

**Naval Information
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PACIFIC

TECHNICAL REPORT 3222
JANUARY 2021

**Command and Control
Collaboration Sand Table (C2-CST)
A Navy Innovative Science
and Engineering (NISE)
Microfund Project**

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NIWC Pacific

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Naval Information Warfare Center Pacific (NIWC Pacific)
San Diego, CA 92152-5001

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ADMINISTRATIVE INFORMATION

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EXECUTIVE SUMMARY

A Naval Information Warfare Center Pacific (NIWC Pacific) Naval Innovative Science and Engineering (NISE) Microfund project titled Command and Control Collaborative Sand Table (C2-CST) examined a new Commercial-Off-the-Shelf (COTS) product, the Microsoft HoloLens. The objective was to examine a new human-machine interface for Command and Control (C2) systems with collaborative classification levels. A Microfund project is a small funded project with quick turnaround for exploration of Science and Technology (S&T) ideas. These ideas are to be executed in a short timeframe with a result that leads to a definitive technology demonstration, proof-of-concept, prototype, or report that has high risk with a potential for high reward.

The C2 system selected for evaluation of the human-machine interface was the Intelligent Multi-UxV Planner with Adaptive Collaborative/Control Technologies (IMPACT), an Autonomy Research Pilot Initiative (ARPI) project between tri-service research laboratories. IMPACT was built to demonstrate agility in tactical decision making, mission management, and control with key elements for enabling heterogeneous unmanned vehicle (UxV) teams to successfully manage the “fog of war” with its inherent complex, ambiguous, and time-challenged conditions. Applied research for IMPACT was based on supervisory control and the machine learning of tactics that combine flexible play-calling, bi-directional human-autonomy interaction, “global” cooperative control algorithms, and “local” adaptive/reactive capability.

The Microsoft HoloLens is an Augmented Reality device which has a see-through lens to the real world upon which computer graphics are overlaid. The operator of this device can interact via gaze, gesture and speech while visualizing the virtual C2-based scene in any defined presentation space. This new modality of user interface provides the premise to investigate effectiveness of human-machine interfaces—such as add-ons—or replacement for existing C2 human-machine interfaces.

The C2-CST project concept connects and interacts with the IMPACT system via an augmented reality device platform. The IMPACT system is a research prototype demonstrating human supervisory control of multiple autonomous unmanned vehicles and thus is an ideal C2 system end target to develop and test the advanced user interface. The goal was to allow human-to-human-to-machine collaboration for situational awareness, decision making, and C2 planning and execution of simulated multi-unmanned heterogeneous autonomous vehicles. The advanced user interface allowed multiple operators to collaborate across a shared holographic sand table (terrain model used for military planning and wargaming), while controlling several unmanned vehicles. Multiple networked frameworks were utilized to offload the computation of vehicle autonomy and planning algorithms while letting the Microsoft HoloLens run more smoothly as the human interface element. An additional concept of pseudo-classified information filtering was examined. This allowed for tiers of classification levels to be applied to each user within the Microsoft HoloLens interface while sharing the same virtual environment or holographic representation. The concept demonstrated a “need-to-know” classification premise within a shared environment. Visualization, interaction, human-to-human-to-machine collaboration, and shared space with filtered classification levels define the potential advantages of this advanced user interface for C2 systems.

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ACRONYMS

AFRL	Air Force Research Laboratory
AMASE	AVTAS Multi-Agent Simulation Environment
API	Application Programming Interface
ARL	Army Research Lab
ARPI	Autonomy Research Pilot Initiative
ASD R&E	Assistant Secretary of Defense for Research and Engineering
AVTAS	Aerospace Vehicle Technology Assessment and Simulation
C2	Command and Control
C2-CST	Command and Control Collaborative Sand Table
CCA	Cooperative Control Algorithm
COTS	Commercial Off the Shelf
HUV	Heterogeneous Unmanned Vehicles
IMPACT	Intelligent Multi-UxV Planner with Adaptive Collaborative Control Technologies
NISE	Navy Innovative Science and Engineering
NIWC Pacific	Naval Information Warfare Center Pacific
NRL	Navy Research Lab
OSD	Office of the Secretary of Defense
S&T	Science and Technology
SO	Sensor Operator
TOC	Test Operator
UAV	Unmanned Air Vehicle
UGV	Unmanned Ground Vehicle
USV	Unmanned Surface Vehicle
UxV	Heterogeneous Unmanned Vehicles

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CONTENTS

EXECUTIVE SUMMARY	V
ACRONYMS.....	VII
1. INTRODUCTION.....	1
1.1 MOTIVATION	1
1.2 AUGMENTED REALITY TECHNOLOGY	1
1.3 INTERFACING TO A COMMAND AND CONTROL SYSTEM.....	2
1.4 CURRENT STATE OF ART.....	3
2. OBJECTIVES	5
2.1 GENERAL DESCRIPTION	5
2.2 C2 SYSTEM CONNECTION AND COMMUNICATION	5
2.3 INTERACTION WITH THE C2 SYSTEM	6
2.4 COLLABORATION	6
2.5 FILTERED CLASSIFICATION	7
2.6 EXPERIMENTATION	7
3. TECHNICAL APPROACH	9
3.1 ARCHITECTURE	9
3.2 ENVIRONMENT – SCENE CREATION	13
3.3 C2-CST COMMUNICATIONS	15
3.4 SHARED EXPERIENCES VIA MIXED REALITY TOOLKIT	16
3.5 CLASSIFICATION FILTERING OF A SHARED VISUALIZATION	17
3.6 A SIMPLIFIED IMPACT PLAY WORKBOOK	18
4. C2-CST EVALUATION.....	21
4.1 HUMAN EVALUATION OF C2-CST	21
4.2 KEY ATTRIBUTES FOR EVALUATION	21
4.3 EVALUATION FOR MULTI-USER COLLABORATION AND CLASSIFICATION FILTERING.....	22
5. FUTURE WORK	25
5.1 DEVELOPMENT AND EVALUATION STILL REQUIRED	25
5.1.1 Complete Set of Play Workbook	25
5.1.2 Voice-based Interaction	25
5.1.3 Comprehensive Human Subject Matter Testing	25
5.1.4 Remote Collaboration	26
5.1.5 Classified Data Filtering	26
5.2 NEAR TERM POTENTIAL.....	26
5.3 TRANSITION PATHWAYS.....	27
6. CONCLUSIONS.....	29
REFERENCES	31
BIBLIOGRAPHY	31

APPENDICES

A: C2-CST PROJECT GOALS AND OBJECTIVES	A-1
B: C2-CST HUMAN EVALUATION QUESTIONNAIRE.....	B-1

Figures

1. C2-CST Architecture Diagram.	10
2. IMPACT Architecture with ZeroMQ based HUB.....	11
3. C2-CST Sand Table Display.....	14
4. Network Connections and Communications.	15
5. Illustration of Sharing Experience in C2-CST. (Image credit to Royal Australian Air Force, Saab Australia and Defence Science Technology Group).....	17
6. IMPACT Interface with Play Calling.	19
7. C2-CST Simplified Play Calling Interface.....	20

1. INTRODUCTION

1.1 MOTIVATION

Advanced human interfaces are key to the improvement in the presentation, understanding, and collaboration for Command and Control (C2) systems to achieve human-based situational awareness, decision making and effective interaction. Human-autonomy teaming requires new advances in display systems which allow an increased human-to-human collaboration and a tri-collaboration capability of human-to-human-to-machine. This can play a critical role in future C2 operational planning as humans collaborate with each other and autonomy simultaneously. Additionally, a new concept in shared visualization is created where multiple classification levels are available but accessible to different collaborators based on their “need to know” status. This allows them to share and collaborate in the same virtual space but only have access to the information specified by their classification. A shared virtual environment with means to filter levels of classification or function has wide application yet serious concerns of information spillage from one classification level to the next. The pros and cons of such an approach are examined via exploration and experimentation within the Command and Control Collaborative Sand Table (C2-CST) capabilities. Such a prototype interface also offers the ability to study how such a display system could be utilized amongst an operational command hierarchy. Questions such as, “which key decision makers would be better suited to use such an interface?” can be explored.

1.2 AUGMENTED REALITY TECHNOLOGY

The Microsoft HoloLens is the first COTS self-contained holographic computer that enables engagement with digital content and interaction with holograms superimposed on the real world (Microsoft HoloLens, 2019). The device is an adjustable-fit headset that uses a visor to display virtual, augmented, and mixed realities (VAMR) to the end user. The headset consists of a self-contained Windows 10 computer system with multiple sensors for advanced optics and holographic computing. A special holographic processing unit (HPU) was designed specifically for VAMR.

Interaction with the holograms displayed through the HoloLens is based on gaze, gesture, and voice. The display is a see-through visor so that hologram elements are overlaid as computer graphics into the view of the real world.

The gaze interaction parallels the action of a mouse cursor in a normal computer display. The gaze acts as a cursor that aligns with the user’s view vector placed into the holograms and moves with the user’s view. The cursor is typically a circular icon that is placed at the intersection of a holographic element in the scene and the user’s view vector. The cursor is placed instantaneously at that point and moves as the view vector changes. This allows the user to gaze upon the scene and highlight or select items via gaze.

Gesture is the means that acts upon the outcome of the gaze. As the gaze selects on item of interest, such as a part of the hologram or a holographic menu, the gesture allows the human to perform a hand gesture to indicate the action to be taken. The HoloLens detects the user’s hand when it is in the view of the device and is built to recognize three gestures: “bloom,” “air tap,” and “tap and hold.” The bloom gesture is the action of closed fingers which are then opened with the fingers spread wide. This gesture represents the equivalent of a “home” gesture or one that can be used to call up the HoloLens menu. The air tap gesture parallels the mouse click in a standard computing system. The user extends the thumb and index finger and then brings them together and releases back to the start state just like clicking on a mouse button and then releasing. This is widely used for the

selection or activation of an interface item. The tap and hold gesture is equivalent to the first part of the air tap, however the index finger and thumb stay together. This allows the user to click and hold onto an item and then drag it if desired. It parallels a mouse click and hold and then dragging.

The final human interface of the HoloLens is voice. Voice commands can be built into the interface to allow interactions with HoloLens and content in the holographic scene which can also be associated with the gaze. Voice is often used as a more direct means of instigating an action. Voice input is powered by the same engine that supports speech in Microsoft Universal Windows Apps.

The HoloLens was developed with the concept of augmented or mixed reality where users can have synchronous shared experiences for presentation, collaboration, and interaction. This augmented reality capability provides an advanced shared interface amongst multiple users collaborating on the same scene and/or scenario. At the same time, the view of real-world surroundings is maintained to allow spatial orientation within the environment and visual cues from users in the same room from their own perspective of the shared environment.

This collaborative environment is considered an innovation of a natural human interface when combined with gaze, gesture and voice actions. These combined capabilities of the HoloLens interface provide a natural and intuitive means to collaborate on a given scene or scenario in a holographic enhanced environment.

