

An Operational Field Study: A Comparison of Piloting Uncrewed Underwater Vehicles and Uncrewed Aircraft Systems

David Thirtyacre¹, Joe Cerreta¹, Pete Miller², Kimberly Luthi¹, and Jolee Thirtyacre³

¹Embry-Riddle Aeronautical University, Daytona Beach, FL 32814, USA

²Warren Community College, Washington NJ, 07882, USA

³University of Washington, Seattle, WA 98195, USA

ABSTRACT

As offshore industries increasingly adopt uncrewed technologies for inspections and operations, the ability to cross-train personnel in both Uncrewed Underwater Vehicles and Small Uncrewed Aircraft System operations has become a focal point for efficiency and workforce optimization. This study presents a comparative analysis of the operational and human factor considerations involved in piloting mini UUV and sUASs, highlighting the key similarities and differences in control methods, environmental influences, navigation, emergency procedures, and situational awareness. A qualitative experimental field study was conducted between July 2024 and October 2024, involving real-world deployments of both systems in maritime and aerial environments. Findings indicated that while UUV and sUAS operators relied on remote control interfaces, sensor integration, and procedural standardization, significant differences exist in environmental, human factors, and control mechanisms. UUV operations required expertise in tether management, underwater currents, and video-based navigation, whereas sUAS operations emphasized GNSS-based positioning, wind resistance, and airspace regulations. Despite these distinctions, aligning control interfaces/mapping and adopting standardized training protocols could enhance operator adaptability between the two systems. The research supported cross-training feasibility in operating both UUSs and sUASs, potentially reducing crew size and operational costs while maintaining safety and efficiency. However, cognitive load management, regulatory compliance, environmental adaptation, and human factors must be addressed to optimize cross-platform competency.

Keywords: Small uncrewed aircraft systems (sUAS), Remotely operated vehicle (ROV), Unmanned underwater vehicle (UUV), Offshore inspections, Situational awareness, Human factors, Workforce optimization

INTRODUCTION

Uncrewed Underwater Vehicles (UUVs), also known as Remotely Operated underwater Vehicles (ROVs), support energy equipment such as offshore oil and gas platforms, via underwater inspections and security monitoring (Mercer, 2010). Gómez and Green (2017) suggested using multirotor Small Uncrewed Aircraft Systems (sUAS) to perform overwater small site inspections, such as offshore oil and gas structures, and fixed-wing sUAS for larger areas or linear infrastructure, such as pipelines. Most major oil and gas companies now use UUVs and sUAS to perform inspections, including Chevron, Equinor, National Offshore Oil Corporation (CNOOC), Repsol, Saudi Aramco, Shell, and Total (Thomas, 2024). The American Petroleum Institute found a 75% decrease in falling accidents when inspecting offshore rigs with sUAS while performing the inspections five to ten times faster than traditional methods (Anonymous, 2024).

Offshore oil and gas facilities have limited personnel and confined space for living and working conditions (Lempriere, 2017). Recent trends in offshore platform rigs leverage technology to reduce the rig's weight and create smaller footprints (Carter, 2000). Limiting the rig's footprint also reduces the crew's size. The ability to cross-train crewmembers supports finding the proper balance between crewmember skills, workload distribution, training, and providing sufficient rest periods for workers, according to Da Ponte (2021). Often, this training occurs on the job. In addition to sUAS, other robotic systems, including UUVs offer benefits for performing necessary tasks on offshore oil and gas platforms, such as integrity inspections.

sUAS pilots focus on flight activities to acquire data supporting general and close visual inspections. Compared to traditional approaches, leveraging technologies such as sUAS can save approximately 25% to 75% in both cost and time (Wanasinghe et al., 2020). Employing both sUAS and UUV creates opportunities to reduce safety risk by lowering probability of accidents than deploying field personnel.

The International Marine Contractors Association (IMCA) provides UUV industry guidelines regarding competency and certification for UUV operators (Mercer, 2010). Mercer also developed a technical and further education (TAFE) framework of competencies required to operate UUVs. These competencies were organized into categories, including several that cross over between UUVs and sUAS, such as communications, mission planning, and operations. Still, the IMCA's guidelines and Mercer's TAFE framework are only guidelines and not compulsory requirements. In the U.S., sUAS operations are governed by Federal Aviation Regulations (14 CFR 107); however, the regulatory requirements are not specific to the competencies required to remain compliant with the regulations.

This research compares the operational considerations required to pilot a mini UUV and sUAS. Understanding the interchangeability of these operational considerations can support cross-training personnel to employ the same operator for both UUV and UAS operations. Rapidly switching between maritime and air domains can provide unique insights and

operational flexibility. However, mastering the specific nuances of each environment, such as wind conditions for sUAS and water currents for UUVs, remains essential. Additionally, the operator must adapt to different sensor systems and data interpretation methods. While cross-platform expertise can be beneficial, specialized training for each platform is still required to ensure optimal performance and safety.

