From Saltwater to Freshwater: Leveraging Uncrewed Vehicles Developed for Offshore Energy Use for Inland Waterway Structural Health Monitoring

HELEN STEWART, RICHARD SIMPSON, PAIGE McCALEB and RACHEL PADILLA

ABSTRACT

Inland waterway infrastructure for drinking water supply, flood control, and navigation safety in the United States is aging and in need of inspection and monitoring to support continuous operations. Current in-situ methods for structural health monitoring are resource-intensive and may carry unacceptable safety risks, particularly with respect to putting human divers or vessel operators into harm's way, while small inspection-class remotely operated vehicles may be limited in range, payload capacity, or available topside-supplied power. These traditional approaches can limit the overall efficiency, effectiveness, and ability to carry out critical monitoring when needed.

Uncrewed Surface Vehicles (USVs) equipped with underwater Electric Remotely Operated Vehicles (eROVs) can offer a safe, efficient, resource-effective inspection of inland waterway infrastructure for challenging infrastructure inspection projects. Developed to conduct subsea asset inspections for offshore energy projects, these combined USV-eROV systems are capable of withstanding harsh environmental conditions with zero access to external power or fuel supplies for up to 14 days. Uncrewed vehicle-based monitoring technologies provide insights to asset owners in challenging locations, offering early context of developing threats to inland waterway structures. Despite these technological advances, conducting inspections with uncrewed systems requires substantial planning and effort well beyond simple selection of payload instruments. In this paper, we will present key lessons learned of USV-eROV asset inspections in the offshore environment and discuss how these methods are relevant to the inland waterway asset management space.

INTRODUCTION

Commercially-operated uncrewed systems have been in use for asset inspections of offshore infrastructure since the mid-2010s. These early Autonomous Underwater Vehicles (AUVs) [1] and Autonomous Inspection Vehicles (AIVs) [2] were intended for inspection of subsea pipelines using pre-programmed mission plans, and focused on

Helen Stewart, Fugro USA, 13501 Katy Fwy Suite 1050, Houston TX 77059
Richard Simpson, Fugro USA, 13501 Katy Fwy Suite 1050, Houston TX 77059
Paige McCaleb, Fugro USA, 13501 Katy Fwy Suite 1050, Houston TX 77059
Rachel Padilla, Fugro USA, 13501 Katy Fwy Suite 1050, Houston TX 77059

inspections of pipelines outside the industry standard 500 meter exclusion zone around platforms. As uncrewed technology advanced, USVs began to acquire condition data from surface-based acoustic instruments and later with acoustic, magnetic, and optical payload instruments on eROVs. The first commercial inspection campaign of offshore oil and gas infrastructure with a USV and eROV was conducted by Fugro in 2021, and the commercial inspection of offshore wind infrastructure with a USV and eROV was conducted in 2023.

Offshore safety is a primary driver of the transition to uncrewed vehicles: transitioning from crewed vessels and diver operations to uncrewed vehicles with eROVs represents a 100% reduction in offshore exposure hours and potential injuries to humans working at sea. In particular, the reduction in diver exposure hours is a significant goal, as the commercial energy-sector diver fatality rate is estimated between 2-11 deaths per 10,000 divers per annum (depending on country and type of work) [3]. Worker safety in Remote Operations Centers (ROCs) is also an improvement relative to ship-based work. There is no need to drive long distances to meet vessels, eliminating a common cause of offshore lost time incidents and fatalities [4]. Crews work 12-hour days in a 14-day-on, 14-day-off rotation which allows them to rest and minimize stress levels and fatigue. Inland waterway infrastructure requiring inspection can be similarly dangerous, particularly for divers, and there is value in reducing overall safety risk with uncrewed systems.

