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Article

Kalypso: An inspection AUV for aquaculture

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Abstract: Kalypso is a 3D-printed underwater robotic system developed to enhance aquaculture management in the Mediterranean Sea, particularly for species such as sea bream, sea bass, carp, and catfish. It functions in two modes: autonomously as an Autonomous Underwater Vehicle (AUV) for routine inspections, and as a teleoperated Remotely Operated Vehicle (ROV) for more complex interventions. In AUV mode, Kalypso detects critical issues such as structural damage to nets, the presence of dead fish, and biofouling or plant growth on net surfaces. In ROV mode, it enables operators to address these challenges directly, including repairing nets, removing debris, and retrieving dead fish. By facilitating proactive maintenance, improving fish welfare, and optimizing resource allocation, Kalypso represents a significant advancement in aquaculture technology. Its innovative use of 3D printing and dual operational modes ensures a cost-effective, flexible, and sustainable solution tailored to the specific needs of Mediterranean fish farms.

Keywords: robotics; AUV; aquaculture

1. Introduction

Aquaculture has become an indispensable component of global food production, addressing the demand for seafood and significantly contributing to economic growth. In Greece, the aquaculture industry holds substantial economic and social importance, particularly in coastal regions where it supports local livelihoods and strengthens the national economy. Greek aquaculture primarily focuses on the farming of species like sea bass, sea bream, and mussels, which are in high demand both domestically and internationally. Exports of these species contribute significantly to Greece's trade balance, highlighting the industry's strategic importance.

Despite its benefits, aquaculture faces numerous challenges, particularly in the maintenance and management of fish farms. Fish escapes due to damaged nets can lead to significant economic losses and environmental consequences, such as the disruption of local ecosystems. Biofouling on nets and other infrastructure can impair water quality and fish health, further complicating farm management. Traditionally, these issues have been addressed through manual inspections and maintenance, which are labor-intensive, costly, and potentially hazardous for divers. These limitations have spurred interest in leveraging advanced technologies, including robotics, to enhance the efficiency and safety of aquaculture operations.

To address these challenges, we have developed Kalypso, an Autonomous Underwater Vehicle (AUV) designed specifically for aquaculture applications (**Figure 1**). Kalypso integrates cutting-edge computer vision and machine learning algorithms to autonomously navigate fish farm nets and inspect for potential anomalies, such as holes, biofouling, or structural weaknesses. By replacing manual inspections with autonomous operations, Kalypso aims to reduce operational costs, enhance inspection accuracy, and mitigate risks associated with fish escapes. The vehicle represents a step forward in modernizing aquaculture practices, ensuring sustainable production while optimizing resource utilization. Our work not only addresses critical industry challenges but also lays the groundwork for the integration of robotics into everyday aquaculture operations, paving the way for more sustainable and efficient fish farming systems.

Figure 1. Our vehicle. Kalypso.

2. Literature work

Similar works could be mentioned. Initially, a ROV with omnidirectional movement capability, designed for fish farm inspection in Norway, featuring three wings integrated with thrusters for propulsion [1]. Furthermore, the "Anglerfish" robotic system comprising tethered surface and underwater vehicles for bidirectional data transfer, with six brushless thrusters enabling six Degrees of Freedom (DoF) underwater [2]. Another ROV, "eROV," featuring five DoF and a multi-motor configuration with aluminum frame-mounted thrusters facilitating motion control [3]. Additionally, a small underwater ROV designed for exploration and video streaming via Ethernet protocol featuring six brushless motors and a Raspberry Pi 3 for integrated control and data processing [4].