The target platform for the study and experiment of advanced C2 interfaces is the Microsoft HoloLens, which is described as a developmental mixed reality headset for Microsoft's vision of interaction with computers (Furlan, 2016). The HoloLens, which contains a Windows-based computer, does not by itself have enough computing power to properly process complex planning, autonomy, and simulation algorithms used in C2 systems. The C2-CST project approached this problem by allowing the Intelligent Multi-UxV Planner with Adaptive Collaborative Control Technologies (IMPACT) system to perform the majority of the C2 computing, however much of the user interface computing was also required to take place on additional computer system with significantly more processing power than found on the Microsoft HoloLens device. This allowed only sending important display and interaction information to and from the HoloLens for improved performance.

1.3 INTERFACING TO A COMMAND AND CONTROL SYSTEM

Key to the evaluation of an advanced human interface is the candidate C2 system to which the interface is applied. The utility of applying an augmented reality interface must correlate to some set of proposed benefits from the C2 system user's perspective. Furthermore, the C2 system must provide a programmable interface that would allow two-way communication between these systems. For this evaluation, the new interface would require a C2 system with a standard computer interface, keyboard, mouse and monitor. The system would need to compare the two interfaces while considering the user's equivalent role and use for the C2 system for both interfaces.

The IMPACT system is a C2 prototype platform for centralized supervised control of multiple simulated autonomous unmanned vehicles [1]. Research related to IMPACT was to demonstrate how a single human can provide supervisory control of many unmanned vehicles through the fusion of several autonomous agents, and the autonomy associated with the unmanned vehicles working in concert to achieve missions in an uncertain and changing environment. The underlying goal of the IMPACT initiative, sponsored by the Office of the Secretary of Defense (OSD) Autonomy Research Pilot Initiative (ARPI), was to invert the applied ratio of humans to autonomous vehicles [2]. This

concept, designed and implemented with a tri-service set of research teams from the Air Force Research Lab (AFRL), Naval Information Warfare Center Pacific (NIWC Pacific), Army Research Lab (ARL) and Naval Research Lab (NRL), was to move away from multiple operators controlling just one vehicle to using IMPACT to support the control of several vehicles by just one operator. The autonomy of the vehicles—and more importantly, the autonomous systems embedded into IMPACT application—better aligns with the Secretary of Defense Third Offset Strategy as applied to autonomous vehicles and systems. The operator manages missions through a “play calling” approach where autonomous agents support the operator in performing tasks.

The IMPACT system has three operator stations, each containing four touch screens, a keyboard, a mouse and a microphone as system interfaces. The primary station is the C2 station, which can have one-to-many stations and is used by the operator performing the human supervisory control of the autonomous vehicles. The second station is for the Sensor Operator (SO) and allows human control and adjustment of sensor systems aboard the unmanned vehicles. The last is for the Test Operator (TOC). This station permits human control of simulated unmanned vehicles with a simulator called Aerospace Vehicles Technology Assessment and Simulation (AVTAS) Multi-Agent Simulation Environment (AMASE), and other blue force simulated entities in the One Semi-automated Forces (OneSAF) application; both support the running, testing and evaluation of IMPACT.

IMPACT currently demonstrates Base/Force protection missions/scenarios utilizing intelligent agents, machine learning and a hybrid planner for multi-level human-automation interaction for collaborative control of up to twelve heterogeneous unmanned systems (air, ground, surface, and soon-to-be sub-surface). A network hub component is utilized for shared data and messaging using the standard web format of JavaScript Object Notation (JSON), a Distributed Interactive Simulation (DIS) format, and the Light-weight Message Control Protocol (LMCP) format. IMPACT includes a rich visual interface for human supervisory control and a set of autonomous agents for task management, plan monitoring, path creation, and resource allocation. This results in improved situational awareness, decision making, and supervisory control of multiple autonomous unmanned vehicles.

The nature of IMPACT aligns with and provides a jumpstart into the DoD Third Offset Strategy for science and technological development of autonomy and human interaction with autonomy. This leads to an insurance or advantage in operations/missions in complex and contested environments. IMPACT demonstrates a highly effective human-machine teaming with supportive and intuitive interfaces that achieves the proper balance between man and machine and serves as a prime candidate for the C2-CST user interface application and experimentation.

1.4 CURRENT STATE OF ART

Advances in augmented or mixed reality—or a hybrid of what is virtual and real—has grown remarkably in the past few years due to the commercialization of the technology. The concepts behind the technology have been around for quite some time, such as the Virtual Fixtures platform developed at the U.S. Air Force Armstrong Laboratory in the early 1990s. NIWC Pacific (formerly SSC Pacific) was also involved with virtual reality in conjunction with the Naval Postgraduate School for a project called CommandVu. CommandVu was utilized for Marine Corp platoon mission development and training within a virtual environment. This same software system was utilized in a mixed-live live fire demonstration at 29 Palms, California. More recently, the Battlespace Exploitation of Mixed Reality (BEMR) Lab has been evaluating, integrating and exploiting commercial mixed reality technology for adaptation into a virtual world’s battlespace. The goal is to

reduce associated costs and risks when bringing the mixed reality technology and capability to the warfighter. The intent of the goal is to increase effectiveness, efficiency, collaboration, innovation, battlespace visualization and speed to response and pace of evolution in decision making and situational awareness. Team members from the BEMR Lab were involved with the programming and development of the C2-CST application, which leveraged their existing experience with the Microsoft HoloLens and associated technologies.

Current applications for mixed or augmented reality have been applied to aviation, healthcare, telework, manufacturing, military training, simulation-based learning and interactive product content management. Microsoft has pushed itself into the lead with a commercial mixed reality headset known as the HoloLens. Microsoft has expanded upon the usages of mixed reality along with the associated community of HoloLens application developers through the hardware and software technologies built for the HoloLens. Microsoft also includes Cortana (virtual assistant), a variety of holograms, HoloStudio (3D modeling application), connections to Skype, HoloTour (virtual tourism), gaming, interactive medical usage, architectural and engineering design, space exploration (NASA and JPL), 3D content cloud, and other entertainment and business-related uses.

The use of the HoloLens in military-based application—and more specifically for C2—has only a few offerings, therefore the field has wide potential. It has found use in the Augmented Immersive Team Trainer for the U.S. Marines, and by the Army Research Lab in Maryland for explored simulation of improvised explosive devices (IEDs). Navy SEAL commandos also have been using a HoloLens-enabled interface for submersibles via the Naval Surface Warfare Center's Disruptive Technologies Laboratory in conjunction with John Hopkins University's Applied Physics Laboratory. Outside of the United States military, Ukrainian armed forces are exploring wargaming applications for use in HoloLens-enhanced helmets. The Israeli army and Royal Australian Air Force have also been investigating the HoloLens for use in planning and training. The use of the HoloLens and mixed reality within a C2 environment is still in its infancy, which allows projects such as C2-CST to discover the space and determine its potential within U.S. Navy operational and tactical system interfaces.

2. OBJECTIVES

The C2-CST was defined as an experiment to examine a new advanced user interface for C2 systems that are based on augmented reality technology. The objectives for the C2-CST project were several. First, connect and communicate with C2 systems, display C2 system information in the augmented reality display, and send commands back. Second, investigate new techniques for more natural human interaction with the display system. Third, collaborate between end users and the C2 system to improve situational awareness, decision making, and performance of operational and tactical tools—all prime reasons for using augmented reality. Fourth, due to the shared environment for multiple augmented reality users, examine classification filtering based on user classification level. The C2-CST system is utilized to separate specific information based on user classification which in turn filters the display accordingly. Lastly, perform a human evaluation experiment that provides human feedback on the utility and effectiveness of each of the previous four objectives. An expanded list of objectives for the C2-CST project is found in Appendix A.

2.1 GENERAL DESCRIPTION

The augmented reality display represents a military sand table (terrain model) upon which plans, actions and decisions are made in coordinating tactical and operational maneuvers. The sand table is virtual and displayed in the end user's environment. An augmented reality display allows the creation of the virtual sand table while allowing the end user to maintain a view into the real world so they can move around and interact with the virtual sand table. The paradigm is similar for a real-world physical sand table.

The information for the virtual sand table display is provided via the IMPACT system, which, for purposes of this project, represents a C2 system. An IMPACT-based scenario is utilized, which consists of supervising and tasking autonomous unmanned vehicles. In the scenario, unmanned air, ground, and sea surface vehicles (four of each) are tasked with base protection. A Microsoft HoloLens (with its associated application programming interface (API)) integrates with Unity3D to provide the C2-CST augmented reality display. The Microsoft HoloLens contains the required set of capabilities needed to fulfill the project requirements to meet the objectives. Unity3D builds the 3D terrain or environment with 3D models of unmanned autonomous vehicles, control measures and user interface controls, menus and related elements. The IMPACT system drives the information presented in the virtual sand box and holographic menus, and other elements permit the end users to interface with objects within the virtual environment.

2.2 C2 SYSTEM CONNECTION AND COMMUNICATION

C2-CST application connects the IMPACT system with one-to-many display systems. The Microsoft HoloLens devices serve as the display systems that share the virtual environment. The virtual environment represents the information in the IMPACT system as a virtual sand table. Details regarding how this connection and communications occurs is described in the technical approach. The IMPACT system contains a component called the HUB. The name used is descriptive of its use as a hub to which external components can connect and communicate with the IMPACT system. The JSON or LMCP data format is used in communicating with IMPACT. The C2-CST application was designed to offload the Microsoft HoloLens from C2-based computations as well as much of the graphical computations. This allows a more responsive display device in terms its visualization and

interaction with the virtual C2 environment. A computer placed in between the HoloLens and IMPACT runs a Unity3D application along with the Photon server, which functions as the middle tier and permits the offloading from the HoloLens. It essentially acts as the communication broker between IMPACT and the HoloLens.

2.3 INTERACTION WITH THE C2 SYSTEM

The previous section covered the direct interaction with the C2 system via a middle tier support layer. This section is concerned more directly with the interaction that the end user can have with the C2 system via the Microsoft HoloLens device and associated software. The C2-CST application leverages the HoloLens capabilities of gaze, gesture and voice to interact with the virtual sand table representation of the scenario running in IMPACT. Each of these capabilities is described in sufficient detail in the technical approach section. The main concept is to allow a more natural interaction for the human to take place as the user attempts to interact with elements of the virtual sand table.

Gaze is used to direct a virtual cursor in the holographic scene in much the same way a mouse is used to move a cursor in a standard computer system. Gesture is performed via user hand signals shown within view of the HoloLens visor or camera system. The HoloLens interprets these gestures and associates them with the virtual cursor (placed by the user's gaze) and its associated intersection with a virtual object in the scene. This permits the selection of objects within the holographic environment, which include representations of the terrain, the autonomous unmanned vehicles, control measures, and menu items. Other gestures allow the user to return to the HoloLens control device menus. Voice is currently used to a minimum, but further development in this area could prove useful for interactions with the C2 system.

