



MURA: a Multipurpose Underwater Robotic Arm mounted on Kalypso UUV in aquaculture

Marios Vasileiou¹ · Nikolaos Manos¹ · Ergina Kavallieratou¹

Received: 30 April 2023 / Accepted: 13 October 2023
© The Author(s) 2023

Abstract

Underwater vehicles utilized in net cages at aquaculture facilities are commonly utilized for the purpose of examining the deterioration of nets and the accumulation of biofouling. The implementation of a robotic system for repairing damages has the potential to decrease the expenses associated with employing divers while reducing the risk of their injury. This study details the development, fabrication, and simulation of a cost-effective subaquatic manipulator, denoted as MURA, which can be seamlessly incorporated into submersible vehicles. The Kalypso unmanned underwater vehicle (UUV) is utilized in this study. MURA exhibits a high degree of modularity, enabling seamless alteration of the end-effector tool. Additionally, its low-cost nature renders it a viable option for integration with any underwater vehicle. Three end-effectors were subjected to testing, one designed for the purpose of disposing fish morts, another intended for removing litters from net cages in fisheries, and a third for repairing net tears. This study outlines the MURA design, including the arm's fabrication and constituent components. In addition, the modeling of the manipulator is presented accompanied by a water flow simulation of the three manipulators. Ultimately, the experimental findings are analyzed and evaluated. These include the field experiments performed at Kefalonia fisheries, along with the duration to complete each task. For instance, the capture of fish morts typically necessitates approximately 30 s, encompassing the entire process from initial targeting to actual capture. In a similar vein, the procedure of mending tears in a net necessitates an approximate duration of 70 s on average, encompassing the stages of initial identification and subsequent detachment. The suggested design exhibits adaptability and durability while upholding affordability when utilized in aquaculture.

Keywords Underwater manipulator · Underwater unmanned vehicle (UUV) · Robotic arm · End-effector · Remotely Operated Underwater Vehicle (ROV) · Marine robotics

1 Introduction

As stated in a study by the European Commission, aquaculture has experienced remarkable rise, making it the most affluent sector of the food production industry [1]. In accordance with the Greek Maricultures Federation, Greece produced more than 127 thousand tons of fish in 2019 with a

value of 553.4 million euros [2]. Regular maintenance of fisheries' infrastructures is essential for sustaining healthy fish growth and preventing the decline of marine life, as is the employment of divers in the process of inspecting and repairing the net cages at fisheries. An aquaculture enterprise, Kefalonia Fisheries, has reported an annual expenditure of 250,000 Euros on its divers [3]. Alongside, divers take risks with their health and life while performing these maintenance operations. In the light of this, Underwater Vehicles (UVs) have the potential to play a substantial role in relation to subsea activities, and the utilization of appropriate apparatuses, such as underwater manipulators, can enhance the range of operations that are possible. In the event that an object becomes entangled in the net cages, prompt removal is imperative to prevent damage to the nets, which could lead to the escape of fish. In this scenario, upon inspection of the cage by the UV, the diving

✉ Marios Vasileiou
mvasileiou@aegean.gr

Nikolaos Manos
manos@aegean.gr

Ergina Kavallieratou
kavallieratou@aegean.gr

¹ Department of Information and Communication Systems Engineering, University of the Aegean, Karlovasi, Samos, Greece

crew will be appropriately notified and assigned the task of carrying out the necessary maintenance actions; however, if the UV is outfitted with a subsea manipulator, the object may be removed without any further hassle. Furthermore, fish mortality in aquaculture is a regular occurrence, and it is necessary to dispose them since they constitute a pollutant [4]. Therefore, divers are employed for this task on a weekly basis and cleaning these cages on a more regular basis has the potential to improve the quality of the water while mitigating the likelihood of fish vandalism. Employing divers more frequently for this kind of operation may not be feasible, but a Remotely Operated underwater Vehicle (ROV) equipped with the proper robotic arm gripper can save expenses associated with disposing of the deceased fish. Correspondingly, while a gripper is mainly a preventive measure, a tool to stitch the holes on the nets can be of

assistance for repair. In the event of a torn net, divers are utilized to patch them.

This paper describes an underwater robotic arm called MURA (Multipurpose Underwater Robotic Arm) mounted on Kalypso ROV with threefold utilization: (i) remove objects, (ii) collect fish morts, and (iii) stitch holes on the nets at Kefalonia fisheries (Figs. 1, 2). The outline for this paper is structured as follows. Section 2 presents the related work. Section 3 shows a comprehensive account of the design and development of MURA, including its electronic components. Section 4 outlines MURA's modeling. Section 5 pertains to the flow simulation and the experimental results of the utilization of MURA, while Sect. 6 concludes the paper.