Concerning autonomous underwater vehicles (AUVs), the AUV named "Argus" [5] features a positioning planning system utilizing a Doppler velocity log to estimate the geometry of the surveyed region. Furthermore, an AUV specifically designed to prevent biofouling and conduct inspection operations is [6]. The conceptual design, operational methodology, and control strategies, including Lyapunov theory and Backstepping Integral Adaptive Control algorithm, are elucidated for data collection purposes. Additionally, the "LAUV" AUV, equipped with acoustic modem and sensors for surveying and inspection applications. Emergency features such as an acoustic pinger, text messaging with GPS position, and positive buoyancy enhance its versatility and safety, making it suitable for various marine tasks [7]. Another notable AUV, "Feelhippo," designed for subsea monitoring and inspection, is characterized by its lightweight construction, positive buoyancy, and reconfigurable thruster configuration [8]. Furthermore, the "Girona 500" AUV is highlighted for its versatility and adaptability, capable of reconfiguration for diverse tasks [9]. Different thruster configurations offer distinct degrees of freedom, enabling mission-specific payloads and interventions tailored to specific aquatic environments. Cheng et al. [10] provide a thorough review of path planning and obstacle avoidance techniques for AUVs, emphasizing their critical role in ensuring safe and efficient navigation in dynamic and obstacle-rich marine environments. Their work highlights the importance of integrating real-time adaptive algorithms to handle environmental complexities, which is essential for effective autonomous operation. Complementing this, Zeng et al. [11] compare optimization techniques for AUV path planning in environments influenced by ocean currents, focusing on maintaining stability and achieving energy-efficient routes under challenging conditions.

Adaptive sampling methods for AUVs are explored by Hwang et al. [12], who review techniques to optimize data collection in marine environments. These methods enhance the ability of AUVs to perform targeted inspections and gather high-quality environmental data, particularly in dynamic and heterogeneous underwater regions. Allotta et al. [13] contribute to navigation advancements by presenting an unscented Kalman filter-based system, which improves localization accuracy and robustness in confined or cluttered underwater settings.

Intervention capabilities are another critical area of AUV research. Ridao et al. [14] discuss the challenges and advancements in intervention AUVs, detailing the operational frameworks required for tasks such as object manipulation, infrastructure maintenance, and environmental cleanup. Similarly, Cook et al. [15] survey simulation tools for multi-vehicle AUV operations, which are vital for testing and optimizing collaborative tasks in complex marine systems.

Further contributions include Zhang et al. [16], who analyze the resistance characteristics of multi-AUV systems, providing insights into hydrodynamic interactions that influence the efficiency and performance of coordinated operations. Chen et al. [17] review terrain-matching navigation methods, emphasizing their role in improving positional accuracy in environments with varying underwater features. Lastly, Venkatesan [18] highlights innovative AUV applications in search and rescue operations, showcasing the adaptability and robustness required to operate in adverse and dynamic underwater conditions.

In 2018, Greece produced approximately 0.2 million tons of fish, including molluscs and crustaceans. The total value of this production was USD 794.4 million. 80% of this value came from aquaculture, while the remaining 20% was from fisheries. Between 2008 and 2018, the quantity of fish produced increased by 5%, but its value decreased by 22% [19].

The intent of this work is to provide a transformative solution that empowers the Greek aquaculture industry, enhances its economic sustainability, and safeguards the environment. Our AUV, named Kalypso (**Figure 1**), is presented in this paper, construction and robotic vision. Our AUV succeed a greek patent.

Next section II, presents the construction details, while section III describes the use of vision for the navigation as AUV. Section IV gives the validation from fisheries [20], while our conclusion is given in section V.

3. Design and construction

The vehicle weighs about twelve kilograms, and its dimensions are 440 × 590 × 182 mm.

Kalypso, the autonomous underwater vehicle (AUV that was designed for inspecting the fish farm cages, embodies a sophisticated design (**Figure 2**) and robust construction tailored to excel in challenging underwater environments. With the primary objective of enhancing inspection frequency while minimizing maintenance costs, Kalypso integrates cutting-edge technology and innovative engineering solutions to ensure optimal performance and reliability.

Figure 2. Top plan of the vehicle.