METHODOLOGY

To compare operational considerations between mini UUVs and sUAS, three researchers with experience in both UUV and sUAS evaluated their similarities and differences. A qualitative experimental field study of UUV operations compared to sUAS operations was conducted from July 2024 to October 2024. Field data were captured from observations during two deployments, one for each domain.

Study Areas

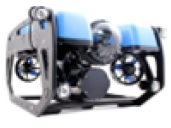
The UUV data collection took place at Friday Harbor, Washington selected due to its mild weather, multiple submerged vessels, and support from the University of Washington's Friday Harbor Marine Laboratory. Four research sites were selected within 30 minutes of Friday Harbor by boat, at a depth of less than 75 feet, and with submerged vessels indicated on NOAA nautical charts and/or the NOAA Automated Wreck and Obstructions Information System (AWOIS). The site offered quick target acquisition with side-scan sonar (SSS) to deploy the UUV and conduct the observations. The research timing was based on local tidal action, which varied daily. All dives occurred with less than two knots of current and over a three-day period. Each site was explored and yielded confirmation of a submerged vessel, although the wreckage was severely deteriorated in all cases. These sites were visited on consecutive days, with multiple UUV dives at each location.

The sUAS portion data collection occurred in Paulden, Arizona chosen for its mild weather, uncontrolled airspace, and landowner permission. The Gunsite Academy provided an operational launch and recovery site (LRS) with electrical power and Internet access. There were two LRSs located on the Gunsite Academy property for day and night operations. The weather was conducive for flight operations with winds at 6 knots gusting to 12 knots, visibility of 10 statute miles, and clear skies.

Research Equipment

This field study used two mini UUVs and two sUASs, consisting of the Blue Robotics BlueROV2 (Blue Robotics, 2024) and the Chasing M2 (Chasing, 2024). The sUAS consisted of the DJI Mavic 2 Enterprise Advanced (DJI, 2022) and the senseFly eBee X (AgEagle, 2024). The selection of this research equipment represented reasonably priced and readily available platforms. The research team was able to operate all four vehicles effectively to collect field observations. Table 1 illustrates the specific robots.

Table 1: Research equipment comparison.

				
Specification	BlueROV2	Chasing M2	DJI M2EA	senseFly eBee X
Dimensions (LxWxH)	56x51x36cm	38x27x17cm	21x9x8cm	50x26x14cm
Thrusters / Motors	6	8	4	1
Weight	20 kg	4.5 kg	0.9 kg	1.3 kg
Maximum Speed	3 knots	3 knots	39 knots	37 knots
Depth / Ceiling	300 feet	328 feet	400 feet*	400 feet*
Operating Time	1–3 hours	4 hours	31 minutes	90 minutes
Cameras	1080p	1080p/4K UHD	4K UHD, 48 MP RGB	12 MP RGB
Control Interface	Tethered	Tethered	2.4GHz, 5.8GHz wireless	2.4GHz wireless
Software	QGroundcontrol	Proprietary	Proprietary, UgCS	Proprietary

Note. Research equipment used for data collection. *denotes a regulatory limitation under 14 CFR 107.

Data Analysis

This study compares the operational differences between mini UUVs in a maritime environment and sUAS in an airborne environment. Qualitative data were gathered using open-ended oral survey questions, in-depth discussions, and field observations of subject matter experts (SME). The SMEs performed a series of scenarios and tasks that UUVs and sUAS might encounter in marine or airborne environments.

- The UUV scenarios included conducting underwater surveys to map known shipwreck locations, inspecting underwater structures, such as pipelines, cables, and offshore platforms, and locating and retrieving objects lost at sea.
- The sUAS scenarios included conducting aerial surveys to map an area of interest, inspecting elevated electrical distribution lines, and searching for a lost person in an austere high desert environment.

For each scenario, SMEs provided field observations about the similarities and differences between operating UUVs and sUAS within nine operational competency key performance categories. These areas included (in alphabetical order) Control Methods, Crew Resource Management, Datalink Management, Emergency Procedures, Energy Management, Environmental Considerations, Navigation, Operational Planning and Execution, and

Situational Awareness. Each researcher coded the qualitative data into key categories, which were then cross-compared to ensure consistency. Through iterative discussions, the researchers reached consensus on the primary operational similarities and differences.

RESULTS

The results of the field study are presented by operational categories. Following a brief description of each category, UUV and sUAS operations are discussed followed by a summary of SME observations when needed.

Control Methods

The UUVs and sUASs used control station equipment to manage the vehicle's orientation, position, and depth or altitude. UUV control station equipment consisted of a handheld remote controller with a two-stick configuration to control depth, yaw, roll, translational movement, and additional wheels for camera and/or pitch directional changes. The BlueROV2's remote controller was connected to a laptop computer running QGroundControl software. Although the Chasing M2 was also configured with a two-stick remote controller, the controller was directly tethered to the UUV. The Chasing M2's remote controller contained a port to connect a mobile device, such as a smartphone or tablet, to observe telemetry and video via proprietary software without a laptop computer. An interesting observation was that the Chasing M2 and the Mavic-2 EA were controlled similarly using a pilot box or remote controller, while the BlueROV2 and the eBee X both utilized a laptop-based interface. Additionally, all systems allowed some customization of the control mapping (i.e., the specific command assigned to each stick or control movement).

