The 8th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications
24-26 September 2015, Warsaw, Poland

Morphologically Intelligent Underactuated Robot for Underwater Hull Cleaning

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***Abstract*— In this paper we discuss a new type of robot for underwater hull cleaning on ships with non-magnetic hulls. This robot is based on the concept that cleaning hulls regularly, without waiting to take them out of the water, will improve the efficiency of the ships and will permit a reduction in the use of the chemicals that are usually employed to prevent the growth of marine life on the hull and which are generally harmful to the environment. The robot described in this paper is an underactuated morphologically adapted robot that through an appropriate morphology and making use of the forces and constraints of the environment solves the most difficult problems that arise when moving along hulls. Some of these are changing planes, negotiating appendices, avoiding portholes, passing corners, and other elements. This greatly simplifies the control mechanisms that are required for its operation making it an ideal candidate for completely autonomous operation. A description of the design of the robot as well as a series of examples of its operation are provided.**

Keywords*— *underwater robots; intelligent robots; hull cleaning

I. INTRODUCTION

One of the most important, and often expensive ship maintenance operations is hull cleaning. With time, ship hulls are invaded by barnacles, algae and other marine life. This biofouling grow up very fast leading two different problems: from an environmental point of view, this is, together with the ballast water of the ships, the main path for the introduction of aquatic invasive species (AIS) in the local environments of the places the ships visit [1]; from a hydrodynamic point of view, fouling increases the drag, causing speed reductions in the ship. These reductions can amount of as much as 10\%, leading to increased fuel consumption, which, according to some statistics, may be as high as 30% to 40%.

Different techniques are used to prevent and clean biofouling. Reviews such as [1], [2] or [3] describe those that are more often used. On the one hand, hull ships are painted with antifouling paints with the aim of reducing and delaying the adherence and growth of organisms. These paints are based on copper oxides and organic pesticides. Thus, they can have adverse effects on the underwater environment and disseminate toxic elements, with their consequent effects on marine life. Currently, a new kind of antifouling paints based on copolymers are being tested. They are not toxic and can work for longer periods. Nevertheless, they are still not able to prevent biofouling, and they are very sensitive to hull cleaning processes. Additionally, using these antifouling substances does not eliminate the need for the ships to undergo cleaning operations at regular intervals as they only reduce and delay fouling effects, they do not prevent them completely. This usually implies that around every 5 years the ship must be taken out of the water and fouling, or even the paint itself, must be removed through different types of techniques, which usually involve blasting and produce lots of toxic waste. These operations are quite costly both in monetary terms and in terms of the time the ship is not operating. According to [4] the US navy spends over 500 million dollars annually to prevent and treat fouling.

On the other hand, other companies perform frequent periodic cleaning of the underwater part of the hull to prevent a relevant buildup of marine life on them. The idea is that it is better to stop marine life from colonizing ship hulls than to clean them afterwards. Obviously, if there has been little time for marine life to fix itself, the buildup will be smaller and a lot easier to clean. However, taking ships out of the water frequently to perform cleaning operations is not economically feasible, making it necessary to find other means to perform these frequent or continuous cleaning operations. This is where robotic systems have the potential of making a difference, especially if one tries to carry out the cleaning operations while the ships are in port (which in the case of military ships is almost half of their operational life and in the case of merchant ships, especially when used for short sea shipping is quite often). This argument has been supported by different authors such as [5] who have made a study of the costs generated by the problems caused by biofouling in US Navy destroyers (fuel consumption, hull protection coatings, cleaning and repainting the hull, etc.), as well as those related to the underwater hull cleaning, including those arising from the research and development of the systems themselves that carry out such operations.

In line with the above, different systems were developed to clean hull surfaces. Initially, these tasks were performed using underwater cleaning systems operated by divers, and, in most cases this is still achieved this way.

Out of the systems controlled by divers, a large number of them use a set of rotating brushes for cleaning the surfaces. They often use a system of drive wheels to move over the surface while fixation is carried out by suction using a propeller. Examples are the SCAMP [6], SEAVAC [7] or SeaRazzor Twin systems [8]. Other systems, such as the MINI-KART PAMPER [9] or BRUSH KART [10] differ from the previous ones in that suction is generated by the rotation of the cleaning brush itself. This makes the system simpler, but involves continuous movement of the brushes for achieving fixation.