Interactions built into C2-CST include the selection and information display for each of the unmanned autonomous vehicles and control measures (points of interest, air routes, ground routes, sea routes and terrain locations). Interactions with two-way communications to and from IMPACT allow the user to call a point search based "play" in the IMPACT system. The user can gaze to a location, select the terrain or water with a gesture, and then use the virtual menu to create and send a point search task to IMPACT. In part, this interaction also serves as collaboration with IMPACT, and additional users could also collaborate in such actions. The final major interaction between IMPACT and C2-CST is the filtering of classified information per user. This interaction is not performed by the user, but rather between IMPACT and C2-CST, based on the identity presented by the user or the specific HoloLens device in use.

2.4 COLLABORATION

The Microsoft HoloLens and supporting APIs permit the building of collaborative virtual environments for the C2-CST sand table. The HoloLens Sharing API permits two or more HoloLens devices to share the same virtual space. In the augmented reality paradigm, as applied to C2-CST, the virtual sand table remains in a fixed location within the physical space where the HoloLens devices are used. This feature allows each user to view the same virtual sand table from his own physical world reference point, relative to the virtual sand table's physical world anchor. The gaze vector is established from the orientation of the HoloLens headset. This sets and correlates a shared virtual environment that all participants can now view and collaborate within because each is seeing the same sand table representation. It is noted that all participants do not have to be in the same physical

space but can be in a remote physical location while virtually present within the virtual sand table environment. Voice and audio over the HoloLens device allow for human-to-human communication. HoloLens API also permits certain voice commands that allow interaction with the virtual sand table in addition to gaze and gesture. These capabilities set the stage for a new collaborative environment with regards to C2-based information sets. A human-to-human-to-machine collaboration is now possible, but the potential may prove to be more effective. The experiment designed for C2-CST purposes was to explore this new form of collaboration on C2 information sets.

2.5 FILTERED CLASSIFICATION

An enhancement to the HoloLens Sharing API described in the previous section can also be utilized to filter display information between end users of the virtual sand table. This effectively allows certain information to be displayed to one or more designated HoloLens devices and not to others. This concept can be repeated for each level of classification of data defined to be filtered within the common virtual environment of the sand table.

For the purposes of the C2-CST project, the classification filter was not applied directly to real-world classified data. Instead, a general concept was applied where certain information could be displayed to certain users of a given classification and not to others without that classification. The far-reaching extension of this concept is for real-world classified data to be displayed and filtered to end users based upon their classification level. The C2-CST experimentation plan also includes a simple case to explore this concept and determine if combined situational awareness, decision making and actions can be followed on without spillage or disclosure of classified information to those not permitted to view such information. The onus for complete containment of classified information spillage is not only upon this new advanced user interface, but also with the humans collaborating within the shared sand table environment.

2.6 EXPERIMENTATION

The C2-CST project included the requirement to perform a human evaluation of the virtual sand table interface. Due to human influence on the utility and effectiveness of an interface, human evaluation can provide critical insight to the C2-CST utility. A survey and experimental procedure were created to allow users to participate and provide feedback on the C2-CST prototype user interface application. The current draft of the human evaluation survey is found in Appendix B. The intent was to explore concepts of the new interface in terms of collaboration, interaction, filtering of classified information and general usage of such a system, as compared to the current or nominal ways in which this is currently performed. Since no official Institutional Review Board (IRB) process could be accomplished within the Naval Innovative Science and Engineering (NISE) Microfund project constraints, a simple human evaluation survey was formulated to provide feedback. Due to complexities in development of C2-CST and constraints of time and funding, the actual experiment was not performed. In addition, the C2-CST application was not sufficiently developed to effectively cover all the areas of the survey. Support for continuance of C2-CST development, performing the evaluation, and further examination of utility is currently being sought.

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3. TECHNICAL APPROACH

The C2-CST NISE Microfund project was required to be prototyped and tested in a short development timeframe with a small investment and to show scientific value in the form of a prototype application or some type of experimentation. The C2-CST project required more technical development than initially considered, therefore the goal to provide human evaluation feedback on the utility of the C2-CST application did not occur within the timeframe allotted. This was determined a potential high risk which is inherent in NISE Microfund projects. Nonetheless, the near completed prototype provided a return on investment through demonstration of a working prototype application that met most of the intended goals of the project, with the exception of human evaluation. Future efforts could realize the full potential outlined by the C2-CST project by including human feedback via the planned experiment.

The technical approach of C2-CST covers the architecture, environment, scene creation, communications via ZeroMQ, the Photon Unity Networking server, the Mixed Reality Toolkit for Shared Experiences, the classification filtering of visualized data, and the simplified Play Workbook interface to the C2 IMPACT system. The C2-CST project provides a start into a new and rich area in human user interfaces for C2 systems. The design for the prototype and experiment is extensible and scalable.

3.1 ARCHITECTURE

The architecture for C2-CST is more than just using the framework provided by Microsoft's HoloLens and its supporting toolset along with Unity3D. The underlying reason for extending the architecture beyond the Microsoft HoloLens APIs and the Unity3D tool is the extra support required for connection to a C2 system and supporting the capability of the HoloLens to successfully display the information of that C2 system. The C2-CST architecture was designed to exchange information with the IMPACT system. Most visualization-based systems generally have insufficient computing power to process C2 related information and provide a real-time visualization and human interaction of that C2 information. With this in mind, the architecture was comprised of the following three core components in order to achieve the underlying goals and overcome the obstacles for such a system.

1. The IMPACT system, which was designed to reside on one-to-many computer systems and provide services such as vehicular autonomy, supervisory control, planning algorithms, path determination, resource allocation, unmanned systems sensor control, and a simulated environment to provide test scenarios.
2. The Unity workstation is a separate computer system with the Unity3D toolset and Unity Photon Server installed. This workstation via the Unity interface acts as the communications mediator between the IMPACT system and the HoloLens devices. Because of this communications mediation and added computational capability, this Unity workstation offloads the HoloLens devices and allows them to work best as visualization and interaction tools of the C2 information.
3. The HoloLens devices and their associated APIs and frameworks support the new approach in visualizing and interacting with C2 information and other users embedded within the same holographic environment.

The C2-CST architecture permits the processing of C2 information and the updating of that information to be handled by a more powerful computing system than that provided by the

HoloLens. The HoloLens can therefore focus on visualization and interfacing to the C2 data that gets represented as a holographic advanced interface. This architecture is illustrated below in Figure 1.

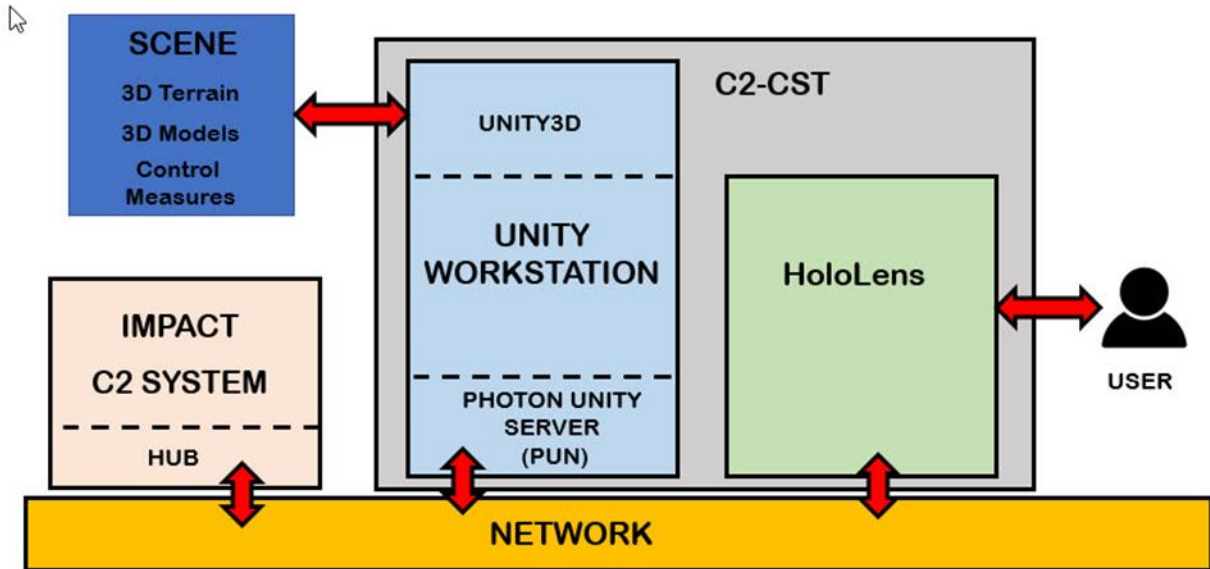


Figure 1. C2-CST Architecture Diagram.

The IMPACT system is a tri-service (AFRL, NIWC Pacific, ARL and NRL) development effort for the Autonomy Research Pilot Initiative (ARPI) sponsored by the Office of Secretary of Defense for Assistant Secretary of Defense for Research and Engineering (ASD/R&E). The concept was to conduct research, development and integration of multiple autonomy-related technologies which would permit supervisory control and management from a single operator for multi-UxV missions. This involves agent reasoning, autonomies, human modeling, Fusion framework, machine learning, cooperative route planning, operator interface design and test and evaluation. The goal is to balance and increase both the human's and autonomous system's ability to be agile in the face of unexpected change and uncertainty, and increase mission effectiveness across a wide range of contexts. A key experiment scenario in IMPACT was designed for base security management that emphasized evolving situations with room for growth towards more realistic challenge scenarios of tasking and supervising heterogeneous air, sea and ground unmanned resources while demonstrating desired agility for both expected and unexpected events.

The C2-CST system communicates bilaterally with the IMPACT system using the ZeroMQ network communications framework that connects to the IMPACT centralized HUB component [3]. The IMPACT HUB component provides the communications framework for all components that comprise the IMPACT system, as well as any components that connect to the IMPACT system as illustrated in the IMPACT architecture diagram in Figure 2.

