Design and development of underwater robotic arm for automated camera calibration for aquatic environment

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***Abstract*—This paper presents the design and implementation of a 4 degrees of freedom (DoF) robotic arm to assist in the calibration process for underwater cameras in aquaculture conditions. New imaging technologies with remarkable accomplishments have come to the forefront, offering a new field of research in underwater domain. To achieve accurate predictions using underwater cameras, it necessitates high estimations with proper camera calibration, especially in the aquatic environments where the challenges arise. Taking into consideration the necessity for accuracy in aquaculture image applications, a proper calibration system had to be made. In this work, we propose a novel, low-cost, user-friendly and easy to handle calibration process using an underwater robotic arm that calibrates the cameras with a pattern of known distances (checkerboard) as reference points. The arm consists of three revolute joints that can position the calibration pattern to the desired orientations, while a prismatic joint can steer it vertically. The system is designed and manufactured to operate in real conditions and has been evaluated at various aquaculture units in Greece, with highly relevant results.**

***Keywords*—CAD, underwater imaging, camera calibration, robotic arm, Precision Fish Farming (PFF)**

I. Introduction

The aquaculture industry is one of the most developing economic sectors worldwide [1], as it is already covering more than 50% of fish consumption worldwide. This trend is expected to continue in the years to come, supplying two-thirds of the world's fish by the year 2030. In Europe, marine finfish aquaculture is mostly performed in floating cages where the fish are contained within net enclosures suspended from plastic/polyester collars floating at the surface [2]. The farming activity requires increased control in order to improve the end product quality, faster growth and more predictable growth rates, all of which contribute to a better ability to deliver fish to the market in accordance with customer needs and desires. The trends of the industry are toward larger and more complex production units located in less accessible sites with harsher environments [3]. Maintaining fish farming as a sustainable industry, there is a need for new solutions for better control and monitoring of the production in fish farms involving new technological approaches, as introduced by the Precision Fish Farming concept [2].

The aquaculture industry brings major challenges when it comes to monitoring and inspection of the deformable structures and biomass inside the fish cages. Nowadays, several fish farming companies are utilizing underwater camera systems either as standalone solutions or attached on unmanned underwater vehicles (UUVs) to gather data from the cage environment [4]. To move from pure observation based on subjective assessment which involved the human factor, research has been conducted on development of novel methods for automated monitoring and inspection of both the cage environment and the biomass [5], [6], [7], [8], [9], [10], [11].

Recently several vision-based applications have contributed to the development of more efficient management procedures for the aquaculture industry [12]. A common base is the use of subsurface cameras for collecting individual or group level data on fish in aquaculture fish farms, with various applications such as the assessment of fish swimming activity (e.g., [13], [14]) size (e.g., [15], [16]), health condition (e.g., [17]), abnormal identification (e.g., [18], [19]) and feeding activity (e.g., [20]). The main common factor and one of the major challenges of all these methods is precise calibration of the underwater camera systems.

Several calibration procedures have been published previously, using different methods and procedures. A camera calibration was presented aiming in solving the lens deformations caused by hemispherical and planar housings by a rectification of the error in the three-dimensional coordinate system [21]. Another study, exploit the light dispersion at various wavelengths as a method for calibration [22]. In [23], calibration methods in the air were used applying, the Snell's Law [24], [25] to correct lens distortions in underwater environment. Furthermore, in several cases manual calibration was performed using a moving pattern of known distances as in [26], where the proposed algorithm was able to estimate fish length, while reading the calibration information. In other cases (e.g., [27]) a steady calibration pattern was utilized as a background while using a stereo camera system. Similar in [28], fish length was calculated by placing the candidate fish close to a calibration pattern at known distances.

Worth mentioning that the majority of the earlier investigated solutions in this domain are challenging to implement in real working environment (i.e., in aquaculture settings) given the interest in using submerged cameras as explained earlier. There is, therefore, a clear need of an automated calibration procedure that could be used in different environments particularly in marine aquaculture set-ups in a cost/time efficient and easily applicable manner. A potential solution to this is the use of an underwater manipulator/robotic arm that could assist and automate the calibration process.