The CAVI-JET system [11], by contrast, uses high-pressure water jets as cleaning method. These jets generate cavitation phenomena near the surface causing the unfixing of biofouling.

Another kind of robotic system is the AHCV, which was developed by the US Navy [12]. It consists of two modules connected by an articulated arm: Whereas the first is used to move and achieve fixation to the surface just as the systems described above, the second one is responsible for carrying out cleaning, also with rotating brushes.

In recent years, various robotic systems have been developed to perform cleaning tasks autonomously. An example of these is the HULL BUG or Robotic Hull Bio-inspired Underwater Grooming robot [4]. It is a wheeled robotic unit that attaches itself to the ship hull and proceeds on to cleaning it much in the same way as current robotic vacuum cleaners basically removing marine organisms before they become solidly attached. A series of prototypes of this robot have been proposed and tested, producing quite promising results.

The HULL BUG presents a traditional four wheel configuration that allows it to move over the hull and it is attached to it using suction. This configuration does not allow it to perform some operations over the ship hull, such as going from one surface to another or over fins or other hull appendices. Thus, its control system is programmed to make the robot avoid these elements and concentrate on areas without obstacles. The remaining areas that the robot cannot access are cleaned by hand, usually by divers who also need to position the robot underwater on the hull, with the consequent cost.

Researchers participating in the HISMAR European project [12] have addressed the problem much in the same way in terms of moving along the hull. The platform they propose in this case is magnetically fixed to the hull surface, limiting the types of ships it can handle and it uses waterjets to clean the fouling. However, there doesn’t seem to be a real implementation of the robot and tests on real cases, just a series of designs.

The aurora robot can be considered a mixture of the preceding two. In this case, the robot is based on a three-wheeled chassis. The equipment for cleaning the surface is a set of rotating brushes. When the brushes turn, a significant hydrodynamic force appears, which helps to fix the robot to the surface. The main attachment force is produced by permanent magnets fixed on the treated surface [13].

On the other hand, different commercial companies have proposed a series of hull cleaning robots. One example is SONARBEAM [14], with its SS100 model, which is very similar in concept to the previous two. This robot is also magnetically attached to the hull which seriously limits the types of ships it can clean. In addition, it also moves over the hull using silicon wheels in a four-wheel configuration, which limits its access to some areas, especially in smaller recreational craft.

Another kind of commercial robots use high-pressure water jets as cleaning method. Examples of them are the ROV called ROVIN-BAT [15] which was developed by the ACE Group. This robot can navigate to the surface of the hull and, once there, move on it via a crawler system. Binding to these surfaces is achieved using thrusters that are oriented perpendicularly to the surface. A similar system is the CleanRov [16] developed by the Clean Hull AS company or the HULL WIPER [17] by Gac. They differ from the previous ones in that the displacement over the hull surfaces is performed by means of wheels that move thanks to the efforts of the thrusters at its disposal.

The VD200 is a robot developed by Urakami Research and Development Corporation which can perform cleanup tasks in submerged and non-submerged surfaces. The system has a completely different morphology to that of the robots seen above. It consists of two discs which are fixed by suction to the surface. They are joined together through a series of linear actuators. These allow zooming the modules towards each other, so that combining these movements with their alternative attachment to the surface allows the robot to perform a crawl. The surface cleaning and scouring is achieved by a suction disc during each contraction and extension movement [18].

Most robotic systems shown so far have been designed for cleaning relatively large sized ships. In recent years, compact solutions for smaller boats (yachts or sailboats) have been developed. The most significant examples of such systems are the Hulltimo and KeelCrab robots [19] and [20], which are formed by a single body and are moved by wheels. Both use suction and fixation system.

Due to the economics of this area, not much on this topic has been published in the scientific literature. Apart from few papers presented in conferences, such as some of the ones mentioned above, proposing different morphologies, and others having to do with the control of this type of robot. We have found just one that has been published in a journal [21]. In terms of control an example of these is the paper by Verners, & Sulcs [22]. In this paper the control of a six wheel wired remote controlled robot that has permanent-magnetic adsorption and magnetic wheels is presented.