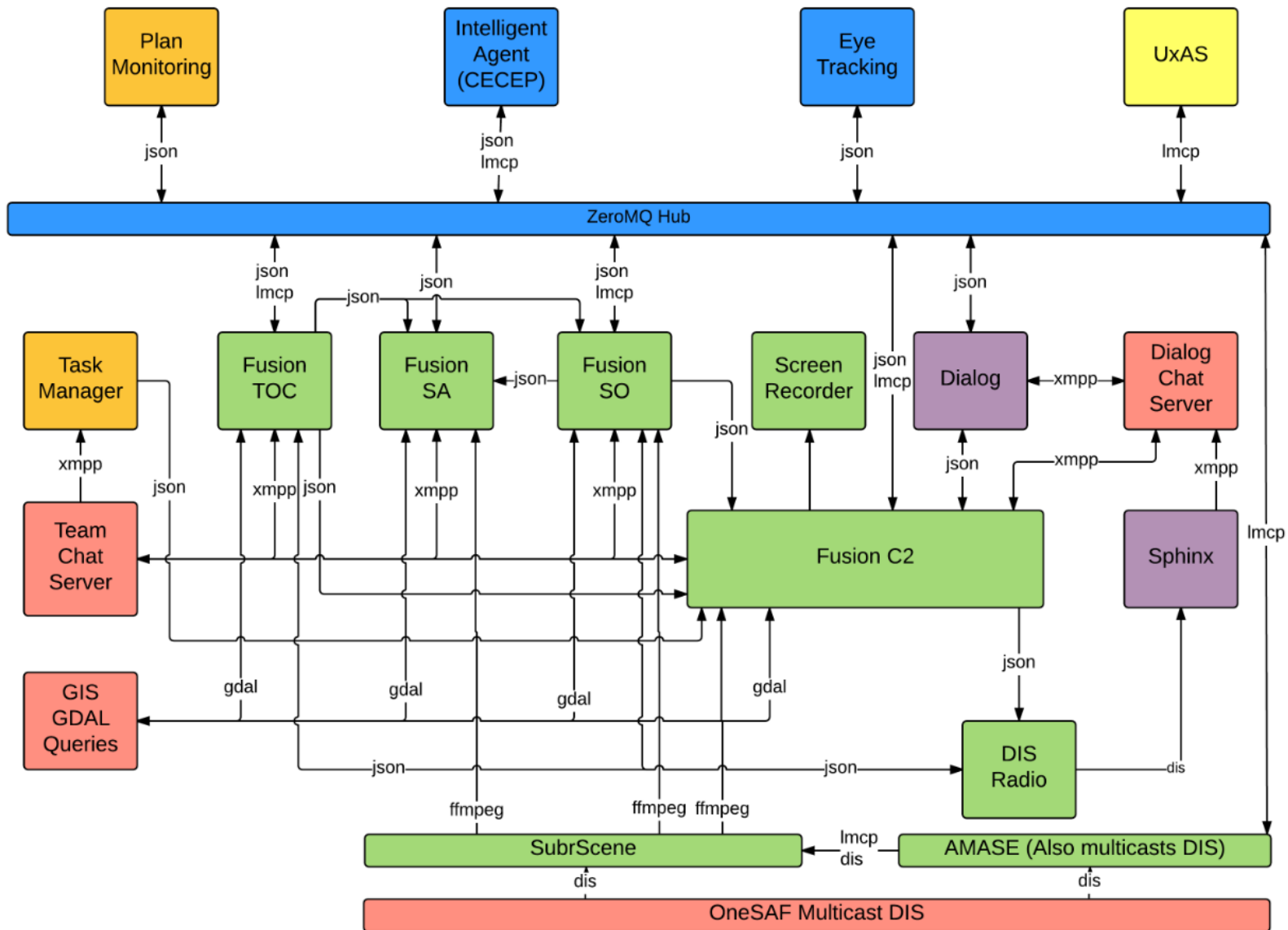


Figure 2. IMPACT Architecture with ZeroMQ based HUB.

With the HUB communications pipeline based on ZeroMQ, the logical choice for interchange of information was to utilize ZeroMQ as the networking communications for the C2-CST application. ZeroMQ is an asynchronous messaging library that can be utilized for concurrent applications as a messaging library based on sockets while providing a message queue. ZeroMQ can also run without a dedicated message broker. This allows for a many-to-many connections amongst the connection endpoints. The use of publish sockets and pull sockets allows the collection of messages from and delivery of messages to the various connected software entities in IMPACT and C2-CST. For IMPACT, the various connections are bridged in the HUB to allow the sending of messages that can be forwarded to all other subscribing connections. Such connections exist in IMPACT for key components such as: AMASE for vehicle simulation, a route planner agent titled Collaborative Control Algorithms (CCA), Cognitively Enhanced Complex Event Processing (CECEP) an intelligent agent for resource allocation and event processing, machine learning integrated components, an autonomics framework for plan monitoring and feedback, a dialog support, a task manager for end user task management, a state server and several Fusion (an AFRL framework) based connections for C2 consisting of a sensor operator console, test operator console, and one-to-many C2 operator consoles. This specific structure allows the C2-CST system to connect to all these systems via the ZeroMQ-based messaging communications system.

The Unity workstation is the second core component to C2-CST architecture. The component provides a middle tier connection between IMPACT and the HoloLens interface. Unity3D has been integrated with HoloLens as a third-party development tool to build mixed reality applications. Integrated features in Unity3D allow applications to be built and ported to the HoloLens and provide key elements of the mixed reality hologram experience. Core building blocks of the HoloLens that are exposed to the Unity API include: camera, coordinate systems, gaze, gesture and motion controllers, voice input, persistence, spatial sound, spatial mapping, shared experiences, locatable camera, focus point, tracking loss and keyboard input. The HoloLens API also permits a Unity application to run on the real HoloLens headset, on a HoloLens emulator and on the Windows Mixed Reality immersive headset simulator.

The C2-CST Unity workstation via ZeroMQ messaging can read autonomy vehicle kinematics and position data for locating the vehicles within the holographic environment of the HoloLens. This allows the placement and movement of the autonomous vehicles as well as the placement and updating of area of interest markers and waypoint information that comes from IMPACT. A real-world location to virtual world creation of the environment is created in Unity3D and viewed in both the Unity workstation and on the HoloLens devices. The messaging through the ZeroMQ interface to the Unity workstation communicates with the IMPACT HUB and allows these holographic elements to be positioned and moved over time in the HoloLens view. The real-world to virtual world representation in the hologram-based visualization remains constant and fixed in physical space in the view of those wearing the HoloLens devices.

The Unity workstation uses Photon Unity Networking as a server which is a third-party package for Unity3D. It was developed by Exit Games [4] for multiplayer games. The Photon Unity Server has a load balancing API which matches “players” (users) to shared sessions and transfers messages synchronously in real time between these connected “players.” The “players” in the case of C2-CST can be considered to be each of the individuals using a HoloLens device that shares the same holographic environment. The Unity workstation adds the support for the shared environment, which is essential given the intended collaborative use of the C2-CST system.

The Unity workstation is also responsible for controlling each of the HoloLens views. For certain elements of the holographic environment, a classification level can be provided for certain information sets. This concept allows all HoloLens participants to view the same shared

environment, yet view and interface to data classified for their view only, based on their specific classification level. This capability filters out specific data to be only viewed or heard by intended users designated with that classification level. This permits a shared environment and collaboration on the supervisory control of autonomous vehicles within a multi-level classified environment. Each HoloLens device filters the view for the intended user. It is up to the user to collaborate appropriately with others with different classification levels in order to avoid information spillage while still allowing a successful and effective collaborative end result. The C2-CST project did not address this issue.

The final core component of the C2-CST system is the HoloLens device hardware and its related software elements. In the C2-CST architecture, each HoloLens device connects to the Unity workstation through the Photon Server. Each HoloLens displays the IMPACT system as a set of holographic elements in a representative sand table of a C2 mission display. All updates to C2 information are processed on the IMPACT system and sent via messaging to the Unity workstation. This information is then transcribed by the Unity workstations to the essential data needed to provide the proper visualization and interaction within the holographic scene that represents the C2 environment of IMPACT. This allows the HoloLens devices to run efficiently without the burden of the computational load. The method used to create a shared collaborative environment with filtered classification of C2 data is as follows: the first HoloLens joins the connection in the shared holographic environment, then downloads an “anchor” to which the other HoloLens devices can use to join that session, and allows those devices to configure to the same shared environment. This is outlined in the Sharing API.

3.2 ENVIRONMENT – SCENE CREATION

The HoloLens holographic environment utilizes the Unity3D development tool to support the HoloLens interface development as well as build the environment for the holographic scene. For IMPACT, the designated default scenario is an air base force protection mission over an assumed Air Force base in the Pensacola, Florida region. The map within IMPACT was created for the HoloLens holographic scene in Unity3D. The air base in the scenario is fictitious in its representation for both IMPACT and C2-CST, but provides a suitable and realistic representation for the simulated environment. Within Unity3D, a third-party terrain tool builder called World Composer provided the means to generate to scale the 3D realistic terrain for the C2-CST sand table display. For definition purposes, the military use of a sand table usually refers to a terrain model used in support of military planning and wargaming. This definition essentially applies to the C2-CST system, but more specifically to C2 planning and execution. This sand table is illustrated below in Figure 3.

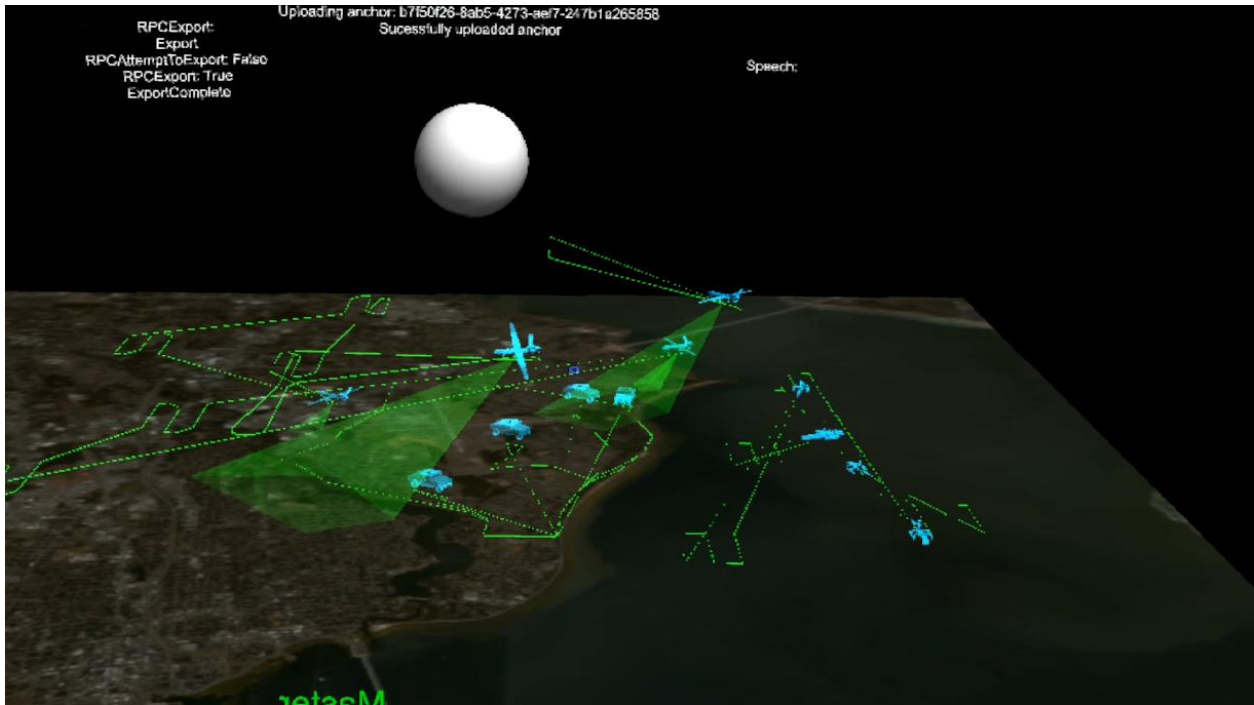


Figure 3. C2-CST Sand Table Display.