Although the working environments are markedly different, useful parallels exist between inshore and offshore asset inspections for USVs equipped with eROVs. Production platforms have legs in the water and multiple deck levels (e.g., drill floor, helicopter deck) above waterline, creating the same partially-obscured sky view and GNSS multipath issues as a USV operating near a bridge. Working near Floating Offshore Production Units (FPSOs) approximates working on the upstream side of a dam or inside a lock. We note that inland waterways, by definition, are water bodies located inshore of the 1972 International Regulations for Prevention of Collisions at Sea (COLREGs) Demarcation Line [5]. Water resources infrastructure (such as treated wastewater outfall pipes) may be located in inland bays and basins that are entirely salt or brackish water, or they may be in subsidence areas which exposes infrastructure designed for freshwater only to saltwater intrusion. This poses challenges for ballasting and buoyancy control for eROVs and subsea inspection equipment similar to what is found in the offshore environment.

This paper presents key lessons learned about safely and effectively conducting USV and eROV asset inspections in the offshore environment with comments and insights on how these lessons can be transferred to inland waterway asset monitoring. These lessons, perhaps surprisingly, do not focus on payload instrumentation or survey and inspection procedures, but rather on the background work and operational planning that must occur many months before arriving on site for an inspection project.

KEY POINT 1: REGULATORY COMPLIANCE

Regulatory compliance for uncrewed vehicles is a complex challenge that reflects the difficulties of incorporating novel technology with the need for ensuring safe operations at sea. USV operators must work to ensure that they know who the regulatory bodies they must answer to are as well as know the regulations that apply to their

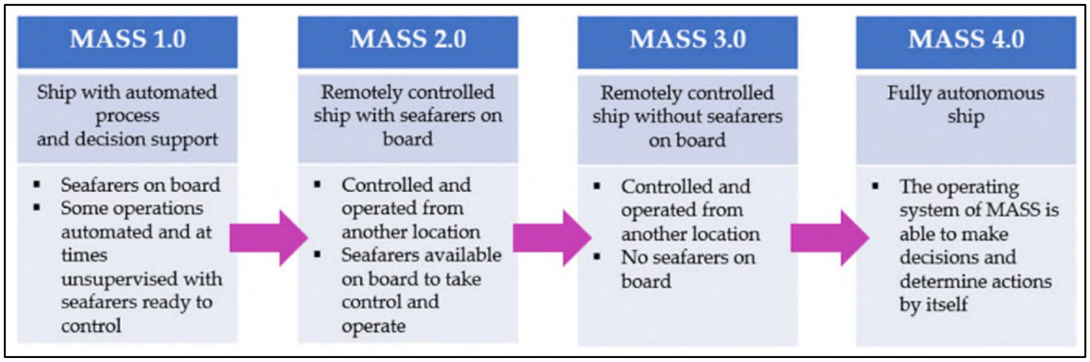

Figure 1. International Maritime Organization Degrees of Autonomy Definitions

vehicles. Significant due diligence by the operator is required to ensure that all regulations are being followed, and the risk of noncompliance range from refusal to issue operating permits to seizure and impoundment of the USV or eROV.

Persistent ocean-going Maritime Autonomous Surface Ships (MASS) are legally considered as vessels engaging in navigation by the International Maritime Organization (IMO) regardless of whether they are under flag or port state control. [6] We note that in the context of this discussion, "uncrewed" and "autonomous" are not synonymous. The IMO defines the degree of autonomy in four levels; "uncrewed" corresponds to MASS Degree 3.0 while "autonomous" corresponds to MASS Degree 4.0. [7] Figure 1 shows the IMO definitions of degrees of autonomy.

Factors influencing regulation and registration include length overall of the vehicle, tonnage, intended degree of autonomy, and intended use. [8] IMO guidelines state that the master of a MASS 3.0 uncrewed USV is analogous to that of conventional crewed ships, from which it follows that the master of a MASS 3.0 surveying vehicle should hold a comparable license to that of a crewed vessel of the same class. [9] There is some ambiguity in the definition of "a crewed vessel of the same class," however, and without explicit IMO instructions, the individual flag state administrations may designate the minimum license requirements for operations in the flag country's waters. The USV operator must liaise with the regulators to determine the minimum license required.

