Command and Control (C2) to Enable Multi-Domain Teaming of Unmanned Vehicles (UxVs)

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***Abstract*— In his best-selling book, War Made New, military historian Max Boot supports his thesis with historical examples to show how technological-driven "Revolutions in Military Affairs" have transformed warfare and altered the course of history. The U.S. military has embraced a wave of technological change that has constituted a true transformation of the way that military forces will fight in the 21st Century.**

One of the most transformational technologies adapted for military use is unmanned and autonomous systems. The expanding use of these systems for civilian and military applications has increased dramatically over the past decade. This should come as no surprise, as these systems represent one of the most rapidly growing areas of innovative technology adoption. In the military trade space, the use of military unmanned systems (UxS) is already creating strategic, operational, and tactical possibilities that did not exist a decade ago. These systems are not only changing the face of modern warfare, but are also altering the process of decision-making in combat operations. Indeed, it has been argued that the rise in drone warfare is changing the way we conceive of and define "warfare" itself.

However, while these unmanned systems are of enormous value today and are evolving to deliver better capabilities to the warfighter, it is their promise for the future that causes the most excitement. Indeed, these systems have created substantial buzz in policy, military, industry and academic circles. One of the most cutting-edge and challenging aspects of autonomous systems is enabling systems that operate in different domains—Unmanned Aerial Vehicles (UAVs), Unmanned Surface Vehicles (USVs), and Unmanned Underwater Vehicles (UUVs)—work together as a heterogeneous whole.

As autonomous systems become more important to military operators, and especially as they are used for more diverse and complex missions, the issue of command and control (C2) of cross-domain unmanned vehicles (UxVs) will become more important. Today, while the performance of UxV in all domains has improved dramatically, the C2 issues of controlling UxVs in multiple domains simultaneously remains an area requiring additional research, modeling and simulation, and operational testing.

This paper will present the results of operational testing of cross-domain UxVs in The Technical Cooperation Program (five-eyes) Hell Bay 4 experiment during international exercise Unmanned Warrior 2016 at the British Underwater Test & Evaluation Centre (BUTEC), in the Kyle of Lochalsh, Scotland, United Kingdom. The primary objectives of this experiment focused on cooperative teaming of a UAV with UUVs to demonstrate extended range C2 of remotely deployed UUVs in a contested littoral environment.

One of the most promising results of this experiment was the ability of the test UAV to travel for one hour at twenty-five miles per hour while carrying a ten-pound payload. This UAV (a United States Vapor 55) was thus able to transit from one ship to the other, autonomously take off and land, and recharge when necessary. This capability demonstrates the potential for these UAVs to operate from ships in international waters (outside a nation's twelve mile territorial sea) and have enough endurance to conduct missions ashore.

The undersea portion of the experiment was equally promising, with the operational team able to effectively control Iver2 and Iver3 UUVs – as well as the UAV – via the ONR CaSHMI control station. Of note, we were able to successfully relay data between UUVs and the UAV at several miles separation.

Finally, this paper will present the details of proposed future experimentation and provide on-ramps for industry, academia, military and allied partners to participate in future events. The presenting author will provide appropriate points of contact at the various organizations that participated in The Technical Cooperation Program Hell Bay 4 experiment during international exercise Unmanned Warrior 2016, and will suggest ways of other parties can join future experiments.

Keywords—unmanned systems, autonomy, cross-domain, multi domain, command and control

I. Introduction

Unmanned and autonomous systems are among the most transformational technologies adapted for military use in the modern era. The expanding use of these systems for civilian and military applications has increased dramatically over the past decade. This should come as no surprise, as these systems represent one of the most rapidly growing areas of innovative technology adoption. In the military trade space, the use of military unmanned systems (UxS) is already creating strategic, operational, and tactical possibilities that did not exist a decade ago. These systems are not only changing the face of modern warfare, but are also altering the process of decision-making in combat operations. Indeed, it has been argued that the rise in drone warfare is changing the way we conceive of and define “warfare" itself.

