplorer be tested last and be removed from the test matrix if time expired. Order of mission presentation was randomized within the joystick block. Fortuitously, all operators completed testing with all five joysticks.

Pilot Testing—Joystick testing was conducted in a single experimental session. The experimental sessions were blocked by input device. The order in which the input devices were presented to participants was counterbalanced according to a Latin square. Mission type was randomly assigned within the blocked presentation.

Test Procedure

All twelve participants were required to fill out an informed consent for minimal risk form and a demographic survey intended to elicit information regarding participants' operational experience and computing/gaming experience.

Training session—Participants were given a short pilot briefing introducing the purpose of the experiment, MUSIM interface, and mission tasks. The pilot briefing was followed by a training trial in each mission in order to familiarize the participant with each of the three different mission types and the simulation environment. Successful performance on a representative, criterion mission task had to be accomplished prior to advancement to data trials.

Evaluation Sessions—For each input device, all participants completed two practice trials followed by a data trial, in succession, for each of the three mission types. Thus, participants completed nine missions, six for practice and three for data, for each of the five input devices. After each input device block, participants were given a NASA-Task Load Index (TLX) rating questionnaire to determine the workload associated with the use of the device. [20] Lastly, a subjective rating questionnaire to assess the comfort and usability of the device was collected.

Post Flight Questionnaire—After the participants completed all five experimental conditions, a final post-experiment questionnaire was administered. This questionnaire asked the participants which input device they preferred and also allowed participants to provide comments regarding the various joysticks tested.

Data Collection

Route Reconnaissance: Target Marking—The total number of targets correctly and accurately marked (hits) was recorded for each route reconnaissance mission. A hit was defined as yielding a payload crosshair center distance of less than .004 radians of visual angle from the center of the target. Total number of misses was also recorded and defined as any marking of greater than .004 radians of visual angle from a target. Because this task was not intended as a target discrimination task, false identifications were not parsed from misses. In addition, time to complete the mission was recorded. Mission time only varied if the participant was able to successfully mark all 80 targets in less than four minutes. If a participant did not mark all 80 available targets, then a maximum four minutes was the mission time recorded for that trial.

MUM Teaming Engagement: Target Tracking RMSE—The operator's ability to continuously and precisely manually track the target was recorded for the MUM-T tracking task. For this reason, root-mean-squared error (RMSE) for tracking the target along its route was collected. In detail, sample deviations, defined as the distance from the center of the crosshairs to the center of the target, were collected for every video frame presented. Video frames were updated at 30Hz. Precision in lasing is operationally relevant due to its impact on accurate and lethal target elimination.

Weapons Engagement: Targeting Accuracy—Precision of the missile strike was recorded in distance (meters) from the center of the payload crosshairs to the center of the target at the time of missile impact. This measure of performance is operationally relevant as it directly relates to target elimination and minimizing collateral damage.

Subjective Ratings—Subjective workload ratings were collected at the end of each blocked joystick session utilizing NASA-TLX. Once testing concluded, participants rank ordered all joysticks by user preference (1 = most preferred, 5 = least preferred). Subjective comments were collected on all devices tested.

5. RESULTS

Separate single factor (joystick) within-subjects analyses of variance (ANOVAs) were conducted on each performance measure. The Bonferroni correction was applied to all analyses and the Greenhouse-Geisser correction was used where applicable. Data analyzed from the fifteen mission trials have been reported separately by population group (UAS Warfighter or Pilot). Due to deviations in training protocol and previous exposure to tested joysticks (i.e., UAS warfighters had hours of combat-experience on the UGCS joystick and the pilots had been exposed to the SpaceExplorer in previous studies), datasets were not combined. It should be noted, that there was deemed sufficient alignment in age, flight knowledge, and gaming exposure to consider the pilot group representative of incoming 15W MOS soldiers.

Route Reconnaissance Mission Performance

Target Marking—For the UAS warfighters tested, no significant effect of joystick was found for the number of targets marked (80 total were possible). Across joystick types and in all but five experimental trials, operators were able to successfully mark all 80 targets available. The number of misses recorded across joysticks types also did not show significant differences. However, it should be noted that the average number of misses (*M* = 8.33, *SE* = 2.22) was the lowest for warfighters and with the least amount of performance variance between test subjects when using the familiar UGCS joystick (Figure 14). The widest range in individual performance variance occurred when using the displacement Logitech joystick (Miss_{min} = 3; Miss_{max} = 57).

