October 16-17, 2024

NATIONAL OCEAN EXPLORATION FORUM REPORT

Tele-operations in Ocean Exploration

CONTENTS

The rapid adoption of uncrewed vessels and vehicles coupled with technology advancements in satellite telecommunications (Low Earth Orbit [LEO] satellites) has laid the foundation for a paradigm shift towards the tele-operation of ocean technology. The potential benefits of tele-operations (e.g., increased access, reduced costs, on-demand high-value expertise) are substantial, as are the challenges of implementation. To address the need for a focused discussion amid this rapid evolution, The NOAA Ocean Exploration Cooperative Institute (OECI) hosted the 2024 National Ocean Exploration Forum (hereafter referred to as "the forum") with the theme "Tele-Operations in Ocean Exploration."

The forum took place at the New England Aquarium in Boston, Massachusetts, from October 16-17, 2024, and gathered a targeted group of participants from 53 organizations, spanning the academic, industrial, philanthropic, federal, and non-profit sectors, to discuss the future of tele-operations. Following introductions from Jeremy Weirich (Director of NOAA Ocean Exploration) and Dr. Adam Soule (Director of the OECI), keynote presentations were given by Captain William Mowitt (NOAA Uncrewed Systems; UxS), Jelmer de Winter (Fugro), and Dr. Darlene Lim (NASA Ames Research Center). The keynote speakers were chosen to set the scene for two days of discussion. Captain Mowitt provided the NOAA perspective and current state of uncrewed systems operations, de Winter provided insight into how industry successfully conducts tele-operations, and Dr. Lim provided the academic or research perspective. Each presentation highlighted key themes participants would discuss in the four subsequent breakout sessions, which included: interoperability, situational awareness, task analysis of expedition scenarios, and the benefits of moving toward tele-operations. The importance of implementing distinct operational pathways and approaches to effectively use tele-operations will continue to grow, and for this reason, it is essential to start cross-domain, coordinated discussions now. A summary of these perspectives and breakout discussions are outlined in this report.

Tele-operations have become a critical component of our operations with the Uncrewed Vehicle DriX. It has allowed us to launch DriX from a mother-ship and operate well over the horizon, freeing the mother-ship to perform other independent operations. It has allowed us to launch and operate our vehicles from Remote Operating Centers (ROCs) ashore without the need for a "mother-ship" when work areas are within a reasonable distance from shore. In this mode it also allows us to more easily maintain 24/7 operations by using distributed ROCs across many time-zones. We have also been able to operate in a "hybrid" mode where the vessel is launched, recovered and operated from a mother ship and we distribute control between the ship and shore-based ROCs to minimize berth requirements on the ship. Finally, we have very successfully used tele-operations to engage scientists ashore and allow them to play a critical, real-time role in making scientific decisions about the behaviors and operations (like mapping or sampling) of both surface and submerged vehicles that are being acoustically tracked by the surface vehicle.

LARRY MAYER,
Director of Center for Coastal and Ocean Mapping (CCOM-UNH)

Definitions

Tele-operations is a relatively new paradigm and thus the terminology associated with it is not, in all cases, well defined. To avoid confusion, we provide these definitions for how we use the terms in this report. Other definitions may apply for different use cases.

Telepresence - Catch-all phrase that indicates shore-side personnel can see, hear, and/or participate in sea-going activities. This may include direct discussions with operations and science teams although most (or all) of the decision making is on the ship. It is also used frequently for education and outreach purposes and represents two-way communication.

Tele-science/Remote Science - Sea-going ocean science primarily led by scientists who are either leading or co-leading from shore. Both locations have telecommunications, networking, and computer technology to support the social interaction among the geographically separated lead scientists. Communication exchanges in real time are enabled by pre-planning for shared tools that include expedition plans, science objectives, expectations of remotely operated vehicle (ROV) configuration for sampling and instrument use, and communications plans (Mirmalek and Raineault, 2024).

Tele-operations/Remote Operations - Sea-going operations of vessels and vehicles wherein full or partial control of the vessel or vehicle is conducted from shore. Control is facilitated by real-time streaming of sensor data (e.g., video) that provide situational awareness and an open network path with limited latency for control of on onboard systems. Vessels and vehicles may be supported by onboard personnel or automated routines in the case of loss of communications. The extent of human interaction from shore is dependent on vehicle type and environment. For instance, an uncrewed surface vessel (USV) may follow a pre-planned mission with a shore-side operator watching for any disruption (e.g., mechanical, obstacle). Alternatively, an ROV might require real-time control of thrust and manipulations in order to achieve objectives that evolve in real time based on observations.

Remote Operations Center (ROC) - Location from where autonomous and remote controlled vessels and vehicles are monitored or tele-operated. This can take the form of a laptop for a system that requires minimal intervention to a space outfitted with visual and audio communications stations, multiple remote operators, and access to 24-7 computer and networking support for systems that require more complex operations and/or are less tolerant to loss of communications.

LEO Satellites - Low Earth Orbit Satellites are designed to provide high-speed, low-latency connectivity. Used by vessels and vehicles to implement telecommunication.

Interoperability - Interoperability refers to the ability for independent systems to work in coordination within a common framework. This can refer, at a broad scale, to multiple robotic systems working collaboratively or, at a smaller scale, to individual sensors being easily integrated on multiple systems. In all cases, interoperability relies on common standards agreed to among operators, developers, and users. These can be as straightforward as common terminology or more complex, such as common coding languages or software tools to enable application program interface (APIs) across systems. The level of interoperability is a sliding scale with low interoperability, for example, enabling a user to 'see' multiple vehicle systems, and high interoperability enabling, for example, one autonomous system to command another.

Latency - A delay in data or information transfer.

Government

Government research and development agencies have long supported the development of technologies for ocean exploration. This takes the form of direct support to academic institutions through grants, direct support of commercial entities through contracts, and support for academic/industry partnerships. One example of a successful federal-academic-industry partnership is the development and operationalization of the DriX USV. NOAA Ocean Exploration supported OECI partner University of New Hampshire (UNH) to purchase one of the first DriX hulls from eXail. Cooperative development of this platform spurred NOAA to purchase two additional DriX USV's to support multiple mission areas (e.g., Fisheries, Coast Survey). Another example is Orpheus Ocean's autonomous underwater vehicle (AUV), which was initially a technology development project funded through NOAA's OECI and is now a successful start up. Orpheus Ocean just deployed the newest version of this AUV to the deepest parts of the ocean in the Mariana Trench in support of an OECI expedition.

These examples offer a road-map for the development of tele-operational capabilities. Without federal support, academic institutions would not be able to advance technology related to tele-operations. Without academia, commercial partners would have fewer opportunities to field-test their developments and optimize them for federal missions. Without commercial partners, the government would be challenged to implement the new technology at relevant scales. Together, federal, academic, and commercial partners can provide mutually beneficial support that advances each of their goals in developing the transition to tele-operations.

Industry

Many private organizations are already conducting remote operations in a range of modalities. Fully remote vessel operations, remote vehicle deployment and operations, and real-time remote data processing are all happening from ROCs worldwide. The industrial remote operations work being conducted is routine and repeatable and thus lends itself well to shore-siding. This proven operational model represents a potential path forward for federal, academic, and non-profit organizations; however, deep-ocean exploration is more complex, and thus is not a 1:1 translation of private sector operating capabilities. Current industry examples that utilize remote operations include: USVs (Saildrone, eXail, Chance Maritime), small ROVs (Fugro), and large vessels (Impossible Ocean).