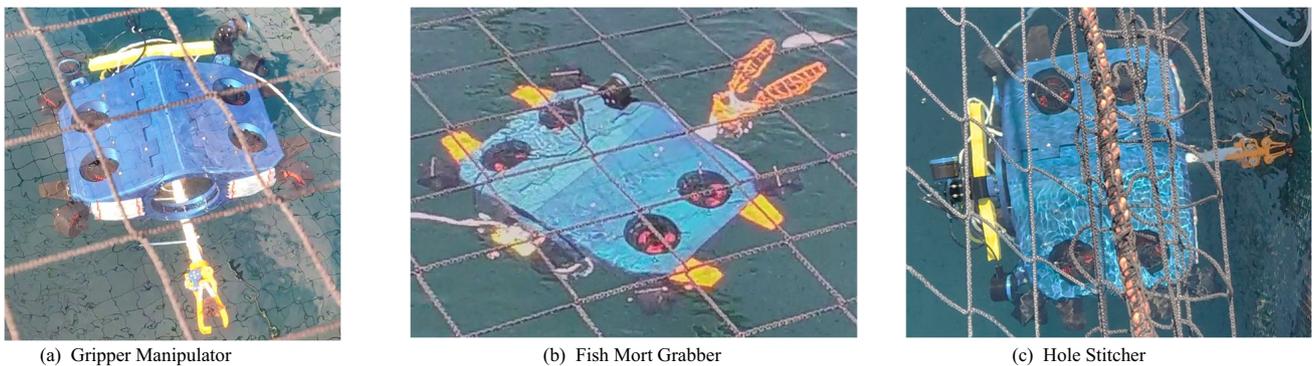


Fig. 1 MURA mounted on Kalypso UV

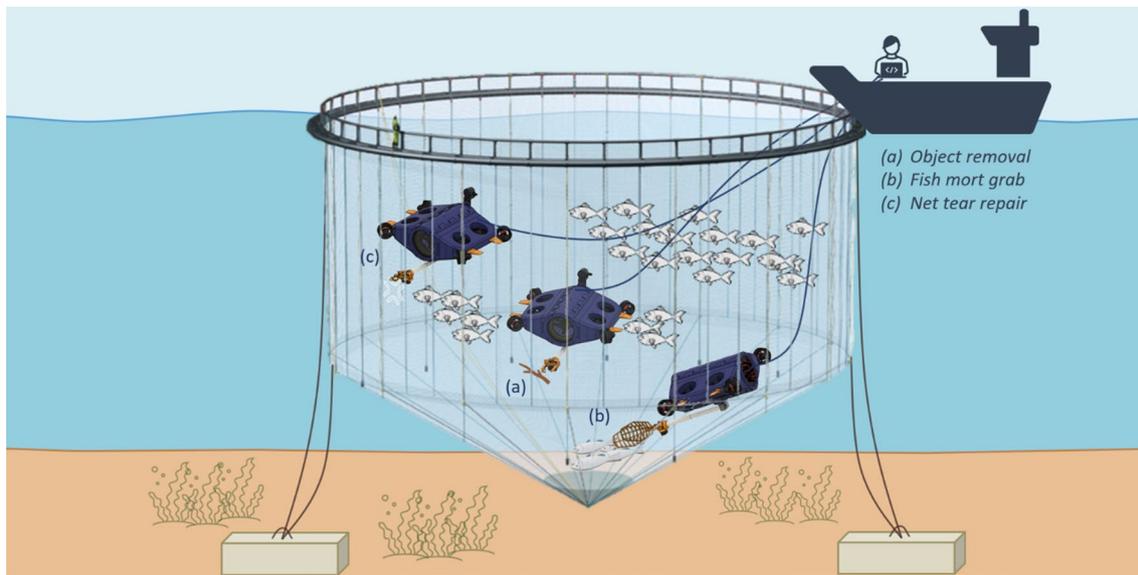


Fig. 2 Graphical representation of the operations in net cages of Kalypso with MURA integrated

2 Related work

Researchers are continuously engaged in the advancement of robotic manipulators, with a focus on addressing specific requirements and considering a range of factors including cost, efficacy, adaptability, maneuverability, customization, and versatility. An example of this can be seen in the presentation of a pliable robotic arm that is powered by Shape Memory Alloy (SMA) coils [5]. It is composed of silicon material, which facilitates secure interaction between the arm and human. The degree of bending is determined by 3 hall sensors located at certain positions. Likewise, ANYpulator is constructed with lightweight carbon fiber links, capable of executing dynamic interaction tasks in a safe manner [6]. Its design allows for efficient and effective performance of its intended functions. Moreover, the presence of an elastic actuator leads to a decrease in impact damage inflicted on the target object as well as this robotic arm.

Notwithstanding the advancements of terrestrial robots, the emergence of subaquatic manipulators has been increasingly observed in recent years. Chiefly, SeaArm, a submersible manipulator designed for small-sized ROVs. It is equipped with several joints to facilitate movement and flexibility [7]. In addition, stainless-steel and aluminium are the primary materials that the arm is comprised and is equipped with a total of five electric servo motors.

The modular design of the manipulator enables its adaptability to meet diverse performance and size specifications across various applications. The manipulator's uniqueness stems from its ability to address the arduous task of creating a manipulator that can be affixed to diminutive observation class ROVs. In another study [8], a modular small-sized underwater robotic arm was presented. The arm was operated using a Master–Slave approach and was designed to be compatible with small-sized ROVs. The main idea of this manipulator is to be used in small exploration-class underwater vehicles. Because of its modular design, the arm may be deployed in a number of various configurations, each of which is defined by the Degrees of Freedom (DoF) associated with it, depending on the kind of task that has to be completed. Also, the arm is furnished with an adjustable gripper that can effortlessly grasp objects of various shapes.

A recent study [9] showcased an additional subaquatic robotic manipulator that features pliable bladders and condensed depth-agnostic actuation while being regulated by pumps. This study proposes a novel approach to designing and controlling underwater manipulators by leveraging the characteristics of soft robots in conjunction with a rigid frame and a soft actuator. The resulting system is expected to exhibit enhanced force and rigidity. Furthermore, it provides uniform actuation through a single hydraulic actuation mechanism that powers all actuators, while the soft bladder

design is fully customizable and has been shown to enhance performance. Correspondingly, an omnidirectional polyhedral manipulator is presented in [10] for subsea creatures sampling. To demonstrate its viability and high adaptability, capture tests on pet fish with delicate tails were carried out using an underwater vehicle and by merely building artificial arms.

Besides the underwater arms presented in scientific papers there are some commercial ones that attribute interesting characteristics. Such a manipulator is “Newton Subsea Gripper” provided by BlueRobotics [11]. It is a passive gripper that can grab objects up to 6.2 cm in diameter. Another gripper is Geneinno Titan MS1021G which is intended for Titan underwater drone [12]. Similarly, the Rovmaker subsea gripper is able to retrieve items, connect recovery lines, or untangle a tether that has become tangled in undersea environment [13]. Likewise, the 2-Finger robotic arm by Qysea gives the operator the greater ability to retrieve objects [14]. These underwater grippers are mainly used for heavy duty operations, and therefore their cost ranges from 400\$ to 600\$. In addition, their maximum rated depth ranges from 100 to 300 m and the maximum clamping force from 90 to 150 Newton, while they utilize a linear piston mechanism to operate.

In addition to the gripper robotic arms, there is a manipulator that can patch holes in net cages in aquaculture offered by Qysea [15]. The user is able to navigate the ROV with the patch attached to repair a net hole.

Furthermore, there exist subaquatic vehicles that are employed for demanding operations and employ manipulators to execute challenging subsea missions. An experimentation in [16] showcased a ROV equipped with a gripper named “Kaxan”. The ROV has a weight of approximately 90 kg and features a maximum rated depth of 120 m. It is equipped with a mechanical passive arm and its analysis demonstrates a non-linear hydrodynamic model, including its associated parameters and components' architecture. Similarly, the ROV trencher, a subaquatic vehicle, is designed to execute subaqueous construction and upkeep operations, including the burial of cables [17]. These operations are accomplished through the utilization of a cable gripper and cutter, while the vehicle is stabilized on the ocean floor via jetting legs. Robotic actuators are frequently utilized in ROVs of a substantial nature; however, they are not financially feasible for our particular scenario. Table 1 quotes articles related to using underwater manipulators and their related application.

This paper centers on the development and experimentation of an underwater robotic arm, which is affixed to the Kalypso ROV, for the purpose of object and net manipulation in net cages at fisheries. It is focused on aquaculture applications in contrast with the presented literature and features inexpensive, robust materials. The impetus for this

Table 1 Related underwater arms

Title	Application	Cost
SeaArm-A subsea multi-degree of freedom manipulator for small observation class remotely operated vehicles [7]	Advanced manipulation tasks	N/A
Design, prototyping and testing of a modular small-sized underwater robotic arm controlled through a Master–Slave approach [8]	Exploration and retrieval	N/A
An underwater robotic manipulator with soft bladders and compact depth-independent actuation [9]	Sampling and service operations	N/A
An omnidirectional encircled deployable polyhedral gripper for contactless delicate midwater creatures sampling [10]	Creatures sampling	N/A
BlueRobotics newton subsea gripper [11]	General	590 \$
Geneinno robotic arm [12]	Retrieve heavy objects	399 \$
Rovmaker subsea gripper [13]	Retrieve objects	525 \$
Qysea 2-finger robotic arm [14]	Retrieve objects	399 \$
Qysea net patch kit [15]	Patch net holes	N/A

research stems from advancements in literature and the difficulties posed by subsea operations in seawater confined environments.

The subsequent section presents the MURA's design, including the arm's fabrication and constituent components is outlined. In addition, the modeling of the manipulator and its water flow simulation are presented. Ultimately, the experimental findings are analyzed.