Underwater manipulation is a challenging task in subsea domain and extensive research has been conducted on the design, development, modeling and control of such systems [29]. In addition, several industrial solutions are currently available in the market to utilize, where the majority of the developed robotic arms are hydraulic and few solutions have been investigated for electrically driven arm concepts (such as solutions developed from Reach Robotics company [30]). In [5], an electrically driven robotic manipulator was developed, attached to a ROV and tested in open water. To evaluate the kinematic and hydrodynamic analysis the robotic arm was tested under various scenarios. Similar, in [31], an underwater manipulator was designed and built in which a monocular camera was also attached to the end effector, providing imaging object detection for maritime missions. Furthermore, the kinematic and hydrodynamic analysis of an industrial 6 DOF electric robotic manipulator was developed and presented in [32], where various scenarios were tested in a simulation environment for applications in land-based fish tanks. However, to our best knowledge none of the previously investigated and developed systems have demonstrated suited applicability in highly complex and dynamically changing environments faced in the fish farming industry for the automated underwater camera calibration process. This remaining challenge concerns not only the research community but the industry as well.

To address this gap and challenge of precise and automated underwater camera calibration process, in this paper, we present a new tool designed and developed for automated calibration in an underwater environment. The robotic arm proposed in this work, with a calibration pattern (attached to the end-effector) provides all the necessary orientations to the reference pattern with the goal of rectifying lens distortion. The arm is equipped with a combination of three revolute joints and a prismatic joint. These joints work together seamlessly to achieve precise positioning and movement of the arm's end-effector (i.e., the calibration pattern). The three revolute joints offer rotational flexibility, allowing the arm to displace the end-effector to any desired orientation, while the prismatic joint provides vertical maneuverability, enabling the arm to adjust its height. This dynamic combination of joints allows the robotic arm to perform intricate tasks that require both precise positioning and vertical mobility. It is designed with emphasis to a user-friendly operation having a low cost, move away from sub-optimal manual calibration processes. These features makes it best suited system for automated calibration in challenging conditions such the ones faced in aquaculture domain. The underwater robotic arm has been evaluated for calibration process in tanks and real aquaculture conditions.

This article is structured as follows: Section II presents the requirements and the design of the robotic system suited for underwater camera calibration process, while the developed system is discussed in detail in Section III. Section IV presents the concluding remarks and suggestions for future work.

II. Requirements and Design of the Robotic Arm

Applications of underwater robotic arms in aquatic environment is a challenging research field to investigate, due to the complexity of the conditions such robotic systems are facing particularly in the fish farming industry. Water salinity, high humidity, operations in presence of ocean currents and in wave zone, low visibility, variable environmental conditions affecting water transparency, underwater distortion and challenges related to waterproofing are some of the prevailing conditions that should be taken into consideration when developing dedicated robotic arm for autonomous calibration process. Therefore, the calibration arm was designed and constructed considering all the aforementioned factors.

A. Requirement and specifications

In the fish farming industry stand-alone camera solutions or underwater camera systems attached to UUVs have been utilized in the last decades to monitor and inspect the cage structures and biomass. However, to obtain accurate estimations from the underwater cameras, the camera's parameters had to be extracted [33], [34], [35]. This leads the challenge to the precise calibration process, which is considered the most crucial part in a survey using cameras for accurate results extraction. Furthermore, as mentioned earlier, the current calibration methods are considered to be time consuming, labor intensive with less accurate resulted estimations since the camera parameters extraction depends on the precise projections of the pattern (e.g., [23], [27], [28]). Therefore, to increase the precision of the obtained results, parameter extraction requires the calibration pattern be attached on a flexible system (e.g., end-effector of robotic arm) and thus be present on the field of few of the camera from certain orientations and distances. This suggests the development of a new system able to move in 3D underwater domain in front of the camera system. In summary, the following requirements and specifications are set for the design and development of the new system:

1. An underwater flexible system should be developed able to move in 3D and carry the calibration pattern.
2. The workspace of the system should be able to guarantee certain orientations and positions relative to the camera for precise parameter extraction.
3. Steady movement of the system should be secured in order to obtain the required data quality of the images for calibration process.
4. The developed system should be protected from harsh underwater environment.
5. The hardware components of the system should lead to cost-effective solutions.
6. The adapted software should satisfy the criteria of a user-friendly and easy to operate system.
7. The system has been designed with ease of use for the user, knowing the difficult aquaculture conditions that prevail.

B. Design

To fulfill the requirements set in the previous section, in this part we will discuss in detail the robotic arm designed to address the challenge of precise and automated underwater calibration process. The proposed system is able to achieve the desired orientations and vertical distributions by using three revolute and one prismatic joint. Fig. 1 shows the design of the proposed system. Each link of the robot has cylindrical shape with diameter of 7.8 cm and length of 7.5 cm. The links were manufactured containing a high torque servo motor (FR0115MC), providing waterproof resistance. To achieve required steady movement of the system, a floating base (Fig. 1 - upper right) was designed with dimensions 49.5 cm x 10 cm, where a main shaft (126 cm) could support the vertical translation of the robotic arm.

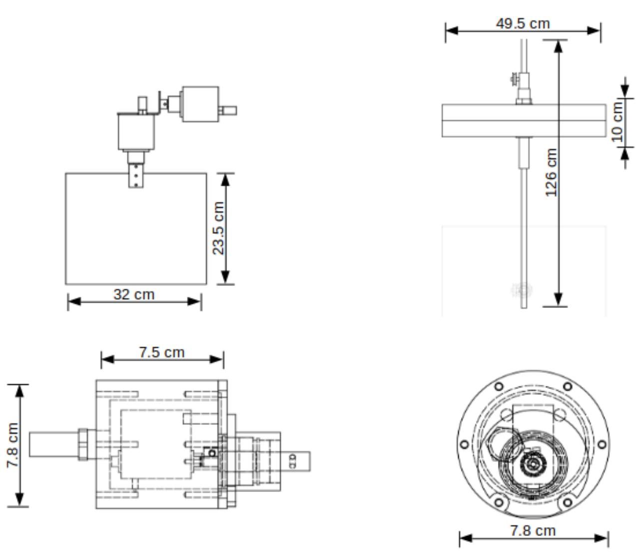

Fig. 1. System design.

The desired orientation of the pattern is a combination of rotation along the X, Y, Z axes, which is achieved utilizing the three revolute joints. As shown in Fig. 2, the three joints can provide a rotation of 180 degrees about its axis. Analytically, joint A, B and C could rotate from –90 to +90 degrees, along Z, X and Y axis, respectively. A chessboard pattern (Fig. 1 - upper left) with dimensions 32 cm x 23.5 cm was attached to the end-effector, where the three joints could give all the necessary projections of the reference point.

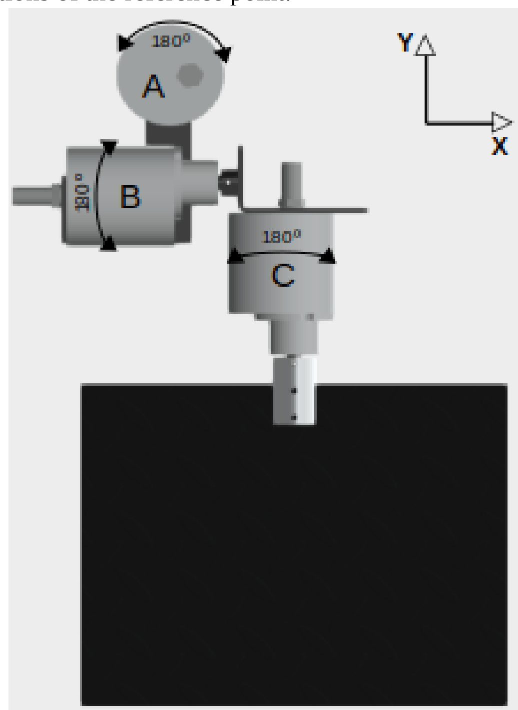

Fig. 2. Presentation of the three revolute joints and the attached calibration pattern.