Summarizing, most robots developed for underwater hull cleaning are usually based on a wheeled configuration, more often than not magnetically attached to the hull. This is, again, the result of the economics of this area, controlled by the military and large cargo companies, whose ships are basically metallic. However, there are many ships that have nonmagnetic hulls (fiberglass, aluminum, etc…) and that present many appendices on their hulls, such as fins, full keels and fin keels. This is generally the case for smaller ships, with a high percentage of them presenting non-magnetic hulls and whose ratio of these types of appendices to unobstructed areas is much higher than larger ships making the use of the above-mentioned robots quite impractical. But not only small ships are inadequate for the current solutions, also ships that present sudden changes in their surfaces, such as flat or V bottom ships may require from human help during the cleaning operations in order to reposition the robots when they have to change planes. Thus, it would seem that in these cases, a more appropriate morphology for the robot must be sought and a different attachment mechanism proposed.

To address these issues, we have designed an underwater cleaning robot that does not require magnetic attachment and that can operate over irregular hulls with appendices, corners, and all types of obstructions. The robot is mainly, but not exclusively, aimed at cleaning hulls of sailing and sport boats. Morphologically, we propose a completely unconventional structure and actuation mechanism for the robot in a sort of a morphological adaptation to the task experiment. That is, we introduce the principles of morphologically intelligent robots taking into account the principles proposed by Pfeifer and Bongart [23], especially with respect to environmental or niche adaptation of robotic morphologies and control. Additionally, we address their economy of operation principle by considering an underactuated robot with a very low number of actuating elements that through interaction with its environment is able to cover all of the needs of the task.

II. ROBOT DESIGN

The conceptual design of the robot has been carried out bearing in mind that it must be effective when cleaning the submerged surfaces of boat hulls that can be made of any material, magnetic or non-magnetic. It has also been considered that these surfaces can be either flat or curved and that they can display sudden changes in their orientation. The robot should be able to fix itself and move over these surfaces and overcome any obstacles present. It should also be able to change to a different working surface by passing over the edges dividing both surfaces even in cases presenting high slope changes, as for instance when full or fin keels are present. The robot should also remain stable in whatever position and orientation it may be placed. Finally, we must minimize the number of actuators in the robot and try to make use of the environment where necessary. The description of the robot is divided into the following five sub-sections that reflect different aspects of its design.

Fig. 1. Mechanical design

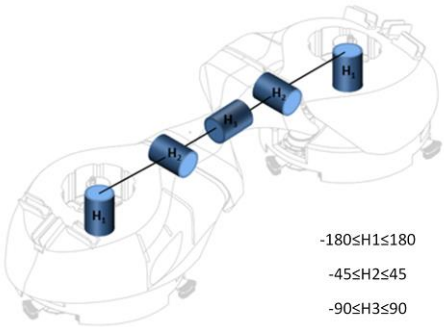

Fig. 2. Degrees of freedom

A. *Mechanical design*

To produce a device that can go over or around an edge and change working planes with different slopes, the robot (Fig. 1) is made up of two identical modules capable of fixing themselves individually to the surface. A rigid arm connects the two modules by means of two articulations. Fig. 2. shows the kinematic model of the robot which can be simplified to a model of 5 degrees of freedom that correspond to its five hinge joints (of type H1, H2, H3).

A suction chamber and an upper housing make up each module. The chamber and housing can rotate concentrically with respect to each other (H1). The rotation is achieved by the action of a DC gear motor at 500 rpm acting on a 1:180 worm gear.

A double articulation is used to link each module to the rigid arm. With this configuration, two different relative rotational movements between the connecting arm and each of the modules are allowed. The first one (H2) is a rotation in the plane perpendicular to the base-plane of the module and coincident with their geometric centers. The other (H3) is a rotation around the axis of the arm. This way, the robot can adapt perfectly to the different types of boat hull surfaces and overcome sudden changes of plane.