The IMPACT scenario utilizes twelve unmanned autonomous vehicles, four for air, four for sea surface and four for land vehicles, each carrying differing sensors and payloads. The goal was to provide human supervisor control over multiple unmanned autonomous systems in a heterogeneous mix of assets. This mix creates a more complicated and realistic scenario for base force protection from the air, ground and sea with a variety of sensors and capabilities. Autonomy used in both the vehicles and by the IMPACT system provided the support a human would require to gain proper situational awareness and to create and act upon tactical and operational decisions. The associated control measures, paths and other graphics associated with this mix of capabilities were also created for the HoloLens holographic environment. All control measures and associated graphics for each of the autonomous vehicles, including updates, were passed along and formatted for the HoloLens shared holographic environment.

The Unity workstation also provided a view into the holographic environment seen by the HoloLens devices within the Unity3D application. This was an added utility in the development, test and evaluation of the C2-CST system.

The process by which the HoloLens presented its holographic environment was an excellent match for the C2-CST. The view of the terrain remained fixed in spatial location relative to the real-world surroundings of the HoloLens end users. This allowed the sand table to stay in place while the end users of the HoloLens devices moved the hologram to gain a new or different view into the scene or environment. This made the holographic environment a truly 3D environment, not just in the view but in moving the user's physical view around the sand table view. This allowed the users to literally walk around to change view and perspective on the scene or environment.

3.3 C2-CST COMMUNICATIONS

As previously outlined in the architecture section, the communication flow between IMPACT and the C2-CST system had to also pass through the Unity workstation, which acted as a mediator and supported the computational offload for the HoloLens devices. The network connections and communications diagram for C2-CST is shown in Figure 4.

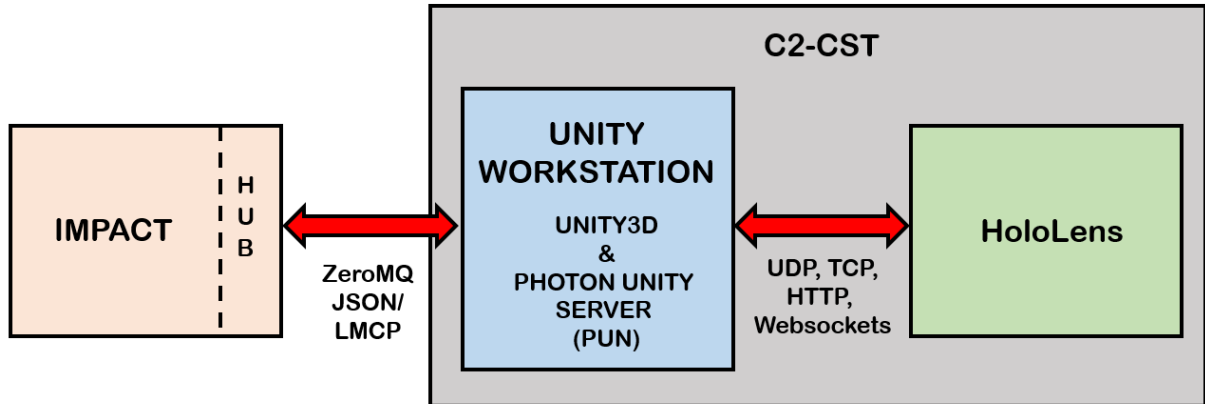


Figure 4. Network Connections and Communications.

One of the key elements to the communications of C2-CST is the ZeroMQ asynchronous messaging library, which is an open-sourced network communications framework for distributed messaging [3]. IMPACT's centralized HUB component distributes all its messages to each component connected to the HUB. The two messaging patterns used throughout the entirety of IMPACT, and by extension, to C2-CST are:

1. Pub-Sub: The first messaging pattern is the Publish-Subscription model, which allows the HUB to publish every message it receives to a port. All services and components subscribe to the HUB's IP and port to receive messages and filter the desired messages to read based on the header information.
2. Push-Pull: The second messaging pattern is the Push-Pull model, which allows all the services to push messages to the HUB's IP and port to be distributed to each end user. The HUB receives these messages by pulling from its port and publishes the message out.

ZeroMQ has been developed for multiple programming languages and is compatible for carrying messages across network protocols such as inproc, interprocess communication (IPC), transmission control protocol (TCP), transparent interprocess communication (TIPC), and multicast. C2-CST uses the NetMQ variation of ZeroMQ. This was developed for the communication service in the C# programming language within the Unity API.

The other part of the C2-CST messaging is based on a multiplayer networking game capability called Photon Unity Network (PUN). This is a free third-party Unity package add-on. PUN acts as a server on the Unity workstation for the connection of the HoloLens devices. The Photon Unity server exists on the Unity workstation and attaches itself to the workstation's IP address. Each HoloLens must be configured in Unity to connect to the Photon Unity server before deploying the C2-CST

application. This can be problematic if the Unity workstation constantly changes IP addresses, but is otherwise a simple and convenient method.

3.4 SHARED EXPERIENCES VIA MIXED REALITY TOOLKIT

The Mixed Reality Toolkit is an open-source collection of scripts and components intended to accelerate development of applications targeting the Microsoft HoloLens and Windows Mixed Reality headsets [5]. The Mixed Reality Toolkit was developed by the Microsoft Corporation and is necessary for C2-CST application to have both collaboration and sharing capabilities. The version of the Mixed Reality Toolkit used for C2-CST was the version built for Unity. The stacked layer for Mixed Reality Toolkit for Unity rests on top of the Mixed Reality Toolkit which rests upon the Windows 10 Universal Windows Platform (UWP) or the Mixed Reality APIs.

The Mixed Reality for Unity has several useful APIs for the HoloLens. These APIs include input, sharing, spatial mapping, spatial sound, user experience (UX) controls, utilities, spatial understanding, build capabilities, and bound rendering. This set of APIs supports many useful features for the development of HoloLens applications. Of particular interest is the Sharing API, which allows applications to span multiple HoloLens devices, and enable holographic collaboration. This enables multiple HoloLens users (via their HoloLens headsets) to allow the applications running on each device to communicate in real-time while still being in sync. This communication can occur within the same location or with users in remote locations.

When the first HoloLens joins the Unity workstation scenario via the Photon Unity Server, it connects to a session and an “anchor.” The anchor is a spatial reference point that allows each HoloLens device to correlate the augmented reality view with regards to the anchor point so they all share the same location for all the same augmented reality graphics in physical and virtual space. The anchor contains the essential spatial coordinates to align the holograms in the environment with these coordinates, which can then be shared by other users so that all users’ views align spatially with the same hologram. Thus, as each subsequent HoloLens joins the session, the first user’s anchor is downloaded, and synchronizes to the holographic environment with that anchor. This aligns the holographic environment amongst all the HoloLenses that use this anchor, and allows them to share the same experience by viewing the C2-CST at their given positions.



Figure 5. Illustration of Sharing Experience in C2-CST. (Image credit to Royal Australian Air Force, Saab Australia and Defence Science Technology Group).

The shared experience described is what makes the multi-user collaboration possible. Using normal desktop computing systems, as in the case for IMPACT, the users either have to gather around a single computing station with the normal monitor, keyboard and mouse setup, or each have their own IMPACT station of the same type. This is not optimal for human-to-human collaboration. The new visualization, interaction and collaboration approach taken with the HoloLens device for C2-CST not only provides a better shared experience environment, but one that is more natural to the end user. This was precisely developed to meet the intended goal of the C2-CST project.

3.5 CLASSIFICATION FILTERING OF A SHARED VISUALIZATION

Shared visualization classification filtering is an extension to shared experiences based on the Mixed Reality Toolkit. In the basic shared experience, all HoloLens users in that session share the same scene or scenario; the only difference is user viewpoint, which is based on physical location and view vector (as determined by the HoloLens position and orientation). The same set of information is available to each user in that session.

Classification filtering changes from the global shared set of information to various subsets of non-shared information within the same visualization environment. This allows access to a subset of information to specified users by classification level. The subset of information is only viewable or accessible to the specified user(s) and not the remaining user(s) within the shared environment. The goal for C2-CST was to determine if such an environment could be useful and still protect against the spillage of classified information from one level to the next.

The C2-CST system handled the classification levels by filtering data between each HoloLens headset via a distinct configuration set on the Unity workstation. When the scenario runs and a HoloLens connects, that particular HoloLens receives a specific filtering configuration, which is displayed in the filtering toolbar. Since real classified material was not utilized in the development and experimentation of C2-CST, the filtering configuration was made accessible and allowed users to select a different filtering level for the HoloLens they were using. In a real-world system, such configuration would be restricted and purposely assigned based on the end user's classification. For this development effort, the Unity workstation user can select a different filtering level for each specific HoloLens that joins the session. In this design, there are five filters:

1. Complete access
2. Ground, air, and sea vehicle information access
3. Ground and air vehicle information access
4. Ground vehicle access
5. No access

The human evaluation experiment also included a means to determine the value and utility of the classification filtering via the survey. The set of human evaluation experiment survey questions broach just the beginning of this capability. A simplistic approach was taken to classification filtering, leaving ample room for exploration.

3.6 A SIMPLIFIED IMPACT PLAY WORKBOOK

The complete IMPACT system allows for a plethora of “plays” to be called for various tasks such as Point/Area/Line inspect, Shadow Hostile, and Overwatch. A play workbook was created in IMPACT; it contains all the developed plays that a set of autonomous vehicles can perform for an intended action that correlates with the mission plan or an adaptation to that mission plan. This is a conditional action based on the current state of events and actions taking place along with the intended mission and operational/tactical goals. From the play workbook, a type of play is selected and is generally followed by a target location and an intended target or goal. IMPACT application-level autonomy supports the determination of solution sets for accomplishing the specified play. This generally includes allocation of resources, along with path determination for the autonomous vehicles, and a projected course of action value. These courses of action are also ranked by the application-level autonomy for human supervisory situational awareness and support for decision making. IMPACT's Play Calling interface is shown in Figure 6.