The joints containing the motors had to be protected by the harsh underwater environment. Fig. 3 shows in detail the designed and manufactured assembly line of the enclosure, an in house made component specifically designed for these conditions. Initially, the protection of the motors had to be resolved. To avoid damaging it from water leakage, two protective caps (red cylinders) were placed on the front of the housing and an O-ring was used to seal the cap of the housing with the rest of the body. As shown in Fig. 3, the motor was placed inside a waterproof housing, keeping it steady, while a bearing (yellow cylinder) could support and maintain the correct position of the shaft.

The system was designed with estimated operational depth up to 10 meters, an operational limit sufficient for underwater applications in the fish farming industry. In this initial stage, the system is tested floating from the surface. However, the modular nature of the developed robotic arm makes it suitable for future integration on UUVs and thus giving the potential for operations in depth up to 10 m.

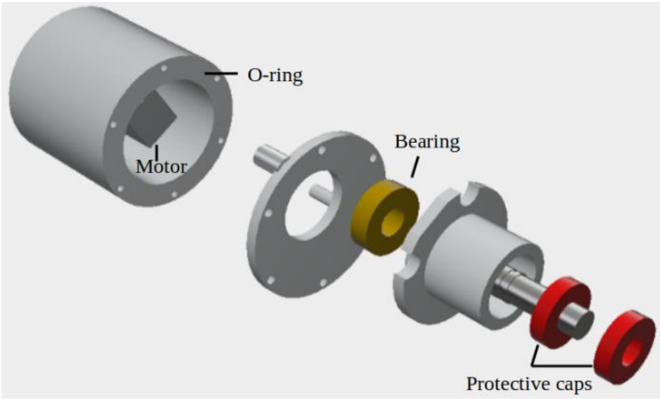

Fig. 3. Housing parts assembly.

In Section II.A, it was mentioned that the camera calibration requires precise orientations and visible projections of the pattern. As shown in Fig. 4, a floating base was designed to provide the necessary buoyancy force to the system, while a motor with a high degree of torque efficiency could cope with the vertical displacement of the end-effector.

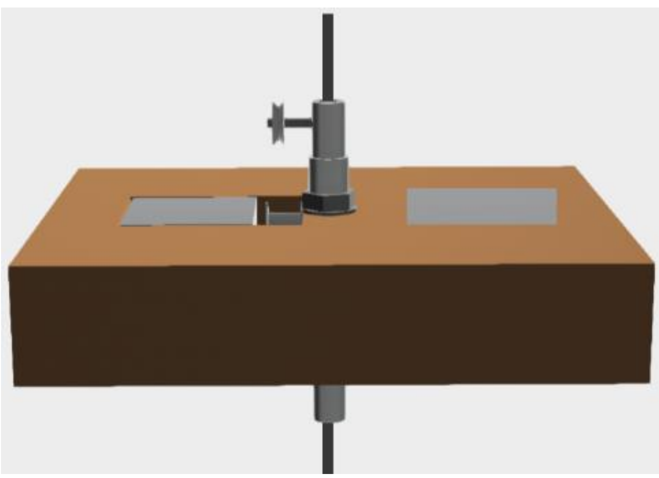
Fig. 4. Floating base

III. DEVELOPMENT OF ROBOTIC ARM

This section presents the developed 4DOF robotic arm consisting of three revolute joints and one prismatic joint. Table 1 shows the technical specifications of the developed system.
Various high-quality materials (e.g., plastic based [36]) in 3D printed technologies have been used as a basis of construction for innovative underwater applications [37]. In our case, the issue that needed to be resolved was not only to provide accurate projections of the calibration pattern but to keep the cost of system fabrication low. Therefore, Polyvinyl Chloride (PVC) was used to build the housing and for the connection shaft, stainless steel (INOX) was used. The floating base was made of polyurethane (which was covered with water resistant liquid) providing buoyancy to the system, while an aluminum cylinder is adapted to support the main shaft in the vertical movement of the end-effector. Fig. 5 shows the developed system.