This configuration gives the robot a large number of large amplitude movements. Fig. 3 shows the extreme positions which the robot achieves for each of the joints.

The motion of the robot is achieved through the rotation of the upper housing of a module that is fixed to the hull surface. This rotation transmits through the arm a translational motion to the other module, in a circular concentric trajectory. By alternatively fixing and turning each module the robot can be displaced.

Table I provides the main features of the robot.

TABLE I. ROBOT CHARACTERISTICS

Length	1690	mm
Width	554	mm
High	340	mm
Suction area	2384	cm^2
Bonding force (each module)	22	kg
Cleaning surface	2862	cm^2
Actuators	24V Dc gear motor / 500 rpm	
Angular velocity	0,3	rad/s

B. Attachment System

As the robot must be able to attach itself to any magnetic or non-magnetic surface, it requires a non-magnetic mechanism to attach itself to the hull. In this

Fig. 3. Extreme positions the robot can achieve.

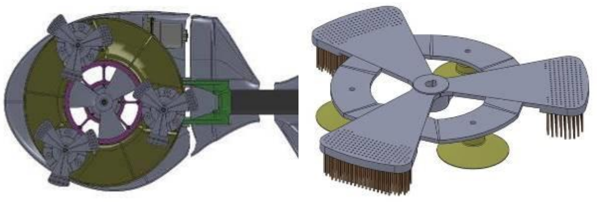

Fig. 4. Cleaning device

case we have chosen an option that combines thruster forces and negative differential pressure. Other possibilities, such as suction cups or thrusters, were discarded. The former because in case of a failure of adhesion, the robot would not be able to return to the surface it was working on and the latter because, for the same power, the adhesion force of the module to the surface would be insufficient.

To achieve the necessary suction each module has a DC geared motor, which is connected to a propeller. This propeller rotates at 500 rpm within the suction chamber leading to a pressure differential between the inside of the suction chamber and the outside. This permits a significant level of adhesion even in cases where there is a certain separation between the module and the surface over which it is working. To prevent slippage, a rubber strip is located on the borders of the suction cups to increase friction. Finally, in the case where the robot becomes unattached, the propeller operates as a thruster, and this can allow driving the robot back to the surface. In fact, this also allows the initial positioning of the robot without having to have a human diver to do it.

C. Actuation

As mentioned before and considering the description provided in previous sections, the robot is underactuated. The rotation between the upper housing and the suction chamber is actuated, the remaining degrees of freedom do not have any actuator. In order to control the free motion in these joints, the arm contains a torsion bar inside that has both ends attached directly to each module. This torsion bar confers enough stiffness to the joint so as to settle the robot on a preferential neutral position in the absence of external forces.

Notwithstanding the previous comments, it is possible to indirectly control the separation between the module and the surface using the DC geared motor responsible for carrying out the suction. As indicated before, this motor and its propeller work as a thruster when the module is separated from the hull surface. Through the control of the rotation direction and the power of the gear motor, the module can approach or move away from the surface.

D. Cleaning System

The cleaning process is performed as the robot moves over the hull surface. Each module is equipped with a cleaning system consisting of three rotating brushes driven by DC electric motors that are housed under the suction chamber (Fig. 4). However, depending on the type of

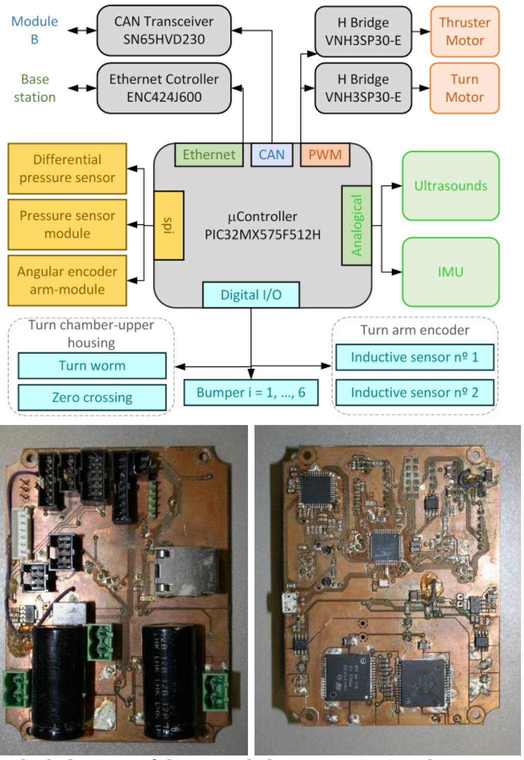

Fig. 5. Block diagram of the control electronics (top) and pictures of the main control board developed (bottom)

treatment to be carried out these brushes may be exchanged for other types of cleaning tools.

