Chapter 15 – US-2: TECHNOLOGY DEMONSTRATOR 10: DELEGATION CONTROL OF MULTIPLE UNMANNED SYSTEMS (DELCON)

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15.1 DATES

The Delegation Control of Multiple Unmanned Systems (DELCON) demonstration was conducted on 24 April 2009.

15.2 LOCATION

Recent research at the U.S. Army Aeroflightdynamics Directorate (AFDD) has focused on delegation control, and delegation interface theory, as a solution for addressing the challenges of multi-UAS control by a single operator. AFDD's delegation control work builds upon previous application of Playbook®, developed by Miller, Goldman, Funk, Wu, and Pate [1]. This research is being addressed through two complementary tracks:

1) A series of empirical studies to test the important tenets of delegation control; and

2) Demonstrations of AFDD's delegation control interface in live flight.

This section describes the first of these live flight demonstrations.

The flight demonstration was conducted at the Military Operations on Urban Terrain (MOUT) site at Ft. Ord, California (Figure 15-1). The site is located on twenty acres of 10% graded terrain. The small city mock-up contains 33 cinder block training buildings of varying heights between 1 and 4 stories high. Narrow alleyways, winding gravel roads, and vegetated surrounding slopes characterize the city.

Figure 15-1: MOUT Site at Ft. Ord, California.

15.3 SCENARIO/TASKS

Support of troops in contact has been identified as a high priority and heavy workload mission for UAV operators due to the inherent time pressure and clear danger for troops on the ground. A Troops-in-Contact (TIC) mission for UAVs involves close air support and surveillance of an area where friendly troops are taking enemy fire. Currently, a TIC may have multiple UAVs offering close air support and surveillance over a common target. In these instances, multiple operator teams control a single UAV per team and coordinate flight paths and airspace through Combined Air Operations Center (CAOC), using mIRC and/or radio, as well as other Command and Control (C&C) channels. Delegation Control offers a solution for multiple vehicle management and coordination over a common target with reduced workload for a single operator.

An appropriate mission context to justify the use of heterogeneous unmanned systems was warranted to best exercise Delegation Control. The use of multiple unmanned assets for persistence on target in dense urban terrain is an understood necessity. As such, a TIC mission, evolving into a weapons engagement with troop re-supply was selected to showcase the capabilities of delegation control.

Initially, all air and ground assets were conducting separate and independent missions. The operator received an incoming message communication that a TIC was in progress. A TIC play was called by the operator through voice recognition control, resulting in all assets directed toward the TIC location. A follow-on communication informed the operator of a second enemy location and third location requiring ammunition re-supply. The operator responded by calling a Prosecute Target play and Quick Supply play. Assets were appropriately removed from the TIC play and new asset allocation was accepted by the operator. All changes were appropriately updated in the Play Status window. The virtual Shadow and Warrior Alpha completed a collaborative weapons engagement as prescribed by the Prosecute Target Play. In further detail, Shadow and Warrior Alpha were directed to deconflicted loiter patterns with payloads pre-pointed over a common target

and placed in notional prelaunch constraints. The operator was prompted to lock-on the target and entered laser Pulse Repetition Frequency (PRF) codes. With laser designator engaged, the operator entered weapons release codes and manually fired the missile. Upon missile impact, a pop-up text window prompted the operator to select a follow-on action. The operator selected *Conduct Battle Damage Assessment (with single vehicle)*. Consequently, battle damage assessment was conducted by the RMAX (upon completion of Quick Supply play).

In parallel, the MAX Rover and RMAX were en route to the resupply location specified by the operator. The RMAX flew in obstacle field navigation mode (scripted behavior) to the quick supply load point. The load weighed approximately 15 lbs. and was transported in a sling extending 5 meters from the bottom of the aircraft. Upon attachment of the sling, the RMAX lifted the load off the ground and took off toward the Drop Zone (DZ). At this time, the operator received intelligence that the DZ had been compromised and should drop at an alternate location. In response to this communication, the operator modified the play accordingly. The Quick Supply play was updated in real-time in the play status window and associated assets were redirected to the new DZ. After scanning the DZ for obstacles, the RMAX dropped the re-supply package. In coordination, the UGV provided overwatch security and video of the DZ and surrounding area. Once all plays were completed, the assets returned to their separate and independent missions.

