FORSSEA ROBOTICS

2025 WHITE PAPER

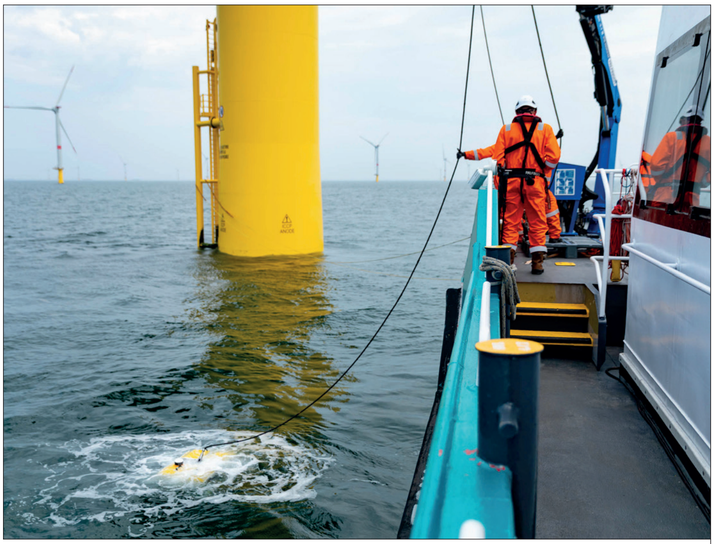
# Underwater Autonomous Inspection of Offshore Wind Turbine

**Automated inspection of offshore wind farms represents a major opportunity for operators: reducing operational costs, improving safety, and decreasing time spent on interventions. The developments carried by FORSSEA follow this vision and aim to increase both the autonomy of the ROV system and the quality of ROC situation awareness during underwater missions.**

**FORSSEA** is anchoring its R&D work in the real-world, where any improvement must quickly bring operational and/or economic added value in its daily operations. All work presented here is based on field-proven ROV systems and technological bricks.

## I. Context, Technical Challenges & Objectives

Coastal operations are progressively evolving towards smaller vessels and reduced crew. While onshore remote supervision is becoming a must, minimum level of autonomy is required onboard the underwater robots to compensate for lack of situation awareness from the ROC (Remote Operating Centers) and potential communication failures or lags. Only a consistent combination of **Remote** and **Smart** functionalities will bring continuous reduction of human exposure, operational and weather risk, thus resulting in cost optimization.



**ARGOS** *ROV deployed from Largo CTV in the Saint-Nazaire Offshore Wind Farm (France, June 2025)*

However, automating underwater inspections around large offshore structures raises a series of domain-specific challenges.

The first major challenge **is absolute vehicle localization**. Precise data georeferencing is increasingly required to match Client GIS (Geographic Information Systems) and preventive maintenance plans. Unlike terrestrial robots, ROVs and AUVs cannot rely on GPS underwater and must instead use indirect methods such as inertial navigation systems (INS), Doppler velocity logs (DVL), visual localization (e.g., SLAM), or acoustic systems.

USBL (Ultra-Short Baseline) systems are widely used offshore, especially in deeper waters, for precise absolute underwater positioning, but their performance deteriorates significantly in the presence of large obstacles. In a wind farm, the massive steel structures of turbines create acoustic shadow zones, blocking or distorting acoustic signals. This leads to degraded or unusable USBL positioning. Moreover, USBL systems generate additional fixed and daily costs which are detrimental to economic competitiveness from a light or coastal vessel standpoint.

The DVL, which is essential to limiting inertial drift in the INS, also suffers from interference when operating close to structures. Multiple reflections from the turbine or rocky seabed can corrupt velocity measurements, compromising the reliability of navigation algorithms in the vicinity of foundations.


*Real-time supervision by ROV pilot and engineers during autonomous wind turbine inspection*

The second challenge **concerns navigation near structures.** While ROVs are well suited for detailed visual inspections thanks to their stability and maneuverability, they remain physically connected to the support vessel via a tether, which must be handled carefully to avoid entanglement, excessive tension, or dangerous wrapping around structures. Poor mission planning can lead to collision risks or tether incidents that may halt operations.