The two side 3D-Printed Parts serve to increase the vehicle's surface area, thereby enhancing stability. They also house the vehicle's thrusters. Additional weights (150 g) are incorporated within these parts to optimize balance, while plastic corks (parts P1, P2) are positioned at the top front and rear to act as fixed ballast tanks, reducing buoyancy.

At the heart of Kalypso lies a meticulously designed main body (part P3), fabricated using advanced 3D-printing technology. Constructed from a blend of blue, black, and yellow PLA plastic, the main body offers a balance of structural integrity and buoyancy crucial for sustained underwater operations. The 3D-printed **Figure 3 and Figure 4**). construction enables precise customization and intricate detailing, allowing Kalypso to navigate intricate underwater structures with ease and agility. A watertight enclosure houses all the electronics and is designed to withstand water exposure. It comprises an https://aegean-gr.zoom.us/j/92751915673?pwd=SEJBam9tWjBwU2w3b3pPSWpNOEpLZz09 tube with a 152 mm inner diameter and 300 mm length, two flanges equipped with three O-rings each, two end caps (one with cable holes), and aluminum plugs with O-rings for cable sealing (**Figure 5**).

Figure 3. Design frontage of the vehicle.

Kalypso's maneuverability and agility are enhanced by an eight-thruster configuration, providing the vehicle with six degrees of freedom. Strategically positioned thrusters grant Kalypso control and versatility, enabling precise navigation and movement in three-dimensional space. This configuration empowers Kalypso to conduct comprehensive inspections of fish farm nets with precision and efficiency.

Kalypso is equipped with a suite of advanced sensors, selected to optimize performance and enhance data collection capabilities. These cutting-edge sensors include leak sensors, underwater ultrasonic sensors, and twin front and rear cameras.

Specially modified plugs with O-ring fittings designed to isolate cables entering and exiting the central tube, ensuring the watertight integrity and protection of internal electronics.

Power supply comprising two 14.8 V, 10,000 mAh, and 30 C Lithium batteries, providing ample energy for extended operational durations and sustained mission capabilities.

The integration of silicone-impregnated LED lighting (**Figure 6**) further enhances visibility during inspection procedures, ensuring accurate data capture even in low-light conditions. 12V LED lights strategically positioned to enhance visibility during underwater operations, ensuring clear imaging and precise inspection results.

Figure 4. 3D printed vehicle.

Finally, in order to run the software, three platform are used:

1) A Pixhawk board responsible for precise navigation and control of the vehicle, ensuring accurate positioning and trajectory tracking during inspection missions.
2) A Raspberry Pi 3 mainboard, serving as the central processing unit for onboard computation and data processing tasks, facilitating real-time decision-making and analysis.
3) A high-performance mini PC, powered by an Intel Core i7 processor, 16GB RAM, 512GB SSD, and Nvidia GeForce GTX 1660 Ti graphics card, dedicated to advanced computer vision tasks and image processing algorithms.

4. Robotic vision and navigation

The navigation system of Kalypso, designed for inspecting fish farm nets, plays a pivotal role in enabling autonomous navigation through the intricate mesh structures of fishing cages. A comprehensive exploration of various navigation methods was conducted during the vehicle's development, aiming to optimize performance and address operational challenges in aquaculture environments:

- Navigation with IMU: Initial navigation attempts relied solely on an Inertial Measurement Unit (IMU), with the robot moving parallel to the net for a predetermined period before making 90-degree turns at corners (for square cage). However, challenges arose due to orientation errors generated by the compass, leading to difficulties in maintaining consistent distance and orientation relative to the net.
- Navigation with IMU and Distance Sensor: Subsequent iterations incorporated a distance sensor to address distance-related issues while maintaining proximity to the net. Despite effectively adjusting distance, orientation errors persisted, posing limitations to overall navigation accuracy.
- Navigation with Two Distance Sensors: Experimentation with dual distance sensors positioned vertically introduced challenges related to signal interference and inaccurate distance measurements, particularly during rotational maneuvers.
- Navigation with IMU and Two Distance Sensors: A revised approach combined IMU data with distance sensor inputs to mitigate orientation errors. However, challenges persisted, necessitating further refinement of navigation strategies.