UUV Control Description

UUV control methods included buoyancy control to maintain neutral to slightly positive buoyancy. A state of neutral buoyancy conserves battery life as the operator does not expend excessive power to maintain vertical position. However, it is common practice to adjust buoyancy slightly positive. This allowed for a successful recovery in case the tether was severed since the "dead" craft would slowly resurface on its own.

Maneuverability considered the required control precision of the UUV's orientation and movement using thrusters manipulated by two control sticks and other rotary actuators. Thrusters (UUVs) and control surfaces (sUASs) were used to achieve this. Sensors like sonar (UUVs), ultrasonic altimeters (sUASs), and cameras (UUVs and sUASs) supported the maneuvering controls.

sUAS Control Description

sUAS Control methods included aerodynamic stability or the tendency to return to its original flight path after experiencing a disturbance. In addition to fuselage design and center of gravity, the control surfaces such as ailerons, elevators, and rudders were used to maintain stability and control flight for the fixed wing aircraft, as well as RPM and differential

torque for the multirotor. Altitude control for a desired height above the ground was essential for data consistency and flight safety. GNSS and barometric-based sensors were used to measure altitude, and control surfaces or trust levels were used for adjustment. The M2EA sUAS was also equipped with obstacle avoidance to detect and avoid obstacles in their environment.

The M2EA used a control station that consisted of a two-stick configuration remote controller with telemetry and video information. In addition, the M2EA's control station could also be operated via a laptop with UgCS software (SPH Engineering, 2024) to provide information similar to that of the operator directly controlling the vehicle. Finally, the senseFly eBee X used a control station with proprietary flight software installed on a laptop computer. The eBee X is an exclusively autonomous aircraft and did not include a remote controller as part of the control station equipment.

Control Methods Observations

Despite the differences in control station hardware, the UUV and sUAS control methods using the two-stick configuration remote controllers functioned similarly. Several control-mapping options are available for most UUV and sUAS systems. The Mode 2 configuration for RC remote control transmitters was used. Mode 2 mimics the control layout of a full-size airplane. In this mode, the operator uses their left hand to control the altitude/depth and yaw and their right hand to control the roll and pitch (left/right and forward/reverse for UUVs). This was a critical observation: matching the control mapping of the UUV and sUAS made it possible to transition between the two without repeated errors due to habitual control patterns. The M2EA, BlueROV2, and the Chasing M2 allowed the selection of Mode 2 control, which is not standard control mapping for many UUVs. When trials were conducted with differing control mapping, the movement of the robot was disjointed and often involved several control inputs before the desired maneuver was initiated. SMEs reported a major loss in efficiency and even safety concerns when operating in a confined area.

Despite these systems using different control station software and interfaces, the control methodology for receiving and displaying vehicle telemetry enabled the operator to determine the vehicle's attitude, depth, and orientation. The sUAS control station software, however, provided higher fidelity, particularly for mission planning. This included mission lines of travel and endurance planning due to the location of the aircraft being known through GNSS versus unknown for UUVs (neither of the UUVs were equipped with positioning equipment).

An interesting observation was the difference in altitude versus depth between sUAS and UUV operations for the operator to monitor and manipulate stability and attitude controls. sUAS operations required the pilot to maintain altitude and awareness Above Ground Level (AGL). However, for the UUVs functioning subsurface, the operations required awareness about the depth below the surface as well as the pilot visually interpreting the height above the sea bottom.

It was observed that pilots operating a sUAS in manual flight mode benefit from GNSS position hold. In other words, when the pilot gives no commands to a multi-rotor sUAS, it holds its position in space until the control station issues a new flight command. With the UUVs tested, there was no GNSS hold due to its lack of positional information. Therefore, it will not hold its position unless it continually receives corrective commands from the operator. This is like a UAS in attitude mode, where the aircraft is allowed to drift with the wind. The result, especially with current present, was a significantly higher cognitive load for the UUV operator since position was only determined through the camera interpretation and orientation required continuous control inputs.

An operator transitioning from the sUAS to the mini UUV faced several human factor challenges, including cognitive load, automation management, spatial orientation, communication, and psychomotor skills. UUV operators can mitigate risks by addressing the challenges before deployment through training. Generally, the UUV operator must build their mental model strictly based on telemetry and camera information. While the sUAS operator also used telemetry, more information was available through the exocentric view (looking directly at the aircraft's position and obstacles) and through auditory feedback of the aircraft's position and movement. In general, the UAS operator enjoyed higher levels of situational awareness with lower cognitive load. In contrast, the UUV operator had to study the telemetry and camera image in order to maintain positional awareness and had more difficulty maintaining high levels of situational awareness.