Academia, philanthropic, and non-profit institutions

Institutional research vessels have been conducting remote science for roughly the last ten years. During the first half of the decade, capabilities were limited. The introduction of LEO satellites allowed for more robust telecommunications, such as live streaming ROV dives which allowed scientists to observe remotely, at-sea educators and scientists to connect with classrooms, and scientists to transfer data to shore for processing. These established pathways increased capacity in 2019 with the launch of Starlink's first satellites which became vital during the COVID-19 pandemic. During this time, most scientists were shore-sided with vessels staffed predominantly by vehicle teams and marine technicians.

As the community works towards transitioning to (and/or increasing the capacity of) tele-operations, it is imperative that we not only focus on the technical aspects of the transition, but we also address the social aspects of the transition as well. Other potential roadblocks that need to be addressed include: situational awareness, communications between shipside and shoreside personnel, emergency response procedures, and more. Technical and social aspects must evolve simultaneously for this transition to be successful.

As a sea-going scientist, I place an incredibly high value on berths on a ship. The berths occupied by operations teams are sacrosanct as they are needed to ensure the safe and efficient operation of vehicles, but they often force difficult choices on who can participate in the research. Of special importance is the ability to include participants from the nations and communities where the work is occurring and students. For the former, they represent an important community connection that ensures the science is beneficial to local and regional people and can more directly benefit from the science and exploration. For the latter, the at-sea experience is critical for student skill development and invariably produces better research outcomes as they are integrated into the data/sample collection at the earliest stages. Despite these benefits, these participants are the first to go when bunks are needed for operations. If even one of those operational berths can be moved to shore, the benefits to the science and exploration can be multiplied many times over.

ADAM SOULE,
Executive Director of the Ocean Exploration Cooperative Institute (URI-GSO)

Keynote presentations were given by Captain William Mowitt (NOAA Uncrewed Systems; UxS) who provided the NOAA perspective and current state of uncrewed systems operations, Jelmer de Winter (Fugro) who provided insight into how industry successfully conducts tele-operations, and Dr. Darlene Lim (NASA Ames) who provided the academic or research perspective. The keynote speakers were chosen to set the scene for two days of discussion. Their keynote presentations are summarized within this section.

Captain William Mowitt, NOAA Uncrewed Systems

NOAA's Experiences with Uncrewed Systems Tele-Operations

Captain Mowitt's keynote address focused on the current state of tele-operations within NOAA's Uncrewed Systems Operations Center (UxSOC). Please see the key takeaways here.

The National Strategy for Mapping, Exploring, and Characterizing the United States Exclusive Economic Zone lays out the goal of mapping 3.4 million square miles of the seafloor in the U.S. Exclusive Economic Zone by 2040. Simply put, this goal will not be achieved without accelerating efforts and finding ways to boost productivity. NOAA established an Uncrewed Systems Operations Center (UxSOC) in late 2020, and accelerating ocean mapping efforts with Uncrewed Surface Vehicles (USVs) has been one of the center's central foci ever since.

Implementing remote operations and uncrewed systems operations can lead to two main benefits. First, ocean data collection can be more productive or accomplished at a lower cost per unit effort. This is accomplished by changing where operators sit – moving them from sea to shore – hereby reducing the number of people (a primary cost driver) from operations. Second, data can be collected that could not have been collected via traditional operations. For example, launching vehicles into dangerous conditions such as hurricanes, where the risk to human life has prevented operations.

Captain Mowitt was previously the Director of NOAA's Office of Uncrewed Systems, and as of May 2025 serves as interim Director of NOAA Ocean Exploration.

- Within its use of USVs for ocean mapping, NOAA is currently exploring and utilizing **three modes of uncrewed systems operations with varying degrees of tele-operations:**
    1. USV + Mothership - all necessary operators are located on the ship communicating with an uncrewed vehicle (Mode 1);
    2. USV + Mothership + Remote Operations Center (ROC) - there is communication between all three locations, with the operators located in the ROC participating through tele-operations (Mode 2); and
    3. USV + Remote Operations - all necessary operators are located in the ROC (Mode 3).
- **Mode 1** operations occur during traditional ocean exploration. In this scenario, the USV is essentially an extension of the ship and a direct analogue of a survey launch. All personnel are located on the ship (and subject to berthing limitations, often a significant limiting factor at sea). This mode frequently is associated with the USVs operating in close proximity to the ship and the ship's bridge providing some oversight and traffic situational awareness to the USV operators.
- **Mode 2** operations combine shore- and ship-based control of USVs. Under this scenario, ship and shore-based ROCs share operation of the USVs. This can occur on a continuum, with the ship serving solely as a fueling and maintenance base for the USVs and all other functions occurring ashore, or in a hybrid mode, with command and control being shared between ship and shore. This mode allows for either operations in close proximity to the ship or over-the-horizon operations, and introduces a new function, ship-USV coordination. Here, some degree of communication and coordination will be needed as control of the USV passes from ship to shore and back again.
- **Mode 3** operations solely utilize the USV and remote operations (i.e., operating without a mother ship), and the USV functions essentially as a shore-based survey launch. While the shore-based ROC can be located anywhere, maintenance personnel are required at the USV launch and recovery site. This usually involves over-the-horizon operations with situational awareness dependent on USV sensors (cameras, radar), potentially augmented by internet-based maritime Automatic Identification System (AIS) services.
- In order to effectively transition to tele-operations, **trust must be established** on multiple levels - operator and machine, ship and robot operations, and customer and suppliers. **Moving to ROCs changes how operators perceive the conditions** in which vehicles are operating. On a ship, this information can be observed first hand through their natural senses. In a ROC, this information has to be delivered to them in a reliable, easily digestible manner in order for the operators to make sound decisions. This involves establishing the aforementioned pathways of trust. This can only happen through an iterative testing process.

It is imperative that our **workforce** be prepared for the transition to tele-operations. Ideally, the new and existing workforce would be trained with a **broad set of skills** instead of intense specialization. The community should aim to provide maritime experience and teach data/technical skills and engineering skills to the new and existing workforce. This could be **accomplished through collaboration** across sectors and the development of training centers dedicated to teaching the skills necessary for this transition.

Overall, while there is much still to be learned and sorted, NOAA and the ocean science community are making great progress. And the efforts are paying off: We have found that replacing one survey launch with USV showed a 20-30% **productivity increase** over traditional methods, with an anticipated 40% increase when using two USVs simultaneously. Operating a government-owned USV costs approximately $1.0M annually but yields about $2.2M in **productivity gains to the survey efforts.**

Continuing to develop remote operations and uncrewed systems technologies, including constructing ROCs, establishing pathways of trust, and training our workforce needs to be a collaborative effort between the government, academia and the private sector. The challenges ahead of us are coming into focus, but to meet our national goals of mapping the oceans, we will all have to work together to overcome them.

Jelmer de Winter, FUGRO

Why the Future of Remote Operations is not just about Technology

This keynote address explored the evolving landscape of remote operations or tele-operations, emphasizing that the future of these domains is not solely defined by technological advancements, but by the people, processes, and philosophies that support them. The speaker, Jelmer de Winter from Fugro, shared a personal and transformative experience that highlighted the power of extreme mission ownership and the human element in remote marine operations. The key takeaways are outlined here.