To address persistent challenges and enhance navigation accuracy, modifications were implemented in the final navigation procedure (**Figure 7**). These refinements included:

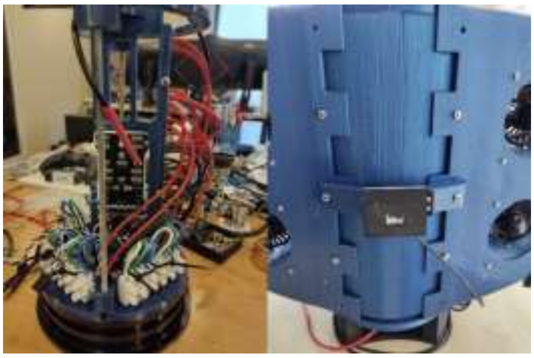

Figure 5. The Acrylic tube that houses all the electronics.

Figure 6. ROV led lights.

- Selective utilization of sensor data when the robot is close to the net, leveraging empirically observed reliability under such conditions.
- Rotation adjustments optimizing rotation speed and timing for enhanced accuracy.
- Implementation of backward movement after distance corrections to realign the robot in case of inadvertent net contact due to sensor inaccuracies.
- Adaptive lateral movement and rotation strategies to mitigate inaccuracies and ensure effective navigation in complex underwater environments.

In tandem with navigation enhancements, a robust vision-based procedure was developed to detect potential holes in the net (**Figure 8**). This procedure involved:

- Frame resizing to enhance processing speed and facilitate real-time analysis.
- Grayscaling and image enhancement techniques to improve contrast and visibility of the net against the surrounding environment.
- Binarization and connected component analysis to identify and classify net openings and potential tears.
- Spatial and temporal filtering to remove noise and identify persistent anomalies indicative of net damage.
- Real-time video processing and analysis, enabling continuous surveillance and timely detection of net irregularities.

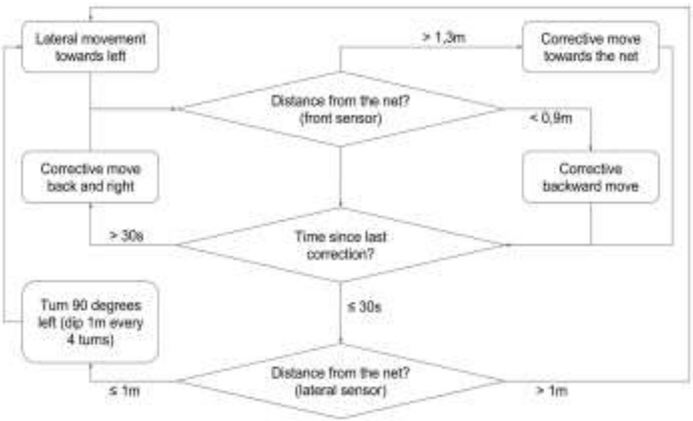

Figure 7. Final navigation procedure.

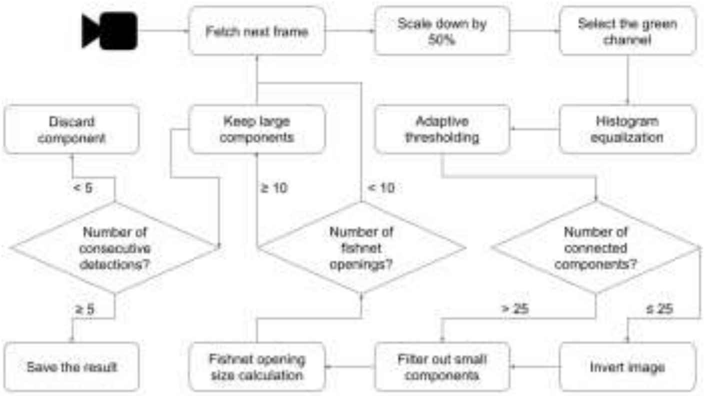

Figure 8. The hole-detection procedure.