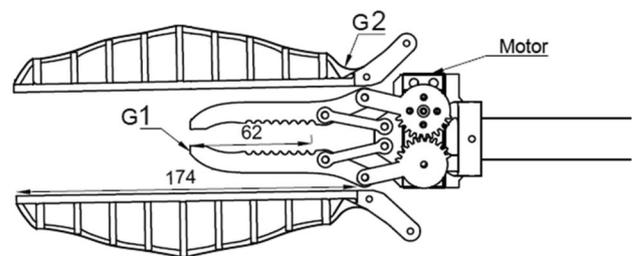
3 MURA's design

MURA's primary purpose is to be as cost-effective and modular as possible. In the light of this, the arm consists of easily replaceable components made with 3D printing and PLA filament, a plastic resistant to water. In this section, the robotic arm's architecture and its components are analyzed along with the design of the interchangeable attachments utilized. MURA is intended to (i) remove objects stuck on the nets, (ii) collect fish morts, and (iii) stitch holes at the nets at Kefalonia fisheries. For each use case, a different end-effector is used.

3.1 Gripper manipulator

MURA is equipped with a versatile gripper manipulator that allows for the removal of objects and the collection of fish morts. By simply changing the end-effector, the system can quickly and easily switch between these two functions. This is accomplished by interchanging the two gripper parts, G1 and G2, which are attached to the system with four bolts and nuts for fast and sturdy replacements during operation (Fig. 3).

In the first type of operation, the gripper is designed to remove objects that have become entangled in the nets (Fig. 3-G1). This includes twigs, algae, and other debris that can cause tears in the net or block the flow of water through

**Fig. 3** MURA gripper and grabber attachments

the cage. The removal of hard objects, such as branches, can result in fewer tears of the net and a reduction in the number of fish that escape, while the deflection of soft objects, such as seaweed, has the potential to augment the flow of water current within the net cages, leading to an increase in the amount of oxygen present [18, 19].

The second tool is a grabber that can collect deceased fish (Fig. 3-G2). The mortality of fish is a prevalent occurrence in aquaculture; hence, the decay of deceased fish can lead to water contamination and an increased risk of disease. Therefore, it is imperative that deceased fish be removed from the environment to prevent further pollution. The grabber manipulator allows for easy collection of morts, which can accumulate on the net cage's surface or bottom. Regular removal of these debris can improve water quality and lessen the likelihood of fish vandalism [4].

3.2 Hole stitcher manipulator

MURA's hole stitcher manipulator is able to staple tears on net cages at fish farms. This attachment is mounted on Kalypso UV, which is accountable for its locomotion and its mechanism has three basic steps in order to repair the teared holes (Fig. 4). (i) It is inserted into the apertures of the nets, and utilizes the two calipers provided by the attachment to

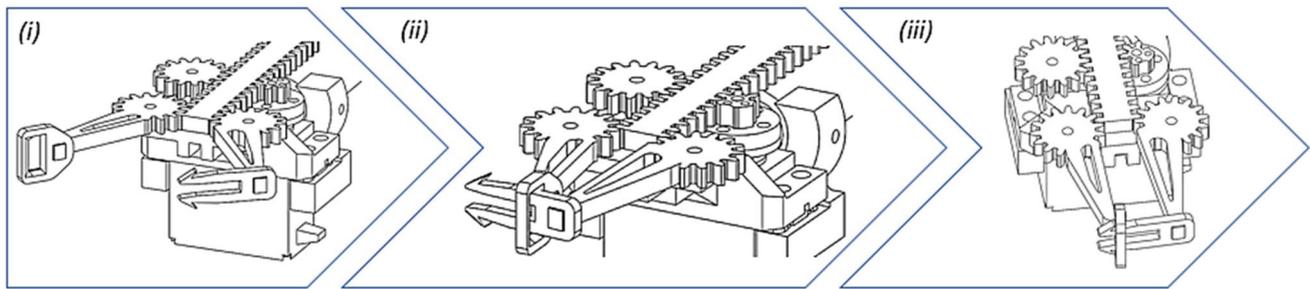


Fig. 4 Basic step of hole stitcher manipulator to repair net tears

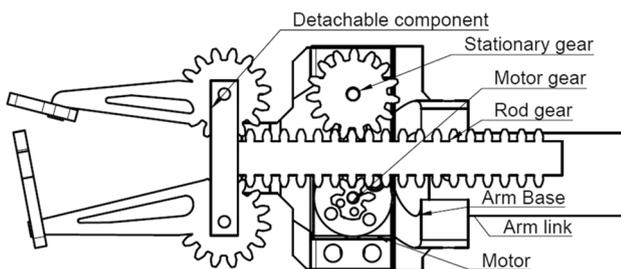


Fig. 5 MURA hole stitcher manipulator

connect the points that have been ripped in the nets. Following that, (ii) the two calipers lock to each other due to a locking mechanism and cannot open until a person is utilized for a permanent fix. Subsequently, (iii) it disengages from its arm base and endures in the nets, thereby resulting in their interconnection. A new stitching apparatus has to be inserted onto the arm base, and the process of stitching other apertures of the net is being carried out in a similar fashion. The cost of the replacement attachment is about 0.40\$ and comprises of 4 bolts and nuts and PLA plastic material.

This manipulator is comprised of seven main components as shown in Fig. 5 that are described as follows:

- (1) *Stapler attachment* which is comprised of two calipers with gears and a base that gets detached after calipers interlocking.
- (2) *Plastic rod gear* which transfers the motion from the servo motor to the stapler attachment.
- (3) *Stationary plastic gear* which keeps the rod gear steady
- (4) *Plastic gear* which is attached to the servo motor and transfers the torque to the rod gear.
- (5) *Servo motor* which controls the calipers and provides the necessary torque.
- (6) *Arm base* in which the servo motor and the stapler attachment are attached.
- (7) *Plastic tube* that links the arm base and the vehicle

MURA stitcher manipulator is designed to operate attached to Kalypso UV in subsea environments allowing for quick and efficient repair of tears and holes in net cages. The manipulator is controlled by one servo motor, which provides the necessary torque to operate the calipers and staple the torn netting together. The stapler attachment is designed to interlock the two calipers and provide a secure connection that can withstand the forces exerted by the surrounding water.

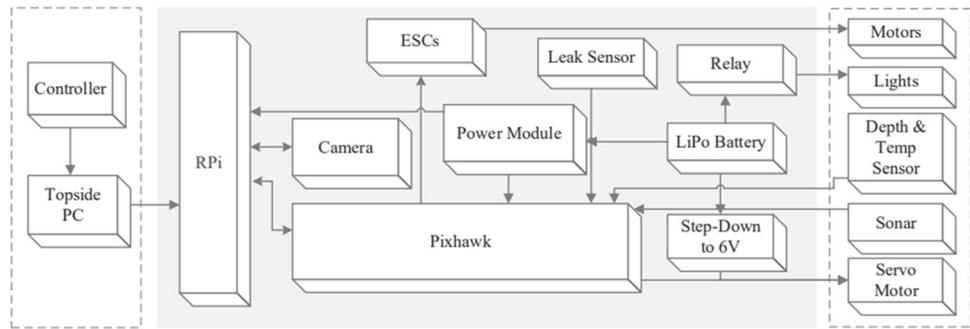
In addition to its robust design, the manipulator is also easy to replace and maintain. The cost of a replacement attachment is relatively low, and the process of installing a new one onto the arm base is straightforward. This ensures that the MURA system can operate efficiently and effectively, even in harsh underwater environments where repairs may be required frequently.