However, while these unmanned systems are of enormous value today and are evolving to deliver better capabilities to the warfighter, it is their promise for the future that causes the most excitement. One of the most cutting-edge and challenging aspects of autonomous systems is having systems that operate in different domains—Unmanned Aerial Vehicles (UAVs), Unmanned Surface Vehicles (USVs), and Unmanned Underwater Vehicles (UUVs)—working together as a heterogeneous unit.

This is especially relevant today as autonomous vehicles represent a crucial component of the U.S. Department of Defense’s “Third Offset Strategy,” which is aimed at extending the United States’ competitive military technological and operational advantages. While UxVs working in each domain (land, air, surface and subsurface) provide their own technological promise, it is the synergy of these systems’ teaming effectively in a cross-domain environment that promises the most exciting technological breakthroughs to support the Third Offset Strategy, and specifically its goals of realizing advanced modes of human-machine combat teaming [1].

At the next level down from the DoD, the U.S. Department of the Navy (DoN) has stated strongly that it intends to prioritize the development and fielding of unmanned and autonomous systems. In a recent Navy study assessing alternative Fleet architectures, a Navy team recommended increasing the number of unmanned surface and subsurface systems in the Fleet circa 2030 from the currently planned 10 to a total of 136 [2]. Similar fleet architecture studies undertaken by MITRE and the think tank Center for Strategic and Budgetary Assessments (CSBA) also recommended significantly increasing the numbers of unmanned system in the future fleet [3].

The Navy recognizes, however, that simply increasing the number of unmanned systems that it fields will not be sufficient—the systems themselves must become more advanced. To that end, the Naval Research and Development Framework makes clear that technology development must focus on maximizing these systems’ capabilities. Specifically, it calls for increasing the “flexibility and reach of the naval force through incorporation of autonomous and disaggregated systems,” while also enhancing “dynamic, synchronized actions across forces” [4].

As autonomous systems become more important to military operators, and especially as they are used for more diverse and complex missions, the Navy’s goals will only be successfully realized if the issue of command and control (C2) of cross-domain unmanned vehicles (UxVs) is addressed. Today, while the performance of UxVs in all domains has improved dramatically, the C2 issues of controlling UxVs in multiple domains simultaneously remains an area requiring additional research, modeling and simulation, and operational testing.

Various defense research groups and organizations around the world are investigating these issues, exploring the boundaries of cooperative missions between suites of unmanned systems (UxS). One such effort is the Center for Innovative Naval Technologies – Information Dominance (CINT-ID) program funded by the Office of Naval Research (ONR). A key effort within the CINT-ID portfolio is the Space and Naval Warfare Systems Center Pacific’s (SSC PAC’s) Heterogeneous Autonomous Maritime Mobile Expeditionary Robots (HAMMER) project. The objective of the HAMMER project is to operationally integrate unmanned surface, aerial, and underwater vehicles to perform cooperative missions in the maritime domain.

Elements of the HAMMER project were successfully demonstrated as part of the international exercise Unmanned Warrior 2016, where participants established the cooperative teaming of a UAV with multiple UUVs. Specifically, this paper reports on the objectives outlined in the Command and Control (C2) of Cross-Domain Unmanned Vehicles (UxVs) section of the Trial Plan. Cross-domain UxV communications were enabled with line-of-sight radio frequency (RF) transmissions at 900-MHz. UxV geometries were exploited to set up and demonstrate UUV control and data exfiltration at extended range by using the Vertical Take-off UAV platform as a communications relay. Both qualitative and quantitative metrics were collected to validate objective completion and made available for further analysis. The SAE Joint Architecture for Unmanned Systems (JAUS) standard services and messaging were employed for bi-directional communications. The Office of Naval Research (ONR)’s Control Station Human-Machine Interface (CaSHMI), which employs the SAE UxV Control Segment Multi-Domain Extension (UCS-MDE) services oriented architecture, served as the primary C2 node ashore.