For the pilots tested, no significant effect of joystick was found for the number of targets marked. Joystick type also had no significant effect on the number of misses recorded during the mission.

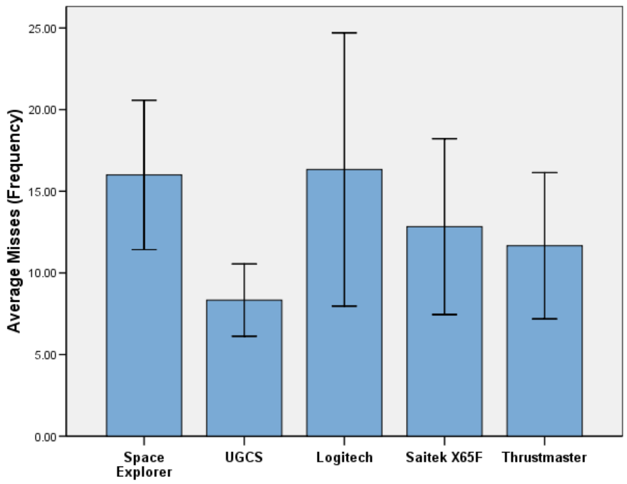

Figure 14 – Average Misses in Route Reconnaissance for UAS Warfighters (+/- 1 *SE*)

Mission Duration— No significant effect of joystick type was found in time to complete the route reconnaissance missions for the UAS warfighters. On average all missions, regardless of joystick type, were completed in under the 4 minute time constraint. Although not statistically significant, average time to complete the route reconnaissance with the SpaceExplorer was the fastest (*M* = 175.85 s), closely followed by the Thrustmaster Hotas (*M* = 177.91 s) and UGCS joystick (*M* = 180.41 s), and slowing down further with the Logitech Force joystick (*M* = 193.99 s). The slowest reconnaissance was performed while using the force sensing Saitek X65F (*M* = 196.51 s), as opposed to the displacement joysticks that supported more rapid target marking.

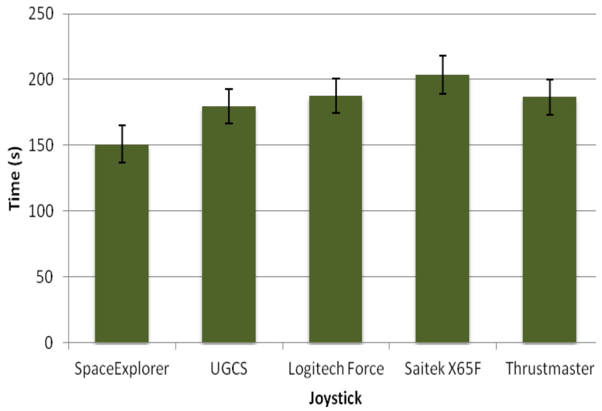

Figure 15 – Mean Route Reconnaissance Mission Duration for Pilots (+/-1 *SE*)

For the pilots tested, there was a significant effect of joystick on mission duration during the route reconnaissance missions, *F*(4, 20) = 7.95, $p < .05$ (Figure 15). Pilots completed the missions more rapidly with the 3D Connexion SpaceExplorer (*M* = 150.93 s) followed by the UGCS joystick (*M* = 197.55 s; *SE* = 13.02 s), next the Thrustmaster Hotas (*M* = 186.79 s; *SE* = 13.41 s), then the

Logitech Force (*M* = 187.62 s; *SE* = 12.87 s), and finally the Saitek X65F (*M* = 203.57 s; *SE* = 14.50 s). All displacement type joysticks supported mission success in a shorter amount of time.

MUM Teaming Engagement Mission Performance

Target Tracking RMSE—No significant effect of joystick was found in the tracking RMSE data for the UAS warfighters (Figure 16). Although average tracking error was lowest (M = 42.85 m) with the force sensing joystick (Saitek X65F) and highest with the SpaceExplorer (M = 50.73 m), performance differences were not statistically significant. It should be noted that a wide range of individual performance variance (RMSEmin = 11.93 m; RMSEmax = 98.42 m) was seen when warfighters tracked targets with the displacement Logitech joystick (SE = 12.77 m).