3.3 Components and electronics

Two servo motors FS5323M are responsible for the movement of the arm. These motors exhibit a functional voltage of 6 V, a torque of 19 kg per centimeter, and are constructed from a combination of aluminum and plastic materials. Moreover, the protection of these components from seawater is ensured through the installation of an O-ring in the entrance of the shaft as well as the utilization of Sikaflex 291i silicone and Bol-Wax on the interior. Fusion 360 CAD software was used to sketch MURA and its replacement manipulators, which were then 3D printed using PLA material.

Kalypso UV powers MURA at 6 V nominal voltage. The current draw of the manipulator is less than 1 Amp in normal operation. The Pixhawk PX4 2.4.8 flight controller board, equipped with ArduSub firmware, controls the operation of the vehicle. This board offers supplementary PWM channels to regulate the servo motors on MURA.

Figure 6 depicts the components and electronics utilized for the operation of MURA. The electronic components of the vehicle are categorized into two groups: those that are designed to be waterproof and capable of

Fig. 6 Connectionism of Kalypso's components**Table 2** Specifications of MURA

Specification	Value
End-effectors' dimensions:	(L × W × H)
G1	465 mm × 64 mm × 62 mm
G2	555 mm × 71 mm × 95 mm
G3	405 mm × 57 mm × 58 mm
Weight (G1-G2-G3)	390-420-315 g
Materials	PLA, Aluminum, PVC
Degrees of Freedom (G1-G2-G3)	2-2-1
Number of motors (G1-G2-G3)	2-2-1
Maximum amperage draw (G1, G2-G3)	1.2–0.8A (6 V)
Conventional amperage draw	0.1–0.45 A (6 V)
Total cost (G1, G2-G3)	45\$–25\$

functioning while submerged in water, and those that are susceptible to water damage and require protection within a sealed enclosure. The electronic components responsible for the operation of the robotic arm are contained within a sealed enclosure, whereas the waterproofed servo motors remain externally exposed to water. More specifically, the watertight enclosure contains a Pixhawk PX4, a mini-Pc, a RPi 3 model B, Electronic Speed Controllers (ESCs), a camera, two LiPo batteries with a total of 20 Ah, a Power Distribution Board (PDB), leak sensors, and relays, while the components that operate in water are thrusters, depth and temperature sensor, sonars, and LED lights. Also, the components of the vehicle have been rated for 100 m of depth by the manufacturer.

The servos are operated through the use of a Pixhawk auxiliary port, which transmits a Pulse Width Modulation (PWM) signal. The motor of the gripper is controlled within a pulse width range of 800–1500 μsec , while the rotational motor is controlled within a range of 700–1750 μsec . When the hole stitcher is equipped the motor signal ranges from 800 to 2200 PWM.

The Pixhawk device functions as both a flight controller and a servo motor controller. It is capable of establishing a connection with Raspberry Pi using the pymavlink

protocol. MURA is capable of being manually controlled through employment of a joystick or via python code executed on the surface computer.

The specifications of the MURA, including dimensions, weight, and materials pertaining to the distinct end-effectors are quoted in Table 2. In addition, it consists of three primary segments:

- *The manipulator* is a component that can be substituted with various actuators based on the specific task at hand and it is 3D printed. At present, three grippers are employed for distinct purposes, namely, the disposal of fish morts, the extraction of objects from net cages, and the mending of net tears.
- *The link* pertains to a structure consisting of a polyvinyl chloride pipe and mounts produced through 3D printing.
- *The joints* consist of a pair of servo motors and mounts that have been fabricated using 3D printing. This component is linked to the vehicle.

Each of these three components can be readily replaced, giving MURA a high degree of modularity. Additionally, MURA costs 25 to 45\$ depending on the end-effector and, to the best of the authors' knowledge, there were no commercially available arms found within this price bracket. However, while utilizing the hole stitcher end-effector the second servo motor is of minor significance and therefore is substituted by a steady 3D-printed mount reducing the price to 25\$. MURA is affixed to Kalypso in the middle of its bottom side, as shown in Fig. 7. The location where it is attached is crucial because it directly affects the buoyancy of the vehicle. For instance, if it was placed on the front of the vehicle, it would exert a great force downwards.

3.4 Vehicle capabilities

Kalypso UV is meant for inspection of the net cages in aquaculture [20]. It has been designed with six DoFs, and the layout of its 8 motors enables it to have improved mobility. The vehicle has measurements of 414 × 590 × 182 mm

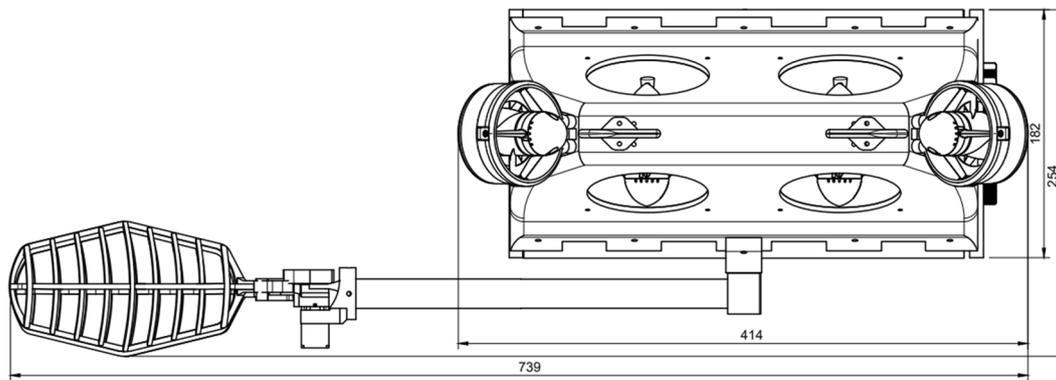


Fig. 7 MURA integrated with Kalypso UV: conceptual design and dimensions in mm

and weighs 12 kg (Fig. 7). In order to incorporate MURA, Kalypso was modified; a mounting part was utilized to secure MURA onto the ROV.

The vehicle’s main capability that supports MURA is stabilization and state hold that enables the vehicle to maintain its 3-axis orientation and depth. More specifically, Pixhawk flight controller applies Extended Kalman Filter (EKF) to analyze sensor measurements and generate estimations for multiple states, such as the quaternion that denotes the rotation from the local earth frame (North, East, Down) to the body frame (X, Y, Z). Additionally, the system provides estimations for the velocity components (North, East, Down) and position coordinates (North, East, Down) at the Inertial Measurement Unit (IMU). It also calculates the IMU delta angle bias (X, Y, Z in radians) and the IMU delta velocity bias (X, Y, Z in m/s). Furthermore, it is capable of estimating the magnetic field components of the Earth (specifically, the North, East, and Down, measured in gauss), as well as the magnetic field bias of the vehicle body frame (measured in gauss along the X, Y, and Z axes), and the wind velocity (measured in m/s along the North and East directions). Thus, Kalypso is able to not only able to remain steady but also stabilize in any given orientation (e.g., Face upwards or downwards). This enables MURA with the required maneuverability to operate successfully.