E. Sensors and control

In addition to being able to operate in manual mode, the robot must be able to carry out cleaning tasks in a semi-autonomous mode without supervision. Thus, the robot must be equipped with adequate sensors that provide all the necessary parameters for perform the task.

A first set of sensors measure the kinematic values of the robot. For that, each joint H_i has an encoder which measures its rotation. Whereas the H_2 encoder is an angular magnetic encoder (AEAT-6012), each of the other two encoders use two inductive proximity sensors (XS212AANAL2). For the H_3 encoder the first sensor counts the worm turns and the other one shows the zero-crossing. However, in the H_1 encoder both sensors are used to get the measure using an incremental circular encoder.

Moreover, each module includes two additional sensors that provide extra information to estimate the position and orientation of the robot on the hull. The first one, it is an inertial measurement unit (IMU) that provides its orientation. The other is an absolute pressure sensor to obtain the depth at which it is operating.

A second set of sensors provides information about the state of the robot. One differential pressure sensor measure the pressure between the inside of the chamber and the environment. This way it can determine whether a module is fixed to the surface. In addition, with the aim of determining the presence of obstacles nearby and avoiding

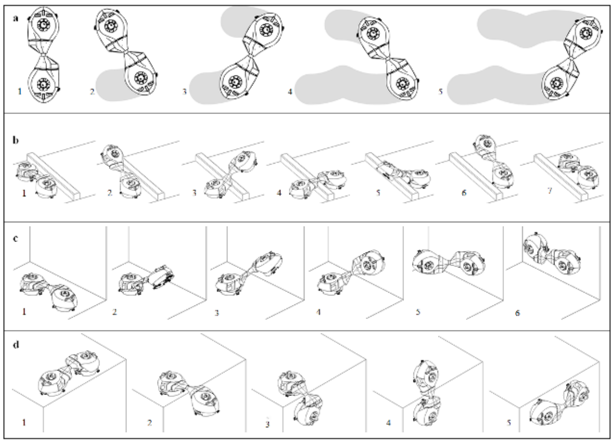

Fig. 6. Maneuvering. A) cleaning surface; b) going over obstacles; c) a 270º change of plane; d) a 90º change of plane

any collision, each module has a set of sonars placed around each module and a set of bumpers placed in both sides of the upper housing. These bumpers are based on a reed relay.

Two are the approaches that can be used for cleaning hulls, on one hand, a random walk type strategy can be implemented and this does not really require any precise positioning of the robot on the hull as, given enough time, it will statistically cover the whole surface. On the other hand a more sophisticated strategy would be to plan the cleaning process when the hull surface is known and available to the robot in some map form (whether self-generated or externally provided). In this case an absolute underwater positioning system would be required. This has not been considered yet, but as different systems based on ultrasonic signals are commonly employed in AUV's and ROV's with a good precision [24], this is the type of approach we are contemplating in the next version of the robot. That is, if we have a robot associated to a given ship, some ultrasonic sensors will be deployed along the ship's perimeter that will allow calculating the position of the robot on the hull as a function of the time of flight of the signal from a beacon placed on the robot.

In terms of the robot control system, even though it is not the object of this paper, which concentrates on the description of the robot and its mechanics, we must mention that it has been structured as a three tier hierarchy. Basically a top level module calculates that path the robot must follow along the hull in order to adequately clean it. This module is different depending on the strategy we are using (random or based on the hull layout). There is also a mid-level reactive system that is in charge of autonomously negotiating obstacles and performing local maneuvers such as changing planes or surrounding appendices as a function of the local sensor information. Finally, there is a low level controller implemented, and for which an operator GUI has been developed, that is responsible for handling the motors and thrusters. This low level controller can be directly accessed when an operator wants to control the robot directly.