Specifically for survey and inspection operations, further due diligence on the part of the USV operator is required to what regulations apply to surveying activities. For example, while the USV is prohibited from towing another vessel, it may tow both surface geophysical instruments such as side scan sonars and eROVs for subsurface inspections in accordance with towing regulations in the United Kingdom and with IMO and COLREGs requirements. The USVs must carry appropriate lights and day shapes for towing, must be able to control the towed equipment or USV entirely from the ROC, and must be able to alert other vessel traffic via radio link or AIS that the vehicle is engaged in towing or is restricted in ability to maneuver. These regulatory compliance questions are separate from standard industry procedures such as operating in the 500 meter exclusion zone around an offshore energy asset.

The USV master must have the same 360° visibility and watchkeeping abilities as found on a crewed vessel, including relief watchstanders, radar, and cameras. The ROC must have enough display monitors for the 360° awareness as well as weather, current, tide, and environmental awareness during operations. Figure 2 shows an example of a ROC with labels describing the different control and viewing monitors. At the time this photo was taken, the USV was engaged in survey operations. Note the camera view of the internal control room, radar and infrared camera monitors, and the day

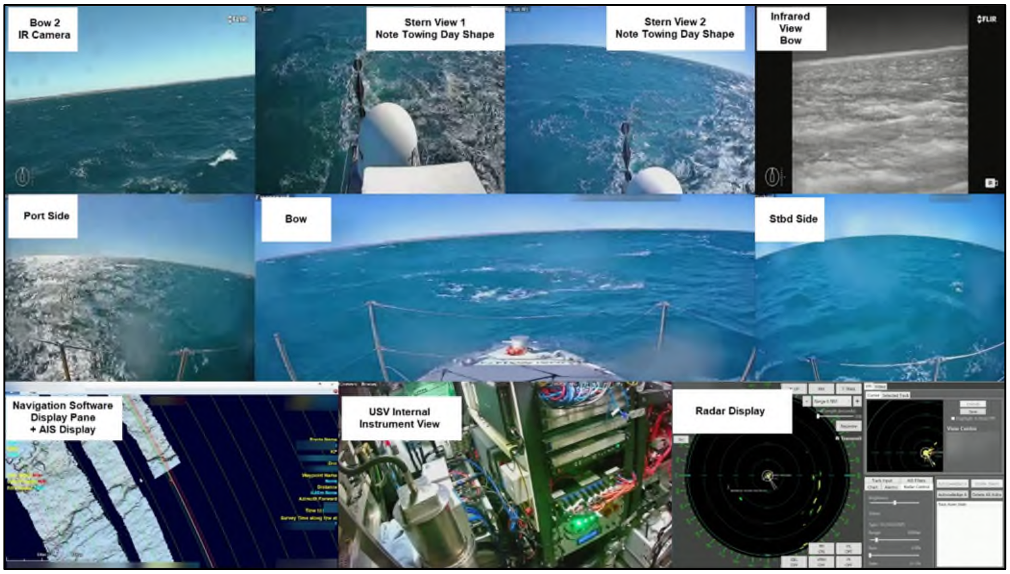

Figure 2. Remote Operations Center vehicle master's control view

shapes shown in the two stern views. For operations in inland waterways, display strings for the USV master could include river current, river stage, air gaps under bridges or overhead pipelines, or lake levels.

KEY POINT 2: REDUNDANCY

Uncrewed vehicles used for offshore inspections must be able to fulfill all tasks undertaken by crewed vessels, including having sufficient endurance for multiple missions without refueling, reliable communications with remote management teams, and having all necessary payload instruments correctly mobilized prior to departure. Without the benefit of an on-site human operating or maintenance crew, the greatest overall requirement for successful USV and eROV operations is having multiple layers of redundant failsafes for every major system category, including multiple redundant layers in physical systems as well as failsafes written into procedural controls.

Relative to projects in inland waterways where distances to safe havens are shorter and additional communications and positioning methods are possible, or to projects using small uncrewed vehicles with limited endurance, the following requirements may seem excessive. Experience with long-endurance USVs in commercial service show that the following requirements are necessary for safety and to ensure that projects are completed in accordance with contractual specifications.