- **Extreme mission ownership is the cornerstone of successful Remote Operations.** The transition to uncrewed and remote operations requires that individuals deeply understand their tasks and take full responsibility for mission outcomes, and are empowered to make decisions beyond what can be captured in procedures alone.
- **A visit to a Remote Operations Center in Perth, Australia,** where a fully uncrewed offshore inspection was being conducted over 1000 miles away, served as a pivotal moment. The experience mirrored the precision and coordination of a lunar landing mission, underscoring the sophistication of modern marine Remote Operations.
- **Remote Operations Centers (ROCs) function as integrated ecosystems.** In one room, vessel masters, ROV pilots, inspectors, surveyors, engineers, and clients all collaborated in real-time, enabled by high quality data streams and immersive visualizations. This setup allowed for a holistic view of the mission, unlike traditional vessel-based operations where teams are physically dispersed.
- **Trust and autonomy are essential.** People must be empowered to adapt the mission plan rather than rigidly follow procedures. The shift from procedure ownership to mission ownership is critical in remote contexts.
- **The paradox of trust in hybrid operations**—where some roles remain onboard while others move to shore—must be carefully managed. Connectivity issues, role clarity, and contingency planning are all vital considerations.
- **Remote Operations opens new career pathways** for individuals who cannot live offshore, such as those with family commitments or health constraints. This inclusivity is a powerful driver for change.
- **Simulation and preparation are key.** Desktop simulations and risk assessments must precede operational shifts to ensure readiness and resilience.

The keynote concluded with a call to action: to prepare for a future where remote and tele-operated missions are the norm, not the exception. By fostering extreme mission ownership and building trust in new operational models, the marine industry can unlock unprecedented efficiency, safety, and inclusivity.

Jelmer de Winter is responsible for Fugro's business of uncrewed vessels and robotics in the Americas region.

Dr. Darlene Lim, NASA

Creating a Shared Exploration Perspective through Collaborative Data Systems

Dr. Darlene Lim's keynote address focused on how to infuse ocean exploration with real-time science decisioning. This included a look at the benefits associated with science integration into exploration operations, what process and technologies support this work, and how various NASA teams have been creating architectures that support the operationalization of science within high-tempo, high-intensity missions. The key takeaways are outlined below.

Dr. Lim is currently the Deputy Project Scientist for the NASA VIPER Lunar Rover Mission, and also leads several NASA-funded research programs that are focused on blending field science with the development of capabilities and Concept of Operations (ConOps) for human-robotic spaceflight to the Moon, Mars and beyond. She is the Principal Investigator of the SUBSEA, BASALT and Pavilion Lake research programs, Deputy PI for FINESSE, and Science Ops lead for RESOURCE.

Effective tele-operations consist of four interconnected components: people, data, hardware, and software. Each component must be evaluated with equal rigor and evolve simultaneously in order for the transition from traditional sea-going operations to tele-operations to be successful.

- Tele-operations are optimized when **shore-side scientists and operators truly participate actively, collaboratively and equally** in operational decision making.
- It is imperative that all participants, regardless of location, are seeing the **same data at the same time.** This can alleviate friction in conversation and expedite decision making. Different data views between participants create a need for scientists or operators to infer information, which can slow the decision making process. Latency in decision making when remotely operating vehicles or determining sample locations equates to not only lost time, but also to potentially unfulfilled mission objectives.
- Integrating data across platforms to **create a shared, democratized view of an exploration environment** facilitates real-time discussion and decisioning during high intensity operations.
- **Data must be presented in a visually meaningful way.** Not everyone has the capacity to extrapolate beyond the restricted lens of robots. Building visual tools that provide broader context for observational scientists can improve tele-operations. For example, NASA utilizes a data view for rover operations that provides situational awareness for scientists and operators. Panoramas are rapidly created from rover images and presented parallel to a top down view of the rover which provides directional context by identifying which swath of space the scientist is viewing. This creates a portal for understanding data for all observational scientists beyond the restricted view of a robot lens. For an ROV, this could look like the top down view provided by the non-working vehicle in a two-body system.
- **Data should be interactive and synchronized.** Time should be used as a guide to design systems and coordinate between people in different places (i.e., time stamped data).
- **Data export must be efficient.** It is essential to utilize predefined data packages and minimal mouse clicking, display relevant data by mission, co-locate team members in mission and science operations centers, and export data in a format readable by popular tools (e.g., MatLab, ARC, JMP, Excel).

Space and ocean exploration have many parallels, but there is a stark difference with regard to how scientists and operators have participated in exploration through time. What would ocean exploration look like today if everyone was shore-sided from its inception? With the communications and data infrastructure available to us all at this time, Dr. Lim believes tele-operations are feasible with some hard work to prepare the systems that will make this possible.

All discussion summaries are based on responses submitted by forum participants to each session's question(s) highlighted below. At the end of each breakout discussion, participants were prompted to submit their final responses to the questions below via *Mentimeter* (a platform used to present questions, collect participant submissions, and calculate votes). At the end of each day, the discussion leads presented a high-level summary of their breakout group's findings to the entire forum during a panel discussion.

Session 1: Interoperability

Discussion summary

The first breakout discussion was focused on interoperability. Discussion was prompted in each breakout space with the following question: **"What are the key technological enablers that need to be developed and/or operationalized to effectively apply tele-operations to a diverse set of vessels and vehicles?"** Upon being presented with this question, participants were asked to generate initial thoughts prior to diving into the group discussion. The key themes from all breakout rooms for this topic are summarized below.

The four discussion groups unanimously agreed on the need to create more robust and standardized communications infrastructure. Redundancy, reliability, and low-latency need to be established, validated, and supported in order to effectively implement tele-operations. Low-latency is essential to receive real-time decision making information and data on shore. Redundancy is necessary to ensure mission-critical operations can continue even if there are failures. Standardizing this infrastructure and generating communications protocols could reduce the overall complexity of interoperability.

Participants also highlighted a need for developing data management standards, such as data formats, compression techniques, and accessible data repositories that will accelerate the rate at which interoperability and tele-operations is made possible. Prioritizing what data is immediately needed for decision making on shore can help to mitigate bandwidth limitations. Establishing data priorities can be accomplished by collecting strong use case stories and experiences across the operator community.

The need for standard user interfaces, middleware, and training platforms was also noted. Not only would this improve collaboration across operators and science teams by providing uniform vehicle information and data sharing via a common dashboard, but this could also greatly simplify the integration of different vehicle systems and operators into a remote operations paradigm. Strong user stories are also necessary to determine what data/information would be required to create the most effective user interface. Due to the increasing desire for and feasibility of multi-vehicle operations spanning both the underwater and surface domain, these interfaces must also accommodate communication from various mediums such as acoustic modems used for underwater communication to Radio Frequency (RF) and WiFi-based surface links.

Lessons learned

The participants recommend establishing a Minimum Viable Product (MVP) for interoperability to maximize cost efficiency while still enabling new capabilities for exploration. Platforms should have a means of interoperating at a "Level 1" threshold (Table 1). At a minimum, this means that they should accept mission plans in a common data format, such as L84 or GeoJSON, which are used by a number of different platforms today. They should also have an open means of streaming their position, heading, course, and speed to a Common Operating Picture (COP) to enhance safety and situational awareness of all vehicles in the water.

Level	Description	Examples
0	No Integration	Systems are coordinated by human operators communicating with each other
1	Common Operating Picture	Multiple UMS export their position in real time to Google Earth
2	Coordinated Behaviors	Directed sampling and swarming behaviors

Table 1. Interoperating level descriptions and examples.

Payloads should also have a "Level 1" threshold of interoperability, where they can be remotely power cycled (Table 2). Advancing towards "Level 2" integration should be considered and integrated into development plans that are enacted to achieve "Level 1" integration.

Level	Description	Examples
0	No integration / free running payloads	Systems are coordinated by human operators communicating with each other
1	Basic communications integration / remote human intervention on payload and basic power cycling	Multiple UMS export their position in real time to Google Earth
2	Information sharing between Payload exports some data payload and platform	Directed sampling and swarming behaviors
3	Coordinated behaviors between payload and platform	Auto-survey; platform executes behaviors based on data collected from payload and/or payload drives platform based on its data

Table 2. Payload interoperability level descriptions and examples.

Session 2: Situational Awareness

Discussion summary

The second discussion centered around situational awareness and was prompted by the following question: **"How do we create situational awareness for humans and sophisticated enough vehicle autonomy to reliably operate a diverse set of vehicles from shore in challenging environments?"** Participants followed the same discussion format as described in the first discussion section.