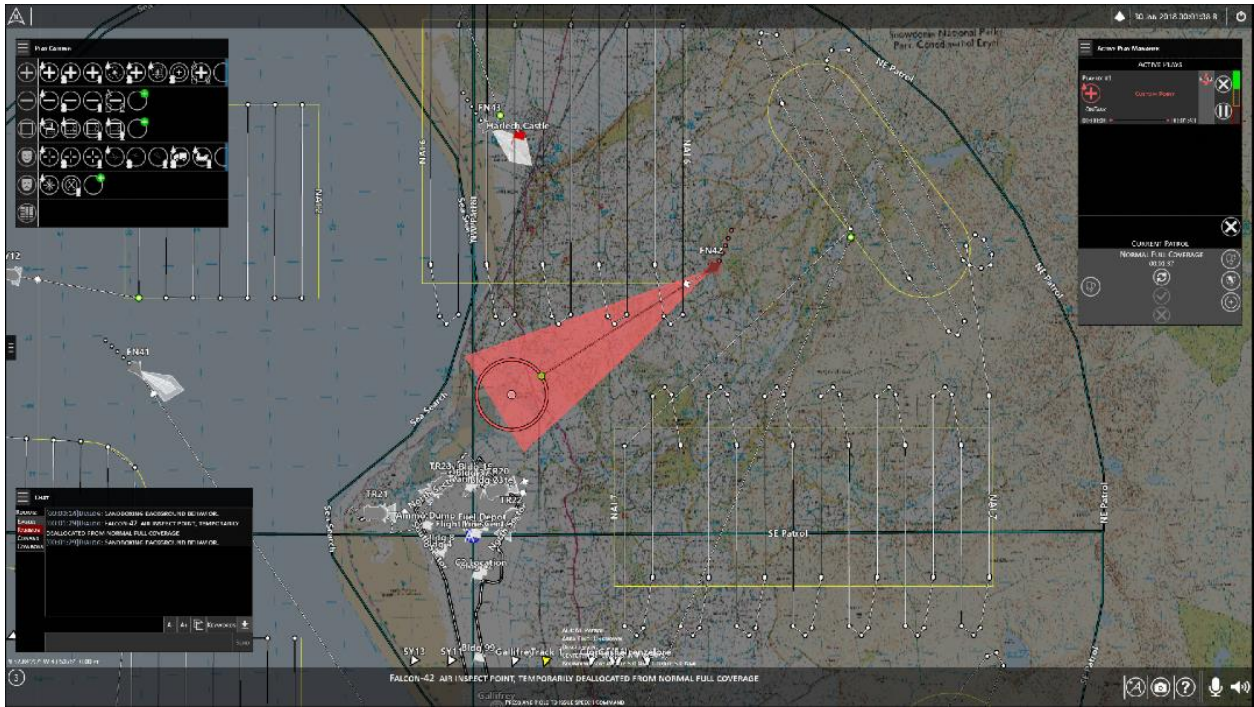


Figure 6. IMPACT Interface with Play Calling.

The play workbook is a key part of the IMPACT system, allowing the ability of the human to provide human supervisory control of multiple UxVs through calling plays. In the C2-CST version of play-calling, HoloLens users have a simplified play workbook. Instead of selecting the type of play and then the location, the HoloLens user's gaze is set to the intended play task location, then an air tap gesture is used to open the simplified workbook and select the desired play. The initial design was primarily intended for point inspect plays consistent with this simplified interaction for play calling. A more robust play in C2-CST was left to future efforts. Utilization of voice commands from the HoloLens for these play calls and a more complete menu of plays and other actions are possible. The simplified play workbook for C2-CST included Point Inspect plays for air, water surface and ground autonomous vehicles. C2-CST simple play calling interface is illustrated by marker and menu holograms shown in Figure 7 with a blue outline and line to location of the play call.

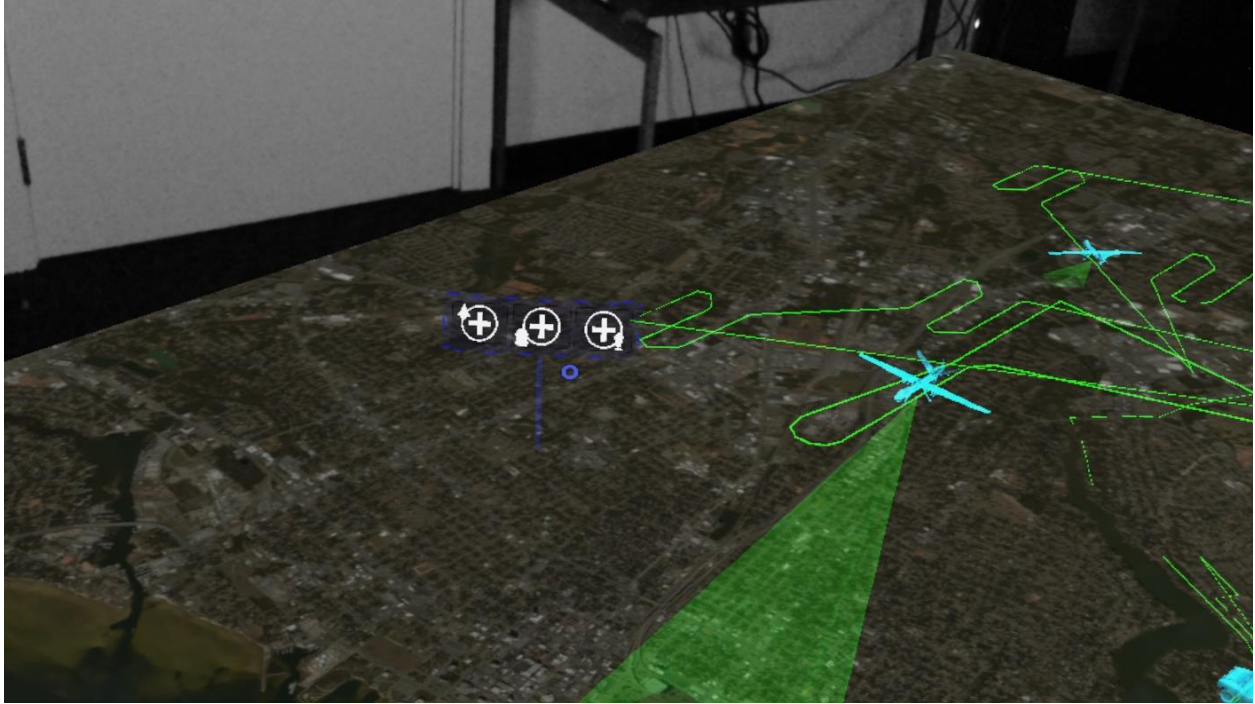


Figure 7. C2-CST Simplified Play Calling Interface.

The simplified play calling capability within the C2-CST interface is a prime example of how the IMPACT interface could be extended as a mixed reality interface. As the scenario and environment are shared and users collaborate on intended courses of action, the C2-CST holographic user interface also allows users to execute decisions via the play calling interface. The C2 interface changes from a single user single interface to a multi-user shared interface, where collaborative decisions and actions can take place. The intended human evaluation of C2-CST was also designed to discover if the execution of play calling from a HoloLens has additional or perhaps different value to the execution of a C2 mission.

4. C2-CST EVALUATION

A C2-CST project goal sought to determine the benefit of advanced user interfaces over conventional user interfaces in augmented/mixed reality. The goal was to measure the effectiveness of the advanced user interfaces as compared to conventional user interfaces to determine the effectiveness of the advanced user interface features, and more specifically, what user role or end use fits best for use with this interface. An evaluation of C2-CST concepts could provide new insights into operational and tactical workflows. Human evaluation of the effectiveness and utility of this advanced display based on augmented reality can provide evidence in favor of or in contrary to the expected utility. Human usage, or lack of, usually defines the fate of an application. Usability, ease of use, and a natural or intuitive interface along with minimal training often defines its success.

4.1 HUMAN EVALUATION OF C2-CST

A key to the effectiveness of the advanced user interfaces is end user feedback. The evaluation proposed the voluntary solicitation of in-house (NIWC Pacific) personnel to provide the human evaluation of C2-CST. The Microfund project effort and schedule would not allow an official human evaluation test covered by an IRB to take place; a simple human evaluation was used instead to collect feedback on the C2-CST user interface (as it applies to C2 systems).

A simple experiment was developed to evaluate conventional and advanced user interfaces, specifically the differences between the current interface for IMPACT and the same scenario through the Microsoft HoloLens. This experiment sought human evaluation of the C2-CST application through a post-use survey. The human evaluation questionnaire was developed for post-experiment data gathering, which included a brief training session for both the IMPACT and C2-CST systems. Questions pertaining to human motor processing, perception and cognition of the information presented in the user interface were to be collected for both the conventional and advanced user interfaces. Most users were assumed to be familiar with conventional user interfaces found in the IMPACT system, but also less familiar with the augmented/mixed reality user interfaces such as used in the C2-CST system. The questionnaire was formulated based on the assumption that the familiarity with one user interface versus the other should not impact the evaluation, rather the utility, natural ability, and the effective use of the interfaces should stand out as a metric. The evaluation supports answering the questions of when, how, where, why, and by whom such an interface becomes beneficial. Do niche roles exist for such an interface (such as advanced decision makers or other key personnel involved in the command and execution of missions)? Or would it be more suited for a general C2 audience?

4.2 KEY ATTRIBUTES FOR EVALUATION

Key attributes for user interface comparison and effectiveness are related to human motor processing, perception and cognition as presented by the interface. The experiment's intent was to extract these differences between the two interfaces and the advantages and disadvantages associated with these specific concepts. The test experiment was designed to cover these and other specific measures of effectiveness provided by the C2-CST interface versus interfaces used by such systems as IMPACT.

Human motor processing for the HoloLens is generally based on gaze and gesture. The HoloLens device is placed on the head of the user. The transparent display allows the user to visualize the real world with overlaid graphics. A cursor also appears in the HoloLens display. When positioned on the user's head, the Microsoft HoloLens headset provides the frames of reference for the gaze cursor positioning. As the user moves their head, and thus the HoloLens headset, the gaze cursor moves and aligns with the virtual overlaid graphics based upon the headset's camera position vector. For the most part, and for this discussion, the graphics do not move with respect to the real world. As the user moves himself and the position of the HoloLens, the associated gaze vector changes the location of the gaze cursor overlaid on the virtual graphics. This establishes the user's current focus spot, which can be used as input to specific items within the display. This is how the gaze cursor works in the holographic scene.

In combination with the gaze, the user can cause action using defined hand gestures, depending on gaze location and intersection with overlaid graphics or the state of the application. This can apply to 3D scene elements or 2D-based menus or controls. These elements provide the key attributes of the HoloLens for motor processing. Additionally, the HoloLens provides speech input commands and auditory feedback as alternate forms of input. The HoloLens attributes of speech commands and auditory feedback were not included in consideration of the human motor processing capabilities.

Human perception was partially explained in the previous paragraph. The HoloLens provides additional modalities of what the user perceives via sight and sound. The sound modality is similar to conventional interfaces in terms of the HoloLens having a microphone and speakers just as the conventional IMPACT system has a microphone and speakers. The HoloLens, however, supports 3D audio for spatial queues. This was not part of this experiment and nor is this supported by the IMPACT system. Visually, as previously explained, the concept is quite different between the two systems. For the HoloLens, the overlaid graphics appear over the real-world environment. This has advantages and disadvantages, which are addressed in the experiment questionnaire regarding effectiveness in display presentation. Notably, display presentation clarity and distraction can differ due to resolution and real-world imagery in the background.

