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Autonomous Aquaculture Net Inspection and Patching on a Low-Cost ROV

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Resumen

Los agujeros no detectados en jaulas de red de acuicultura pueden provocar escapes masivos de peces; sin embargo, la inspección y reparación autónoma de estas estructuras sigue siendo un problema abierto. Los sistemas actuales suelen limitarse a la inspección o requieren teleoperación para desplegar el parche, por lo que el ciclo detección–reparación permanece parcialmente autónomo. Este artículo presenta un pipeline autónomo implementado en un ROV de bajo coste y uso general, BlueROV2 Heavy, capaz de cerrar dicho ciclo en un entorno controlado sin intervención del operador tras iniciar la misión. El vehículo busca visualmente la red, estima su posición relativa mediante percepción a bordo, inspecciona la superficie, detecta agujeros que cumplen un criterio de tamaño predefinido y ejecuta la maniobra de parcheo. El sistema fue desarrollado en Stonefish y validado experimentalmente en el tanque interior CIRTESU. Las principales contribuciones son la autonomía extremo a extremo en una plataforma económica y el enganche terminal mediante seguimiento de posición en bucle cerrado.

Palabras clave: Acuicultura, Agarre y manipulación robótica, Percepción y sensado robótico, Robótica marina, Navegación autónoma

Autonomous Aquaculture Net Inspection and Patching on a Low-Cost ROV

Abstract

Undetected holes in aquaculture net cages can cause massive fish escapes; however, autonomous inspection and repair of these structures remains an open problem. Existing systems usually focus on inspection only or require teleoperation for patch deployment, leaving the detection-to-repair cycle only partially autonomous. This paper presents an autonomous pipeline implemented on a low-cost, general-purpose ROV, the BlueROV2 Heavy, capable of closing this cycle in a controlled environment without operator intervention after mission start. The vehicle visually searches for the net, estimates its relative position using onboard perception, inspects the surface, detects holes that satisfy a predefined size criterion, and executes the patching maneuver. The system was developed and tested in the Stonefish simulator and experimentally validated end to end in the indoor CIRTESU test tank. The main contributions are end-to-end autonomy on an affordable robotic platform and terminal patch attachment through closed-loop position tracking, improving deployment repeatability under moderate underwater disturbances.

Keywords: Aquaculture, Robotic grasping and manipulation, Robot perception and sensing, Marine robotics, Autonomous navigation

1. Introducción

Aquaculture now supplies a substantial fraction of global fish consumption, making the integrity of fish-cage net pens economically and environmentally critical. Damage caused by predators, mechanical contact, corrosion, or material fatigue can produce holes in the net structure that allow large-scale fish escapes if left undetected. These escape events generate significant financial losses and ecological disruption, motiva-

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ting the development of automated inspection and maintenance systems for aquaculture infrastructure.

Current inspection practice remains largely manual. Human divers, or operators piloting remotely operated vehicles (ROVs), visually inspect the cage surface searching for tears and structural degradation. Although divers remain effective in practice because they can inspect and repair concurrently, manual inspection is costly, slow, weather-dependent, and difficult to scale across large offshore facilities.

Robotic approaches have therefore received increasing attention. Existing systems primarily focus on autonomous or semi-autonomous inspection, using visual servoing, deep learning, or structured navigation to detect defects in net pens. However, most reported systems stop at defect detection and reporting. Intervention is typically separated from inspection and delegated either to a human diver or to a teleoperated repair tool. Commercial systems such as UCO NetFix can deploy temporary patches, but still require operator supervision and subsequent manual repair. As a result, the detect-to-repair loop remains open.

This paper presents an autonomous detect–inspect–patch pipeline implemented on a low-cost commercial ROV platform, the BlueROV2 heavy. The vehicle autonomously searches for and visually acquires the net structure, estimates its relative position using onboard perception, performs surface inspection, detects holes satisfying a predefined size criterion, and executes a patching manoeuvre without operator intervention. The system was developed and integration-tested in the Stonefish simulator, and experimentally validated end-to-end in real experiments conducted in the CIRTESU indoor tank.