Communications Redundancy

Commercial USVs are controlled by users in shore-based Remote Operations Centers (ROCs) for over-the-horizon capable vehicles or in ship or land-based Control Centers (CCs) for line-of-sight-only capable vehicles. Regardless of distance from the vehicle, operators must have redundant communication and control mechanisms. Data bonding with combined replication and aggregation provides resilience against

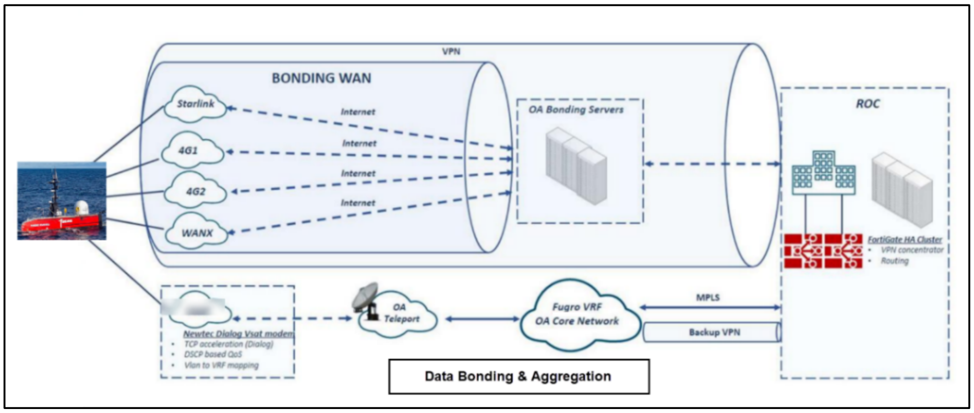

Figure 3. Data bonding and aggregation example

communications outages. Replication sends data packets over multiple links to reduce the impact on operations of outages on any one link. Aggregation spreads data packets through all available channels to reduce network latency, while dynamically detecting packet loss or delays and adjusting traffic priorities accordingly. Figure 3 shows a schematic diagram of the data bonding used for the remote inspection USV.

Power & Control Redundancy

All USV power systems have redundant backup capability: dual motors, dual propulsion shafts, dual generators, and redundant battery packs for continuous clean power to payload instruments. Azimuthal thrusters, while intended for station-keeping use during inspection operations, may be used to steer the USV in close quarters or to guide the vehicle to a safe spot to loiter in the case of primary propulsion failure.

USV & eROV Positioning Redundancy

USVs and eROVs used for inspection purposes in commercial service are typically equipped with high-specification Inertial Navigation Systems (INS), both for positioning quality and for ensuring that inspection data is fit-for-purpose. USVs with GNSS positioning may add redundancy by selecting systems with access to multiple constellations (GPS, GLONASS, Galileo, Beidou), which together can provide adequate surface positioning satellite geometry even with partial sky blockage. A Doppler Velocity Log (DVL) on the USV simultaneously observes currents, to determine if station-keeping is possible in those conditions, and acts as an aiding source to the INS. DVL aiding is especially useful in GNSS-denied environments or in high-multipath environments.

An Ultra Short Baseline (USBL) transceiver aboard the USV is used to provide positions to an INS system aboard the eROV via redundant beacons. The eROV also has a DVL system for inertial positioning as well as optical and acoustic cameras for relative positioning. The eROV INS can be configured to accept lines of position from a sparse subsurface transponder array, although these cannot currently be deployed by the USV itself.

KEY POINT 3: OPERATIONAL PROCEDURES

Successful execution of a remote inspection project begins with developing standing orders and project-specific operational procedures.