II. Trial Objectives

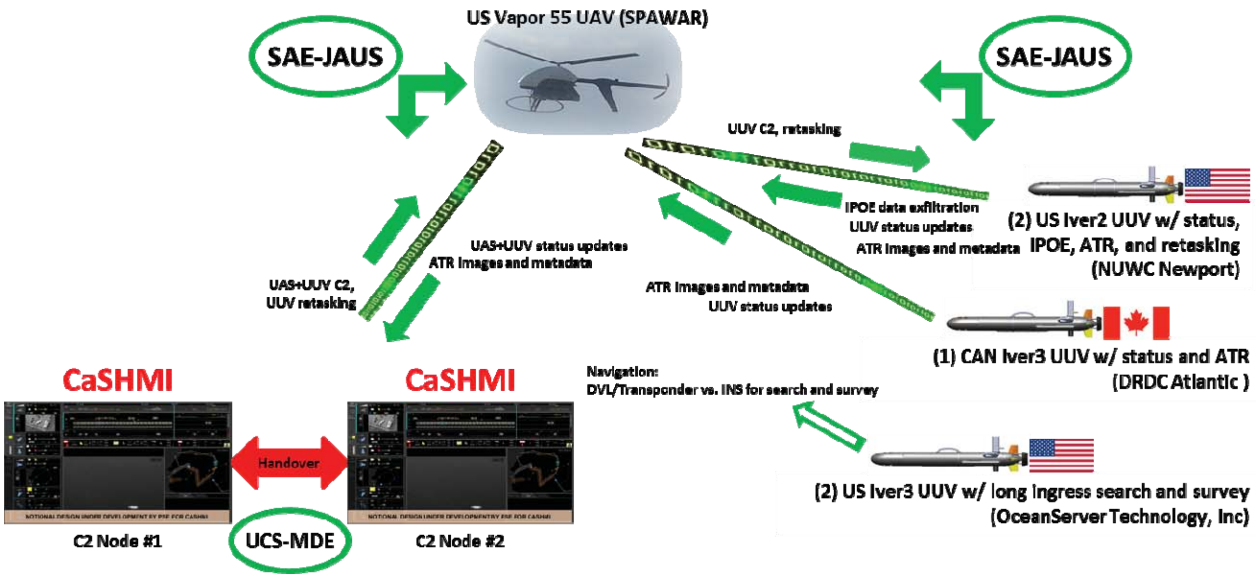
Unmanned Warrior 2016 was a large-scale UxS demonstration, hosted by the United Kingdom (UK) Royal Navy. It demonstrated the latest unmanned system technologies including air, surface, and sub-surface vehicles and sensors in a tactically representative environment. The purpose of the exercise series was to explore the feasibility of increasing the use of unmanned and autonomous systems in delivering maritime capability. To support the overall capability development of UxS, SSC PAC utilized the opportunity provided by the Unmanned Warrior 2016 exercise to investigate the feasibility of establishing a cooperative communications network between a deployed UUV and an afloat and/or ashore C2 node, using a UAV as a communications relay, thereby achieving beyond line of sight (BLOS) C2.

A common limitation of Unmanned Underwater Vehicle (UUV) operations is that mission data are unavailable for download and analysis until after the UUV is recovered. As a general planning factor there is a 1:1 ratio between data

it takes to get the information needed for future mission planning because PMA can begin well before the UUV is recovered.

SSC PAC established a cooperative UxS C2 network in support of UUV operations being conducted as part of the

Fig. 2 Cross Domain C2 Experiment Configuration



collection time and post-mission analysis (PMA), that is, for every hour of mission data collected by a UUV an hour is required for post-mission analysis. This does not include the time required to recover the UUV or to transit back to the command center that will perform the PMA. For example, a four-hour UUV mission will require approximately four hours of PMA time. Thus, data collected from that one mission will not be available to support follow-on operational planning for at least eight hours, not including transit time as shown in **Fig 1. Notional UUV mission timeline**

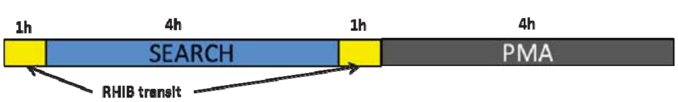


Fig 1. Notional UUV mission timeline

Using an Unmanned Aerial Vehicle (UAV) as a communications relay can decrease the operational timeline significantly. To reduce the time between collection, analysis, and integration of collected data into follow-on planning, communications windows can be built into the UUV's mission profile at specific intervals and/or following the completion of a specific mission event. During the communications window the UUV can transmit data to the UAV, which can relay the information to a Command and Control (C2) node to begin the PMA. The cross-domain system architecture is shown in **Fig. 2 Cross Domain C2 Experiment Configuration**. While this method does not reduce the PMA time, it does reduce the time

Unmanned Warrior 2016 Hell Bay IV trials. Demonstration of this capability was a primary objective of the Hell Bay IV trials. The Unmanned Warrior 2016 exercise took place within the range areas of the UK Ministry of Defence (MOD) British Underwater Test and Evaluation Centre (BUTEC) range at Kyle of Lochalsh in the western reaches of Scotland from 2 - 16 October 2016.