Human cognition with the HoloLens interface will determine if the advanced user interface enhanced or degraded knowledge acquisition and understanding from the IMPACT scene. The IMPACT scenario can test the end user's cognition on key elements. In the scenario, one could determine if there is any difference in the user's understanding and situational awareness of the scene, including the actions taken by that user. The study was to include the examination of end user roles that would be most applicable for a collaborative mixed reality interface. Would this role be one of an IMPACT station operator, key decision maker, or commanding officer? The questionnaire touches on the end user's role to determine if one role is better suited to the intended end user.

4.3 EVALUATION FOR MULTI-USER COLLABORATION AND CLASSIFICATION FILTERING

Comparing the human-based interfaces between IMPACT (conventional interface), and C2-CST (mixed-reality interface) has some degree of merit for comparing their effectiveness. This effectiveness tends to break down when multi-user collaboration and collaboration under classification filtering are embedded within the user interface and played-out in the scenario. The proposed human evaluation experiment for C2-CST does not work when comparing IMPACT and HoloLens interfaces with respect to the areas of collaboration and classification filtering. The same motor processing, perception and cognition will be the key elements to examine for collaboration and

classification filtering. The human evaluation experiment was designed to examine the advantages and disadvantages of having a shared collaborative interface that can also be subdivided by classification. Typical experimental concepts to be covered by the evaluation include the following:

- Does collaboration improve cognition and perception (based on similar studies on teaming versus individual performance benefits)?
- Are there inherent problems of collaborators “overwriting” each other’s work?
- Will one collaborator dominate the others thus eliminating the value of the collaboration?

The experiment design attempts to avoid the last two situations. The focus is to evaluate the unique benefit of an immersed collaborative environment of the HoloLens. Such experiment designs will attempt to have two participants collaborate: first, on situation awareness and scenario understanding; and second, to determine an action, and then work together to complete the action. The IMPACT system “Test Operator Console” supports monitoring and modification of events within the scenario, which can be useful for the experiment.

Filtered classification of the display—or having two collaborative test subjects see a common scenario with slightly differing data—provides the design for the last and most unique portion of the experiment. This collaborative experiment will be repeated; however, the data information will differ for certain elements in each of the two views. One end user cannot see the added holographic information that is specific to the classification of the other collaborative end user. The assumption is that the data differs under assigned classification. The collaborative experience will be observed and feedback obtained from both participants. Users will be asked to share how they collaborated (with slightly differing sets of information) while withholding their information and still adding value to their collaborators. The experiment has the participants strive to withhold their filtered data while working together to take the appropriate actions for the given conditions. This test will be simplified by placing in the scene colored flags that could represent known enemy locations, known sensor locations or other operational and tactical based information. This collaborative scenario will not be classified, but will have the appearance of having classified data in a shared and collaborative environment. The experiment will not attempt to answer the many questions associated with this filtered classification concept, rather initialize the investigation for collaboration in multi-level classified environment. User feedback via questionnaires will provide the bulk of the results to be analyzed for the effectiveness of the C2-CST user interface.

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5. FUTURE WORK

The C2-CST project was short in duration but has just begun to examine the usefulness of this interface. The objective of the effort was to provide evidence of a given technology or science which has potential. The development to date has proven successful in being able to demonstrate the technology. Currently the C2-CST application requires additional work to perform the human evaluation experiment. If the capability and experiment as proposed for this Microfund project effort were to be completed and successful, it would only serve as a starting point for future work.

5.1 DEVELOPMENT AND EVALUATION STILL REQUIRED

The C2-CST project was implemented and then demonstrated its potential to work as a new advanced interface in a C2 environment. The development (slowed by complexity and limited development time) was still of limited use for the designed C2-CST experiment, but clearly demonstrated the technical ability to allow such an experiment. The following sections describe some C2-CST project components that could use further investigation.

5.1.1 Complete Set of Play Workbook

A subset and simplified version of the IMPACT play workbook was used in the development of C2-CST. This consisted of a simple Point Inspection play call for air, sea surface, and ground autonomous vehicles. Although not necessary for a preliminary human evaluation, expanding to include all plays in the workbook would be useful as a more complete experimental evaluation. An evaluation of the new interface would provide keen insight as the complexity and increased interaction is required for certain plays. Classified filtering during play calling as well as collaboration for these more complex plays would provide more conclusive results regarding the ability to use larger and more complex interfaces for a larger set of functions.

5.1.2 Voice-based Interaction

The IMPACT system allows automated task generation, play calling, and some operator-to-operator communications over the chat box interface. A voice-based interface was not included into the C2-CST project goals, nonetheless, the HoloLens also has a speech recognition and speech command based API for this user interface action. The middle tier of C2-CST could process and translate HoloLens voice input to an acceptable format to go across the IMPACT HUB and be processed in IMPACT. The reverse of this voice communication is also possible. Voice could play a significant role in user interface improvement to advanced user interfaces for C2 systems and should be considered in future efforts.

5.1.3 Comprehensive Human Subject Matter Testing

A key element in evaluating HoloLens (or similar mixed reality interface) usefulness is the enhancement to the operator and support of tasks like situational awareness, decision support, and human-to-human-to-machine collaboration. For any new or revised operational or tactical

application, subject matter experts and end user feedback is essential to understanding the level of utility and improvement in existing or proposed new systems. The human evaluation feedback for new advanced user interfaces has been an overarching purpose of the C2-CST project. Additional development, refinement of the evaluation survey, and applying for an IRB-approved human subject matter experiment would provide the opportunity for a more comprehensive and extensive evaluation of experimental metrics for determining the C2-CST advanced display system's value.

5.1.4 Remote Collaboration

Remote collaboration is built in as part of the HoloLens system. This proves beneficial in C2 systems in cases where collaboration regarding C2 information for mission planning or execution may come from non-present locations such as a ship at sea or a land-based command center. HoloLens provides the means to allow this remote collaboration via a network connection and joining to the same session for the holographic environment. Within that environment, the remote participants appear as virtual avatars. Their location, view vector, and an identified avatar representation can be shown within the shared holographic environment. Audio can be transmitted at the same time for person-to-person communications. These HoloLens capabilities are ideal for C2-related remote collaborations. Examination of this particular concept was out of the scope for the C2-CST project. The modification to allow remote collaboration as part of the human evaluation of C2-CST would not be a difficult additional task, but would require sufficient network bandwidth between remote locations in order to avoid lag or interrupted communications and data flow. Low bandwidth conditions can be detrimental to augmented reality interfaces from the human perspective because of the disjoined visual and audio impairment due to network lag.

5.1.5 Classified Data Filtering

One of C2-CST's unique features that requires additional research and feedback from the information assurance community is the classification filtering between users that share the same holographic environment. The requirement to prevent classified information from "spilling" from one level to another of a lower classification is of prime importance. Being able to collaborate within the same environment without spillage provides some key benefits where collaboration must occur across multiple domains, organizations and nationalities. Adapted augmented reality interfaces, such as C2-CST, permit such a situation to be possible while engaging with other humans in the same environments. Many questions remain unanswered and need further exploration and examination.

5.2 NEAR TERM POTENTIAL

C2-CST in its current state is merely the start of applications in C2 systems using a new interface tool for C2 mission planning, execution and after-action review. Further research and refinement is required to arrive at the point where an effective evaluation can take place via the experiment that was initially outlined in the project goals. Common to many research efforts, this problem was more difficult to formulate and implement into a testable form required in order for the experiment to take place. Going forward, there needs to be a determination on the potential return on investment based on basic research efforts that could be developed and demonstrated based on the C2-CST design. C2-CST could serve as an excellent application to continue researching the value of a mixed reality

interface for a collaborative environment. C2-CST is positioned as a means to kick start further research and answer the basic research questions. Potential investment to continue this effort would most likely come from sponsorship from internal NISE S&T, the Office of Naval Research (ONR), the Defense Advanced Research Projects Agency (DARPA), or as part of an extension to continuing efforts with the IMPACT project.

5.3 TRANSITION PATHWAYS

Further research based on the concepts of C2-CST with valid return on investment would provide the foundation for C2-CST related technologies to be adapted to many current and future C2 systems. The door is open to multiple transition paths, but it is currently too premature to determine which programs would benefit from this new advanced interface. Near term pathways need to provide metrics that would provide the most benefit to C2 system end users and direction to be taken with mixed reality interfaces for C2 systems. Obtaining these metrics would require continued research, development and experimentation. An immediate pathway for transition would require an active project to further the development and run the experiments as originally planned for the Microfund effort, and then proceed forward with future research. Potential sponsorship paths are through an internal NISE S&T In-house Innovation Program (IIP) effort, ONR, DARPA, or perhaps within the transition paths that the IMPACT project is taking.

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6. CONCLUSIONS

The C2-CST project provided an opportunity to examine a new user interface for C2 systems. C2-CST leveraged the Microsoft HoloLens API and associated capabilities to provide a unique user interface based on current state of the art COTS mixed reality technology. The IMPACT application based on human supervisory control of multiple unmanned autonomous systems and collaboration with in-application autonomous agents was utilized as the baseline C2 system for the evaluation. Comparison of the HoloLens mixed reality interface to that of the conventional monitor, keyboard, mouse and microphone interface of IMPACT provided the fundamental components of the study for human motor processing, perception and cognition. The HoloLens device with its software offered a new paradigm in user interface of mixed reality using gaze, gesture and voice with a unique holographic environment overlaid on the user's view of the real-world surroundings.

A two-way communication connection was developed between the IMPACT system and the C2-CST system, which allowed the passing of information necessary to re-create the IMPACT scene and scenario and place it as a holographic environment inside the view of each HoloLens device connected. Specialized code was developed and placed on a "Unity workstation," which acted as a middle tier processing machine between IMPACT and the HoloLens. This allowed the HoloLens devices to perform the processing required for the visualization of the IMPACT scene and the users' interaction within that holographic environment and off-load other processing onto the middle tier. The Unity workstation consisted of the Unity3D and Unity Photon Server applications and specialized code to communicate with the IMPACT system and HoloLens devices.

Beyond the usual mixed reality interface, the C2-CST's unique features were the shared collaborative holographic environment, as well as a filtered classification capability for information displayed in that collaborative environment.

C2-CST leveraged several capabilities to permit an immersed collaborative environment. These capabilities are also possible for remote users. It should be noted that there is no other mixed reality system known to exist or has been modified to attempt a filtered classification of information within the same shared environment as demonstrated in C2-CST. This feature alone proposes many new approaches in multi-classified environments, and just as many questions regarding the control on the spillage across classification boundaries. Both of these capabilities were developed within C2-CST, however, due to project constraints, true human evaluation studies of these unique features were unable to be performed. Moving forward, studies are poised to provide potentially valuable research in this area.

The development alone of the C2-CST system proved several important concepts. For instance, that a new user interface based on current state of the art mixed reality technology would bring potentially useful application within the realm of C2 system interfaces. Completion of the C2-CST human evaluation study, as well as improvements and extensions to the C2-CST application, will provide the initial step in demonstrating the utility of augmented reality based user interfaces in a C2 environment.