All the electronics of the construction appears in **Table 1**:

Table 1. The electronics.

No.	Name	Quantity
1.	Motors	8
2.	ESC Motor driver	8
3.	Raspberry Pi 3	1
4.	Pixhawk	1
5.	Leak sensor set	1
6.	Power module	1
7.	Power Relay	1
8.	Relay for led	1
9.	USB camera	2
10.	Led strip 12v	1
11.	Ultrasonic distance sensor	1
12.	Pressure sensor	1
13.	14.8v LiPo batteries	2
14.	Cables (m)	10
15.	Mini PC	1
16.	Plugs	4

5. System validation

Kalypso was tested in fish farm cages at Kefalonia Fisheries S.A., with the maximum depth reached at 16.8 m, while the vehicle's components are, theoretically, for depths of up to 100 m according to the specifications of the Bluerobotics [21] components. The experiments were conducted under varying weather conditions, with observed wind speeds ranging from 0 to 20 knots. The presence of net cages in the water altered underwater currents, resulting in restricted flow conditions. Nevertheless, the robot was able to cope with the adverse weather conditions.

The experiments at Kefalonia Fisheries involved two main approaches to testing Kalypso's functionality. Firstly, the vehicle was operated as a tethered manual vehicle, allowing an operator to inspect nets using semi-automatic maneuvers. These maneuvers included stabilize mode, which maintains heading, and depth hold mode, an enhanced version of stabilize mode that maintains the current depth. Secondly, Kalypso was tested as a tetherless autonomous vehicle (AUV), performing missions inside net cages to record video footage for post-processing analysis.

To evaluate Kalypso's effectiveness in inspecting net cages, an experiment was conducted in a square net cage measuring 7 × 7 m with a depth of 3.5 m, covering a total area of 98 m^2. The objective was to assess Kalypso's capability to locate yellow rectangular labels randomly positioned inside the net cage, which simulated objects of interest.

Prior to the experiment, a diver placed ten yellow rectangular labels at diverse locations within the net enclosure. These labels were numbered from 1 to 10 and served as visual indicators for Kalypso to detect during its inspection mission. Bringing a camera, Kalypso autonomously navigated through the net cage, capturing visual content of the inspection process. The primary objective was to locate and capture all ten yellow labels within the net cage.

Upon completing the inspection, the recorded visual media was reviewed to assess Kalypso's performance. The video frames were analyzed to determine the number of yellow labels successfully detected by the AUV. The experimental results demonstrated the effectiveness of Kalypso, as all ten yellow labels were successfully located and captured, resulting in a 100% success rate for the mission.

Furthermore, the evaluation revealed that seven out of ten labels had their numerical values identified, while the numbers of the remaining three labels could not be discerned due to image blurring. The successful capture of all labels validated Kalypso's ability to efficiently execute underwater inspections, demonstrating its effectiveness in detecting points of interest within net cage environments.

In addition to label detection, Kalypso underwent testing to assess its capacity to locate damaged regions of the net using partitioning methods. The vehicle demonstrated excellent accuracy in distinguishing between clean net sections and those that were damaged or covered in algae, essential for identifying potential issues and preventing disease spread among the fish population.

Moreover, the leak sensor integrated into Kalypso was evaluated several time during the initial testing, proving to be a crucial component for detecting water leaks in the watertight enclosure and alerting the operator. This capability enhances the vehicle's security and helps prevent damage or malfunction.