Standing orders are generally required by law where commercial vessels, including USVs, are working. For work in inland waterways, where navigation room is restricted by channel width, standing orders must include procedures for narrow channels and traffic separation schemes. [10] USVs with or without eROVs engaged in survey or inspection operations must have standing orders that follow existing laws and best practices, and the project-specific procedures must be in agreement with standing orders. It is common for commercial clients to have their own standing orders, particularly for safety and for operations within the 500 m exclusion zone around an offshore structure. Again, due diligence is key, and USV operators are advised to carefully review internal and client-specific standing orders for discrepancies well in advance of commencing survey or inspection operations. Figure 4 shows a sample USV standing order decision matrix for safe operations during Simultaneous Operations (SIMOPS) within the 500 m exclusion zone around a structure.

Project- and site-specific procedures act as bridging documents between operator and client standing orders and inform survey and inspection crews of expected local conditions at each inspection site in the project. Conducting a desktop study of expected environmental and vessel traffic conditions is strongly recommended as the first step to creating project and site procedures, especially for commercial projects with crews or contracted client representatives who may not be familiar with the project site. The desktop study should include expected environmental conditions, known environmental risks or hazards, factors that may lead to downtime, and an understanding of what are the safe working limits at the project sites. The crew of a USV working in a large lake or dam reservoir will need to understand wave and wind conditions, while crews working a project in an estuarine river will need to understand streamflow and river stages, wind-driven fetch, tidal currents, and the inshore extent of the tidal prism.

Regardless of location, for safety the desktop study should identify safe harbors or anchorages for the USV for different expected environmental conditions and a thorough plan for collision avoidance in restricted channels. This will inform crews on how to plan for and manage operations in high-traffic conditions, in SIMOPS situations, or what to do in the case of a USV position runoff.

Activity Specific Operating Guidelines - SIMOPS					
SIMOPS		Green	Advisory	Yellow	Red
	Notify Master, USV Supervisor, Client Rep, Surface Facility	NO	YES	YES	YES
		Continue Normal Operations	Bring USV/ROV to Safe Position Inform/Consult/Risk Assess Consider Ongoing Operations	Cease Operations. Confirm Safe Position. Prepare to exit Work Site if Necessary	ABORT OPERATIONS - Initiate Contingency Measures. Confirm USV/ROV Recovery, Exit Site
	Change from Green DP Status of any other Vessel in the Field	Green	Advisory	Advisory	Advisory
	Comms / Interaction with other Vessels	Vessels operating normally with no known problems	Comms Problem or possible position conflict	No Comms or definite position conflict	
	Helicopter Operations	No planned operations	Unplanned Helicopter Operations Pending	Operations with landing / take-off Conflicts	
	Comms with Surface Facility	Redundant Comms	Comms Problem	One Comms System Remaining	

Figure 4. Sample Standing Orders for SIMOPS

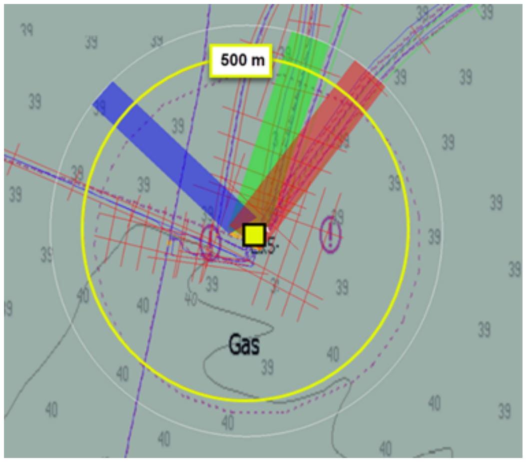

Figure 5. GNSS correction satellite shadows around gas platform (blue, green, & red rectangles)

The desktop study should also identify risks to telecommunications or GNSS coverage throughout the entire project area. If required, additional modes of communications (such as 5G networks inshore or temporary repeater antennas) may be proposed and added to the work scope. In areas where GNSS shadowing and multipath is a concern, position planning should include considerations for instrument selection (e.g., a higher-specification INS or DVL bottom tracking), additional shore-based positioning support (e.g., total stations or transponders), or deployment of subsurface positioning equipment in advance of USV/eROV arrival. Figure 5 shows the 500 m exclusion zone around a gas platform (yellow square) and shadow zones for three different communications satellites (blue, green, and red rectangles) that broadcast GNSS position corrections. Red lines are survey runlines for the project. In this instance, the project-specific operational procedures must include instructions on automatic or user-directed selection of broadcast corrections sources and ways to validate the selected source, and the procedures should include instructions for running survey lines to minimize the effects of corrections outages.