Deliverables from this effort were twofold: qualitative and quantitative data collected by SSC PAC during the exercise were provided as input into the overall Unmanned Warrior 2016 report and lessons learned database; and an independent SSC PAC test report that captured the results and observations was used to inform U.S. Navy specific research and technology development. Data transfer performance metrics were captured to evaluate the effectiveness of this nascent Concept of Operations (CONOPS).

III. Equipment and Setup

Each of the teams that participated in the command and control of cross-domain UxVs contributed the systems, components, and personnel that were required to achieve the experiment's objectives.

SSC Pacific provided a Vapor-55 rotary wing UAV, shown in **Fig. 3 Vapor 55 UAV**, along with a Ground Control Installation and flight operations crew supported by U.S. Navy Reserve personnel. The unmanned aircraft was equipped with a payload module consisting of a radio and single-board computer. The radio in the UAV was configured as a master node, allowing it to seamlessly and automatically act as a relay between shore C2 stations and UUV nodes. SSC Pacific also provided CaSHMI (Control Station Human Machine Interface) on two laptops and operators for the C2 nodes ashore. CaSHMI is an effort funded by ONR code 34 to bring a single common display into use for monitoring multiple simultaneous cross-domain unmanned systems. These nodes were connected to the network of UxVs through their own radios.

Defense Research and Development Canada – Atlantic (DRDC-ATL) provided a single Iver3 UUV with on-board navigation and sonar. This vehicle and all other UUVs directly participating in this objective of the Unmanned Warrior/Hell Bay IV trial were also equipped with the same radio.

OceanServer Technology, Inc. (OTI) provided two Iver3 UUVs and a time-based transponder system for precise underwater navigation, as well as sidescan sonars and other sensor payloads.

Naval Undersea Warfare Center Division Newport (NUWCDIVNPT) provided two Iver2 UUVs, which are shown in **Fig. 4** as well as the JAUS messaging service code for platform communications.

Fig. 3 Vapor 55 UAV

Fig. 4 Iver UUV

The overall goal of the team's participation in Unmanned Warrior was a demonstration of extended Command and Control of cross-domain UxVs. The goal was discretized into the following technical objectives:

1. Utilization of CaSHMI as a single Fleet solution for UxV C2 in a stand-alone implementation independent of combat system integration
2. Networking of two CaSHMI workstations to demonstrate shared C2 of UxVs
3. Utilization of a uniform messaging service for cross-domain UxV operations
4. Utilization of a UAV for bi-directional relay of C2 data between extended range UUV operations and a remote C2 node
5. Broadcast of UUV status and position via UAV relay for display and tracking on CaSHMI
6. In-stride exfiltration of data to support near real-time PMA during UUV operations
7. In-stride exfiltration of data collected, processed, and formatted for transmit and display in CaSHMI
8. Re-tasking of assets for action on Contacts of Interest (COIs). For example, reacquisition for new mission geometries and payloads, neutralization; or survey extension in a single-sortie CONOPS
9. Evaluation of continuously submerged long transit operations of UUVs for cued search, survey, and reacquisition missions.

All of these technical objectives were fully achieved during the scheduled in-water events. All but one were achieved in continuous end-to-end operational scenarios where UAV/UUV status and position, survey data, and imagery and text were exported from the UUVs, relayed through the UAV in flight, and rendered on the CaSHMI display. The exception to continuous operational scenarios was the in-stride exfiltration of data by the DRDC-ATL Iver3. UxV deployments and mission areas within Balmacara Bay are represented in Figure 5.