The developments performed by **FORSSEA** therefore aims to:

1. **Design a compact ROV** for underwater inspections and integrity surveys, able to acquire highly accurate georeferenced data, independent of vessel and associated surface-based acoustic positioning.
2. **Improve situational awareness** for an onshore pilot by enriching the 3D visualization with a more accurate and complete representation of the underwater environment and thus allowing better tether management from ROC.
3. **Strengthen the autonomy capabilities of the ROV**, both in mission planning and execution, to reduce operator workload and shorten inspection times.

## II. Developments &. Methodology

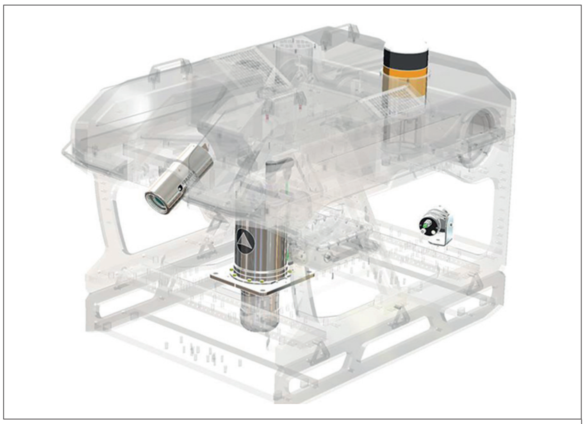
### ARGOS SURVEY PLATFORM

**ARGOS** ROV is a new generation and all-electrical ROV benefiting from a compact design and latest embedded positioning technology. It is the first observation class ROV integrating high grade positioning technology allowing intuitive dynamic positioning control, with market leading INS/ DVL sensor permanently mounted. It is specifically designed for harsh shallow water offshore conditions, improving the efficiency of subsea operations where accurate position, heading and attitude are key requirements.

**ARGOS** ROV is also the first ROV platform delivered with a complete web based and secured remote control mode. Both the main camera (**OBS CAM**, 4K quality) and the rear camera (**MINI CAM**) stream (< 100ms latency) to the onshore web server with numerous network dynamic and real-time visibility enhancing modes.

**Note:** *The latency observed on a local network remains below 100 ms. Furthermore, the technology used is at the cutting edge of current standards, enabling distribution over the Internet while ensuring optimal latency.*

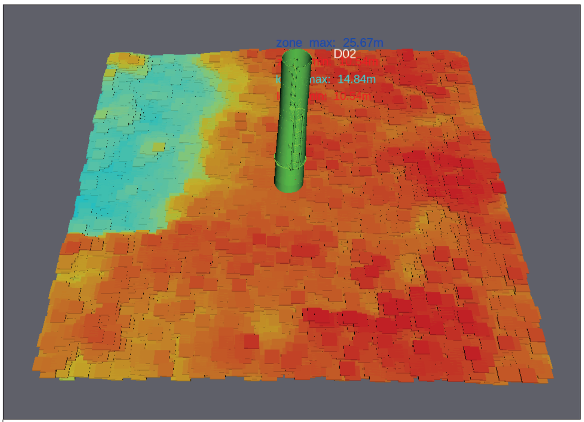
Finally, **ARGOS** ROV is a versatile platform, which can carry a variety of NDT and survey payloads thanks to numerous Gbit Ethernet and serial ports, and modular skid integration system. It has proven itself in various offshore environments, from shallow water wind farm surveys to deeper Oil & Gas applications.



***ARGOS** is one of the word's most compact and advanced Obs-class ROVs, fully integrated with INS/ DVL, GNSS and multiple survey payload options*

### INCREASED SITUATION AWARENESS THROUGH DIGITAL TWIN

Preparatory work includes enhancing the digital twin of the site, integrating new environmental and structural data (bathymetry, points of interest, ICCP anodes, support vessel), and developing new autonomous inspection missions (GVI, CVI, POI inspection). These aspects are essential to overcoming current operational limitations and demonstrating the feasibility of advanced autonomy—paving the way for fully autonomous underwater inspections in the future.