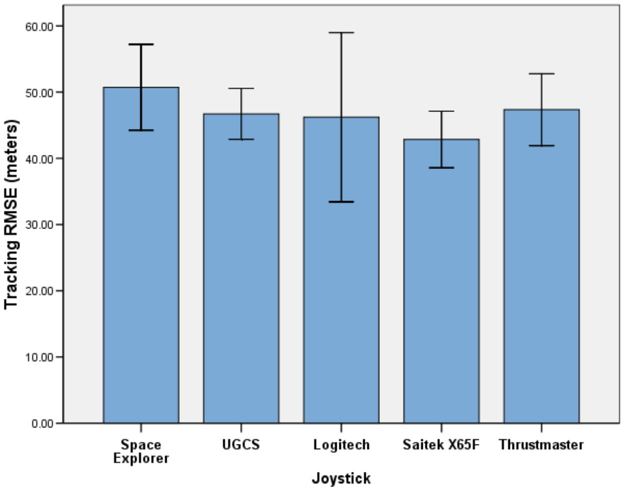

Figure 16 – Mean Target Tracking RMSE for UAS Warfighters (+/- 1 *SE*)

After comparison of pilots' tracking errors, no significant main effect of joystick was found in the target tracking RMSE performance. Regardless of joystick type, pilots performed similarly when tracking the maneuvering HVT (Figure 17). Similar individual performance differences were found across both displacement and force sensing joysticks.

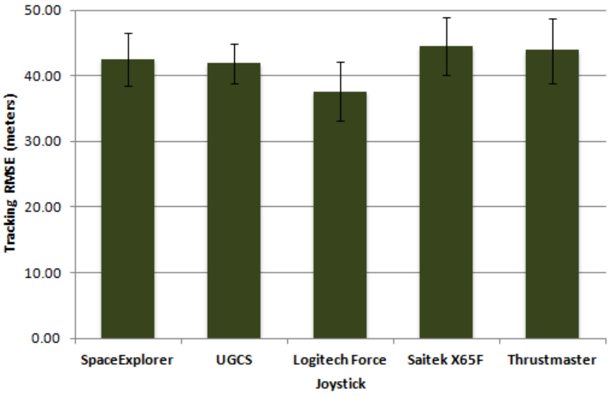

Figure 17 – Mean Target Tracking RMSE for Pilots (+/-1 *SE*)

Weapons Engagement Mission Performance

Targeting Accuracy—Analysis of targeting accuracy during the weapons engagement revealed no significant performance differences in the UAS warfighter population as a result of joystick used (Figure 18). Although not statistically significant, average offsets from the target were greatest for the experimental SpaceExplorer and force sensing joystick (Saitek X65F) (*M* = 10.55; *M* = 7.92, respectively). Operators' data showed small performance variances when using displacement joysticks. Mean targeting accuracy for displacement joysticks ranged from 4.05-4.66 m.

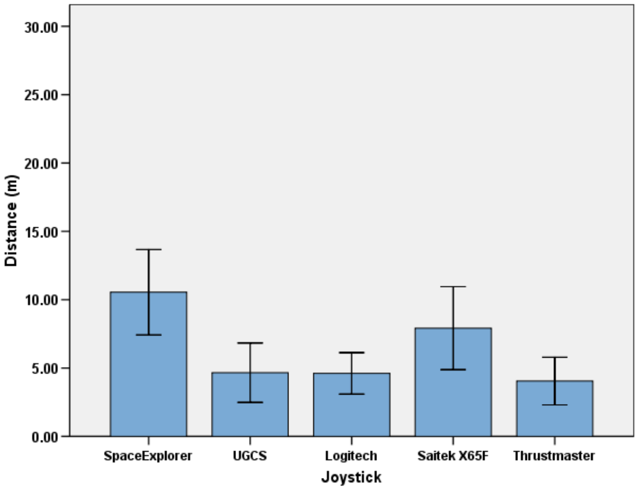

Figure 18 – Mean Distance from Target for UAS Warfighters (+/- 1 *SE*)

Analysis of the pilots' targeting accuracy revealed no significant main effect of joystick on distance to the target during the weapons engagement. Targeting accuracy was similar for each pilot, regardless of joystick used (Figure 19). In a comparison of average targeting accuracy across test groups, the pilot population exercised less targeting precision with every joystick than the UAS warfighter demonstrated.