There was a general agreement that the rapidly advancing Artificial Intelligencel/Machine Learning (AI/ML) technologies would be an important component of remote operations. The applications discussed included: fault-detection in uncrewed systems, environmental awareness (e.g., obstacle avoidance), creation of simulation environments, and adaptive user interfaces. Recalling the keynote presentation from Captain Mowitt, the concept of 'trust' in AI/ML systems was viewed as crucial and required extensive testing and proving. The discussion results are summarized below.

It is clear that to develop the level of sophisticated autonomy needed for operations in challenging (or any) environments, AI/ML capabilities must be heavily tested. However, this testing must also include activities to establish and maintain trust between operators and autonomous platforms. In order to establish a trust-based relationship, operators must be able to understand the fundamental aspects of AI/ML capabilities while AI/ML capabilities are tested in an iterative and gradual manner. Starting with repeated simple tasks and moving to more complex scenarios (only when previous tasks have been mastered) will increase operator trust in autonomous platforms. Robust, curated repositories of training data with stringent data quality control and collection standards will be necessary to develop complex ML-supported autonomy in challenging environments. For gradual testing, data with variable levels of complexity, in terms of mission goals and environmental scenarios, is necessary. The ability to adapt based on real-time information will also be vital for the success of operating in challenging environments. Existing knowledge from other domains (e.g., aerospace) should be leveraged to streamline the development of training processes.

Human awareness in challenging environments is different onshore compared to at sea. At sea, operators physically experience local conditions in the course of regular activities; for example, while working inside the control van, they can feel the motion of the vessel, or they have the ability to walk on deck to assess the sea state. In ROCs, operators receive information about local at-sea conditions through monitors, user-interfaces, and sometimes via phone conversations with operators at sea. For building and maintaining trust between on-shore and at-sea operators, whether human or AI/ML, it is imperative to bridge the gap between these two experiences so that both parties have a shared sense of local conditions and situational awareness. While it is often the at-sea local conditions that take priority, it is important to have on-shore local conditions valued as well.

Simulations of varying complexity can be used to train operators to identify which real-world information that is critical for communicating situational awareness. These simulations could yield data for the development of user interfaces. The need to discern which information to provide and when is essential to not overwhelm operators with unnecessary information. It should also be considered that different missions and vehicle systems will require varying levels of situational awareness. This should influence the design of the (preferably) standardized user interface. Augmented Reality and Virtual Reality technologies can be leveraged to create immersive and informative interfaces that present mission-critical information to operators in a clear and concise manner.

Trust in autonomy and effective user interfaces will not be possible without ensuring data quality control. The training data used in simulations and in ML training data sets determine the overall effectiveness of autonomous vehicle operations in challenging environments. Standards for data collection, validation, and curation must be meticulously adhered to by the entire ocean exploration community.

Tele-operations is a tool and process that I began studying among the ocean science community over ten years ago. Currently I use tele-operations in a NASA project involving lunar remote science operations and continue to examine and develop operations for telepresence and remote science with ROVs. The 2024 National Ocean Exploration Forum workshop highlighted the community's ongoing interest in understanding changing conditions of technologies that are needed for tele-operations as well as the social interactions that enable technologies to operate and support science investigationS.

ZARA MIRMALEK,
Social Scientist, Work Ethnographer
(NASA Ames/BAERI)

My research group integrates and deploys instruments on deep submergence vehicles. Typically berthing is tight so we can often only send one person out to sea, and they cannot work 24 hours per day. Tele-operations could enable a remote pilot to see our instrument data. This could enable the pilot to determine if something has gone wrong with the instrument or to change the trajectory of the vehicle based on the data. We are slowly transitioning from prototype instruments to those capable of being operated by anyone where we will not necessarily need someone on the ship to be watching the data. It could easily be someone ashore.

ANNA MICHEL,
Chief Scientist of National Deep Submergence Facility (WHOI)

Lessons learned

Communicating information for situational awareness between operators, whether human or machine, includes trust in data quality control, vehicle health monitoring, and real-time measures of mission effectiveness.

The following should be considered when advancing this topic:

- Codify a hierarchy of levels of situational awareness and/or specific capabilities as a step towards right-sizing the situational awareness requirements for different unmanned systems'
- Create and share a ML database to develop common AI tools for situational awareness for different vehicle types
- Have a simple AI/ML option to aid an operator rather than solely focusing on developing an option for complex decision making

Developing trust between human operators and robots needs to build on existing human-trust building habits. Human operators need an increased ability to see how the autonomous vehicles and AI/ML are operating, and they need information and experience with what constitutes "a functional relationship."

Session 3: Task Analysis

The third breakout discussion asked participants to complete a **simplified Task Analysis** using a work breakdown structure (WBS) of two different expedition scenarios. The goals of this exercise were to identify tasks and roles that need to remain on a ship versus those that can be moved to shore, and to identify specific tasks and roles that need to be further considered before determining the best location (i.e., ship or shore). The activity stated, **"Complete a work breakdown structure for an expedition scenario to determine what tasks/roles need to remain on the ship, what tasks/roles can be moved to shore, and what roles/tasks are we unsure of."** The goals and scenarios provided to the participants are listed below. Two breakout groups completed a WBS for Scenario 1 (ROV) and the other two breakout groups completed a WBS for Scenario 2 (ASV).

Goal: Identify all necessary tasks within each scenario, assign responsibility for each task, determine which tasks need to have someone physically present on the ship to carry out (versus onshore). [N.B. feel free to add more detail to the scenario as it arises during conversation.]

Scenario 1 - ROV

You are going to launch a work-class ROV rated to 4,500 m water depth to survey and sample at a hydrothermal vent on a mid-ocean ridge. You know the vent's location from past dives in the area. The science party has indicated that they would like to locate the area of highest temperature using a temperature probe, collect biological samples, and collect water samples. When sampling is complete, the scientists would like to conduct a low altitude photo survey of the vent site.

Start
Preparing for 8am launch

Tasks
Imagery, video, sample collection, and normal background data collection *(salinity, temperature, etc.)*

Depth
3,000 m

Area
Hydrothermal Vent

End
Vehicle recovery at midnight

Scenario 2 - ASV

You are tasked with surveying a large area off the coast at water depths of 200-800 m. Your autonomous surface vessel (ASV) can survey at 7 kts and the total survey time would be ~15 days. The ASV has an endurance of 5 days before it needs to be refueled and potentially serviced. The area has some ship traffic, but is not near a large commercial port. Large marine mammals can be present in the area. Weather is expected to deteriorate about a week into the survey for a period of 4 days. The scientists would like to have the processed data upon completion of the survey. There is an additional request to check the status of deployed seabed instrumentation at several sites that are equipped with acoustic modems that can transmit data 1.25 times the water depth.

Start
Early morning at pier

Tasks
Mapping a region in the Gulf of Maine to characterize benthic habitat

Depth
200-800 m

Sea State
1-3, Rescue Boat Available, Launch from shore

End
End of day at pier

Example of WBS

A WBS is an exercise that involves dividing a complex task into its component tasks and to further classify those tasks within a parent-daughter framework that indicates both hierarchy (i.e., order) and dependencies between tasks. For example, in the process of conducting an ROV dive, pre-deployment checks may be a parent task and checking hydraulic fluid levels might be a daughter task within that.

Discussion summary

In the discussions that took place, it became clear that ocean exploration activities, whether ROV deployments in unknown areas or UxS deployments can vary significantly based on objectives, conditions, etc. In many ways, this highlighted the difference between the application of tele-operations for commercial purposes (e.g., pipeline inspection) versus ocean exploration. There was consensus across the groups that some tasks are currently well-suited for onshore positions, especially those related to data quality assurance and quality control and processing. However, the unconstrained nature of the hypothetical scenarios led to very different conclusions across the groups.