IV. Trial Execution

Changes to the mission profile were made as needed, but a typical mission consisted of the following series of events:

1. U.S. Iver UUV was deployed on survey mission to map depth contours
2. Images and text were pre-staged on the Iver UUV
3. UAV was launched and assumed various orbits to evaluate communications performance
4. UAV status and position were continuously updated on CaSHMI chart display
5. Iver UUV surfaced at completion of survey to broadcast status and position through UAV relay to CaSHMI
6. CaSHMI received continuous UUV status and position updates for chart display

7. CaSHMI operator remotely accesses the UUV via the UAV relay and reviews data files that were available onboard UUV

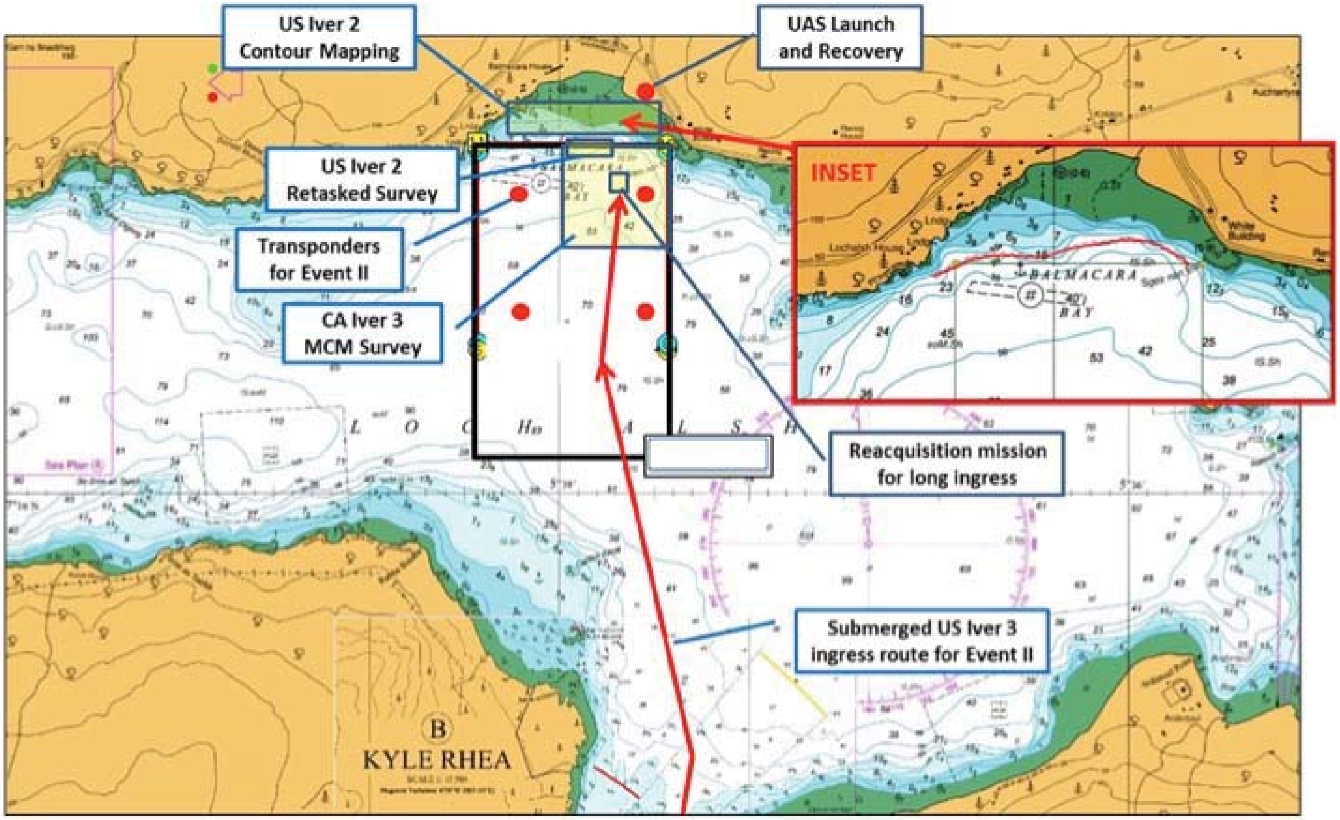


Fig. 5 Operating Area

8. CaSHMI operator queried data files from the UUV for exfiltration of data, then displayed on chart
9. CaSHMI operator re-tasked UUV for new survey mission via UAV relay