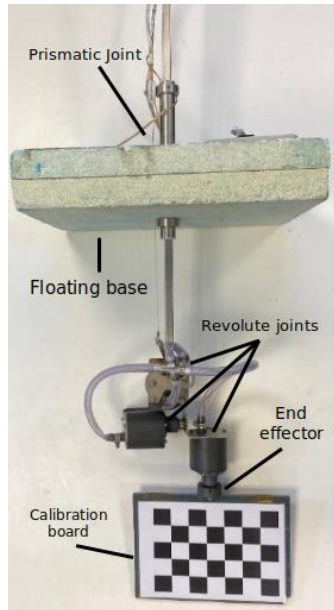

Fig. 5. Actual representation of the robotic arm.

The 4 DOF calibration arm has a maximum depth sampling up to 1.26 m (e.g., Max reach in Table 1). As mentioned in the previous chapter, the three servo motors can provide the rotation movement of the end-effector, while a rotation gear motor with 6 rotation per minute (RPM) can provide the vertical displacement. The system has total mass of 6.2 kg and 2.6 kg in the air and underwater, respectively.

Table 1. System specifications.

Parameters	Value
Degrees of Freedom	4
Weight (air)	6.2 kg
Weight (water)	2.6 kg
Max reach	1.26 m
Number of Servos	3
Servo	FR0115MC
Gear type	Metal
Rotation	180 degrees
Speed (6v)	0.16sec/60 degrees
Torque (6v)	15kg-cm
Servo control system	Digital
Direction	CCW
Vertical Motor	6 RPM Precision Gear Motor
Type	Brushed DC
Torque	58 kg-cm
Communication	RC
Bandwidth	500KHz
Channels	6-10

To establish a safe and proper communication with the robot arm, all the electronic parts were placed in waterproof box and cables, as depicted in Fig. 5. Fig. 6 depicts the in-house made electrical circuit that controls the robotic arm. In particular, the user transmits the signal through remote control to the receiver. Each channel from the receiver controls a specific motor of the manipulator. The whole system is powered by a 7.4 voltage lithium polymer (LiPo) battery. The electronic speed controller (ESC) controls the high torque geared motor to a commanded speed, which has an input voltage range from 3 to 12 volts. Based on the battery voltage, the appropriate adjustments had to be made to provide the correct input voltage to the servo motors. In that case, a voltage converter (DC STEP UP) was able to step down the 7.4 battery voltage to the appropriate 5.2 input voltage for the servo motors. As shown in Fig. 6, the dotted line represents the signal, while the grey and black lines represent the power input and ground, respectively.

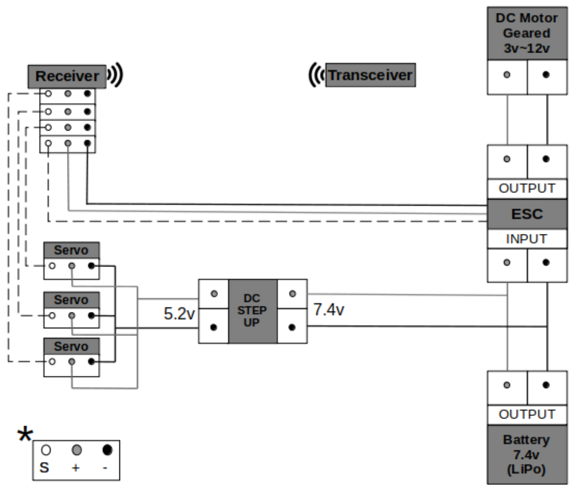

Fig. 6. Circuit diagram.