Lessons learned

Through completing this exercise, participants agreed that conducting a formal task analysis would be valuable to determine what tasks require personnel to remain on a ship. However, due to the unique nature of ocean exploration and the variety of systems employed, it will be necessary to evaluate each system. The task analyses could increase in complexity depending on what sampling systems are utilized during each expedition as well. Because of this, there is likely value in creating a standard operating procedure for conducting task analyses that could be appended to expedition plans. This could be conducted in early expedition planning stages to establish how expeditions should be staffed.

Preliminary steps could include:

1. Creating better documentation of tasks, edge cases, and conditions that may impact tele-operations (e.g., bandwidth, latency, staffing) during regular operations in order to inform future and more complex tele-operation activities.
2. Applying tele-operations for specific activities that are more consistent and routine in order to de-risk initial steps.
3. Seeking opportunities for sharing experiences between commercial tele-operations and academic partners.

Session 4: Benefits and Workforce Needs

Discussion summary

The final discussion was prompted by the following questions: **"What are the cost-benefit drivers of moving towards remote operations? Is our current workforce ready? What skills should we be teaching to prepare students?"** Participants followed the same discussion format as described in the first discussion section. The results are summarized below.

Benefits

Remote operations enable greater flexibility in how expedition teams are organized. Specialists who may not be able to commit to extended time at-sea or whose expertise may only be needed for specific phases of an expedition could instead provide expertise from shore. Anecdotally, the ability to receive, analyze, and calibrate mission plans from shore may improve interdisciplinary decision-making during expeditions. Greater flexibility in onboard space on a vessel enables reallocation for other roles, including additional educational opportunities. In addition, this flexibility enables greater access to jobs for those that cannot go to sea (e.g., due to disability, caregiving obligations).

Staffing flexibility would benefit the ability to conduct concurrent multi-robot operations from a single vessel. Incorporating multiple robotic technologies on an expedition can provide a greater quantity and variety of data and samples leading to a richer understanding of the environment. However, the operational teams needed for each vehicle or system can stress the available berths on a vessel. By enabling remote operations, portions of the entire operations teams can work from shore while shipboard personnel can assist with launch and recovery and routine maintenance. This approach requires developing a collaborative community across vehicle teams in a new modality (i.e., remotely). While some vehicles handle automated surveys, operators can oversee multiple systems simultaneously, improving staffing efficiency. Ultimately, this enhances the overall effectiveness and efficiency of oceanographic research.

Other potential benefits include overall operational costs for tele-operations expeditions, especially if reduced shipboard staffing enables the use of smaller vessels, which is the primary cost driver for expeditions. In addition, remote operations may provide a greater ability to adapt to changing circumstances that arise when one vehicle system can no longer operate (e.g., due to mechanical failure, weather window), allowing one shoreside team to stand down and others to stand up, rather than sit idly on a working vessel.

Challenges and other considerations

Remote operations require additional considerations, many of which still need to be fully understood by the community to ensure success. First, there are additional costs associated with infrastructure development, training personnel, and maintaining remote operations infrastructure. Infrastructure to support the growing fleet of remote vehicles will need to be developed, staffed, and maintained. It should be noted, however, that much of the foundational infrastructure is in place for most vessels, including connections to LEO satellite networks that enable bidirectional communication with minimal latency.

Failure modes for remote operations are not fully understood. For instance, the operating procedures in a loss-of-communications scenario present a significant challenge. Are autonomous behaviors incorporated into otherwise human-operated vehicles or are emergency recovery and/or stand-by states defined for when communications are lost? How frequent and how extreme loss-of-communications events might occur need to be considered in order to effectively manage them.

Moreover, the community needs to assess what the current workforce will need to learn and what new roles or expertise will need to be added to current operations. Staffing the operations centers for maintenance and operations will require a range of expertise from technical (IT, data systems, networking) to persons to work with remote teams on work practices. Understanding the new social dynamics that result from a distributed workforce and developing new strategies to ensure effective and efficient operations will also be important. Part of this dynamic will include new safety and robust risk management strategies and communications to address potential challenges and ensure the safety and reliability of remote operations.

There are also limitations to conducting operations remotely as data, cameras, and communications between the ship and shore cannot entirely replace being on the vessel. Without the ability to directly observe and interact with the marine environment, the community will need to develop ways to address these deficits and raise awareness for required at-sea personnel and how they should interact with shore-side participants. For example, current limitations in remote sampling and data collection techniques may require shipboard presence of certain technicians or researchers. Additionally, there is a risk of losing valuable at-sea experience, which is crucial for understanding the operational environment and making real-time decisions. The shift away from intensive, cruise-based operations may also have hidden social costs, such as the potential isolation of new hires and challenges in maintaining collaborative efforts among dispersed teams, which will also need to be addressed.

The research community can learn from existing marine remote operations programs to understand infrastructure needs, and skills and requirements for operators and technicians, and to understand strategies to mitigate the aforementioned challenges; however this community will also need to conduct studies to understand the challenges arising from the complexity of ocean exploration scientific research, which is different from industry or single platform ocean robotics operations.

Workforce needs

The forum unanimously determined that the current oceanographic workforce is not prepared to operate remotely. Tele-operations require a workforce that is different from the traditional seagoing technician or researcher, and thus, there are new skills that must be developed and practiced by the community. The marine tele-operations workforce needs to be facile in data management, telepresence systems operations, communication, and teaming in a distributed workspace. The future workforce will require additional experts in network engineering, data visualization and analysis, and rapid prototyping, alongside traditional scientific and engineering expertise. Traditional maritime operations models will need to expand or be adjusted to incorporate additional roles and responsibilities, advanced planning, communications tools and protocols, and workflows necessary for the success of tele-operations and remote science. Although work practices for skilled technicians, engineers, and scientists will change when fully autonomous, uncrewed systems are operational, it remains to be seen if there is a reduction in total persons participating in these missions, or perhaps the addition of persons to support the missions in new capacities.

There was consensus that solutions to ensure that future workers are ready to fill the roles created through tele-operations are needed. One approach to developing a workforce to meet these needs includes the creation of new career tracks within existing maritime academies and universities that incorporate engineering, marine science, and social science knowledge. New opportunities should emphasize the need for multidisciplinary skill development and training across robotic platforms. Although tele-operations will allow workers greater flexibility and work-life balance, programs should incorporate hands-on and at-sea experience to complement theoretical learning. The community can leverage existing successful examples of remote operations in platforms, such as seagliders, for training program best practices.

Lessons learned

Tele-operations can increase the effectiveness and efficiency of ocean expeditions, however the community is still in a learning phase. Multiple robotic assets deployed from a single vessel can collect complementary datasets and incorporate a broader range of expertise. These expeditions can be widely interdisciplinary and will require new types of expertise to develop, execute, and staff. Our current programs are not sufficient to prepare the tele-operations workforce, but there is interest in developing new ways of cultivating skills for tele-operations, many of which are afforded through the distributed work environment (e.g., vessel and shore locations).

The responsibility of implementing these recommendations should be shared across sectors and leverage the natural advantages of each. However, the aim is to continue working though this transition collaboratively, and the divisions below simply provide a suggestion for sectors that might lead particular collaborative efforts. In some instances, we have identified where multiple sectors might take leadership positions.

Government

- Develop and enhance collaborations with U.S. industrial partners who have taken a leadership position in the application of remote operations.
- Support, through funding and operational opportunities, the burgeoning U.S. companies that can contribute to remote operations activities.
- Evaluate and refine standards for remote operations: communication protocols, command and control software, concepts of operations, and documentation/reporting.
- Advance programs for training and up-skilling workers that can directly contribute to commercial remote-operations and likewise support federal and academic ocean exploration enterprises.