In addition, it utilizes ultrasonic distance sensors in order to effectively regulate and maintain a particular distance from the net. This holds significance in the scenario of stitching net tears where the manipulator should be activated in specific distance when attached to the net.

In order to remotely control the underwater vehicle QGroundControl (QGC) is used, which is an open-source ground control station that provides flight control of any mavlink enabled drone. This interface provides the necessary information to the users, such as sensor data, visual feedback, and enables the vehicle’s control. Moreover, it is easy- moderate to use as indicated by a usability test

performed by Intel UX Design team who observed final users dealing with QGroundControl interface [21].

Overall, Kalypso is able to aid the operator through the inclusion of semi-automatic functionalities by utilizing its sensors. These features encompass its ability to maintain its position in any given orientation as well as the execution of motion based on given preconditions, such as pose, distance from the nets, depth, or speed.

4 Mura’s modeling

This section presents the modeling of MURA, encompassing. The mathematical expression regarding the movement of an arm with n DoF is represented by an equation of motion [22]:

$$M(q)\ddot{q} + C(q, \dot{q}) + G(q) = T \tag{1}$$

where T and $G(q)$ are gravitational torques’ vectors, q is the vector of the joints’ angles, $M(q)$ represents the links’ inertia matrix, and $C(q, \dot{q})$ is the links’ Coriolis and centripetal vector matrix. $C(q, \dot{q})$ and $\dot{M}(q)$ are skew-symmetric.

The robotic arm, without the end-effector, features one Degree of Freedom and the dynamic model is expressed as follows [23]:

$$J\ddot{\theta}(t) + b\dot{\theta}(t) + \frac{1}{2}mgl \cdot \sin\theta(t) = u(t) \tag{2}$$

where $u(t)$ stands for the torque control, $J = \frac{1}{3}ml^2$ is the moment of inertia, $\theta(t)$ denotes the angle of rotation, and b the viscous friction coefficient. The mass, acceleration, and length are represented by m , g , and l , respectively.

In the event that MURA comes into contact with the body requiring removal, the damping and spring models will serve as the points of contact. It is worth noting that contact

friction will be disregarded due to its insignificance and the simplified Hertz contact model is expressed as follows [23]:

$$F_c = k_c d^{\frac{3}{2}} + b_c \dot{d} \quad (3)$$

where k_c and b_c represent the contact damping and stiffness coefficients, respectively. At impact d denotes the surface penetration, while \dot{d} the velocity of the penetration between the surface and the end-effector.

By converting the contact force into torques acting on the joints, the impact force is transmitted to the motors/joints as follows [23]:

$$\tau_c = J^T n F_c \quad (4)$$

where τ_c is the impact force's direction, J represents the Jacobian matrix of the arm, and n denotes the vector of contact surface.

MURA comprises a single joint and an end-effector manipulator, which are interconnected via a solitary link. The coordinate frame of origin is situated on the joint R , positioned at the intersection of the x and y axes of the vehicle. Z-axis is

oriented perpendicular to the plane and aligned with gravitational direction (Fig. 8).

The dynamic model of MURA can be derived from the equations presented in [24]:

$$M\ddot{q} + C\dot{q} + G(q) + k\Delta q = \tau_c \quad (5)$$

where:

$$M = \frac{1}{3} \cdot m \cdot l^2 \quad (6)$$

$$C = 2\delta(M \cdot k)^{\frac{1}{2}} \quad (7)$$

$$G(q) = \frac{1}{2} \cdot l \cdot m \cdot g \cdot \cos(q) \quad (8)$$

where the rotational angle and stiffness of R joint are represented by q and k , respectively. The impact's velocity angle direction is denoted by θ , while p is a vector originating from joint R to the end effector. The link's length is denoted by l .

Moreover, the robotic arm affixed to Kalypso exhibits an increased drag force in comparison to the UV itself. This force is given by [25]:

$$F_D = \frac{1}{2} \cdot v^2 \cdot \rho_{sw} \cdot C_d \cdot A \quad (9)$$

where v is the velocity of the water that impacts the arm, ρ_{sw} represents the seawater's density, and A denotes the projected area. C_D is the drag coefficient and can be calculated by:

$$C_D = \frac{2 \cdot F_D}{v^2 \cdot \rho_{sw} \cdot A} \quad (10)$$

5 Experimental results

This section entails a discussion of the experimental findings in Kefalonia fisheries and the water flow simulation derived from the design study.

Table 3 Flow simulation parameters

Parameter	Value
Fluid	Sea water
Density of fluid	1.0212 g/cm ³
Pressure	201,549 pa = 1.989 atm
Temperature	18 °C
Velocity	1.5 m/s
Iterations	300