As illustrated in Fig. 7 below, a brief description of the user-system communication is presented. The user through remote control manages to give the desired angles to the pattern.

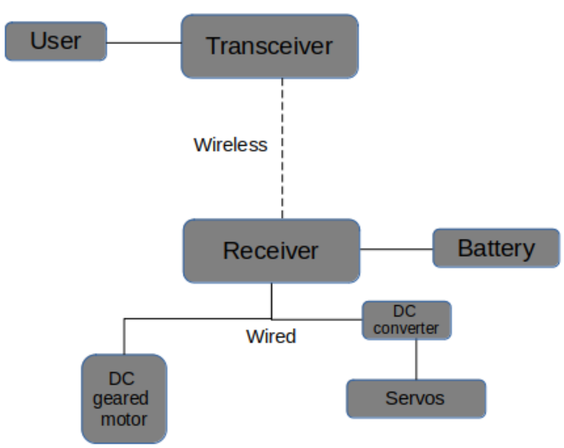

Fig. 7. User - system communication.

The developed system was tested initially in tank environment in HCMR facilities and afterwards in full scale demonstrations in fish farming facilities in the pilot scale cage farm of HCMR located in Souda bay, Crete, Greece while it has been also tested and used in several commercial aquaculture farms in Greece. The calibration samplings were conducted by adjusting the top of the system to the side of the aquaculture cage and through a remote-control (RC) transceiver, the user was able to control the joints and subsequently the calibration pattern. Both of the nodes (transceiver and receiver) communicate with wireless signals through a bandwidth frequency of 500KHz (see Fig. 7). As shown in Table 1, the transceiver consists of six channels that each one controls the motors. Specifically, the three servo motors take as an input PWM signals to position the end-effector and the DC geared motor controls the vertical maneuvering of the pattern. To operate in the proper voltage range, the necessary adjustments had to be done to electrical circuit (Fig. 6). A demonstration of the robotic arm during calibration process in an aquaculture farm in Central Greece is shown in Fig.8. In this case, the robotic manipulator assisted in the on-site calibration of a stereo camera developed by our research group and extensively used for fish size estimation [15].

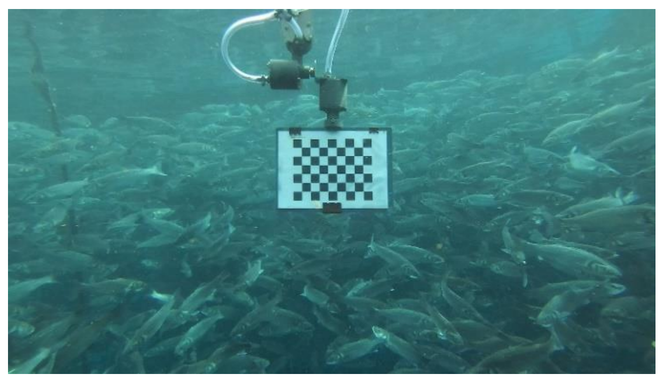

Fig. 8. Demonstration of the developed system during calibration in aquaculture.

To evaluate the efficiency of the calibration arm, images of the pattern was acquired by an underwater camera under different conditions (300 images per condition). An algorithm based on OpenCV [38] was able to identify a corner detection pattern (Fig. 9) on the calibration frame, counting the resulting detections while measuring the geometric error, in pixels. The error, also known as re-projection error, is the difference between the projected and a known point on the pattern.

Fig. 9. Corner detection.

The evaluation experiments were implemented for both automatic and manual calibration in three aquaculture farms in Greece with different turbidity levels. Table 2 shows the detections from each evaluation experiment, with an assessment of the turbidity level, the type of calibration and the re-projection error.

Table 2. Evaluate calibrations from different aquaculture regions.