Industry

- Advance programs for training and up-skilling workers that can directly contribute to commercial remote-operations and likewise support federal and academic ocean exploration enterprises.
- Establish AI training data sets and digital test beds that can be utilized for developing remote operations capabilities.
- Identify gaps in software, communications, and networks that can enhance and accelerate remote operations paradigms.

Academia, philanthropic, and non-profit institutions

- Develop and enhance collaborations with U.S. industrial partners who have taken a leadership position in the application of remote operations.
- Evaluate the potential on-shoring of tasks for the specific types of operations conducted during ocean exploration expeditions.
- Consider emerging deep-sea applications that could rapidly adopt and benefit from remote operations.
- Ensure that the development of new technologies and systems are readily adaptable to remote operations paradigms.
- Advance programs for training and up-skilling workers that can directly contribute to commercial remote-operations and likewise support federal and academic ocean exploration enterprises.

Conclusion

It is evident that the path to implementing tele-operations is paved by collaboration across sectors. The 2024 National Ocean Exploration Forum was effective in fostering that collaboration through facilitated, intentional discussions. Participants identified challenges, discussed potential solutions, and generated recommendations on how to accelerate this transition. The benefits are clear: expanding access to ocean exploration and research though opening berths for students and community members, utilizing ROCs to increase operational potential (geographically distributed ROCs lends to 24-hour operations) and further expand access to members of the community unable to go to sea, as well as potentially reducing costs after tele-operations is implemented. Moving through this transition together will solidify this operational paradigm shift.

Researchers can build research expeditions encompassing broader participation and more technologies using remote science and tele-operations. I've been working to define and develop telepresence and remote science so that program staff and marine operations personnel can support researchers and students in their use of our vessels and facilities. Retrofitting the R/V Western Flyer and establishing a shoreside facility for remote science requires expertise that is new to traditional marine operations or university staff. Additionally, much of the oceanographic community is not yet familiar with definitions and work practices that support successful remote science or hybrid expeditions. Together with work ethnography and telepresence technology experts, we have a ship, shoreside facility, and work practices to allow people to participate in ROV expeditions from shore.

NICOLE RAINEAULT,
Associate Director of Research and Technology (FIO)

07

Appendices

pg. 21-28

APPENDICES

The primary goal of this small, discussion-based forum was to generate actionable next steps to advance tele-operations. To achieve this goal, participants were intentionally divided into four smaller groups for facilitated discussion.

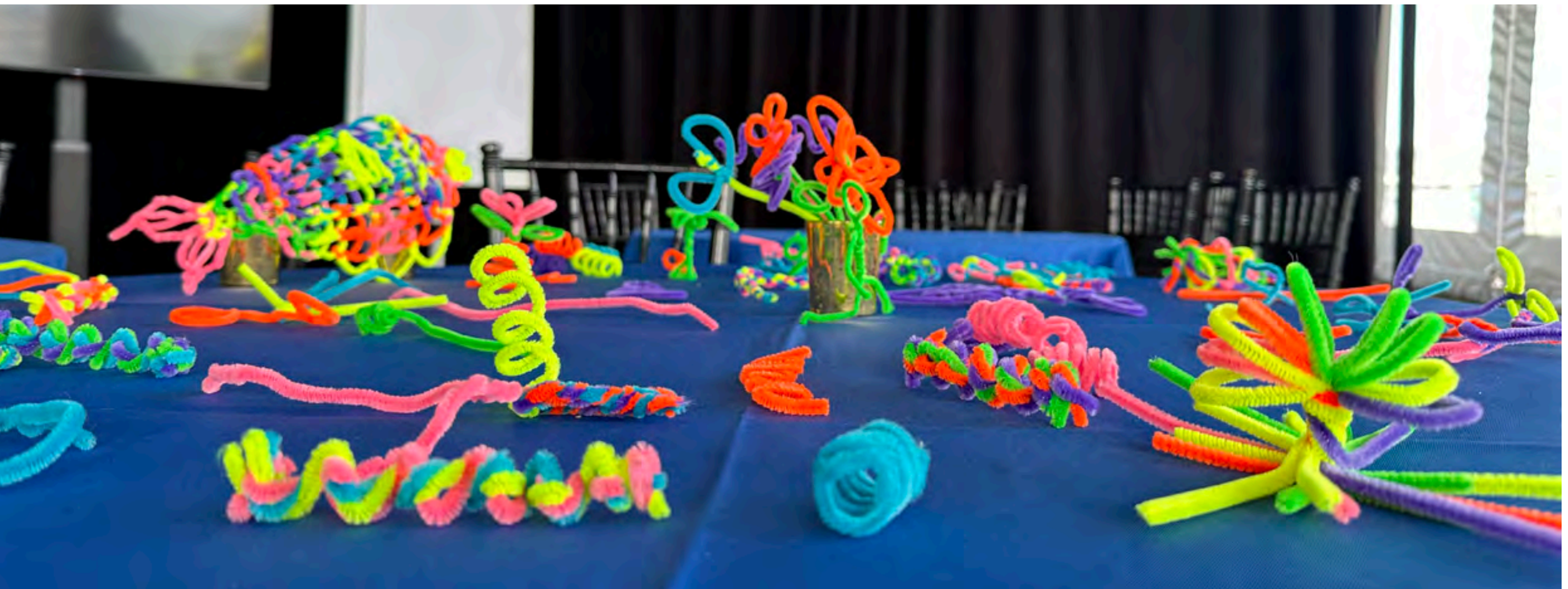
Science Facilitation

Prior to the forum, eight OECI early-career researchers (ECR) participated in six weeks of science facilitation training with Divergent Science LLC. The ECRs learned the science and theory of science facilitation, how to promote psychological safety in group discussion settings, the role of conflict in discussion, and how to manage moments of tension. The lead ECR facilitator undertook an extra six weeks of one-on-one training, which focused on creating agendas, refining breakout room procedures, and intentionally dividing participants in each breakout space. The agenda creation process was guided by topics and objectives determined through discussion with various subject matter experts prior to the forum (Dr. Adam Soule, Jason Fahy, Andy Bowen, Dr. Larry Mayer, Fugro, Dr. Darlene Lim, Dr. Aurora Elmore, Dr. Mashkoor Malik).

Breakout Room Structure

Two ECR science facilitators were present in each of the four breakout spaces to ensure participants stayed focused, respectful, and active in the discussion. They worked to promote psychological safety and equal turn-taking among participants. Participants were placed in breakout spaces based on the criteria below:

- Ensuring equal gender distribution;
- Ensuring equal sector representation;
- Ensuring equal age distribution;
- Placing colleagues in separate spaces;
- Placing early careers or graduate students in separate spaces than their superiors;
- Placing two subject matter experts (discussion leads) in each space to support facilitators;
- Allowing no more than 15 participants in each breakout space; and
- Ensuring equal participant distribution (Note: Breakout room 3 had fewer participants due to no shows on the days of the event).