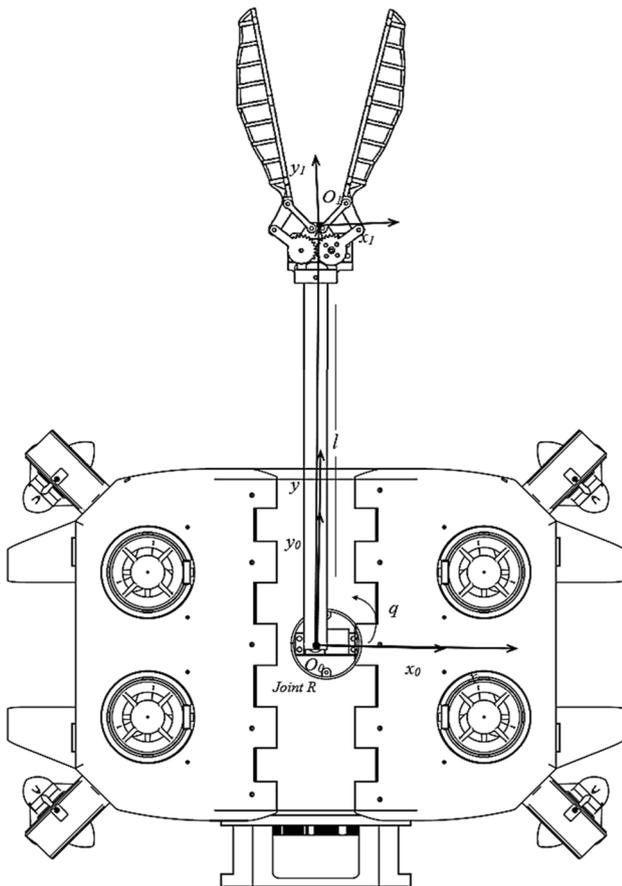


Fig. 8 MURA integrated to Kalypso coordinate frames

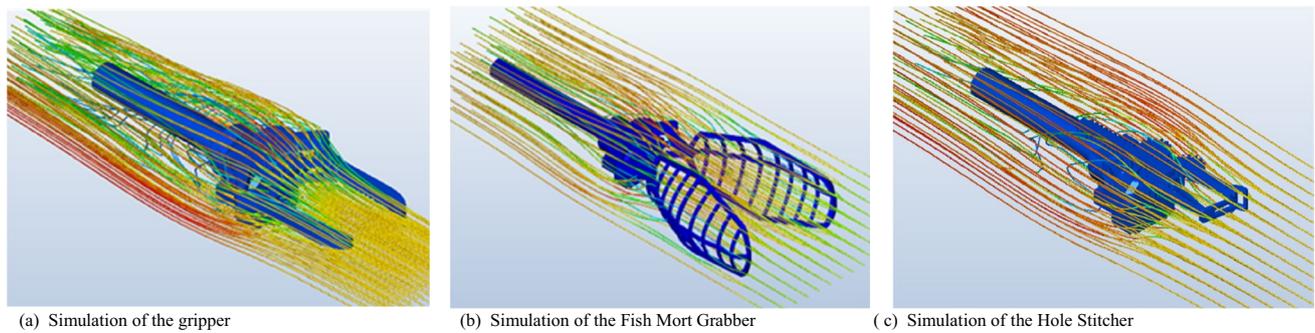


Fig. 9 MURA's attachments flow simulation trajectories

5.1 Flow simulation

Before conducting the experiments at Kefalonia fisheries, it was necessary to examine the impact of MURA on the Kalypso's movement. In order to accomplish this, a tool was employed to compute the forces acting on MURA. Namely, the simulation software Autodesk Computational Fluid Dynamics 2023. The purpose of its utilization was to visually represent the flow of water on MURA and calculate the overall drag coefficient. Table 3 presents the parameters utilized in the flow simulation.

MURA is mainly utilized at a maximum of 10 m in depth in net cages, thereby necessitating the selection of corresponding parameters for the simulation. Furthermore, the fluid temperature was adjusted to approximately the mean temperature of the seawater at fisheries, specifically 18 degrees Celsius. Additionally, the velocity was set to 1.5 m per second corresponding to the greatest water speed that impacts the vehicle relative to the vehicle's velocity. Figure 9 presents a visualization of the water flow trajectories associated with MURA's three attachments, the gripper, the fish gripper and the hole stitcher.

The results indicate that the gripper exerted a force of 5.35 Newton, the fish mort grabber 18.03 Newton, and the hole stitcher 1.5 Newton. The corresponding drag coefficient values are 0.4352, 0.7426, and 0.1012, as determined by the utilization of Eq. 10. The hole stitcher end-effector features the less drag coefficient and drag force which means that has the least effect on the vehicle.

5.2 Kefalonia fisheries' experiments

The main field experiments conducted were in net cages at depths less than 10 m. Nevertheless, the components of the system have been rated for 100 m of depth by the manufacturer, and due to limitations in our experimental capabilities, we were only able to conduct tests at a maximum depth of 16.8 m.

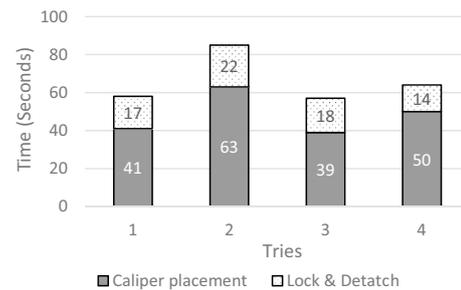


Fig. 10 Duration of both caliper placement on the nets, and lock and detach

The efficacy of Kalypso, in conjunction with MURA, was evaluated at Kefalonia fisheries for the purposes of object removal, fish mort disposal, and net tear stitching. The execution of all experiments necessitated the assistance of an operator to accomplish the assigned tasks.

Despite having only two degrees of freedom, MURA is capable of functioning effectively in any given environment as Kalypso UV is accountable for the movement, thereby replacing any other requirement for motion. Therefore, Kalypso's high maneuverability contributes greatly to the actualization of MURA. Moreover, the UV can maintain stability across all pitch angles, enabling the arm to effortlessly capture morts and objects in any orientation. In the event that morts are observed floating on the surface of the sea, the ROV must execute a rotation around its transverse (Y) axis to orient itself towards the surface. On the other hand, in cases where the morts are situated at the lowermost part of the fish net cage, it is imperative that the ROV is equipped with the necessary functionality to orient itself towards the cage bottom. Overall, Kalypso has the capability to maintain stability throughout all rotations, thereby enabling MURA to function in all orientations.

The duration required to complete each task is subject to variability based on factors such as the skill level of the operator, prevailing weather conditions, and the nature of the issue at hand. For instance, the process of capturing fish

morts typically requires approximately 30 s, from initial targeting to capture. Correspondingly, the process of stitching net tears requires approximately 70 s, from initial targeting to detachment. The data presented in Fig. 10 display four distinct timings pertaining to the process of repairing net holes. The experiment involved the creation of perforations on the nets, which were subsequently repaired by

the operator who guided the vehicle to the location of each perforation. More specifically, the duration of the process was measured from the point of hole identification until the detachment of the arm component. In addition, the time elapsed between the complete locking of the limb and its detachment was measured. Therefore, the figure depicts the duration of the operator's actions in placing the two ends of