Crew Resource Management

With both sUAS and UUV operations, the crew's size depends on the mission's complexity and the equipment used. Therefore, experienced sUAS pilots will find the process of determining safe and efficient crew size for UUV operations somewhat familiar once the RPIC understands the operational environment. However, there are some differences due to the UUV not being within visual line of sight, the need for tether management, and an additional surface vehicle to operate. The following support positions can be added to a crew as the operational complexity increases.

Remote Pilot in Command

The RPIC is the individual piloting the UUV/sUAS and is primarily responsible for vehicle control and mission safety. They monitor the robot's positioning, depth/altitude, navigates to targets, and collects data. When operating alone, the RPIC also conducts launch and recovery duties. In UUV operations, once the mission extends beyond shallow (visual contact with craft), still water operations, a single-person crew is unlikely to be adequate to maintain operational safety. The RPIC is the final authority on safe and effective operations and is fully responsible for the operation of the robot.

Visual Observer/ UUV Assistant

As in sUAS flight operations, all crew members in maritime operations contribute to situational awareness and function as Visual Observers (VO). It should be noted that underwater operations are primarily conducted

beyond visual line of sight (BVLOS) whereas, sUAS operations are usually conducted within the aircraft's line of sight. The designated VO, in this BVLOS environment, typically supports situational awareness below the surface through a secondary viewing screen. The VO aids in navigation and subject acquisition and helps identify obstacles and issues in the piloting of the UUV. The VO is in continuous verbal communication with the RPIC and often contributes information such as depth, heading, battery level, and obstacles, while the RPIC concentrates on positioning or locating a target.

Tether Manager

The UUVs used in this research utilized tether systems for communication between the control unit and the robot. As a result, it was necessary to add a Tether Manager (TM) to the crew. The TM is responsible for the launch and recovery of the UUV, monitoring and manipulating the tether, and keeping the vessel captain apprised of the operation. This includes managing the tether as the UUV moves away from launch as well as retrieving the slack line as the UUV moves closer. This problem is compounded as the water current and surface winds strengthen, requiring constant vessel movement to remain in position. As the vessel maneuvers and modifies its relative position to the UUV, the TM must ensure that the tether does not come into danger of being encumbered by obstacles or the vessel itself (e.g., propellers). The TM and the vessel captain maintain constant communications so the vessel can be repositioned as necessary. The TM may also give updates and cautions to the RPIC and VO as necessary. One way to consider this is that the TM is the VO for above the water, while the VO is responsible for aiding the RPIC below the water.

Vessel Captain

The prime responsibility of the Vessel Captain is to pilot the vessel that carries the UUV team to the locations where data is to be collected and maintain position once the operation begins. A prepared captain will have an intimate knowledge of the area being explored through local experience or pre-mission research with maps, tidal charts (operating during slack tide), weather, etc. The captain should also possess an appropriate level of knowledge to understand the currents and other variables that will act on their vessel and be able to negotiate these situations to keep the vessel safely on mission and in position for a safe, successful dive. The skill level and certification necessary for safe operations are determined by the vessel being employed and the type of water body in which the operations are conducted.

As with sUAS operations, a mission and safety briefing are necessary to ensure all crew members understand the goals of the operation and their specific roles as team members. This briefing includes a review of environmental conditions, possible hazards, and any other mission-specific concerns. This includes state and local regulations the crew needs to be aware of, such as buffer zones for wildlife. While a safety/mission briefing is the responsibility of the RPIC, the captain is the logical person to brief on maritime conditions relative to tides, currents, and other navigational concerns as well as any pertinent regulations and safety. The vessel captain is the final authority to ensure safe and effective vessel operations.

As discussed above, good communication among the crew members is vital for efficient and safe operations. Protocols and terminology must be standardized and included in mission briefings. Voice communications are adequate on a small vessel. However, on a larger vessel where the captain may be isolated from the rest of the crew, hands-free radio communication on deck would be more appropriate. Our research revealed that communications are most efficient when the RPIC and VO talk to the TM, and the TM relays pertinent information to the captain.

Datalink Management

All the equipment used in this research employed a datalink system to relay information such as position, performance parameters, and sensor information to the operator. The datalink also passed commands to the robots for maneuvering, sensor manipulation, and functionality. Although these datalinks are similar between the UUVs and sUASs and are critical to operational success, the method of communication and management of the link can vary drastically.