The work makes two primary contributions:

(i) Autonomous intervention on a commodity platform. A complete search-to-patching mission pipeline is demonstrated in a controlled experimental environment on a low-cost BlueROV2 heavy platform, substantially reducing the hardware complexity and cost typically associated with intervention-class underwater robots such as the GIRONA500.

(ii) Closed-loop terminal engagement. The system performs terminal approach via closed-loop vehicle position control relative to the estimated hole position. Hole localisation is obtained during the detection phase, while terminal engagement tracks the estimated target position without sensing or continuous visual servoing.

The proposed architecture follows the operational pattern used by human divers: inspection and intervention are interleaved, allowing the robot to repair defects immediately upon detection.

2. Related Work

2.1. Aquaculture net inspection and repair

Automated inspection of aquaculture net pens has received increasing attention due to the environmental and economic impact of undetected structural failures. Early and recent approaches have primarily focused on *inspection only*, leaving repair to human divers or separate teleoperated interventions.

Akram et al. (2022) propose a vision-based visual servoing scheme for ROV-guided inspection using reference ropes for relative positioning, demonstrating stable net traversal under controlled conditions. In later work, Akram et al. (2023) extend this direction by integrating deep learning-based defect detection with an edge-density controller to enable autonomous scanning of net structures. While these systems improve coverage and detection robustness, they do not address physical intervention.

More recently, López-Barajas et al. (2024) present a BlueROV2-based inspection system developed at Universitat Jaume I, combining CNN-based net distance estimation with hole detection in the CIRTESU facility. Although this represents a more integrated perception pipeline, the system remains limited to detection and reporting. Similarly, commercial solutions such as UCO NetFix and Deep Trekker platforms provide teleoperated patch deployment, but do not close the loop autonomously, requiring subsequent diver intervention for permanent repair.

Overall, existing work demonstrates reliable perception and partial intervention capabilities, but no system provides a fully autonomous detect-to-repair pipeline under a unified control architecture.

2.2. Underwater localisation using fiducial markers

Accurate localisation underwater remains a fundamental challenge due to the absence of GPS and the degradation of visual features in turbid environments. Fiducial marker-based systems have therefore become a standard solution for structured environments such as test tanks and confined operational areas.

The ArUco marker system introduced by Garrido-Jurado et al. (2014) is widely used in robotics due to its robustness, computational efficiency, and ease of deployment. In underwater robotics, such markers are typically combined with inertial sensing to provide a stable pose estimate for waypoint navigation and task execution. While effective in controlled environments, these approaches depend on environmental instrumentation and are not directly transferable to unstructured offshore deployments.

2.3. Underwater manipulation for intervention tasks

Physical interaction with submerged structures introduces additional complexity beyond perception and navigation. Hydrodynamic disturbances, visual uncertainty, and latency make open-loop manipulation unreliable in practice.

A comprehensive review by Sivčev et al. (2018) highlights that reliable pose control and contact awareness are critical enablers for robust underwater manipulation. Earlier work by Marani et al. (2009) similarly emphasizes the importance of tightly coupled perception-action loops in intervention-class AUVs, particularly for tasks requiring sustained contact.

Within this context, several experimental systems have explored interactive underwater manipulation. The GRASPER system developed at IRS-Lab/UJI integrates multisensory feedback to improve reliability during grasping and manipulation tasks in the CIRTESU facility (Sanz et al., 2013). More recent paradigms in robotic manipulation, including vision–tactile–language frameworks, further reinforce the role of multimodal sensing in enabling robust interaction in unstructured environments (Dutta, 2026).

Despite these advances, most existing systems either focus on grasping or manipulation in isolation, or assume high-end intervention-class platforms. Fully integrated autonomous pipelines that combine detection, navigation, and physical repair on low-cost ROV platforms remain largely unexplored.

3. System Overview

The proposed system combines autonomous navigation, visual inspection, and contact manipulation on a low-cost underwater vehicle platform. The architecture is organised into three layers: localisation, mission autonomy, and manipulation/control (Figure 1). The platform is based on a commercial BlueROV2 heavy configured for 6-DOF operation and integrated with ROS 2 running on an onboard companion computer.