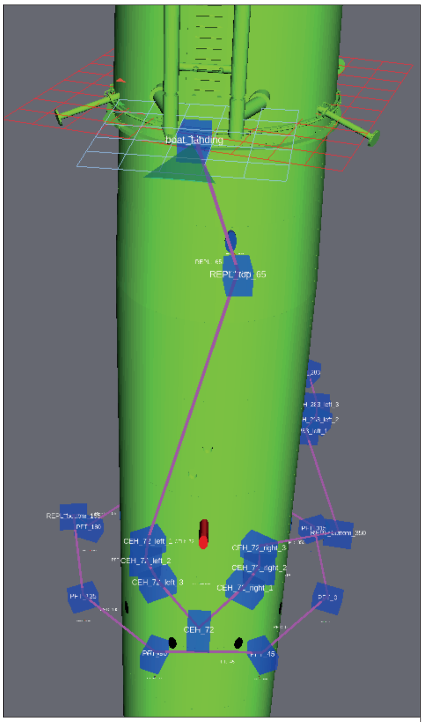

*New bathymetric profile uploaded in digital twin*

A substantial set of improvements was developed by **FORSSEA** and integrated into the system to enhance environmental awareness and enable more complex, reliable autonomous missions.

- Real-time support vessel localization
- Bathymetry integration
- Integration of ICCP anodes and CEH/REPL/PFT holes
- Vertical reference consistency (LAT vs. model elevations)

## AUTONOMOUS MISSION PROFILES

Inspection points are then manually extracted from technical documents and precisely integrated into the turbine 3D model. This gives ROV operators immediate access to the spatial locations of all critical inspection features without relying on 2D drawings or repeated mental calculations. Automatic waypoints were also generated two meters in front of each POI, greatly simplifying autonomous mission planning.




*Example of CVI Flight Path*

Thanks to the newly integrated waypoints, the system can autonomously perform, **using absolute positioning,** complete inspections of CEH, REPL, and PFT holes, including specific orbital trajectories around the CEH to inspect cable exits and surrounding areas.

- **GVI** (General Visual Inspection) cover broad inspection paths both vertically and horizontally around the turbine structure. Missions are split into two segments per turbine to avoid tether risks and maintain operational safety. They check for marine growth and any potential structural damage, with the objective of visiting each Point of Interest within a single pass.

- **CVI** (Close Visual Inspection): are dedicated missions that are typically created for ICCP anodes, boat landing and any other complex sub-structure. These trajectories are explicitly designed to minimize tether hazards, prioritizing paths beneath the anodes to reduce snagging risks and account for tidal variations.

## INS DRIFT CORRECTION USING POIS

The need for a simple solution to reduce INS drift is especially important when maneuvering near structures, due to the increased drift caused by acoustic interference described previously. Thanks to the waypoints that were added in front of the POI, and given that the turbine is localized in an absolute frame, we can extract the position in Latitude/Longitude/Altitude.

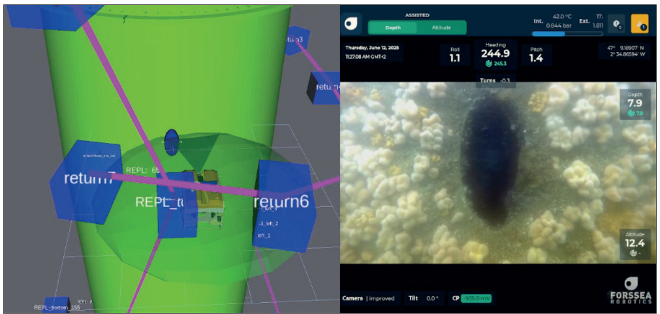
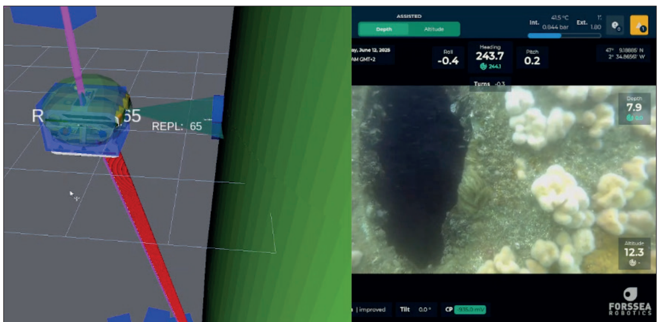



*Illustration of INS position drift 3m below the ICCP*

This allows simple and effective manual correction of INS drift: the operator pilots the ROV toward a visual/sonar-identifiable POI, then applies a direct coordinate correction in the Rovins. This significantly increases long-duration mission accuracy in environments where USBL cannot be relied upon.