UUV Datalink Management

The environmental differences require different communication mechanisms as UUVs employ a tether/wired connection and sUAS uses radio frequency (RF) communications. Potential UUV challenges include limits to mobility and navigation of the UUV to accommodate the restrictions of the tethered connection. Water currents can dramatically affect the amount of drag acting on the tether and, thus, the UUV. This condition only increases as more line is put into the water. However, the UUV requires a certain amount of slack line to facilitate unencumbered maneuverability. This is the prime responsibility of the TM, in communication with the pilot/operator, as they need to strike this balance and give the craft the most efficient condition in which to operate.

sUAS Datalink Management

The sUAS use of RF offers a greater range of movement, allowing control and maneuverability to be more unencumbered than an UUV. RF and GNSS can be affected by terrain and interference but maintaining communication with a sUAS while within a visual line of sight is relatively simple compared to the UUV. The biggest challenges to sUAS datalink health are distance, obstacles between the GCS and sUAS, and interference in the 2.4 and 5.8 GHz frequency ISM bands. The sUAS also employs pre-programmed lost-link logic to return the sUAS toward the GCS to reestablish the link. Since sUAS utilizes GNSS, the aircraft can climb to a safe altitude to avoid obstacles and return to the launch position. The sUAS will either regain communication or land at a preselected point should communication not be reestablished.

Emergency Procedures

Emergency procedures (EP) for sUAS operations concern the aircraft and its immediate environment. EPs for maritime operations are more complex and can be divided into two categories: EPs concerning the support vessel and EPs concerning UUV operation. While handling EPs in the air and water has

commonalities, the main difference is time. Often, an emergency situation with a sUAS must be quickly resolved based on available power and flight time, while UUV emergencies tend to be less time-critical but more complex.

UUV and Vessel Emergencies

Emergency procedures for the vessel can vary greatly depending on the size of the vessel. In an emergency, all crew members would follow the captain's commands. UUV operations may occur from large civilian or naval ships, requiring extensive crew coordination or from small vessels as in this research. During support vessel non-normal operations, the captain will determine the appropriate actions and relay them to the RPIC via the VO. The decision to retrieve the UUV, sacrifice the UUV, or continue operations is paramount and should be discussed during the operations briefing prior to the dive. The RPIC should be ready to surface, abandon, or retrieve the UUV should it be necessary.

A UUV encountering a non-normal situation can quickly turn into a compounding situation with multiple emergencies. For example, a loss of telemetry and video can lead to tether entanglement if the UUV is maneuvered without sufficient situational awareness. Emergencies may include collision with a submerged object, severed communications, UUV or tether entanglement, system failure, or software and/or hardware issues. In all cases, the UUV crew must work together to determine the proper action to safely retrieve the UUV. This may include simply restarting software or initiating an emergency retrieval of the UUV. In general, the first step for a UUV anomaly is to ensure the UUV is in a safe position, then troubleshoot the issue; time and battery power are typically not the critical factors as they are with airborne operations. This may include moving the UUV away from nearby objects or reducing its depth to avoid entanglement. Once the UUV is in a safe position, troubleshooting can begin. For mini UUVs like those used in the research, it may be prudent to simply surface the robot and bring it onboard to troubleshoot the issues. In all cases, the UUV crew must coordinate with the captain through the TM and determine any maneuvering required of the vessel.

sUAS Emergencies

Non-normal situations with a sUAS may include lost link, low power, mechanical failure, sensor and video failure, and other anomalies. Due to the short battery life of a sUAS (typically less than 20 minutes), maintaining control of the aircraft and landing as soon as practicable to troubleshoot the issue on the ground is recommended. The VO can be vital in maintaining sight of the aircraft and determining an acceptable landing area while the RPIC attempts to recover the aircraft. In extreme cases, a safe landing may not be possible, and intentionally ditching the aircraft may be the most prudent action.

Energy Management

All systems tested were powered by rechargeable LiPo (lithium polymer) batteries. With both sUAS and UUV, battery life is greatly influenced by the severity of the environment in which they are operated. When holding

position or maneuvering, an sUAS may have to fight the wind, and an UUV may have to fight water currents. Ambient temperatures can also harm battery life in either air or water. Batteries in aircraft, depending on the model, generally last from 20 to 30 minutes. In the case of UUVs, batteries can last several hours or more. As with the aircraft, both UUVs tested had replaceable batteries. However, the operation must pause while the aircraft is landed or the UUV is surfaced to exchange batteries. This may not be true for controllers, additional sensors, or GCS/computer batteries. While they last much longer than batteries in the UUV/sUAS, they are not generally replaceable and, therefore, must be taken out of service for recharge/replacement. In cases where multiple flights/dives are required, the non-replaceable battery equipment may limit the day's operation.

Environmental Considerations

UUVs and sUASs face significant environmental challenges that affect their performance, though the specific factors differ based on their operational domains. A key similarity is that both systems must contend with environmental forces that impact stability and maneuverability; UUVs struggle with ocean currents, while sUASs must adapt to wind conditions. Additionally, extreme temperatures affect both types of vehicles, with cold temperatures reducing battery efficiency and high temperatures causing potential overheating. Sensor functionality is another shared concern, as water clarity and air pollution can impair visual and data-gathering capabilities.

UUV Environmental Considerations

UUVs operate in challenging underwater environments, where various environmental factors impact their performance, durability, and operational efficiency. Water temperature and pressure are two of the most critical factors. In deep-sea exploration, UUVs must withstand immense hydrostatic pressure, which increases with depth and can potentially damage or compromise structural and hardware integrity. Additionally, extreme cold temperatures in deep waters can affect the performance of electrical components, batteries, and hydraulic systems, leading to malfunctions or reduced operational efficiency.