15.4 TECHNOLOGIES EXPLORED

15.4.1 Ground Control Station (GCS) Hardware

GCS hardware consisted of all computers required to perform the demonstration safely and reliably. For safety measures, each unmanned system had a computer and an assigned backup operator to monitor system health and performance. In addition, a secondary backup operator monitored payload and telemetry functions for the RMAX.

Primary MUSIM software and Delegation Control interface resided on a 2.4 GHz Intel(R) Core™2 Quad computer with 2 GB RAM. The graphics card was an NVidia 9800GTX+. A Samsung 2333SW monitor with 1280 x 720 display resolution was utilized. Audio feedback was monitored by the operator using a Sennheiser PC 136 USB headset.

15.4.2 Payload Hand-Controller

The gimbaled sensor was operator-controlled via a 3D Connexion SpaceExplorer input device (Figure 15-2). This input device was pressure sensitive and required right/left and up/down twisting motions to control the starepoint of the selected active payload. A standard optical mouse was used for navigation of operator control panels and cursor control throughout the operator interface (including messaging page).

Figure 15-2: Connexion SpaceExplorer with 6 DOF Control Movement.

15.4.3 Multi-UAS Simulation (MUSIM) Software

MUSIM software resided on a Suse Linux 10.3 operating system. Internally developed by AFDD-contracted software engineers, the software suite was constructed utilizing OpenSceneGraph for graphics and FLTK for the graphical user interface. A simulated terrain database of Ft. Ord, correlated to the real-world was created using Creator Terrain Studio 2.2 and Creator 2.5.1. Terrain imagery was obtained from U.S. Geological Survey aerial photography. The simulation utilized 10-meter terrain data along the MOUT site perimeter and 1.25-meter terrain data within the "city" at the MOUT site. Display of sensor imagery from the virtual UASs was updated at 60 Hz.

15.4.4 Voice Recognition Control

A custom application developed by the U.S. Air Force Research Lab (Wright-Patterson Air Force Base) from an integration of two Commercial-Off-The-Shelf (COTS) products was added to MUSIM software for combined speech recognition and text-to-speech capabilities. The custom application was comprised of SRI International's DynaSpeak 1.5.32 Speech Recognizer and integrated with Cepstral's Text-to-Speech to accomplish voice recognition control. SRI's speech recognizer was Linux-based, offering speaker independent capabilities with natural language in North American dialect. Text-to-speech was annunciated by the female voice "Callie" developed by Cepstral for Linux (v5.x).

Customized grammar including play commands, stored geographic locations, and strike window times were defined for operator use during the flight demonstration. Integration between MUSIM and the voice recognition application was accomplished through UDP messages sent from the speech recognition system to MUSIM as a set of key value pairs in a character string. At a minimum, messages always contained a "command" associated with a value [i.e., TIC (command) at Tango (location = value)]. In cases where the system was unable to recognize a voice command, the system issued a "No rec" statement via audio feedback. Operator voice commands were acknowledged with echoed verbal confirmations from "Callie."

15.4.5 System Architecture and Integration

Play origination began with operator input to the Delegation Control interface. For RMAX and MAX Rover, MUSIM software propagated aircraft/ground waypoint and payload specifications to the associated vehicle control system for movement in the x, y, and z axes. Thus, complex collaborative vehicle behaviors were decomposed and relayed in a series of simple commands to the aircraft and ground vehicle. In cases where the RMAX control system possessed a resident script for a unique behavior (e.g., obstacle field navigation, safe determination and landing), MUSIM evoked script execution. Command of navigation for both RMAX and MAX Rover were executed through TCP/IP messages generated by MUSIM and sent to the aircraft and UGV control system, respectively. For RMAX navigation, Cartesian coordinates represented in the MUSIM database were first translated to UTM coordinates and then sent to the aircraft control system. For MAX Rover ground track navigation, MUSIM software communicated Cartesian coordinates which were translated by the resident control system to GPS lat./long. coordinates. Serial sensor images were sent in jpeg format from RMAX and MAX rover via UDP packets to the MUSIM computer.