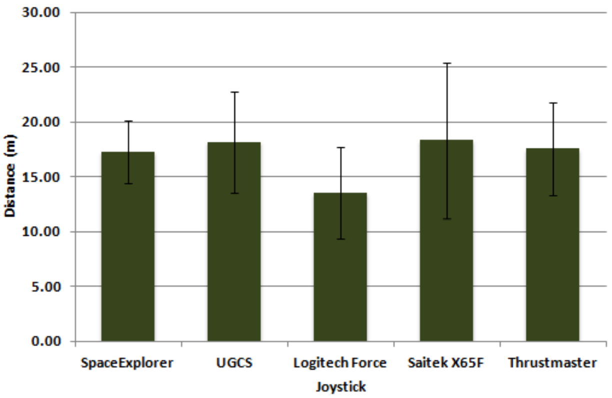

Figure 19 – Mean Distance from Target for Pilots (+/- 1 *SE*)

Subjective Ratings

Perceived Workload—NASA-TLX ratings collected from UAS warfighters showed no significant differences in perceived workload as a result of joystick used.

In a comparison of means calculated from the pilot's NASA-TLX ratings, collapsed across dimensions, no significant differences were found as an effect of the joystick tested. Incurred workload was reported perceptually similar across joysticks for the pilots tested.

Joystick Preference—UAS warfighters showed greatest favor (1 = most favored, 5 = least favored) for the force sensing Saitek X65F joystick with half of the operators rating it "number one." The unfamiliar, mouse-like SpaceExplorer controller was rated least favored by half of the operators. Noteworthy, the familiar UGCS joystick was unanimously ranked #3 (Figure 20).

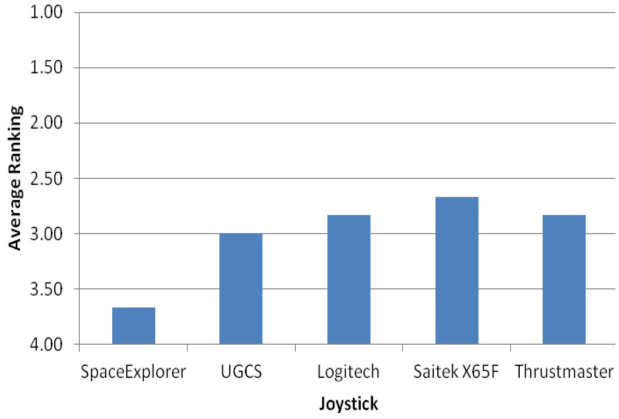

Figure 20 – Mean Ranking for UAS Warfighter's Joystick Preference

Preference rankings for the pilots revealed greatest favor for the SpaceExplorer followed by UGCS joystick, Thrustmaster, Logitech, and Saitek X65F (Figure 21). The force sensing joystick (Saitek X65F) yielded lowest overall preference in mean rank ordering (M = 4.50). Unlike the warfighter population, rankings suggest that pilots preferred a familiar "mouse-like" controller with down-facing hand orientation over either the displacement joysticks or the force sensing joystick.

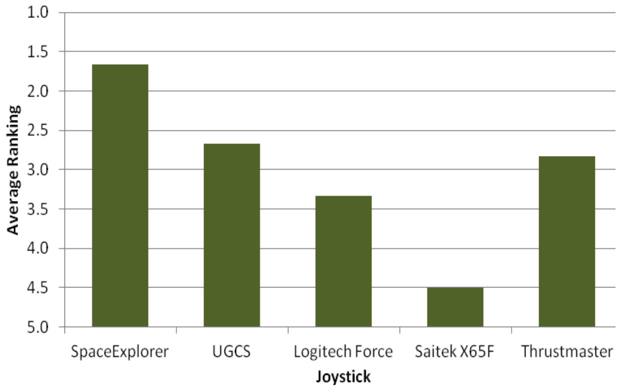

Figure 21 – Mean Ranking for Pilot's Joystick Preference

UAS Warfighter Comments

In both written comments and oral debriefings, warfighters expressed favor for the force sensing joystick (Saitek X65F). Specifically, warfighters believed that the controller design "forced a gentle grip to precisely control the sensor." The requirement for less pressure on the joystick was viewed positively because it was less fatiguing than the tendency to overexert pressure on the displacement joysticks. In particular, both Logitech and Thrustmaster joysticks were disliked for the necessary pressure required. For these joysticks, being overly flexible (Logitech) or rigid (Thrustmaster), required operator force to overcome. From the perspective of the warfighter, comfort over long duration missions (e.g., 4.5-5.5 hrs. for Shadow operations) was a foremost concern, influencing their preferences.