Breakout Room 1

Aaron Marburg	UW APL Ocean Engineering
Allisa Dalpe	WHOI
Darlene Lim *(Discussion lead)*	NASA Ames Research Center
Edward Cassano	Pelagic Research Services
Eric Martin	MBARI
Holly Pettus *(Lead facilitator)*	OECI/URI
Katy Croff Bell	Ocean Discovery League
Larry Mayer *(Discussion lead)*	UNH
Mark Mueller	BOEM
Nina Pruzinsky *(Facilitator)*	NOAA OER/UCAR
Rachel Medley	NOAA OER
Scott Willcox	Liquid Robotics
Shayan Haque	Exail
Stuart Chance	Chance Maritime Technologies
Zara Mirmalek	NASA BAER

Breakout Room 2

Adam Soule *(Discussion lead)*	OECI/URI
Allison Miller	SOI
Anand Hiroji *(Facilitator)*	USM
Anna Michel *(Discussion lead)*	WHOI
Captain William Mowitt	NOAA OMAO UxSOC
Jennifer Lukens	NOAA OER
Jeremy Weirich	NOAA OER
John Ryan	MBARI
Kevin Harnett	XOcean
Lee Ellett	Scripps
Nina Yang *(Facilitator)*	WHOI
Regina Yopak	Greensea IQ
Richard "Kitch" Kennedy	Saildrone
Stephane Vannuffelen	Exail

Breakout Room 3

Andy Bowen *(Discussion lead)*	WHOI
Kristen Crossett	NOAA OER
Kristine Beran	Teledyne Marine
Leila Hamdan *(Discussion lead)*	USM
Noelle Helder *(Facilitator)*	OET
Olivier Moisan	Exail
Pushyami Kaveti	Northeastern University
Shannon Hoy	NOAA OER
Tara Hicks-Johnson *(Facilitator)*	UNH
Ellen Fisher *(Facilitator)*	Divergent Science

Breakout Room 4

Aurora Elmore	NOAA OER
Ben Kinnaman	Greensea
Dana Manalang	UW APL
Daniel Wagner *(Facilitator)*	OET
Darren Moss	Teledyne Marine
E.C. Helme	Leidos
Hannah Love *(Facilitator)*	Divergent Science LLC
Jason Fahy *(Discussion lead)*	OECI/URI
Jelmer de Winter *(Discussion lead)*	Fugro
Jenna Ehnot	UNH
John Tucker	Terradepth
Mashkoor Malik	NOAA OER
Michael P Scherer	Chance Maritime Technologies
Sebastien Grall	Exail

Dates: October 16-17, 2024, New England Aquarium, Boston, Massachusetts

Meeting Purpose: To determine best path forward to enable government and academic operational exploration to move towards tele-operations

Day 1 : October 16, 2024

Time	Activity	Location
0830	Participant arrival, check - in, coffee & pastries	Simons Theatre Lobby
0900	**Welcome:** Jeremy Weirich, NOAA OER Director **Introduction:** Adam Soule, URI/OECI **Keynote Presentation:** Captian William Mowitt, NOAA UxS **Keynote Presentation:** Jelmer de Winter, FUGRO	Simons Theatre
1025	Coffee/Restroom Break	Simons Theatre Lobby
1040	**Keynote Presentation:** Darlene Lim, NASA Ames Presentation of Breakout Room Process/ Topics	Simons Theatre
1125	Off-site Lunch	Boston Wharf
1300	**Breakout 1:** Interoperability	Harbor Terrace Tent
1510	Coffee/Restroom Break	
1525	**Breakout 2:** AI/ML + Situational Awareness	
1710	**Panel Discussion:** Breakout 1	Simons Theatre
1740	**Panel Discussion:** Breakout 2	
1810	Reception & Dinner	Aquarium Main Gallery

Day 2 : October 17, 2024

Time	Activity	Location
0830	Participant arrival, check - in, coffee & pastries	Simons Theatre Lobby
0900	Welcome Back & Double DriX	Simons Theatre
955	**Breakout 3:** Task Analysis	Harbor Terrace Tent
1120	Coffee/Restroom Break	Entrance to Terrace Tent
1135	Breakout 4 - Cost/Benefit	Harbor Terrace Tent
1300	Off-site Lunch	Boston Wharf
1435	**Panel Discussion:** Breakout 3	Simons Theatre
1510	**Panel Discussion:** Breakout 4	Simons Theatre
1540	Plenary	Simons Theatre
1600	Coffee/Restroom Break	Entrance to Terrace Tent
1615	Voluntary Writing Retreat	Harbor Terrace Tent

Ocean Exploration Cooperative Institute

University of Rhode Island Graduate School of Oceanography
Adam Soule
Jason Fahy
Holly Pettus
Deb Smith
Lori Jaccolucci
Grietje Olmstead

University of Southern Mississippi
Leila Hamdan
Anand Hiroji

Woods Hole Oceanographic Institute
Andy Bowen
Allisa Dalpe
Anna Michel
Nina Yang

University of New Hampshire
Larry Mayer
Jenna Ehnot
Tara Hicks-Johnson

Ocean Exploration Trust
Daniel Wagner
Noelle Helder

National Aeronautics and Space Administration

Jet Propulsion Laboratory
Darlene Lim

Ames Research Center
Zara Mirmalek

Greensea IQ

Ben Kinnaman
Regina Yopak

Liquid Robotics

Scott Wilcox

National Oceanic and Atmospheric Administration

Office of Ocean Exploration
Jeremy Wierich
Aurora Elmore
Kristen Crossett
Jennifer Lukens
Mashkoor Malik
Shannon Hoy
Nina Pruzinsky (UCAR)
Rachael Medley

Office of Marine and Aviation
Captain William Mowitt

University of Washington

Applied Physics Laboratory
Aaron Marburg
Dana Manalan

Schmidt Ocean Institute

Allison Miller

Teledyne Marine

Kristine Beran
Darren Moss

Leidos

E.C. Helme

Pelagic Research Services

Ed Cassano

Divergent Science

Ellen Fisher
Hannah Love

MBARI

Eric Martin
John Ryan

Fugro

Jelmer de Winter

Terradepth

John Tucker

Ocean Discovery League

Katy Croff Bell

Scripps

Lee Ellett

Burea of Energy Management

Mark Mueller

Chance Maritime Technologies

Stuart Chance
Michael P. Scherer

EXAIL

Olivier Moisan
Sebastien Grall
Shayan Haque
Stephane Vannuffelen

Northeastern

Pushyami Kaveti

Saildrone

Richard "Kitch" Kennedy

Thoughts on Standards for Interoperability

Michael P. Scherer

A variety of standards exist for uncrewed systems interoperability that have been created for both commercial and government purposes. The U.S. military has established standards such as the Unmanned Maritime Autonomy Architecture (UMAA) spearheaded by the Navy, and the Joint Architecture for Unmanned Systems (JAUS) which is now managed by the Society of Automotive Engineers (SAE). International militaries use standards such as MAPLE and STANAG 4187. In general these standards are not broadly supported by commercially available platforms that NOAA could use, thus enforcing any of them as a requirement would increase acquisition cost by incurring non-recurring engineering costs.

Open communication standards such as Robotic Operating System 2 (ROS2) have adoption in commercial, academic, and government organizations. ROS2 is an open source framework for programming robotic systems and their behaviors. Existing commercial UMS such as those made by Chance Maritime Technologies, Exail, ..., utilize ROS2. Hardware manufacturers, including for navigation technologies, are also offering ROS(2) drivers. OECI participating academic institutions such as the University of New Hampshire, University of Rhode Island, Ocean Exploration Trust, Woods Hole Oceanographic Institution, and University of Southern Mississippi also utilize ROS2. The broad acceptance of this architecture creates synergies between new developments in academia, as well as workforce development, and to create new autonomous behaviors that can port across academic and commercially available UMS.

Although using a standard framework such as ROS2 has many advantages, it can still be restrictive for new and innovative UMS. For instance, extremely low power UMS may not have sufficient processing power to leverage ROS2, and as such may not be well suited for the standard. Additionally, any existing mature UMS which does not use ROS2 may incur significant non-recurring engineering cost in order to convert. Thus, requiring any standardized architecture, may create barriers to entry even for incumbent providers of UMS.