15.4.6 Delegation Control Interface

The Delegation Control interface developed by U.S. Army AFDD for this demonstration was comprised of three separate display elements:

1) A digital moving map;
2) A Plays Multi-Function Display (MFD); and
3) A multi-sensor display window (Figure 15-3).

Figure 15-3: Delegation Control Operator Interface.

A digital moving map resided in a fixed-size window in the upper left corner of the operator display. Mission assets were depicted with vehicle shape-specific icons and uniquely color-coded. Flight paths and/or ground tracks matched the color of the related vehicle icon. In cases where dynamic re-planning of a flight path occurred, the intended flight path was depicted in white. Once confirmed by the operator, the flight path was displayed in the associated vehicle's color. Sensor direction and field of view for each vehicle was displayed using similarly color-coded sensor "whiskers." The sensor actively controlled by the operator displayed a sensor footprint highlighted in yellow. Direction of aircraft orbit was presented utilizing a clockwise or counter clockwise curved vector symbol. Map navigation and zoom buttons were located along the right side of the map display. Real-time vehicle position was displayed and updated at 60 Hz.

Below the map display, a Plays page was located for the purpose of building, editing, and displaying the status of a play (Figure 15-4). Before describing a play build, it should be noted that development of a multi-play library began with the definition of a single play. Plays had a data structure, assigned assets, and specific event timing. Initial defaults for altitude, loiter diameters, vehicle assignments, and sensor behaviors were defined prior to populating the play library. These assignments were given with regard to current Tactics, Techniques, and Procedures (TTPs). Consideration of cost was also important when defining the plays. Thus, vehicles navigated the shortest path to a designated waypoint, unless guided to an alternate route through operator editing. In total, the play library consisted of five previously defined plays.