For most trial dates, the two CaSHMI C2 stations were co-located, and a hard-wired Ethernet connection was used to connect the two. In one case, a longer range test was conducted by moving one of the CaSHMI stations to a location approximately 6.4 km (4 miles) to the east. In this event, the secondary (remote) CaSHMI station had no role in actual control of the UAV, as it was too far to have visual reference on the small airframe. However, telemetry indicating UAV and UUV position was reliably received at the remote station. Additionally, data products of small file size were received at the remote station. Images with larger file sizes were not successfully passed at this range.

V. Results

A. *Objectives 1 and 2*

Two CaSHMI workstations were co-located on the shore of Balmacara Bay and manned by SSC Pacific personnel. The CaSHMI workstations were housed in the Ground Control Station for SSC Pacific's Vapor 55 UAV and utilized a directional antenna for TX/RCV operations with the UAV in flight. CaSHMI workstations were dedicated to bi-directional information exchange and UUV C2 through the UAV relay, and UAV C2 was managed independently by the GCS.

CaSHMI was used to receive and display information from the UAV and from the UUVs through the UAV relay. Broadcast UxV status and positional data from all platforms were automatically received and plotted on the CaSHMI chart. CaSHMI was able to view files on the independent UxV platforms, select files of interest for download, and then make specific requests to each UxV platform to move data files to CaSHMI. Re-tasking of UUVs was accomplished through CaSHMI and the UAV relay by reviewing and selecting missions already onboard the UUV for execution.

The two CaSHMI workstations were networked with the UxV platforms and supported distributed control. During the operational scenarios, UxV status and positions were displayed on both workstations. Onboard file review and queries were initiated by the two workstations to demonstrate the shared operator interaction to multiple vehicles. Re-tasking of the UUVs was performed independently by each of the CaSHMI workstations as another example of shared control. This implementation of CaSHMI did not provide exclusive control to limit access to a unique UxV platform by a designated workstation with OPCON. Coordination was required among the CaSHMI operators to prevent control conflicts. The designation and transfer of exclusive control remains an area of continued development in extending the distributed control paradigm beyond local, interacting operators.

B. Objectives 3-8

These objectives were focused on establishing and evaluating the bi-directional exchange of C2 information.

Successful exfiltration of contour and image data on an integrated display along with the status and position of unmanned assets facilitated in-stride PMA, which in turn enabled single-sortie or reduced timeline operations based on imagery and text that was extracted from UUVs while they were still deployed.

The many factors impacting the ability to achieve dependable RF communications for C2 information exchange include the following:

- implementation of messaging services
- radio selection and integration
- radio configuration
- antenna selection and integration
- firmware/software implementation
- mission geometries and profiles
- environmental conditions
- message size and type
- compression and encryption overhead
- interference from outside sources
- bandwidth competition from concurrent traffic

With so many variables, a disciplined approach to experimentation is required to optimize communication ranges and establish an operationally robust CONOPS for cross-domain UxV RF communications. Messages of < 1 KB demonstrated excellent dependability in information exchange during exercise events under a large range of settings, and optimization of these variables was not an apparent requirement. Transfer of messages with a file size greater than 1 KB, however, proved problematic with the configuration used successfully for the smaller messages. UAV flight times and other considerations precluded full evaluation and grooming of all potential factors to optimize reliability in the transfer of these larger files, but ultimately, successful transfer was dependably achieved.

An analysis of the bit-rate, file and packet size, and expected time to completely transfer a file from the UUV led to the realization that we were interrupting one file by making another data request before it had reasonable time to finish the first. A modified data query strategy was implemented wherein data requests were queued and cycled on the CaSHMI shore station. Priority was given to any data products that had not yet been received, and a reasonable (or even generous) time delay was instituted before asking for the next item in the queue.