The controller that was initially used was a Simatic S7-300 PLC placed in an external unit at the base station. This means that the tether had to include the power, and a cable for each actuator and sensor. Currently, and to make the tether simpler, the controller is placed inside the robot and only needs to be provided with two cables: power and data. Each module has an identical controller based on the PIC32MX575F512H microcontroller, however, automatically, one of them will become the main module and will be responsible for carrying out communication with the base station and the other module will be its slave. Fig. 5 shows the block diagram of the control electronics and one picture of the main control board developed.

III. MANEUVERS

As the main objective of the morphological and mechanical design of the robot is to enable it to perform complex maneuvers such as changing planes or avoiding obstacles in a simple manner, this section is devoted to the description of these operations.

A. Moving over or cleaning a surface

Fig. 6.a shows the sequence of steps needed to move the robot over a surface while performing the cleaning task. Starting from the initial position (1) the robot fixes one of the modules to the surface by suction and turns the upper housing (2). Next, it repeats the previous step but now fixing the module that was previously moving. These steps are repeated to keep the robot moving (3, 4, 5). This figure also shows the pattern of the cleaned surface after the passage of robot. The cleaned area and the speed of the robot depend on the angle used to turn each module around the other each step.

B. Jumping over obstacles

The procedure for jumping over obstacles can be seen in Fig. 6.b. First, the robot is placed parallel to the obstacle (1) with a module fixed to the working plane while the other module moves away from the surface far enough to attain sufficient height to avoid the obstacle (2). Then the robot rotates the upper housing of the fixed module and places the other module on the other side of the obstacle (3). By actuating on the propeller of this second module it attaches to the surface and is fixed there (4). Finally, the first module is released and is then moved to the other side of the obstacle in a procedure similar to the previous movements (5, 6, 7).

C. A 270º change of plane

Fig 6.c shows the sequence of movements of the robot when going from a current working surface to another that is oriented 270º from it. The robot starts to move from a position parallel to the edge of the plane with one module fixed to the initial working surface (1). The next step consists in separating the other module with the thrust produced by its propeller (2). Then, the robot is rotated until the module touches the new working surface (3). At

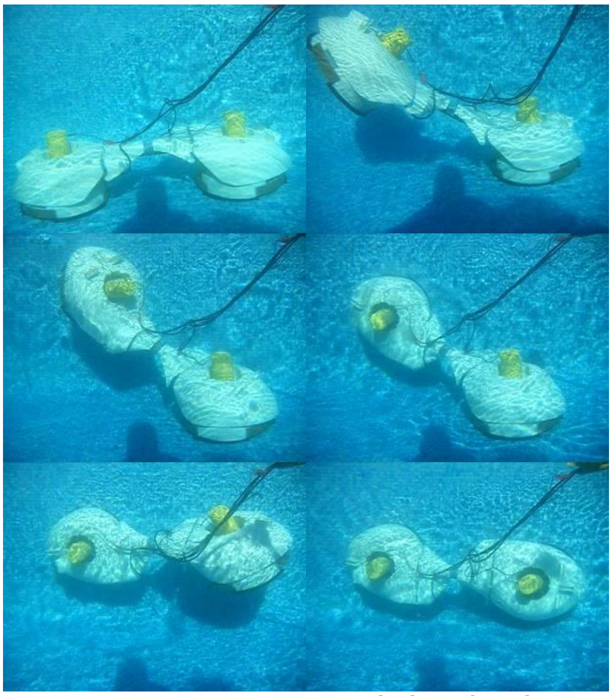

Fig. 7. Maneuver to move to a perpendicular working plane

this moment, its propeller changes the rotation direction causing the module to be placed on the new surface (4). This step is possible due to the friction between the fixed module and the surface. Then, the module placed on the initial working surface is released and the other module rotates to separate this module from the surface. Finally, the torsion bar rotates the module to achieve the preferred position of the robot and this module is fixed to the new plane (5, 6).