A forward-facing camera performs net and hole detection, while a downward-facing camera observes a floor-mounted fiducial-marker array used for global localisation inside the experimental tank. Vehicle state estimation combines visual marker observations with inertial measurements to provide waypoint-level navigation accuracy throughout the mission.

Mission execution follows a phase-based autonomy pipeline composed of search, approach, inspection, and patching states. Once a target hole satisfying the size criterion is detected, the vehicle transitions directly into a patching manoeuvre using a custom end-effector mounted on the subsea gripper.

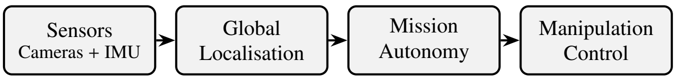

Figura 1: High-level architecture of the autonomous inspection and repair system.

4. System Architecture

The proposed system combines localisation, autonomous mission execution, and contact manipulation on a low-cost underwater vehicle platform. The architecture is organised into three loosely coupled layers: global localisation, mission autonomy, and manipulation/control (Figure 1). This modular structure simplified debugging and integration during development.

4.1. Hardware Platform

The platform is a BlueROV2 heavy configured for 6-DOF operation and integrated with ROS2 running on an onboard companion computer. A forward-facing camera performs net inspection and hole detection, while a downward-facing camera observes a floor-mounted fiducial-marker array used for global localisation. Manipulation is provided by a commercial subsea gripper fitted with a custom patching end-effector. The patching end-effector incorporates a spring-loaded mechanism that, upon contact with the net surface, compresses and releases to press the patch firmly against the net material, aiding retention.

Figura 2: BlueROV2 heavy platform with integrated patching end-effector.

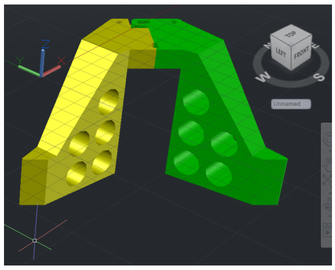

Figura 3: Custom end-effector used for patch deployment.

4.2. Localisation and Mission Autonomy

Global pose estimation is obtained by combining downward-camera observations of known fiducial markers with inertial sensing. The resulting pose estimate provides sufficient accuracy for waypoint-driven navigation throughout the mission.

The execution of the mission is composed of four phases: search, approach, inspection, and patching (Figure 4). The vehicle first navigates to the net structure, then performs a surface sweep searching for holes satisfying the predefined size criterion. Once a target is detected, the system transitions directly into the patching phase.

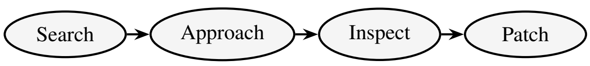

Figura 4: Phase-based autonomous mission pipeline.

4.3. Terminal Engagement and Patching

The final intervention stage uses a custom end-effector mounted on the subsea gripper. During terminal approach, the vehicle regulates its pose relative to the previously estimated hole position using closed-loop position control. Hole detection is performed prior to engagement; continuous visual servoing and tactile contact sensing are not currently employed during the final patching manoeuvre. This strategy improves repeatability during terminal approach under moderate underwater disturbances.

5. Experimental Results

The complete autonomy pipeline was initially developed and debugged in the Stonefish underwater simulator, which provided a safe environment for controller tuning and integration testing. The primary experimental validation was conducted on the physical BlueROV2 platform in the CIRTESU indoor tank, where all perception, navigation, and patching experiments were performed.

5.1. Localisation Performance

Global localisation was evaluated using the downward-facing camera observing the floor-mounted fiducial-marker array. Marker detections were fused with inertial measurements to estimate vehicle pose during autonomous navigation.

Across all recorded missions, the fused pose estimate remained sufficiently stable for waypoint-driven navigation and inspection. No localisation failures or drift events large enough to interrupt mission execution were observed during the experiments.