Water clarity and ocean currents are additional environmental considerations for UUV operations. Visibility can be significantly reduced due to sediment, biological activity, and pollution, making it difficult for onboard cameras and sensors to provide clear imagery and accurate data. This can hinder seafloor mapping, pipeline inspections, and marine research. Additionally, reduced visibility can create an additional workload on the operator when conducting proximity inspections of submerged infrastructure. Strong ocean currents pose another challenge by affecting the stability and maneuverability of UUVs, requiring advanced propulsion systems and real-time adjustments by operators.

sUAS Environmental Considerations

sUASs also operate in diverse atmospheric conditions, where environmental factors significantly impact their performance, reliability, and operational effectiveness. Wind speed and air pressure are the most critical variables influencing sUAS flight. Strong winds can destabilize sUASs, making navigation difficult and reducing battery efficiency as more power is required for stability and course correction. Similarly, changes in air pressure, particularly at high altitudes, affect aerodynamics and aircraft performance.

Weather conditions such as temperature extremes, precipitation, and humidity are additional considerations for sUAS operations. High temperatures can overheat electronic components and batteries, reducing lifespan and overall performance. Conversely, cold temperatures affect battery efficiency, leading to shorter flight durations. Rain, snow, and fog impair visibility, disrupt sensor readings, and compromise communication datalinks between the sUAS and its operator.

Human-induced environmental changes, such as air pollution and electromagnetic interference, further impact sUAS functionality and safety. Particulate matter in the atmosphere can clog air intake systems and reduce sensor accuracy. In contrast, electromagnetic interference from urban infrastructure, communication networks, and power lines can disrupt GNSS signals and telemetry data transmission, leading to potential flight instability. Additionally, sUASs operating in extreme storm conditions must be designed with enhanced resilience to withstand unpredictable wind shifts.

Navigation

The navigation capabilities of UUVs and sUASs shared common principles, such as autonomous control, sensor integration, and real-time data processing. However, they differed significantly due to their distinct operational environments. Both rely on positioning systems, with sUASs predominantly using GNSS for localization, while UUVs, lacking GNSS access underwater, depend on pressure sensors. Regarding movement control, sUASs navigate in three-dimensional airspace using barometric altimeters, LiDAR, and computer vision to maintain altitude and avoid obstacles. UUVs relied on pressure sensors and visual systems for depth control. sUASs often faced challenges related to wind conditions and airspace regulations, necessitating adaptive flight control systems. In contrast, UUVs contend with underwater currents and limited visibility, requiring real-time thruster adjustments and sensor interpretation for precise maneuvering. Both platforms employed automation and environmental sensing; however, sUASs benefit from broader GNSS availability and faster real-time communication. UUVs require more complex tethered or acoustic communication due to underwater electromagnetic signal transmission limitations.

UUV Navigation

Navigation is fundamental in operating UUVs, ensuring precise movement and positioning within underwater environments. Unlike sUASs, UUVs encounter unique navigational challenges, including limited visibility,

dynamic water currents, pressure variations, and the absence of reliable GNSS signals.

More advanced UUVs, not used in this research, may use Ultra-Short Baseline (USBL) and Long Baseline (LBL) acoustic positioning systems (Tomczak et al., 2022), which enable them to determine their location relative to a fixed reference point, such as a surface vessel or seabed transponder. In situations where external positioning data is unavailable, UUVs are operated via dead reckoning. This estimation method determined location based on velocity, directional changes over time, and visual displays.

Depth control and distance above the sea bottom (under keel clearance) is an essential function of UUV navigation. Pressure sensors integrated into the UUVs measured hydrostatic pressure and maintain a designated operational depth. It was noted that UUV depth continued to increase in negative value as the UUV moved further away from the surface. This is similar, but in a polarized direction, to the sUAS altitude, which increased in positive value as the aircraft moved further from the surface.

Additionally, sonar-based altimeters, can assist in determining the vehicle's under keel clearance by measuring the distance from the seafloor or underwater structures (Zhang et al., 2022). These systems work in tandem to ensure precise depth control, which is important for inspections.

The UUVs used in this research featured automated and assisted navigation capabilities. They were equipped with either an Ardupilot-based autopilot (BlueROV2) or a manufacturer-proprietary autopilot (Chasing M2) that enabled the UUV to maintain a fixed position and attitude using dynamic positioning (DP) systems. The depth hold feature of these UUVs was similar to the altitude hold for sUAS and significantly reduced the operator workload to maintain a specific depth in the water.