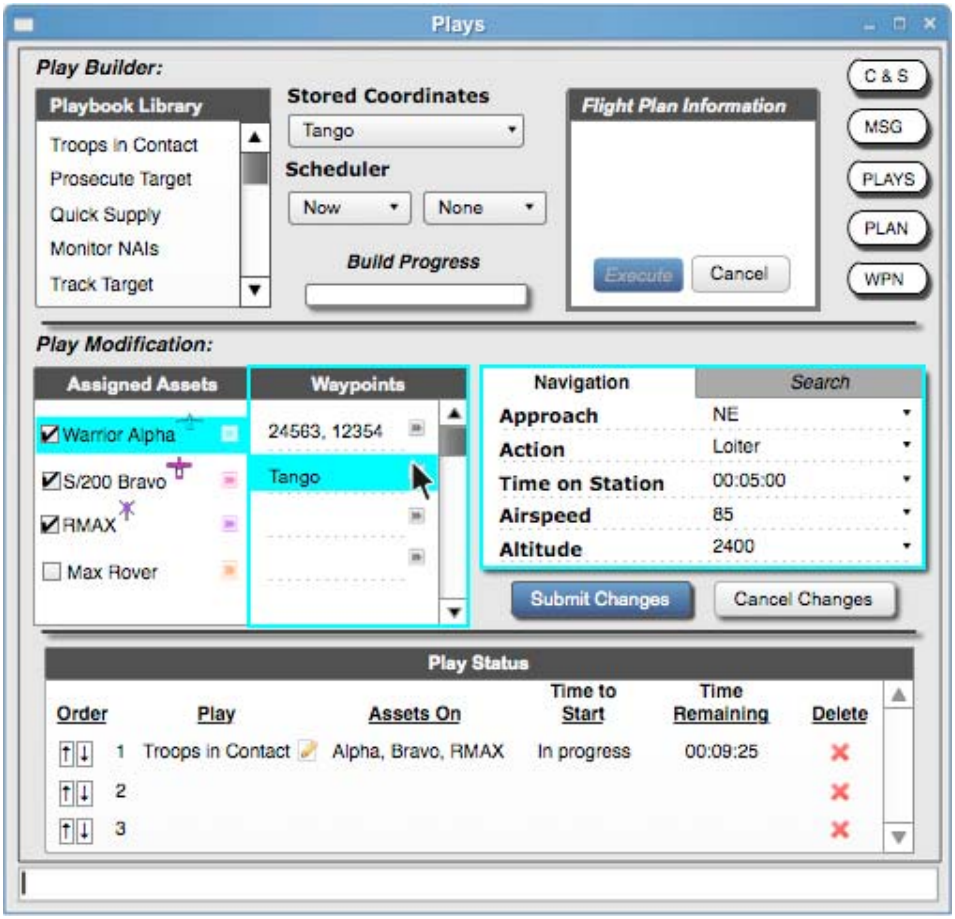

Figure 15-4: Plays MFD Page (e.g., Editing Waypoint Information Shown).

The Plays page was divided into three sections vertically:

1) Play Builder;
2) Play Modification; and
3) Play Status.

The top section, Play Builder, contained the menus for selecting and building a play from the Play Library. The middle section, or Play Modification section, displayed detailed information about a selected play and allowed for operator editing of navigation and sensor behavior parameters. The bottom portion of the page was reserved for display of play status and play priority order.

Delegation control of unmanned assets was accomplished through operator selection of a single play from the Play Library. To begin, the operator selected a play from the scrolling menu of stored plays. Next, the operator designated a location for play execution. Location could be selected from a list of stored coordinates, typed manually (e.g., numerical grid coordinate entry), or designated by clicking on a coordinate point on the digital map. Subsequently, the operator specified a time window for play execution, to include an option for immediate action (i.e., now). In the case of target prosecution, the time entry served as a strike window for earliest possible and latest acceptable time for target strike. Once the operator specified a location and time, a flight plan was generated on the digital map and the play was displayed in the Play Status window. In cases where assets were already in use on an existing play, the flight plan information box displayed the impact of allocating assets between plays (i.e., RMAX and Rover will be removed from TIC for quick supply.) During simultaneous play execution, the flight plan information box served to enhance automation transparency for the operator. When simultaneous plays competed for unmanned systems resources, the operator was required to select Execute in acceptance of the vehicle allocation before the new play initiated. No alternate remediation for vehicle allocation was offered.

Capability for real-time play modification is a central tenet of AFDD's Delegation Control over less flexible, scripted vehicle behaviors. The center portion of the Plays page was dedicated to play editing. The operator was able to modify default assets assigned to a play and waypoint navigation in real-time. To further refine the play, the operator could change navigation parameters and/or search geometry associated with a waypoint. Waypoints could be added or deleted by the operator on any play in real-time.

The lower portion of the Plays page contained a Play Status window for all plays uninitiated and in progress. Plays were listed in order from highest to lowest priority. The operator had the ability to increase or decrease a play's priority through selection of up and down arrows. As additional plays were built, both the listing of plays and priority of plays were updated. Plays were automatically removed from the status window upon completion. Details of play status included: priority order, assets assigned, time to start, and time remaining on the play. Operator changes to a play were immediately updated in the play status window. Deletion of a play was accomplished by selecting a red *X*, thereby "closing" the play.

The sensor display was located on the right side of the Delegation Control operator interface. The sensor display was divided into four sensor windows. Sensor windows were outlined in the correlated color of the vehicle icon offering visual cues to imagery source. In the upper left corner of each window a text description of the vehicle source was displayed. In further detail, the top sensor window displayed the actively controlled sensor. The lower side-by-side sensor windows displayed a second and third vehicles' imagery. The bottom thumbnail image contained the fourth vehicle's imagery. Although small, the fourth thumbnail display remained a live image instead of a static jpeg. Continual presence of all four sensor displays, regardless of size, was a design decision made to support the operator's situation awareness and serve as a reminder of

controlled payloads. Operator selection of a vehicle for active sensor control was accomplished by selecting a vehicle's payload feed with the mouse. Once selected, the vehicle's imagery replaced alternate imagery in the top window. Replaced imagery switched display locations with the recently selected active vehicle sensor.