*CCP anodes were correctly localized and visualized after INS recalibration*

Several successful manual INS recalibration were performed during the autonomous tests, and these features could easily be automated using basic GIS commands or an API.

These improvements provide the foundation for a more robust autonomous control system capable of operating despite the acoustic and structural disturbances inherent to wind farm environments.

## III. Offshore Demonstration Results & Analysis

Recent test campaigns were carried out over two days: one day of manual inspection to observe current practices and validate the digital twin, and one day dedicated to autonomous mission trials to evaluate stability, precision, and operational performance.

> **About ARGOS ROV Piloting Modes:**
> The ROV has the following modes of control available to the pilot: **Manual Piloting** where the pilot directly controls the force of the motors ; **Assisted Piloting** where the pilot controls the setpoint (the desired position) of the ROV for any degree of Freedom; and **Dynamic positioning mode (GoTo)**, which is a fully autonomous movements to a given location, either relative to the ROV or in absolute coordinates.

### ANALYSIS OF MANUAL PILOTING

Collected data show that pilots rely heavily on full manual control, with automatic assistance modes used only occasionally (e.g., Keep Heading & Keep Depth). According to pilots, due to constant risk of collision, they tend to maintain complete control of the machine. Thus, advanced position and velocity control modes are rarely used. The manual piloting data also shows significant variations in roll and pitch, reflecting the difficulty of maintaining consistently stable orientation during close-proximity operations, especially in 1 to 1.5 knt tidal current.

The analysis confirms that pilots spend notable time compensating for environmental disturbances (currents, tether tension) and focusing on small positional corrections. This reinforces the need for autonomous support systems that can offload these tasks.

> **Control Modes Usage:** Manual piloting dominated horizontal and vertical movements, while automatic Keep Heading was engaged 50% of the time.
>
> **Roll & Pitch Variation:** S90 intervals were 15° for roll and 20° for pitch.
>
> **Inspection Time per Turbine:** Average manual inspection duration was 90 minutes, with a total of approximately 100 hours dive time for 66 turbines.

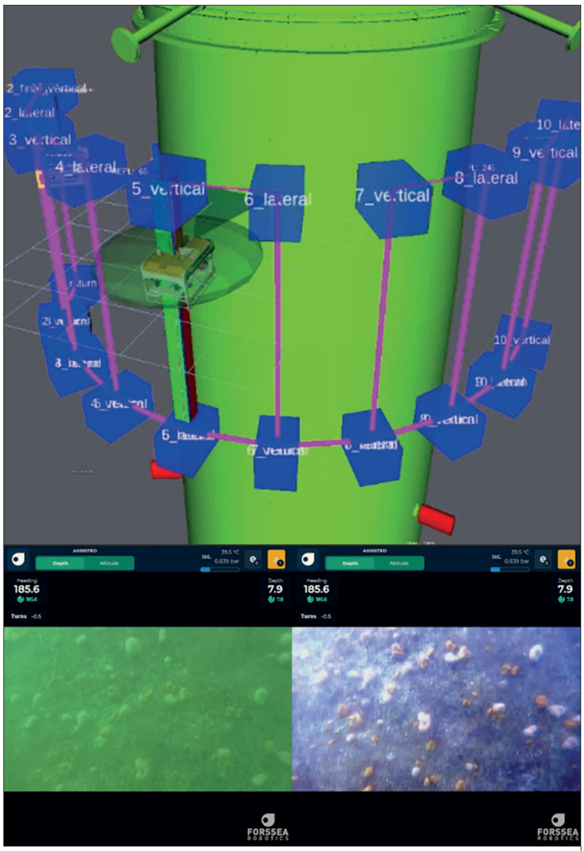
### AUTONOMOUS MISSION PERFORMANCE

Autonomous GVIs demonstrated highly stable ROV behavior with consistent tracking of predefined waypoints.