The integration of navigation data with other onboard systems, such as a video feed, further enhanced UUVs' functionality to navigate, via pilotage and dead reckoning, around submerged shipwrecks. The inability to access GNSS signals underwater necessitated reliance on pressure sensor- and video-based dead reckoning, both subject to error due to environmental interference and human interpretation. Water currents and turbulence present additional challenges, requiring continuous thruster adjustments to maintain position. Furthermore, limited visibility in subsurface environments necessitates the use of advanced sonar and sensor technology for effective navigation than was used on the UUVs in this research.

sUAS Navigation

An aspect of sUAS navigation is positioning and localization, which is predominantly achieved through the GNSS system onboard the aircraft. GNSS provides accurate geolocation data, enabling sUASs to follow predetermined flight paths, maintain stability, and execute autonomous flight operations. In environments where GNSS signals are weak or unavailable, sUASs employ alternative positioning techniques such as inertial navigation systems (INS), which estimate location based on accelerometer and barometric pressure sensor data. Some advanced sUASs also integrate

vision-based navigation systems, leveraging cameras and artificial intelligence (AI) to identify landmarks and construct spatial awareness (Loianno and Scaramuzza, 2020).

Barometric pressure sensors in the M2EA and eBee X, LiDAR in the eBee X, and infrared sensors in the M2EA enable sUASs to maintain precise altitude, which is particularly important for terrain-following missions and low-altitude operations. Additionally, the M2EA uses optical cameras to detect and avoid obstacles in real-time. These sensors generate high-resolution environmental data, allowing sUASs to avoid obstacles.

SUAS incorporated fully autonomous navigation capabilities and manual and semi-autonomous control. Ground control software enabled the operator to design and execute pre-programmed missions, including aerial surveying and infrastructure inspection. Sensor fusion, which combines inputs from GNSS, inertial measurement units, LiDAR, and vision-based navigation, allowed the sUASs to navigate with high precision, even in GNSS-denied environments. Data collected from navigation sensors was transmitted in real-time to the ground control stations, enabling live monitoring and mission adjustments.

Despite significant advancements, SUAS navigation presents ongoing challenges. GNSS dependency remains vulnerable, as signal disruptions caused by jamming, interference, or environmental obstructions can impact flight accuracy. Wind gusts, turbulence, and varying atmospheric pressures can introduce additional complexities, requiring adaptive control mechanisms for stable operation. Furthermore, regulatory limitations on sUAS flight operations necessitate compliance with airspace management protocols, limiting autonomous flight capabilities during Beyond Visual Line of Sight (BVLOS) operations.

Operational Planning and Execution

sUAS operations require regulatory considerations regarding airspace restrictions, pilot certifications, and no-fly zones, which are more restrictive than UUV operations. While each has a unique certification requirement and safety standard, UUV operations have fewer safety concerns regarding collision and potential human interference. UUVs are regulated by maritime organizational standards focusing on underwater operations and environmental regulations that may apply to protected water. Additional regulatory constraints were recognized with sUAS compared to UUV in planning. Specifically, pre-deployment planning is necessary to determine differences in regulations regarding the use of airspace by sUAS as well as data collection authorities for any privacy concerns (Wanasinghe et al., 2020). As a result, operators must be well-versed in the regulations governing operations in both environments.

Situational Awareness

Whether underwater or in the air, maintaining high situational awareness (SA) is essential to prevent collisions, optimize mission performance, and ensure operational safety in challenging environments. Situational awareness

for UUVs and sUASs share similarities in the need for real-time sensor feedback, telemetry, and environmental monitoring. While both systems relay data such as the camera image, velocity, depth/altitude, etc., each control station displayed the information in a different format. An RPIC transitioning from an airborne to subsurface vehicle must be familiar with and experienced in each control station to maintain high SA.

While interpreting the different displays and feedback systems may sound simple, the habitual patterns established in one domain can differ drastically from the other. For a sUAS, the position, heading, altitude, and attitude can be obtained subconsciously by observing the aircraft and the direction and intensity of its sound. Conversely, the UUV requires reference to the camera, heading indicator, depth, and the pitch ladder, then the heading of the UUV must be compared to the surface picture to determine which direction the robot is headed in relation to the ship and land. In general, building SA for a sUAS is relatively simple and many of the cues are subconscious while a UUV requires interpretation and a heavy cognitive load. Knowing where to look on the UUV display to quickly identify and interpret parameters and build a mental picture of the robot's orientation takes experience and should not be overlooked. Maintaining situational awareness during subsurface operations was substantially more difficult for the UUV than with the sUAS.

Another key difference was the need to maintain SA on the UUV tether. The tether restricted movement and required careful management to avoid entanglement, especially when maneuvering near vertical developments in limited visibility. Strong current also affected the tether and movement of the UUV requiring the pilot to maintain SA on not only the UUV, but potential entanglement structures, drag on the UUV, and the host ship position and heading.

Despite these differences, human factors and automation played a crucial role in UUV and sUAS operations. Effective user interfaces, team coordination, and standard operating procedures enhanced situational awareness by helping operators process complex data efficiently. Autonomous features, such as assisted navigation and obstacle avoidance, were integrated into both technologies to reduce cognitive load and improve decision-making. Whether underwater or in the air, maintaining high SA should be a priority and will often require more than one crewmember to ensure adequate SA, particularly in the subsurface environment.