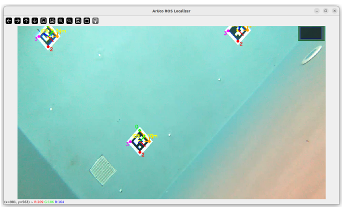

Figura 5: Downward-facing camera view of the fiducial-marker array used for global localisation. Per-marker pose estimates are overlaid during runtime.

5.2. End-to-End Mission Execution

Complete autonomous missions were demonstrated repeatedly in the CIRTESU test tank. After mission initialization, no teleoperation commands were issued during autonomous mission execution. The vehicle successfully executed the full search–approach–inspect–patch sequence without operator intervention.

Figure 6 shows a representative mission trajectory in the global NED frame. The vehicle first navigates toward the net structure, performs a surface sweep while searching for holes satisfying the predefined size criterion, and transitions autonomously into the patching phase once a valid target is confirmed.

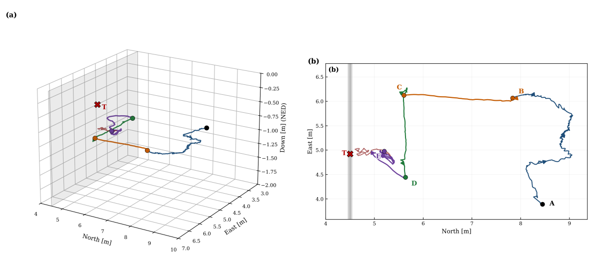

Figura 6: Representative autonomous mission trajectory recorded in the CIRTESU tank. The vehicle searches for the net, performs surface inspection, and engages the detected hole target.

5.3. Terminal Engagement and Patching

The final intervention stage was evaluated through repeated contact trials using the custom end-effector. The vehicle converged to the estimated hole position in approximately 70 % of trials, with occasional false positives from the hole detector contributing to unsuccessful engagements. Failures were primarily associated with alignment errors during the final centimetres of approach.

Figure 7 shows vehicle pose convergence toward the target hole position during terminal approach.

Although reliable engagement was achieved, unsuccessful trials were primarily associated with alignment errors during the final centimetres of approach. Improving terminal guidance robustness remains part of ongoing work.

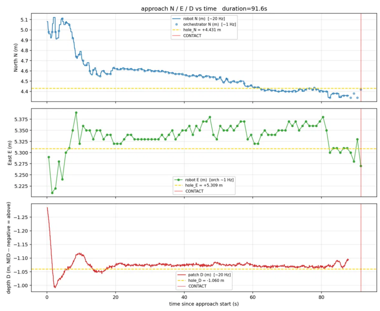

Figura 7: Vehicle pose convergence toward the target hole position during terminal approach. The vertical dashed line indicates the detected engagement event.

6. Limitations

The reported results are obtained in a controlled indoor pool with clear water, an instrumented floor of pre-mapped markers, and a flat vertical net mock-up of fixed geometry. The system has not been tested in turbid water, in current, on a real fish-cage net under tension, or against marine biofouling on the markers; the localisation strategy assumes that floor markers remain visible throughout the mission. The hole detector is trained on a relatively small custom dataset and its generalisation to real-net textures has not been characterised. The vehicle currently carries a single patch per deployment, and multi-patch capacity remains an engineering question for future work. All reported success is based on a limited number of trials in a single environment and should be read as an existence proof rather than a statistical performance characterisation.

7. Conclusions

An end-to-end autonomous underwater intervention pipeline has been demonstrated on a physical BlueROV2 heavy platform operating in the CIRTESU tank environment. Simulation in Stonefish was used during development and controller integration, while all reported mission executions and contact-interaction experiments were performed on the real vehicle. First, the complete inspect-detect-engage workflow can be executed autonomously in a controlled instrumented environment on a commodity platform substantially cheaper than research-class intervention AUVs such as the GIRONA500; prior work on commodity platforms had demonstrated individual sub-tasks but not the end-to-end pipeline. Second, terminal engagement is performed via closed-loop position control. Within the limitations of Section 6, human divers remain the practical reference for multi-hole operations; the present work establishes that a complete autonomous intervention pipeline is reachable from a commodity starting point.

Acknowledgments

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