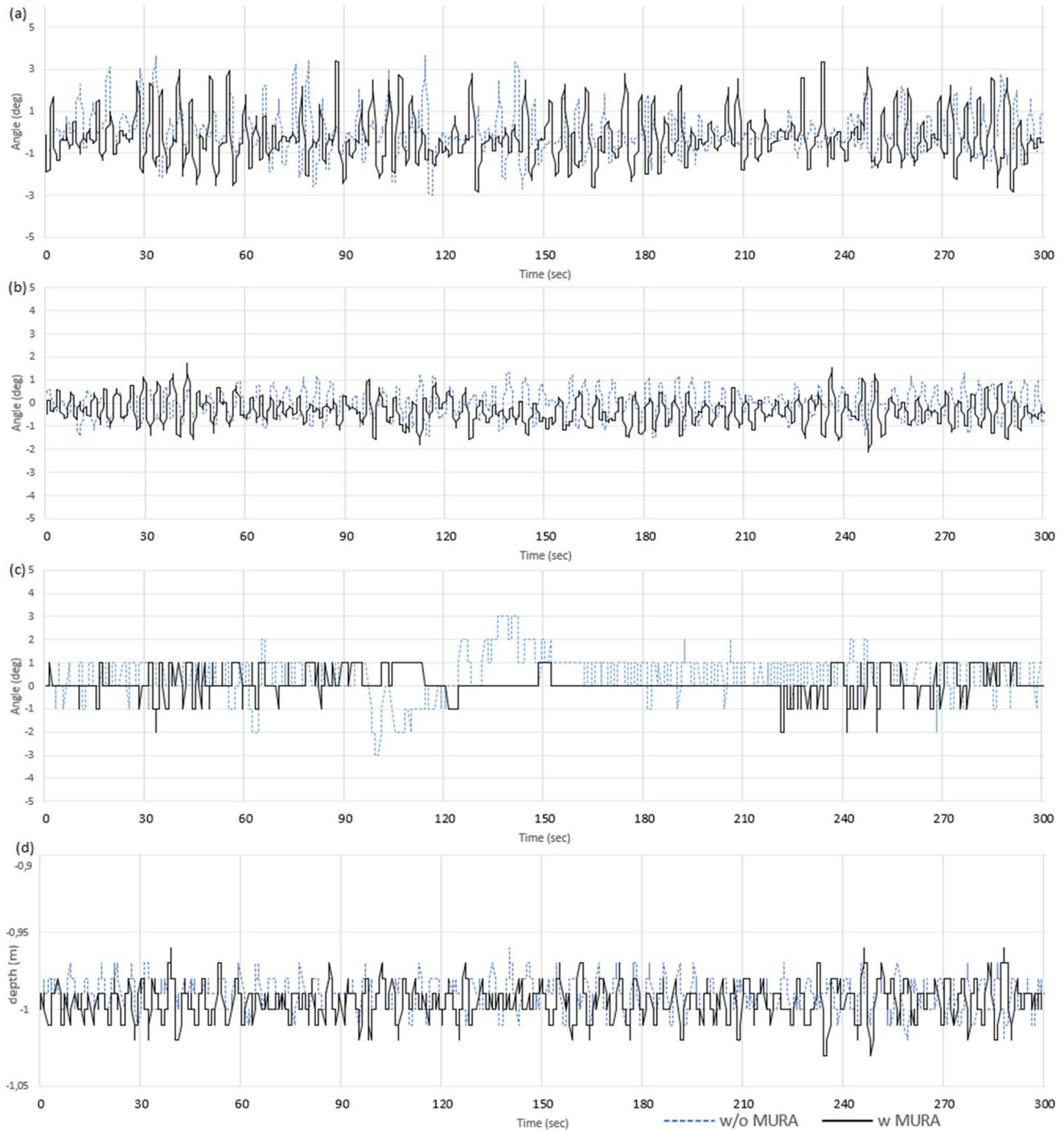


Fig. 11 Sensor values to evaluate the stability of the vehicle prior and subsequent to MURA's addition: **a** Roll, **b** Pitch, **c** Yaw, **d** Depth

the calipers in the nets, as well as the duration of the locking and disengagement processes.

The total time for each measurement is 58, 85, 57, and 64 s, respectively.

Furthermore, in order to evaluate the impact of MURA on Kalypso, regarding the vehicle’s stability, field measurements were conducted using the onboard IMU and depth sensor prior and subsequent to the MURA’s addition. More specifically, the vehicle was tested in 1 m depth and on stabilization and state hold mode which enabled the vehicle to maintain its 3-axis orientation and depth. During the 5 min test the vehicle was recording its sensor values (Fig. 11). The results encompass the three rotational axes minimum and maximum values in degrees and the respective values of depth in metres. In addition, the average deviations of the values are calculated for each measurement and are quoted in Table 4. The findings indicate that MURA has a minor impact on the vehicle and particularly the pitch axis had the

most influence, resulting in an average tilt increase of 12.6%. This was followed by the roll axis, which showed an increase of 8.92%. On the contrary, the yaw axis and depth remained unaffected. Overall, the increase in the use of thrusters due to MURA resulted in a 2.1% rise in the motors’ power draw.

In addition, the implementation of the fish mort grabber attachment has the potential to decrease the frequency of divers, thereby leading to reduced costs and mitigating the health risks associated with diving activities. Kefalonia fisheries provided data pertaining to a fish net cage over the course of one year, specifically focusing on the mortality of fish due to natural causes, which were subsequently removed by divers (Fig. 12). Based on the data provided the task of collecting fish morts is performed twice a week on average and three people are utilized, two on the surface and a diver. Moreover, it appears that during the summer season, there is a rise in fish mortality. In contrast, the operation of the system necessitates the involvement of a single individual, albeit at the cost of approximately triple the time required to complete the same task. Taking into consideration the aforementioned factors, including the cost of personnel, it can be inferred that if the entire task were to be replaced by the vehicle, there would be a reduction in costs of approximately 16.27%. However, the substitution of divers to this extent is not a feasible solution. If this task were to be replaced by the vehicle in one third, it could potentially reduce costs by 5.42% while simultaneously mitigating the health risks associated with diving activities.

Table 4 Peek values and deviation average of the measurements in 5 min stabilization test

Values in deg	With MURA	W/o MURA	Difference	% incr
Roll MIN	− 3	− 3	0	0
Roll MAX	3.37	3.65	− 0.28	− 7.67
Roll average	0.83	0.762	0.068	8.92
Pitch MIN	− 2.25	− 1.5	− 0.75	− 50
Pitch MAX	1.76	1.43	0.33	0.33
Pitch average	0.545	0.484	0.061	12.6
Yaw MIN	− 2	− 3	1	− 33.33
Yaw MAX	1	3	− 2	− 66.6
Yaw average	0.28	0.623	− 0.343	− 55.06
Depth MIN	− 1.03	− 1.02	− 0.01	0.98
Depth MAX	− 0.96	− 0.96	0	0
Depth average	0.005	0.009	− 0.004	− 44.44

6 Conclusion

This study details the development of a cost-effective sub-aquatic robotic arm, encompassing the design, construction, modeling, simulation, and experimentation phases, which was subsequently integrated into the Kalypso UV. MURA

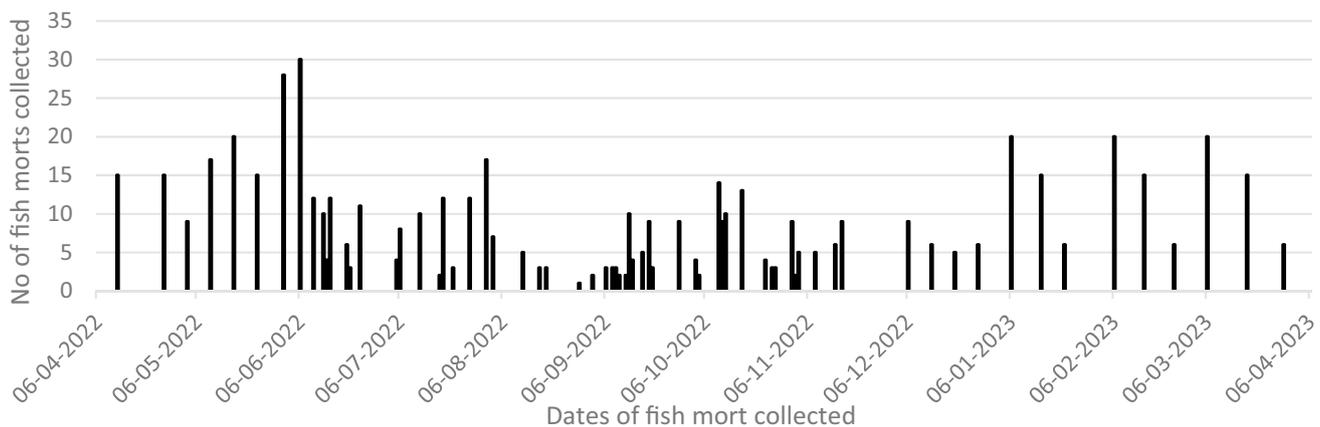


Fig. 12 Fish morts collected over the course of 1 year

appears to have practical utility across diverse applications at Kefalonia fisheries, including object removal, fish mort disposal, and net tear stitching. The device has a price range of approximately 25–45\$, depending on the servo motors used, and is readily deployable by fisheries due to its affordability and user-friendly design.