The experimental results from Kalypso's initial testing phase underscored the vehicle's effectiveness and potential in the fish farming sector. With its robust design, advanced sensors, and precise movement capabilities, Kalypso emerged as a reliable option for inspecting nets in fish farms. Its success in identifying potential problems were also validated by the staff of the fisheries that noticed as positive points:

> *...All these above actions are a key part of the management of a floating facility and require the employment of a large part of the unit's workforce and especially divers. Diving operations in a fish farm are outsourced, increasing the overall cost of production. However, their work is governed by the specific legislation that mainly concerns diving hours, limiting the realization of daily tasks.*
>
> *Also, with the use of the ROV, the monitoring of the fish population itself is achieved, which implies the early detection of a change in its behavior. It can*

contribute to the first diagnosis of diseases or stressful situations, allowing derivatives to take preventive actions, improving both living conditions and the production process.

Also, monitoring the population via ROV can contribute to feeding control by checking in real time the appetite for nutrition. The feeder monitors the population and stops feeding if for some reason the fish stop feeding. In this way we ensure the appetite and health of the population. Otherwise, we limit the loss of food, preventing the waste of resources and the burden on the environment.

By adding appropriate sensors, the robotic machine can become a machine for measuring and recording physicochemical factors throughout the water column, even in the most inaccessible places. Thus, it is possible to continuously monitor and record environmental indicators of well-being such as oxygen saturation, temperature and others.

A positive feature of this particular robotic vehicle is that there is no disturbance to the fish inside the cage. The fish swim normally without any sign of stress, which could burden their well-being and growth rate.

However, the ROV is easy to use by the fish farmer and no specific user training is required. The user places the ROV inside the cage and it automatically controls the cage. The other positive feature of the robot is its speed, which means it can handle cage control in a short amount of time. Finally, the low cost of the robot (up to 5,500 euros), is an advantage as it allows the purchase of more than one system, which can work simultaneously and thus the control of the unit that is completed in a shorter period of time.

As negative points, they mentioned:

The weight of the vehicle, as the large number of cages requires its frequent movements from one cage to another, making it easier to use if it were lighter.

The lack of a user interface (interface), there is no control of the robot's position while it is in automatic mode inside the cage. In case it stops working or the robot does not complete the cage control for many reasons the user cannot know, except when checking the video on the computer. Downloading data from the robot requires either transporting it to land, or transporting equipment (laptop, router) to sea, which makes its use difficult. Also, at this point of use specialized personnel to receive the data, so automation of this process would be desirable.

Polymerization of the exterior of the robot was observed when exposed to the sun. The working conditions in the floating cages are not reminiscent of the possible preservation of the robot after its use, making it too exposed to the sun. It is recommended to use more durable material, due to the special conditions of floating breeding units.

6. Conclusion

In conclusion, this research presents a novel approach to aquaculture inspection by developing Kalypso, an autonomous underwater vehicle (AUV) equipped with advanced computer vision capabilities. Kalypso's ability to autonomously inspect fish farm nets and detect anomalies, such as structural damage or biofouling, represents a significant advancement in reducing operational costs and improving the efficiency of aquaculture maintenance. While the system has demonstrated considerable potential, there are some limitations, including challenges related to environmental factors such as water turbidity, which can affect the accuracy of vision-based inspection in certain conditions. Additionally, further integration with other environmental monitoring systems could enhance its ability to track water quality and fish health in real time. Future work could focus on improving the robustness of Kalypso's navigation algorithms in dynamic and cluttered environments, enhancing its intervention capabilities, and expanding its application to larger-scale aquaculture operations. By addressing these areas, Kalypso and similar systems could play a crucial role in advancing sustainable aquaculture practices worldwide.

Future work for Kalypso will focus on expanding its capabilities to address a wider range of aquaculture challenges. Enhancements could include integrating advanced environmental monitoring sensors to measure water quality parameters like dissolved oxygen, salinity, and pH, enabling real-time detection of conditions that impact fish health. Further improvements in navigation algorithms and computer vision systems will enhance its ability to operate in dynamic and complex underwater environments, such as those with low visibility or strong currents. Multi-robot collaboration could also be explored, enabling synchronized operations across large fish farms. Finally, connecting Kalypso to cloud-based data analytics platforms could provide actionable insights for farm management, optimizing operations and promoting sustainability in aquaculture.

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