CONCLUSION

This operational field study highlighted the similarities and differences between piloting a UUV and sUAS. While both technologies rely on remote control, sensor integration, and situational awareness, their unique environmental challenges require distinct skill sets and operational considerations. The research demonstrated that cross-training personnel to operate UUVs and sUASs is feasible, but operators must adapt to different control methodologies, navigational constraints, and understand the environment in which they are operating. A key finding was that aligning control interfaces, standardizing operational procedures, emphasizing crew coordination, and methods to gain and maintain high SA will enhance cross-platform competency, reducing human error and improving efficiency.

The comparative analysis underscored the impact of environmental factors on both systems. UUV operations were influenced by underwater currents, visibility limitations, and lack of accurate position data, while sUAS operations contended with wind conditions, altitude control, and GNSS dependency. The study found that situational awareness varies between the two domains, with sUAS operators benefitting from external visual cues and GNSS data. In contrast, UUV operators relied on video feedback and sensor interpretation which required more training and interpretation skill than piloting a sUAS. These differences suggested that while cross-training is advantageous, specialized training is still necessary to master the unique operational challenges of each domain.

Integrating UUVs and sUASs within offshore operations presents enhanced efficiency, cost savings, and risk reduction opportunities. The findings indicated that a hybrid approach—where operators/crews are trained to use both systems—could optimize workforce capabilities and reduce the need for specialized personnel. However, challenges such as regulatory requirements, equipment standardization, and cognitive load management must be addressed to realize the benefits of cross-platform training. Future research should explore advancements in automation and AI-driven decision-making and navigation to streamline operations.

REFERENCES

- AgEagle (2024). senseFly eBee X. [apparatus and software]. <https://ageagle.com/drones/ebec-x/>.
- Anonymous (2024, April, 26). Offshore Oil Rig: A Comprehensive Guide. JOAV Unmanned Aircraft System. Retrieved from <https://www.joUAS.com/blog/offshore-oil-rig.html>.
- Blue Robotics (2024). BlueROV2. [apparatus and software]. <https://bluerobotics.com/product-category/UUV/>.
- Carter, G. (2000). *Offshore platform rigs adapting to weight-space restrictions for floaters*. Offshore Technology. Retrieved from <https://www.offshore-mag.com/drilling-completion/article/16763331/offshore-platform-rigs-adapting-to-weight-space-restrictions-for-floaters>.
- Chasing (2024). Chasing M2. [apparatus and software]. <https://www.chasing.com/en/chasing-m2.html>.
- Da Ponte, G. P. J. (2021). Risk management in the oil and gas industry: offshore and onshore concepts and case studies. Gulf Professional Publishing.
- DJI (2022). DJI Mavic 2 Enterprise Advanced. [apparatus and software]. <https://enterprise.dji.com/mavic-2-enterprise-advanced>.
- Gómez, C., & Green, D. R. (2017). Small unmanned airborne systems to support oil and gas pipeline monitoring and mapping. *Arabian Journal of Geosciences*, 10(9), 1–17. <https://doi.org/10.1007/s12517-017-2989-x>.
- Lempriere, M. (2017). *The ins and outs of offshore accommodation*. Offshore Technology. Retrieved from <https://www.offshore-technology.com/features/featurethe-ins-and-outs-of-offshore-accommodation-5799637/?cf-view>.
- Loianno, G., & Scaramuzza, D. (2020). Special issue on future challenges and opportunities in vision-based drone navigation. *Journal of Field Robotics*, 37(4), 495–496. <https://doi.org/10.1002/rob.21962>.
- Mercer, T. L. (2010). *A vocational education training model for UUV pilots and AUV operators*. ProQuest Dissertations & Theses.

- Thomas, E. (2024). *Drones reducing risk in offshore oil and gas inspection*. Offshore Technology. Retrieved from <https://www.offshore-technology.com/features/drones-reducing-risk-in-offshore-oil-and-gas-inspection/>.
- Tomczak, A., Stepień, G., Abramowski, T., & Beijer, A. (2022). Subsea wellhead spud-in marking and as-built position estimation method based on ultra-short baseline acoustic positioning. *Measurement: Journal of the International Measurement Confederation*, 195, 111155-. <https://doi.org/10.1016/j.measurement.2022.111155>.
- Wanasinghe, T. R., Gosine, R. G., De Silva, O., Mann, G. K., James, L. A., & Warriar, P. (2020). Unmanned aerial systems for the oil and gas industry: Overview, applications, and challenges. *IEEE access*, 8, 166980–166997.
- Zhang, Y., Zhang, Q., Zhang, A., Chen, J., Li, X., & He, Z. (2022). Acoustics-Based Autonomous Docking for A Deep-Sea Resident UUV. *China Ocean Engineering*, 36(1), 100–111. <https://doi.org/10.1007/s13344-022-0009-8>.