Despite possessing a limited number of degrees of freedom, MURA is capable of operating efficiently in any given environment, as Kalypso is accountable for motion, thereby obviating the need for any additional movement requirements. The UV exhibits stability throughout various pitch angles, facilitating the arm's ability to capture morts and objects with ease, regardless of their orientation. The duration necessary to accomplish each task is contingent upon various factors, including the operator's level of expertise, current weather conditions, and the complexity of the matter at hand.

In general, the utilization of subaquatic robotic systems such as MURA confers noteworthy advantages to the aquaculture sector. The implementation of such systems has the potential to enhance productivity and efficiency, while concurrently mitigating labor costs and augmenting safety measures. Aquaculture systems have the potential to enhance the health and welfare of fish populations through facilitating efficient removal of fish mortalities and expedited repairs to net cages. Notwithstanding, the utilization of underwater robots in aquaculture is not without its challenges and limitations. The procurement and upkeep expenses of these systems may be substantial, and their optimal operation may necessitate specialized training. Despite the aforementioned obstacles, it seems that MURA possesses capacity to improve the operations at Kefalonia fisheries and enhance the physical welfare of aquatic species through regular interventions.

Subsequent research endeavors entail conducting various tests on Kalypso in conjunction with MURA integrated within diverse automated operations. To elaborate, the vehicle's software will be expanded by integrating its computer vision functionalities with the utilization of MURA. Additionally, the inclusion of a secondary arm to the vehicle is deemed necessary for the purpose of manipulating the nets upon identification of a net tear. In addition, the arm possesses the capability to extract items from the nets through the utilization of the pre-installed gripper. However, the manipulator's efficacy will be evaluated through the implementation of alternative tools, such as a scissor-equipped gripper, which can be utilized to sever algae, or any other potential obstructions ensnared within the nets.

Acknowledgements The authors would like to thank the editor and the anonymous reviewers for helpful and constructive feedback on an earlier version of this paper. Also, the authors would like to thank the Kefalonia fisheries S.A. for their cooperation and the data provided. This research has been co-financed by the European Union and Greek

national funds through the Operational Program Competitiveness, Entrepreneurship, and Innovation, under the call RESEARCH-CREATE-INNOVATE (Project code: T2EDK-02504).

Funding Open access funding provided by HEAL-Link Greece. Open access funding provided by HEAL-Link.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. J. Guillen, A. Motova, "Summary of the 2013 Economic Performance Report on the EU Aquaculture Sector (STECF 13–30)," Brussels, Belgium (2013)
2. Federation of Greek Maricultures, "Aquaculture in Greece 2020," (2020)
3. M. Vasileiou, N. Manos, E. Kavallieratou, "An Underwater Vehicle for Aquaculture Inspection," in 2023 International Conference on Control, Automation and Diagnosis (ICCAD'23) (2023)
4. M. Shakouri, *Impact of cage culture on sediment chemistry. A case study in Mjotifjordur* (Fisheries Training Programme, The United Nations University, 2003)
5. H. Yang, M. Xu, W. Li, S. Zhang, Design and implementation of a soft robotic arm driven by SMA coils. *IEEE Trans. Industr. Electron.* **66**(8), 6108–6116 (2019)
6. K. Bodie, C. D. Bellicoso, M. Hutter, "ANYpulator: design and control of a safe robotic arm," in 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (2016). 1119–1125
7. O. A. N. Eidsvik, B. O. Arnesen, I. Schjolberg, "SeaArm-A Subsea Multi-Degree of Freedom Manipulator for Small Observation Class Remotely Operated Vehicles," in 2018 *European Control Conference (ECC)* (2018) pp. 983–990
8. L. Barbieri, F. Bruno, A. Gallo, M. Muzzupappa, M.L. Russo, Design, prototyping and testing of a modular small-sized underwater robotic arm controlled through a Master-Slave approach. *Ocean Eng.* **158**, 253–262 (2018)
9. Z. Shen et al., An underwater robotic manipulator with soft bladders and compact depth-independent actuation. *Soft Robot* **7**(5), 535–549 (2020)
10. Q. Xia et al., An omnidirectional encircled deployable polyhedral gripper for contactless delicate midwater creatures sampling. *Adv. Eng. Mater.* (2022). <https://doi.org/10.1002/adem.202201416>

11. BlueRobotics, “Newton Subsea Gripper.” <https://bluerobotics.com/store/thrusters/grippers/newton-gripper-asm-r2-rp/>. Accessed 09 Jan 2023
12. Geneinno, “Geneinno Robotic Arm.” <https://geneinno.us/collections/all/products/geneinno-robotic-arm>. Accessed 09 Jan 2023
13. Rovmaker, “Rovmaker Subsea Gripper.” <https://rovmaker.org/product/subsea-gripper/>. Accessed 09 Jan 2023
14. Qysea, “2-Finger Robotic Arm.” <https://store.qysea.com/2-finger-robotic-arm-v-evo-version.html>. Accessed 09 Jan 2023
15. Qysea, “Net Patch Kit.” <https://store.qysea.com/net-patch-kit.html>. Accessed 09 Jan 2023
16. L.G. García-Valdovinos, T. Salgado-Jiménez, M. Bandala-Sánchez, L. Nava-Balazar, R. Hernández-Alvarado, J.A. Cruz-Ledesma, Modelling, design and robust control of a remotely operated underwater vehicle. *Int. J. Adv. Robot. Syst.* **11**(1), 1 (2014)
17. J. H. Li et al., Conceptual design of optimal thrust system for efficient cable burying of ROV threncher, in 2014 Oceans - St. John’s (2014) pp. 1–5
18. L.H. Stien et al., Skirt around a salmon sea cage to reduce infestation of salmon lice resulted in low oxygen levels. *Aquac. Eng.* **51**, 21–25 (2012)
19. D. Johansson, J.-E. Juell, F. Oppedal, J.-E. Stiansen, K. Ruohonen, The influence of the pycnocline and cage resistance on current flow, oxygen flux and swimming behaviour of Atlantic salmon (*Salmo salar* L.) in production cages. *Aquaculture* **265**(1–4), 271–287 (2007)
20. M. Vasileiou, N. Manos, N. Vasilopoulos, A. Douma, E. Kavalieratou, Kalypso autonomous underwater vehicle: a 3D-printed underwater vehicle for inspection at fisheries. *J. Mech. Robot.* (2024). <https://doi.org/10.1115/1.4062355>
21. B. Palmeiro, C. Felipe, F. Novak, *QGroundControl Usability Test Report* (Intel Corporation, 2016). <https://qgroundcontrol.gitbooks.io/qgroundcontrol-usability-test-report/content/>. Accessed 19 Aug 2023
22. S. Ganjefar, M.H. Sarajchi, S. Mahmoud Hoseini, Teleoperation systems design using singular perturbation method and sliding mode controllers. *J. Dyn. Syst. Meas. Control* (2014). <https://doi.org/10.1115/1.4027164>
23. J.J. Craig, *Introduction to robotics* (Pearson Educacion, 2006)
24. M. Vasileiou, N. Manos, E. Kavallieratou, “IURA: An Inexpensive Underwater Robotic Arm for Kalypso ROV,” in 2022 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), (2022), pp. 832–837
25. H. J. Sønstabø, “ROV tool to repair fish cages,” Norwegian University of Life Sciences (2017)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.