Negative impressions of the mouse-like SpaceExplorer were further explained by reports of unintentional cross-coupled inputs on the pitch and zoom axes. For example, Operator 1 stated that the "payload zoom occurred inadvertently when trying to use the controller one-handed." Unexpected payload motion and requisites for more focused attention to prevent such movement were reported across the warfighter test group. For this reason, the warfighters could not see a viable implementation in the UGCS.

Although familiar with the UGCS joystick from its similarity to the Shadow payload joystick, a majority of operators desired a design change. Operators suggested that frequently used "hot key" functions should be located on buttons directly on the joystick for easy access. Placement of functions that required left hand manipulation was not as desirable as having buttons on the stick. Several operators reported "missing" the ability to zoom the payload from the stick (i.e., Shadow joysticks have a twisting hat that enables zoom in/out).

A majority of operators expressed a desire to individually set the joystick gains. In this way, operators believed their manual inputs would be better calibrated to equipment motion. Several operators likened the joystick controller to a mouse at a desktop computer and the desired ability to change mouse speed by individual preference.

Pilot Comments

Comments collected from pilots supported their preference rankings. Preference for the SpaceExplorer was explained by the perception of comfort and belief that finite control of the payload movement was achieved in an intuitive manner. Specifically, ease of control was cited by several pilots with the comment that control was achievable with the "fingertips." Although, one pilot offered that "occasional inadvertent zooming seems to be the only issue."

For the least preferred force sensing joystick, pilots reported frustration and discomfort using the Saitek X65F stick. One pilot commented that "a non-moving stick was awkward." While another pilot stated that "it was hard to track the target smoothly and he felt tense trying to accomplish the task."

6. DISCUSSION

This study evaluated mission performance and subjective experience of both displacement and force sensing joysticks against a baseline joystick and one exploratory, mouse-like device. Findings related to significance of joystick type, influence of joystick familiarity, and necessity for comfort are discussed below. A final note on test group differences has been included.

Displacement vs. Force Sensing Joysticks

Mission performance in targeting, tracking, and weapons firing were not significantly impacted as a result of using displacement vs. force sensing joysticks. While the pilots were able to accomplish the route reconnaissance more rapidly with a mouse-like device (SpaceExplorer), it is questionable whether the small average differences would translate to operational relevance. Workload ratings for both test groups showed no significant differences between perceived workload with either displacement vs. force sensing joysticks or baseline and alternative devices. Noticeable differences in joysticks were best revealed in preference ratings and subjective comments. Aggregated subjective comments revealed favor for a *comfortable* stick with predictable motion and less operator force required, regardless of type. For these reasons, UAS warfighters preferred the force sensing joystick. Although viewed as physically comfortable because of hand position, the SpaceExplorer was disliked by warfighters due to unpredictable motion resulting from inadvertent cross-coupled operator input. The UGCS joystick was viewed as sufficient for searching tasks, but lacking functional buttons on the joystick itself.

Joystick Familiarity

Pilots' performance and preferences may have been influenced by joystick familiarity. Pilots had previously experienced the SpaceExplorer in earlier UAS studies, which may have improved their mission performance when compared with the warfighter group. Objectionable, inadvertent inputs on the SpaceExplorer may have been mitigated with prolonged use for the Pilots. Although training may be sufficient to eliminate cross-coupling, it is not advisable to introduce a new controller design with this inherent challenge.

Joystick Comfort

For both test populations, joystick comfort influenced their preferences and comments. UAS warfighters preferred the force sensing joystick due to perceived comfort. For this population, comfort was equated to less physical force required over a hypothetical 5-hr. mission. With combat experience characterized by high operational tempo for 7 days/week throughout deployment, warfighters sought the relief of a comfortable joystick requiring less physical force throughout the mission.

Pilots also preferred a comfortable controller, which they deemed characteristic of the SpaceExplorer. Both hand orientation and the light pressure required for inputs was viewed positively. However, for the reasons previously mentioned regarding unintended controller inputs, this device cannot be recommended.

Test Population Differences

Although between-subjects ANOVAs were not conducted on datasets due to variability in protocols and joystick exposure, it would be remiss to omit two salient differences in test groups. First, UAS operators with combat experience perceived even simulated weapons engagement with the gravitas of inherent lethality. Crosshair placement was slow and steady with intent to successfully eliminate the enemy. Across all devices, warfighters showed greater accuracy in targeting. Second, warfighter workload and preference was influenced by knowledge of UAS operations. Specifically, battle fatigue and long mission durations were considered when rating joysticks. Instead of simply comparing utility and comfort across joysticks, the UAS warfighter considered the context and employment limitations of the battlefield.