Number of Images	Detections	Farm	Turbidity	Calibration	Re-Projection error (pixels)
300	62	1	Low	Manual	0.0802
300	34	1	Low	Manual	0.1480
300	115	1	Low	Manual	0.1022
300	234	1	Medium	Automatic	0.0696
300	163	2	Low	Automatic	0.0674
300	113	3	Low	Automatic	0.0680
300	135	3	Medium	Automatic	0.0888

The automatic calibration could achieve more detections with less error even at medium turbidity levels. For instance, in an automatic sampling that was conducted in Farm 3, the algorithm could detect 135 out of 300 images in medium turbidity level, and the re-projection error was almost the same as the lowest error achieved by manual sampling. The mean re-projection error between the manual and the automatic calibration was 0.1101 pixels and 0.0734 pixels, respectively.

Through demonstrations, we can conclude that the proposed system provided a more cost and time effective automated camera calibration process during image samplings. The user-friendly framework implemented made it possible for the users to deploy the system on-site and manage the calibration pattern to the desired positions and orientations, with the aim of extracting the camera parameters. Therefore, this directly addresses the current challenges and contributes to resolve the difficulties that arise during the calibration process, such as manual calibration on the cage, errors that will occur in “dry water” calibration [39] and the bad weather conditions on-site. Furthermore, the system proposed in this paper contributed to reducing the sampling time in comparison to manual calibration. To the best of our knowledge this is the first robotic system developed which is dedicated to addressing the problem of underwater calibration processes in aquatic environments.

The demonstrations also showed that not only it can reduce the time of calibration process, but through the camera parameters extraction from different environments, many conclusions can be drawn about the distortions resulting from different underwater environments. From several samplings that have been made, the camera distortions do not only occur from the camera lenses but also from water turbidity and salinity. Therefore, we expect that the proposed system can be utilized in several domains in maritime industry even though it is primary developed with the aim to be used in fish farming industry. Nevertheless, it is important to mention that fine-tuning may be necessary to enhance the system's resilience in diverse application domains. For instance, optimizing cable management and downsizing the housing can contribute significantly to increased flexibility and ease of system management. Furthermore, to fully automate the calibration process, control methods should be incorporated [40], [41]. Finally, by tailoring the hardware to specific needs, the system can adapt more readily to different applications, ensuring optimal performance.

IV. CONCLUSIONS

The aquaculture industry has witnessed significant transformations in recent years, driven by technological innovations like Unmanned Underwater Vehicles (UUVs) and vision technologies. These advancements have paved the way for novel approaches to fish management. However, despite these strides, the industry continues to grapple with various challenges, particularly in the realm of vision-based solutions. Notably, factors such as optical disturbances, including the presence of algae and microorganisms, as well as image distortions, demand thorough consideration. Consequently, the calibration process becomes indispensable for achieving the utmost precision and accuracy in estimations. While numerous studies have explored calibration techniques, they often overlook these prevalent environmental conditions, leaving room for the development of more robust and tailored calibration methods.

In this paper, we introduce an efficient, affordable and remotely operated 4-degree-of-freedom (4DOF) underwater robotic manipulator designed to facilitate camera calibration in authentic aquaculture settings. This manipulator comprises one prismatic and three revolute joints, enabling precise adjustment of angles and orientations for a calibration pattern attached to its end-effector. Our developed system is actively deployed to achieve precise calibration of underwater cameras, as shown by the manual-automatic calibration comparison, enhancing the accuracy of outcomes in the realm of monitoring and inspecting cage structures and estimating fish biomass.

The current system operation relies on the assumption that the calibration board remains within the camera's field of view, allowing users to maneuver it using commands to obtain footage. A crucial next phase of this project involves integrating the camera and calibration unit for automated calibration. This entails acquiring precise data on the camera's position and orientation. These data points will play a vital role in generating reference signals for the robotic system's controllers. By interconnecting these components, we aim to streamline the calibration process, reducing manual intervention and enhancing overall efficiency.

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