Superimposed payload symbology displayed information related to vehicle heading and sensor direction on the active sensor window. Specifically, the symbology included a screen-fixed, compressed heading tape, marked in 10-deg increments and labeled in 30-deg increments. The sensor direction carrot (sensor heading) remained in the center of the 180-deg heading tape as it moved across the top of the display. A vehicle icon, identical to the moving map, depicted vehicle heading with a screen-delimiting arrow appearing when sensor and vehicle heading diverged more than 90 deg. At such time, vehicle heading was displayed to the right of the arrow as a digital readout, as this information was no longer visible on the compressed tape.

Superimposed, geo-referenced waypoint markers representing vehicle flight path / ground track overlaid sensor imagery. This use of augmented reality was intended to assist the operator in navigation and map-to-video correlation.

Crosshair symbology was displayed on vehicle sensor windows during plays involving weapons engagement. For example, during a Prosecute Target play, message prompts to ready and engage the laser designator were concurrent with the display of superimposed flashing brackets around the crosshairs. Once target lock-on was accomplished, brackets continued to be displayed without flashing. Crosshair symbology and brackets were positioned only on sensor windows of vehicles assigned to the play and disappeared with play termination. This design decision supported operator SA of vehicle collaboration in a weapons engagement.

In addition to menu selection by mouse, an operator could exercise voice commands to select a play from the Play Library. By utilizing voice commands, the operator was able to rapidly initiate a play during time-critical mission phases (e.g., response to TIC). Operators were able to circumvent mouse navigation of multi-level menus by annunciating an exact parameter to be changed. Use of voice commands was incorporated as an intuitive supplemental capability to augment Delegation Control. It was considered a time saving measure and assisted in the reduction of operator workload.

15.5 HUMAN FACTORS ISSUES EXPLORED

The purpose of this flight demonstration was to successfully demonstrate delegation control of multiple unmanned air and ground vehicles by a single operator in a collaborative urban scenario [2]. In an extension of empirical studies [3],[4],[5] and flight demonstrations, it was hypothesized that a single operator could effectively monitor four unmanned heterogeneous assets with reasonable workload levels and high situational awareness using Delegation Control employment.

Specifically, demonstration objectives focused on showcasing solutions related to Human-Machine Interface (HMI) challenges involved with control of multiple payloads and vehicle platforms. Best practice solutions from human factors principles and literature were applied. A Delegation Control interface was developed by U.S. Army AFDD to support control and monitoring of four payloads. In addition, voice recognition control was implemented for multiple vehicle control in high workload mission segments (e.g., response to troops in contract.) Automation transparency was deemed significant to operator SA. Therefore, textual presentation of automation feedback related to simultaneous play execution was generated within a flight plan information window. Overall, demonstration success was defined as the ability for a single operator to execute a mission with multiple unmanned assets in collaboration with tolerable workload and high situation awareness.

15.6 UNMANNED SYSTEMS USED

Two live unmanned assets and two virtual unmanned aerial vehicles were used in this flight demonstration: a Yamaha RMAX helicopter modified for high-level autonomous operations was flown in the demonstration (Figure 15-5); and a Max 5A Rover Unmanned Ground Vehicle (UGV) manufactured by Senseta, Inc. and operated by Carnegie Mellon University Silicon Valley (Figure 15-6).

Figure 15-5: Live Yamaha RMAX (VTOL UAV).