7. RECOMMENDATIONS

Although the force sensing joystick supported similar mission performance as the baseline joystick and received positive subjective comments from warfighters, there is not a preponderance of data to recommend this design. If comfort is viewed as small operator inputs and sustained comfort is the goal, then additional tests to stress these design objectives should be conducted. Alternate designs might also be identified and evaluated on the requirement that small operator inputs are sufficient for actuation. In order to ensure the best possible joystick design consideration for the UGCS, additional study is warranted with the following guidance:

Test Scenarios: Mission Duration

The current study evaluated joysticks in three 4-5 min. mission scenarios with training and data collection exposure to a given joystick totaling one hour. Typical tactical UAS mission durations are 4.5-5.5 hrs. It is hypothesized that differences in mission performance might be elicited with longer exposure to a low impact vs. fatiguing controller. It is further hypothesized that workload ratings might then reflect incurred frustration and elevated operator efforts required.

Joystick Comfort

Placement of frequently accessed functions on the joystick itself is recommended to avoid operator strain. Selection of critical functions to be placed on joystick buttons should accommodate reach capabilities for both female and male operators. Final design selection for the UGCS joystick should meet requirements of utility, logical button placement, and sustained comfort.

8. FUTURE RESEARCH

In related UGCS Human-Machine Interface studies conducted at Joint Systems Integration Laboratory (JSIL), Redstone Arsenal, UAS operators were familiarized with an Xbox 360 game controller for payload control and mouse-pointing functions. Initial impressions were positive with user-acceptance based on device comfort and familiarity. Self-reports of familiarity with the game controller and experience with first-person shooter games may impact ability to perform well with less fatigue. With consideration to designing for extended mission durations and a focus on sustained operator comfort, further empirical study of the Xbox game controller will be conducted with UAS warfighters for comparison purposes.

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BIOGRAPHIES

Susan R. Flaherty completed her undergraduate degree in Psychology at University of California, Berkeley, followed by an M.A. in Experimental Psychology from San Jose State University. Since 2002, she has worked for the U.S. Army Aeroflightdynamics Directorate in the Human Systems Integration Group at Moffett Field, CA. Ms. Flaherty has attended Shadow UAS operator training at Ft. Huachuca, AZ. Her research interests include delegation control of multiple unmanned systems and manned-unmanned systems teaming.

Lisa Fern received a B.S. in Psychology from the University of Calgary in 2005, and an M.S. in Industrial and Systems Engineering from The Ohio State University in 2008. Since graduation, she has been with the San Jose State University Research Foundation conducting collaborative research with the US Army Aeroflightdynamics Directorate (AFDD) at NASA Ames Research Center. Her current research efforts are focused on examining human-automation interfaces to support Unmanned Aerial Systems (UAS) operations, with a focus on 1) supervisory control of multiple UAS and 2) civil and combat airspace integration. Previously at The Ohio State University she studied issues of team coordination and decision making in urban fire fighting, addressing data overload challenges in inferential analysis, and developing research innovations for the NSA-sponsored Institute for Collaborative Innovation.

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Terry S. Turpin is the sole proprietor of Turpin Technologies with offices in Foster City, CA and NASA Ames Research Center at Moffett Field, CA. He founded this small business research company in 1994 following a successful 24 year military aviation career. Since inception, the company has provided research support to the Army Aeroflightdynamics Directorate at NASA Ames Research Center, as well as other government organizations (Air Force, Navy, FAA). Areas of research emphasis have been human systems integration, modeling and simulation support, military specifications and standards development, and design and testing of controls and displays for manned and unmanned aerial vehicles. Mr. Turpin has acted as the research project pilot and primary investigator on numerous aviation projects over the past 17 years at Ames. In addition to his government contract work, Mr. Turpin flies as a commercial helicopter pilot supporting aviation contracts in the San Francisco Bay area.

Scott Scheff received a B.A. in Psychology from the University of Arizona in 1997, and an M.A. in Human Factors and Applied Experimental Psychology from California State University Northridge in 2002. He has been the founder and principal of HF Designworks, Inc. since 2006. A human factors psychologist with a focus on the user experience and system safety, he has worked in government, commercial, and medical fields both as a designer and a manager. Prior to HF Designworks, he worked at Monterey Technologies, Alion Science and Technology, and TRW.

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