As an example of one particular form of lower priority communications, the autonomy software was generally running on the computer aboard the UAV. This added to overall traffic on the RF network. Namely, the operators on shore would open a secure shell (ssh) session to the onboard computer and initiate the autonomy software mission. It should be noted that the mission in this case did not include any actual autonomous control, but did include monitoring and recording of status and pose information from the aircraft. In truth, the aircraft telemetry is secondary to the mission of monitoring the UUV and its data products. Thus, in an attempt to reduce network traffic, the real-time telemetry from the UAV was suppressed. Its pose information was still recorded onboard for later analysis.

Attempts were made to modify low level radio settings – packet size relative to file size, number of retries (zero to three). The strategy with zero retries was that we already have the capacity for a "full file" retry with the built-in query strategy of CaSHMI, maybe multiple retries on the packet level is not an effective use of bandwidth.

Additional significant gains in transfer efficiency and dependability may be realized by changes to the JAUS services and transfer protocols. These improvements will provide benefit to all UxV communications with JAUS services, regardless of the hardware system utilized, and this work is identified as a focus item in near-term development for multi-domain UxV C2.

VI. Lessons Learned and Next Steps

Energy efficiency for the Vapor 55 was generally less than anticipated. Rotary wing aircraft are more efficient at speed. Our flight profiles of slow circles or hovering near the UUV park point location were inherently inefficient.

Relatedly, the racetrack patterns (elongated ovals with one end located near the UUV park point) provided similar communications performance to the closer hovers and circles. By employing racetrack patterns, a greater average speed is maintained, and the flight efficiency (and thus duration) are increased.

A. Additional Field Experiments

In April of 2017, the U.S. Navy and Marine Corps conducted the Ship to Shore Maneuver Exploration and Experimentation (S2ME2) Advanced Naval Technology Experiment (ANTX) at Camp Pendleton, CA. During this exercise the SSC-PAC and NUWCDIVNPT teams used the same C2 system architecture as was employed at Unmanned Warrior 2016 with the Vapor 55 serving as a relay between the shore-based C2 node and Iver UUVs that were operating offshore. Further diversity to the mix of UxVs was added with an additional maritime platform, and a fixed-wing aircraft participating in subsets of the test events. Beyond the real-time data transfer between the shore station and the UUVs, an additional data transport capability was demonstrated. To take advantage of higher data rates that are achievable over shorter ranges, the

UAV approached the UUVs, transferred data sets that were too large for effective long-range transmission, and carried those data back to a close enough range to be downloaded to the C2 node.

As the CaSHMI software, the communications payload, and the UxV autonomy are still under development, newly implemented features and technologies will be tested during upcoming field experiments both independently at their respective labs and collaboratively during events like UW16 and S2ME2. The next anticipated collaborative field test will be at the upcoming ANTX hosted by NUWCDIVNPT in Newport, RI during August 2017.

VII. Conclusion

As the U.S. Navy commits to its mission of winning wars, deterring aggression, and maintaining the freedom of the seas, it must prepare to succeed in complex future operating environments. These environments are expected to be contested, to feature hybrid challenges (a mix of low-and high-end warfare), and to include sophisticated threats to the information environment. As a result, the Navy must prepare to operate in radically new ways going forward—simply continuing current operations with the addition of new technologies will not be sufficient.

One way in which the Navy is focused on changing its operations is in continuing to advance the art and science of integrating unmanned systems into the fleet. Specifically, the Navy is focused on developing the ability to conduct cross-domain unmanned operations. In recent years, unmanned vehicles operating in discrete domains—unmanned surface vehicles, unmanned undersea vehicles, and unmanned aerial vehicles—have each made impressive strides, especially in increased endurance and capability. The challenge facing the Navy now is to integrate these disparate vehicles into a cohesive system, able to conduct cooperative missions.

Such missions promise to help to solve future operating challenges, including the issue of operating unmanned vehicles in environments where satellite communications are not assured. Specifically, a cooperative team of heterogeneous unmanned vehicles could address the latency challenge that unmanned undersea vehicles currently face in transmitting their data to be processed. The successful realization of the Navy's plans in this area will enable unmanned systems to reach their full potential, serving as warfighting partners rather than simply tools. These advancements will ensure that U.S. Navy forces remain capable of operating forward, maintaining their relevancy and actively contributing to Navy missions even in complex future environments.

VIII. References

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