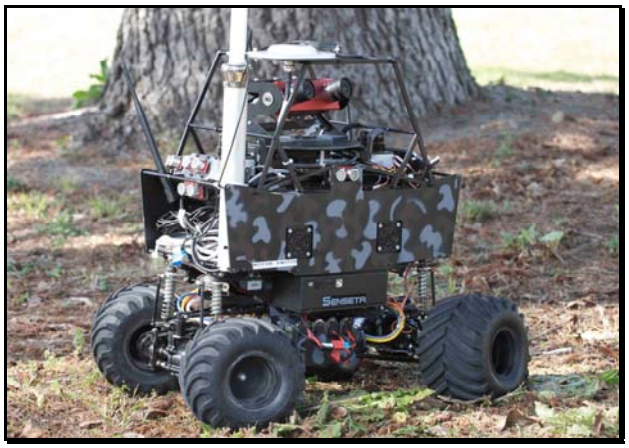

Figure 15-6: MAX Rover UGV.

A standard RMAX features a 3 m diameter rotor and maximum take-off weight of 94 kg. Additional payloads consisting of a 3D scanning hemispherical LADAR and autonomous flight control system mounted on the aircraft increased the original baseline weight to 172 lbs. Custom payload modifications were made by U.S. Army AFDD to achieve autonomous flight capabilities to include obstacle navigation. Flight controls and navigation were all processed onboard utilizing a Pentium III computer and NovAtel SPAN/LN200 Inertial Navigation Systems. Mission duration for the RMAX was approximately 60 minutes.

A UGV was a 4-wheeled, man-portable Max Rover weighed approximately 9 kg and had a cruise speed of 11 mph. The onboard computing platform consisted of a 2.0 GHz entium-M with 1 GB RAM.

Two virtual, fixed wing flight assets were included in the flight demonstration for the purpose of showcasing collaborative multi-vehicle plays. Nominally, a Shadow tactical UAS and Warrior Alpha were simulated. Typical altitudes, airspeeds, and payload characteristics were emulated through the U.S. Army AFDD's Multi-UAS Simulation (MUSIM) software.

15.6.1 Sensor Payloads/Imagery

The Yamaha RMAX was equipped with a fixed forward electro-optical, color camera with ability to pitch +10/-100 deg. 640 x 480 grayscale images were telemetered over Wi-Fi at a quality of 25% and updated at 8 Hz.

The sensor platform on the MAX Rover consisted of a Videre synchronized stereo pair system camera. Camera manipulation was accomplished in pitch (-30/+80 deg) and pan (+/-170 deg) axes. A series of jpeg images was transmitted and updated at 15 Hz to the Delegation Control operator display. Imagery capture and resolution was 320 x 240.

The virtual Shadow UAS was nominally equipped with Electro-Optical/Infrared (EO/IR) sensor and laser designator. The virtual Warrior Alpha was nominally equipped with EO/IR and four Hellfire missiles. For the purpose of demonstration, virtual sensors had 360 deg pan capability and +45/-110 deg pitch limits. Sensor slew rate was set at 60 deg/second. Zoom capabilities supported a progressive change in FOV from 2 to 16 deg (x – 8x). Precise modeling of the laser designator and weapons delivery system was not considered necessary for this demonstration. Thus, a low fidelity emulation of the weapons systems was employed.

15.6.2 Telemetry

The mobile ground station was equipped with two antennas for 900 MHz and 2.4 GHz telemetry. Payload telemetry for the RMAX used the 902 – 928 MHz frequency range. The 72.11 and 72.13 MHz frequencies were used for backup aircraft control. An omni-directional antenna for datalink transmissions to the RMAX was mounted on the tallest building at the MOUT site, allowing for complete site coverage. Adjacent to the RMAX antenna, a manually swiveled Yagi-Uda antenna was utilized for Wi-Fi datalink transmission to the MAX Rover.

15.7 SUMMARY OF ANY NATO COMMUNICATIONS/COLLABORATIONS/ INTERACTIONS

The NATO working group served as an informal crew-station working group. The demonstration plan, plays and data collection were presented, discussed and vetted at numerous meetings prior to the demo. The USAF integrated and provided technical expertise for the voice recognition system.