However, INS drift inevitably accumulates unless corrected by external absolute measurements, such as acoustic positioning or SLAM as mentioned previously. This drift was particularly visible after having completed several missions involving long linear trajectories parallel to turbine surfaces. This is because the drift accumulates faster when the DVL is disturbed by the turbine structure. This drift was occasionally corrected using the waypoint method as described previously.

CVI missions exhibited strong promise: the system can maintain safe distances from assets and follow the designed path while avoiding obstacles. Inspections over ICCP anodes showed good repeatability across multiple runs, validating the waypoint-based approach.

POI inspection missions confirmed the operational value of precise POI integration. The ROV could reliably navigate to the CEH/REPL/PFT holes and perform inspection loops, although minor drift occasionally required manual correction.



*Example of GVI mission*

**Roll & Pitch Stability:** S90 reduced to 5° (roll) and 10° (pitch), representing respectively up to 70% and 40% stability improvements.

**Angular Velocity Stability:** S90 for roll velocity decreased from 11°/s to 3°/s and pitch velocity from 24°/s to 7°/s (70% reduction)

**Inspection Time Reduction:** Automated missions averaged approximately 50 minutes per turbine, a 40% reduction compared to manual operation.

95% of autonomous inspection positions were within 10cm of target waypoints.

Maximum observed error never exceeded 40cm, but still above the 10cm capture radius used in waypoint sequencing.

These figures demonstrate improved efficiency, accuracy, and operational repeatability under autonomous control.

**HIGHLIGHT**
Autonomous missions can bring time savings around 30% to 40% compared to fully manual ROV piloting. This would also maximize chances to complete one foundation inspection per tidal window and thus facilitate planning and vessel chartering preparation under changing metocean conditions.

## IV. Lessons Learned and Future Developments

Overall, our campaigns demonstrated strong progress toward reliable semi-autonomous and autonomous inspections, with quantifiable benefits in stability, inspection time, and pilot workload reduction. One can highlight that:

- **Environmental understanding** can easily be improved using existing state-of-the-art Digital Twin functionalities. This shall greatly increase ROC situation awareness and confidence during remote maneuvers.

  **Note to Site Operators:** *Future subsea O&M tender should include standardized 3D model coming with absolute georeferencing data and POI description / localization to facilitate digital twin and mission profiles preparatory work.*

- **Autonomous missions using absolute georeferencing are viable**, but their reliability depends on managing drift in the absence of consistent acoustic positioning. Manual INS drift correction via POIs is practical and will remain important until improved localization methods are deployed. Visual SLAM and odometry techniques are soon expected to boost absolute positioning performance.

  **Technology focus on VPVL (Visual Positioning & Velocity Log): FORSSEA** *will soon commercialize a new generation stereo-camera with high embedded computing capacity. Based on real-time SLAM algorithms, the system will feed INS with precise velocity data in the vicinity of structures, and thus considerably improve accurate georeferencing.*

- **ROV Tether management** remains a limiting factor, and further automation will need to incorporate tether-aware path planning algorithms. According to our analysis, NDT work in contact of the structure, complex CVI path (especially in strong current) and spot cleaning easily represent 50% of all subsea O&M work and will be hard to automate without real-time supervision and sufficient power supply. Although battery powered vehicles (ie: hybrid ROV) are entering the market, we believe they do not fully substitute existing ROV as they are mostly adapted to GVI work with generic data acquisitions profiles.

**Index**

**API:** Application Programming Interface
**AUV:** Autonomous Underwater vehicle
**CEH:** Cable Entry Hole
**CTV:** Crew Transfer Vessel
**CVI:** Close Visual Inspection
**DVL:** Doppler Velocity Log
**GVI:** General Visual Inspection
**ICCP:** Impressed Current Cathodic Protection
**INS:** Inertial Navigation System:
**NDT:** Non Destructive Testing
**PFT:** Pile Fixation Tool
**POI:** Point of Interest
**REPL:** Replenishment Hole
**ROC:** Remote Operations Centre
**ROV:** Remotely Operated Vehicle
**S90:** Spread 90%, meaning the middle 90% of data points
**SLAM:** Simultaneous Localization and Mapping
**USBL:** Ultra Short Base Line
**VPVL:** Visual Positioning Velocity Log