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APPENDIX A

C2-CST PROJECT GOALS AND OBJECTIVES

1. Display a representative virtual sand table of the IMPACT system as seen from the Microsoft HoloLens which is based on the default IMPACT project scenario. This would include at a minimum an equivalent 3D terrain, and 3D models of unmanned vehicles (4 UAVs, 4 UGVs, and 4 USVs). Optional items would be 3D representation of control measures seen within the scenario and the sensor based sweep areas of the unmanned system sensors and other amplifying control measures within the scenario.
2. Stream and display real-time network-based feeds from the IMPACT system of the unmanned vehicle movements which are to be reflected within the HoloLens view. Provide updates to control measures where possible for changes in control measures due to updates in the scenario or entry of new control measures due to user actions.
3. Allow HoloLens-based user input and selection to be able to query existing entities within HoloLens view with the view responding with a correlated data tag to identify selected item thus giving the end user information that corresponds to the selected item. At a minimum, this would include each of the 12 unmanned vehicles in the scenario with options for control measures, terrain or other items of interest within the HoloLens view.
4. Optional (not currently known if speech can be correctly converted): Allow HoloLens speech based controls be used in combination with the HoloLens gaze and selection tools. This would allow a set of speech commands to be input by the user that applies to current gaze and select cursor location. The commands are interpreted, converted and sent out over the real-time network feed from IMPACT. The speech is interpreted to equate to existing IMPACT based speech input. HoloLens view should react according to entered speech command. A typical command may be the calling of a “play” (defined action such as perform a point inspection at a given point) upon an unmanned vehicle while the selection gaze icon rests upon the unmanned vehicle and the user supplies the speech command. Other based actions are possible.
5. Allow HoloLens-based user input and selection be able to call a “play” upon an existing unmanned vehicle. This will most likely require a HoloLens based user interface (UI) for multiple input selections required to successfully call a play on an unmanned vehicle.
6. Purchase a second HoloLens device in order to demonstrate collaborative capabilities between two HoloLens (already have one HoloLens). Leverage “sharing” HoloLens API to provide a shared IMPACT scene or environment. Both users will be able to view the same IMPACT scene and share input/commands within the same scene. Both HoloLens views will update and be synchronized for each of the views as updates are processed. Optional: Allow for one of the views to be removed (other location) yet still collaborate on the same view. An avatar representing remote user shall be represented to indicate location to another HoloLens user.
7. Enhance the “shared” API to permit a collaborative environment which filters the view based on end users’ classification. This represents a shared environment for collaboration, however additional data is only viewable based on the classification of the user and the HoloLens device used. The distinction will be represented as specific color-coded objects (one view green, one view red) and/or UI based displays of information, which differ in each view based upon the classification given. The specific data from one classification cannot be viewed or shared with the other HoloLens view even though they continue to share the overall IMPACT generated space. The data appearing in one view but not the other will

indicate the filtering of classified data within a shared environment. Please note that the systems will always remain as an UNCLASSIFIED display and the representation of classification filters is only symbolic to demonstrate the capability.

8. Show case product demonstration to certain personnel for evaluation of potential to be included in briefs within the Command Center of the Future (CCoF) or the IMPACT lab and demonstration suite in building A38. This measure of utility is based on subjective human judgment for potential use for visitor demonstrations and potential marketing for further development of the advance user interface concepts.

APPENDIX B C2-CST HUMAN EVALUATION QUESTIONNAIRE

Thank you for your participation in the evaluation of the C2-CST. This questionnaire is voluntary and will not identify you as a participant. The questions relate to your experiences using the HoloLens device and how it compares to standard user interfaces of monitor, keyboard and mouse, as used in the IMPACT system. Please fill out the following questionnaire to the best of your ability. There are no wrong answers.

Questions 1-10 relate to general question about use of the HoloLens system

- 1) This system seems like it would be used frequently.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

- 2) The system seems unnecessarily complex.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

- 3) The system seemed easy to use

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

4) The support of a technical person to be able to use this system seems necessary.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

5) The system seemed to be well integrated.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

6) The system did not seem like it would be useful for the intended purpose shown.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

7) Most users should be able to learn to use this system very quickly.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

8) The system was cumbersome to use.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

9) A sense of confidence in using this system was felt.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

10) There are a lot of things to learn before being able to effectively use the system.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Questions 11 – 20 relate to specifics about the HoloLens interface as they apply to the usage of the HoloLens device in the environment provided. The following are some reminders of the terminology used in these questions.

Gaze: While wearing the HoloLens the cursor used in the display, like a mouse cursor on a computer system, is controlled (movement) by the direction you look in. A filled circle with an empty outer circle surrounding it is the usual representation for the gaze cursor. The concept is

that the cursor points to where your attention is focused and thus allows interaction with the item of focus under the gaze cursor.

Gestures (selection/activation included): There are three (3) basic gestures in the HoloLens which are like mouse clicks on a desktop and works in conjunction with gaze. With gaze, an object or items is targeted and then a gesture can be used to select or activate the target. With this you usually get an activation event which can be triggered by a change in the cursor or by some other means.

- Bloom – With your hand in view of the HoloLens view hold hand with palm up and fingers all together, then open your hand in a flower bloom motion. This is used to activate menus to perform other functions.
- Tap and Hold – With your hand in view of the HoloLens view and the activation event ready for a given object or items you tap your index finger to your thumb but hold it in place when they come together. This is like a mouse click which you hold down and then move the mouse to move the current targeted item. You can perform rotation and zoom by movement of your hand around within the HoloLens view while holding the tap position.
- Air Tap - With your hand in view of the HoloLens view and the activation event ready for a given object or items you tap your index finger to your thumb. This is like a mouse click which acts on the currently targeted item.

11) Using gaze to control the cursor was intuitive and easy.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

12) Focusing the gaze to make a selection was difficult and inaccurate.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

13) Combining gaze and gesture together was intuitive and easy to perform.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

14) The selection of an object was difficult to remember and perform.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

15) The basic HoloLens gestures were easy to remember and execute.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

16) The gesture actions seemed to correspond to their usage.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

17) The visual display was clear and recognizable.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

18) Objects in the visual scene were difficult to discern and understand what they represented.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

19) A see-through HoloLens better supports the intended use than a full immersive device.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

20) The device was heavy and uncomfortable to wear.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Questions 21 – 30 relate to the comparative evaluation of standard application interfaces such as in the IMPACT system (monitor, keyboard, mouse) versus the concept interface provided via the HoloLens user interface.

21) The use of gaze and gesture is a better system interaction than keyboard and mouse.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

22) The visual presentation from one to many monitors is better than the single HoloLens view.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

23) Selection of an object is more intuitive and easier to perform with the HoloLens' gaze and gesture versus using a mouse or pointing device in a system like IMPACT.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

24) Scene understanding and situational awareness for equivalent scenes and objects in IMPACT was much better than in the HoloLens.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

25) Interaction with objects and related menus or popup screens seem easier to use, understand, and applicable in the HoloLens vs. IMPACT.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

26) Creating a play was easier and better understood using the IMPACT system vs. HoloLens.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

27) The HoloLens interface seems better suited for a decision maker vs. an operator of a system like IMPACT

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

28) Scene understanding and/or situational awareness was more quickly obtained via the IMPACT interface vs. the HoloLens interface.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

29) The HoloLens interface could with further development replace the IMPACT interface.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

30) Larger number of tasks can be performed easier and faster on the IMPACT system.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Questions 31-35 relate to the collaborative use of two or more HoloLens'.

31) There is a definite advantage to being able to collaborate on the same scene/scenario with other individuals using HoloLens devices.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

32) I was not clear at all to determine the location of and gaze of other collaborators within the HoloLens created scene.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

33) Collaboration seemed much easier using the HoloLens devices versus collaborating around or near an IMPACT station.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

34) It was not evident or was difficult to determine the action of the other collaborator.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

35) I would be easy to collaborate and then come to a unified decision in the HoloLens system.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Questions 36-40 relate to a dual HoloLens filtered collaboration, that is where one HoloLens user has certain information that the other cannot see and vice versa.

36) There is a definite advantage to being able to collaborate in a filtered environment thus allow different classification of information to be utilized in the same space without disclosing it to others.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

37) I was not clear at all if a shared but filtered environment would work without having to reveal the filtered information.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

38) Providing undisclosed recommendations of a filtered view in order to collaborate on a decision or understanding of a scene/scenario was easy to do.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

39) It was not evident which objects, items or information was filtered for my view and not visible to others.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

40) I was easy to digest undisclosed recommendations from others and incorporate that into the decision process.

Strongly Disagree				Strongly Agree
1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

The following questions are opportunities to provide any additional free format (descriptive text) information regarding the C2-CST program to evaluate the HoloLens use with IMPACT.

41) What elements of the HoloLens interface do you consider to be an advantage over the IMPACT interface, given equivalent components (only a few features on the HoloLens)?

42) What elements of the HoloLens interface do you consider to be less effective than that of the IMPACT interface (same conditions given in 41)?

43) Please circle the number that best describes your opinion for each of the questions below.

Mental Demand: <i>How mentally demanding was the HoloLens interface?</i>	1 Not at all Demanding	2	3	4	5	6	7 Extremely Demanding
Physical Demand: <i>How physically demanding was the HoloLens interface?</i>	1 Not at all Demanding	2	3	4	5	6	7 Extremely Demanding
Temporal Demand: <i>How hurried or rushed was the pace of what was performed?</i>	1 Not at all Rushed	2	3	4	5	6	7 Extremely Rushed
Effort: <i>How hard did you have to work to accomplish your level of performance?</i>	1 Not at all Hard	2	3	4	5	6	7 Extremely Hard
Frustration: <i>How insecure, discouraged, irritated, stressed, and annoyed were you?</i>	1 Not at all Frustrated	2	3	4	5	6	7 Extremely Frustrated
Performance Degradation: <i>How degraded was your ability to meet task goals?</i>	1 Not at all Degraded	2	3	4	5	6	7 Extremely Degraded

44) Is there anything we haven't covered that you think we should know?

Thanks for your help!

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14. ABSTRACT A prototype of a Command and Control Collaborative Sand Table (C2-CST) examined a new human-machine interface for collaboration at various classification levels. This interface was connected to an Autonomy Research Pilot Initiative (ARPI) system that demonstrated tactical decision making, mission management, and control with key elements for enabling heterogeneous unmanned vehicle (UxV) teams to successfully manage the "fog of war" with its inherent complex, ambiguous, and time-challenged conditions from a supervisory control and the machine learning point of view. The C2-CST system interacts with this connected system via an augmented reality device platform. The goal was to allow human-to-human-to-machine collaboration for situational awareness, decision making, and C2 planning and execution of simulated multi-unmanned heterogeneous autonomous vehicles. The advanced user interface allowed multiple operators to collaborate across a shared holographic sand table (terrain model used for military planning and wargaming), while controlling several unmanned vehicles. An additional concept of pseudo-classified information filtering was examined.					
15. SUBJECT TERMS command and control; autonomy; augmented reality; unmanned systems; classification; collaboration					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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