	Planning/Design	***Execution***	***Analysis***
Communication	*All*	*All*	*All*
Coordination	*USAF, Canada, Germany*		
Collaboration	*None*		

15.8 SUMMARY OF TD RESULTS

The TD demonstrated simultaneous control of multiple vehicles by a single operator. The workload was acceptable and situation awareness reasonable. These were actual vehicles in-flight and on the ground as well as virtual aircraft. This was accomplished via Playbook (DELCON) methodology. Voice recognition to “call” the plays was also demonstrated.

15.9 LESSONS LEARNED

Under these circumstances, a single UAS operator can simultaneously control multiple UAS. Voice recognition can be integrated seamlessly into this environment.

15.10 STUDY CONSTRAINTS/LIMITATIONS

The study was limited primarily in that it was concept demonstration not a flight test. That is, it was not an actual experiment, it was demonstrating concepts previously tested in the laboratory. Further, no actual UAS operators controlled the system, they were controlled by one of the experimenters. Additional limitations included:

- Unfavorable weather conditions for flight testing of the RMAX proved to be one of the largest obstacles faced by the research team. This is being addressed in future demonstrations/flight tests through selection of a more suitable location (with more favorable weather conditions), as well as investigation of a weather impacts and route planning tool developed by ARL, called MyWIDIA (My Weather Impacts Decision Aid).
- Inability to integrate differential GPS onto the MAX Rover within the allotted timeframe, combined with limited GPS reception and safety concerns regarding road widths at the Ft. Ord MOUT site prevented the research team from allowing MUSIM to send automatic waypoints to the vehicle, despite having developed and tested this capability beforehand. Again, this limitation could be overcome by using a more suitable location, e.g., one with larger areas for transit to offset location errors, or one with better GPS reception.
- Lack of access to trained operators significantly hindered the research team's ability to collect any human performance data. This is being addressed in a future flight test by using general aviation pilots that have been trained on the MUSIM system and participated in simulation experiments in AFDD's laboratory.

15.11 CONCLUSIONS

This demonstration was deemed a success for aptly showcasing Delegation Control of multiple unmanned systems by a single operator. Navigation and payload control of four unmanned systems was successfully monitored by a single operator in a collaborative urban mission scenario. Delegation Control employment strategy and interface design supported the build, initiation, modification and monitoring of simultaneous plays in progress. Use of voice recognition was considered an advantage to the operator during time critical mission phases. The operator's ability to bypass menus in favor of voice recognition control, significantly decreased reaction time to external mission events. Dynamic route re- planning was effectively accomplished while plays were in progress. In addition, play status was efficiently depicted and real-time updates were accomplished when play modification and play terminations occurred. Automation transparency was increased through messages generated by the MUSIM software that described impacts of conflicting plays. Lastly, the Play Status window was considered a significant contribution to operator SA for rapid, at-a-glance awareness of asset allocation and play scheduling.

15.12 FUTURE RESEARCH NEEDS AND PLANS IN THIS AREA

This demonstration served to test and extend Delegation Control concepts initially sourced from empirical studies and Subject-Matter Expert (SME) interviews. Operational limitations of Delegation Control were explored during the demonstration without benefit of formal data collection or control comparison. Future research will include flight-tested data to support Delegation Control employment strategies over alternative control strategies. Performance data and subjective ratings of operator workload and SA will be collected in future flight tests. To ensure operationally relevant and tactically valid play definitions, U.S. Army AFDD has

plans to vet and expand play definitions with the user community. Interviews with returning warfighters will be conducted and subjective ratings collected on play usefulness, feasibility, and projected frequency of use. Modifications to the play library and play defaults will be made where appropriate. U.S. Army AFDD will continue to explore Delegation Control as an effective means for multi-vehicle unmanned systems control by a single operator. AFDD plans to continue testing Delegation Control in lab studies and flight tests. Near-term plans include the testing of the top five user-rated plays, expanding play definitions, and providing intelligent automation feedback when plays have been degraded. Possibilities for play rehearsal will also be explored. In the out- years, plans exist to implement Delegation Control from a manned platform in support of manned-unmanned teaming.

15.13 ACKNOWLEDGEMENTS

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