Participants discussed what a minimum viable product for interoperability might look like, and the needs were often for a Common Operating Picture (COP) of all active UMS and crewed vessels in a region to help with coordination. In its simplest form, a COP could be an existing tool such as Google Earth, where all vehicles provide their location and basic telemetry in the open KML format.

Platform-Payload Integration

A UMS platform generally refers just to the boat or submarine, its mechanical and electrical systems, as well as the software and communication systems to control and monitor those electro-mechanical systems autonomously or remotely. The Payload is all the other equipment that rides along on the platform to collect scientific data, such as sonars, weather stations, magnetometers, eDNA samplers, and any acquisition computer that may be onboard. Similar to on a crewed vessel, platform and payload are distinct so that the operator can swap different payloads onto their existing UMS based on mission need.

Historically, many payloads were designed to be operated manually. Because of this, the majority of existing payloads have a proprietary interface. Even if the interface is openly provided, it remains specific to the payload itself. Thus, two payload devices produced by different manufacturers are not interchangeable without software development effort to interoperate with both. The workaround for this lack of interoperability is to purchase existing data acquisition software such as Hypack, Qinsy, or Beamworx that brings the payload into a common representation. No open source solution exists currently for data acquisition that can fully replace proprietary software. Partial solutions include Espresso for multibeam sonars, OpenSidescan for sidescan sonars, and the work of the ROS2 maritime group to unite many sonars to a common data standard.

There are different levels of payload and platform integration that are possible:

Level	Description	Examples
0	No integration / free running payloads	Data logger runs independently from platform it is installed on
1	Basic communications integration / remote human intervention on payload and basic power cycling	Payload computer with remote desktop connection to remote operating center; operator ability to power cycle some systems
2	Information sharing between payload and platform	Payload exports some data to the platform for monitoring purposes
3	Coordinated behaviors between payload and platform	Auto-survey; platform executes behaviors based on data collected from payload and/or payload drives platform based on its data

In general, increasing levels of integration require increased costs to implement. However, mission needs may drive those costs. In particular, a Level 0 integration, although inexpensive, is disadvantaged because it does not provide the ability for an operator to remotely provide quality control for any data collected. Level 0 integration may not be avoidable on some systems where interfaces are not provided by the original equipment manufacturer of the payload.

Level 1 integration is a middle ground, which generally allows a remote operator to use OEM software to control the payload. This reduces training burden as the operator can use the same software suite that they have been trained on for a crewed vessel. It also reduces acquisition cost because little to no software development is required to integrate to this level.

Level 2 integration adds a minimal amount of monitoring of the payload by a UMS platform. The most typical example might be the sharing of an Inertial Navigation System (INS) between the survey acquisition software and the UMS platform autopilot. The rest of the payload is controlled in the same manner as a Level 1 integration.

Level 3 integration is more intimate, where custom autonomy behaviors direct UMS platform activities based on payload sensors. One example includes automatic multibeam survey coverage, where the sonar coverage from the payload is used to dynamically generate lines that are driven by the UMS platform.

Inter-Platform Integration

Integration can also occur between platforms, both within the same domain such as the use of multiple force multiplier UMS of the same type, and cross-domain such as the deployment of a tethered ROV from a USV. This integration can take on multiple levels:

Level	Description	Examples
0	No Integration	Systems are coordinated by human operators communicating with each other
1	Common Operating Picture	Multiple UMS export their position in real time to Google Earth
2	Coordinated Behaviors	Directed sampling and swarming behaviors

Level 0 integration is the most common reality for multi-UMS operations. In this mode, human operators coordinate between all UMS ensuring they are navigated safely and do not conflict with one another.

Level 1 integration uses a Common Operating Picture (COP) to give visibility to all remote operators essential telemetry. This minimal level of integration helps to increase safety for multi-UMS operations so that the captain of the mothership and all the UMS operators are able to understand the location of vessels. A minimum viable product only requires the current position, course, speed, and heading (if available) of each UMS and crewed vehicle to be streamed to a COP. Simple COP's include Google Earth, which can utilize the open standard Keyhole Markup Language (KML) format to plot the position of all vehicles.

Level 2: Coordinated Behaviors

- Directed sampling
- Note for some coordinated behaviors, it may require each platform to be deeply integrated with its payload.

[May want to note that platform-payload and platform-platform integration (as described) are endmembers of a spectrum and that some integrations such as a deployable autonomous sampling system from an autonomous platform may draw insight from both endmember cases.

A variety of standards exist for uncrewed systems interoperability that have been created for both commercial and government purposes. The U.S. military has established standards such as the Unmanned Maritime Autonomy Architecture (UMAA) spearheaded by the Navy, and the Joint Architecture for Unmanned Systems (JAUS) which is now managed by the Society of Automotive Engineers (SAE). International militaries use standards such as MAPLE and STANAG 4187. In general these standards are not broadly supported by commercially available platforms that NOAA could use, thus requiring them would increase acquisition cost by incurring non-recurring engineering costs.

Open communication standards, such as Robotic Operating System 2 (ROS2), have adoption in commercial, academic, and government organizations. ROS2 is an open-source framework for programming robotic systems and their behaviors. Existing commercial uncrewed marine systems (UMS), such as those made by Chance Maritime Technologies, Exail, and more, utilize ROS2. Hardware manufacturers, including for navigation technologies, are also offering ROS2 drivers. All OECI institutions, including the University of Rhode Island (URI), University of New Hampshire (UNH), Ocean Exploration Trust (OET), Woods Hole Oceanographic Institution (WHOI), and University of Southern Mississippi (USM), also utilize ROS2. The broad acceptance of this architecture creates synergies between new developments in academia (and non-profit organizations such as OET), as well as workforce development, and creates new autonomous behaviors that can port across academic and commercially available UMS.

Although using a standard framework, such as ROS2, has many advantages, it can still be restrictive for new and innovative UMS. For instance, extremely low power UMS may not have sufficient processing power to leverage ROS2, and as such may not be well suited for the standard. Additionally, any existing mature UMS which does not use ROS2 may incur a significant non-recurring engineering cost in order to convert. Thus, requiring any standardized architecture, may create barriers to entry even for incumbent providers of UMS. However, broad-based adoption is likely to result in work-around solutions, even for these types of 'edge' cases.

Abbreviations

V

AI - Artificial Intelligence

API - Application Program Interface

AR - Augmented Reality

ASV - Autonomous Surface Vessel

AUV - Autonomous Underwater Vehicle

COP - Common Operating Picture

DSL - Deep Submergence Laboratory

ECR - Early Career Researcher

IT - information technology

JAUS - Joint Architecture for Unmanned Systems

LEO Satellites - Low earth orbit satellites

OECI - Ocean Exploration Cooperative Institute

MAPLE

ML - Machine Learning

MVP - Minimum Viable Product

NASA - National Aeronautics and Space Administration

NSF - National Science Foundation

NOAA - National Oceanic and Atmospheric Administration

RF - Radio Frequency

ROC - Remote Operations Center

ROS2 - Robotic Operating System

ROV - Remotely Operated Vehicle

SA - Situational Awareness

SAE - Society of Automotive Engineers

UMAA - Unmanned Maritime Autonomy Architecture

UMS - Unmanned Systems

USV - Uncrewed Surface Vessel

UxS - Uncrewed Systems

VR - Virtual Reality

WBS - Work Breakdown Structure

References

VI

Manda, Damian. Development of autonomous surface vessels for hydrographic survey applications. MS thesis. University of New Hampshire, 2016.

Mirmalek and Raineault. Remote Science at Sea with Remotely Operated Vehicles. Frontiers in Robotics and AI. 2024.

OCEAN EXPLORATION COOPERATIVE INSTITUTE

oeci

EXPLORING THE NATION'S BLUE FRONTIER

NOAA OCEAN EXPLORATION