Project-specific procedures related to minimize satellite uplink downtime should consider data transmission and on-board data storage capability. If there is no provision for data storage on board, or if telemetry operations include real-time asset integrity decision-making by inspectors in the ROC, extra steps must be taken to determine what fail-safes are required. For projects where large data volumes are expected, such as a multibeam sonar inspection, this must be planned for in advance and suitable on-board data storage and data transfer protocols must be established. In inland areas, additional shore-based telemetry connections may be added.

Finally, crew requirements and expected workflows during inspection operations must be carefully assessed. Many years of experience with AUV operations and with limited onboard crew projects has shown that expected crew workload for survey or inspection tasks does not change simply because crew members are working on shore (for example, an inspection project that requires four online surveyors and four data processors for 24-hour operations on a crewed vessel will require the same number of people in an onshore role). If different types of inspection will be conducted during the same USV mission or eROV dive, crew procedures should explicitly state the order of inspections and provide instructions on adapting workflows should an anomalous condition be observed on the asset.

SUMMARY

In the offshore industry we are facing multiple challenges that have parallels in the inshore industry that is driving companies like Fugro to develop remote and autonomous solutions. It is crucial that such solutions are safe, compliant and fit for purpose. Over the past 5 years since Fugro has developed USV and eROV solutions for offshore scenarios, many lessons have been learned but this is still nascent technology and it is in a constant state of evolution with respect to the key points outlined.

If there is a single lesson to be learned in the USV development it is early engagement with all stakeholders is necessary, especially regulatory agencies and clients that have lived with a very entrenched mindset. Having said that, it is clear industry adoption of remote operations has been met with enthusiasm even if tempered with a very healthy dose of caution. Also, like with many new technologies, the technology is ahead of regulation, so it becomes a learning experience for all parties involved.

Given the challenges faced in asset integrity both offshore and inshore the future is decidedly tilted towards more and more remote and uncrewed operations, but it must be supported with a robust infrastructure, strong cybersecurity and a workforce trained in the new ways of acquiring data.

REFERENCES

1. Kongsberg Maritime. 2013. "Pipe Dreams." *The Full Picture*, January 2013, 12-16
2. Offshore Engineer. 2014. "Subsea 7 AIV completes trials. *Offshore Engineer*, August 2014. https://www.oedigital.com/news/455242-subsea-7-aiv-completes-trials
3. Woods, A. 2023. "A Report on Fatalities in Commercial Diving," Institute of Energy and Environmental Flows, University of Cambridge.
4. International Marine Contractor's Association. 2021. "2020 Safety Statistics," International Marine Contractor's Association, London.
5. International Maritime Organization. 2003. "Convention on the International Regulations for Preventing Collisions at Sea, 1972." International Maritime Organization, London, UK.
6. Defence Safety Authority. 2024. "DSA03-DMR Guide to Regulation of Maritime Autonomous Systems." Ministry of Defence, London, United Kingdom.
7. M. Issa, A. Ilinca, H. Ibrahim, and P. Rizk. 2022. "Maritime Autonomous Surface Ships: Problems and Challenges Facing the Regulatory Process," *Sustainability,* 14(23): 15630.
8. Transport Canada. 2024. "Tier 1 – Policy – Oversight of small Maritime Autonomous Surface Ships (MASS)." Transport Canada, Ottawa.
9. IMO Maritime Safety Committee. 2023. "Development of a Goal-Based Instrument for Maritime Autonomous Surface Ships (MASS)." International Maritime Organization, London.
10. United States Coast Guard. 2023. "Navigation Rules 9.e.i." Department of Homeland Security, Washington D.C.