D. A 90º change of plane

In this case, the new working plane is oriented 90º from the original one. The movements needed for this operation are similar to the ones of the previous case. Fig. 6. d. shows the sequence of operations to move the robot to this plane. As in the previous case, the robot is first oriented in a position parallel to the edge of the plane and has one module fixed to the surface (1). This module rotates its upper housing until it places the robot on a plane perpendicular to the new working surface (2). At this moment the propeller of the unfixed module is turned on allowing the module to approach and be fixed to the surface (3). Next, the module placed on the old plane is released and the torsion bar turns the robot to its preferred position (4). Finally, the module rotates its upper housing to place the robot in the new current surface (5).

IV. TESTS

The robot has been built and is being tested in two conditions: In a swimming pool in order to check its controllability in all kinds of movements and on a real sailing ship. These tests were performed with manual control accessing the lower level controller through a

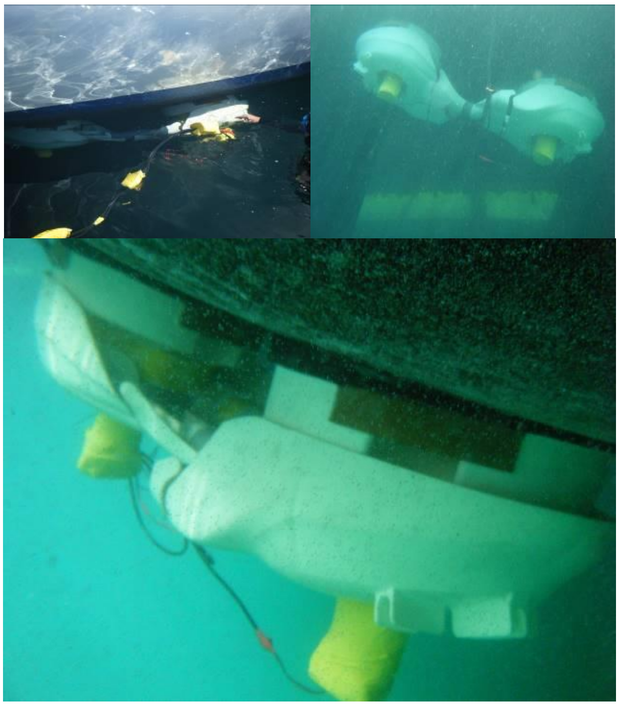

Fig. 8. Robot working in a real environment

graphical user interface developed for testing purposes or remote controlled operation.

For the sake of clarity and space, as an example of the multiple experiments we present in Fig. 7 the maneuver the robot performs to move from a surface to another that is perpendicular to it. The movements of the robot have been previously described in section B and the whole sequence was described in Fig. 6.b. The robot has also been tested on real environments. An instance of these tests can be seen in Fig. 8, which displays the robot operating on a real sailing ship.

V. Conclusions

In this paper we present the design and operation of a novel design of a robot which has been built to carry out the cleaning of nonmagnetic and complicated ship hulls. We have designed a robot that can move over and around obstacles on the hull as well as change from one surface to another with a different orientation in a very simple manner. We introduce a design strategy based on the ideas of morphologically intelligent robots with respect to environmental or niche adaptation of robotic morphologies and control. Additionally, we address the economy of operation principle by considering an underactuated robot with a very low number of actuating elements that through interaction with its environment is able to cover all of the needs of the task. This way, by adequately using its actuators taking into account its passive spring elements and the conditions of its environment, it can be controlled to perform the cleaning task in quite complicated hulls as well as to recover from accidentally becoming unattached to the hull. In fact, it can even position itself on the hull to be cleaned, simplifying its use on recreational ships. The robot has been built and tested and the results obtained are quite promising.

Acknowledgment

We would like to gratefully acknowledge the support of Innovación y Logística S. L. of Spain as well as the Real Club Náutico de la Coruña of Spain in the tests and experiments in real environments. This work has been partially funded by the EU's H2020 research and innovation programme under grant agreement No 640891 (DREAM project) and by the Xunta de Galicia and European Regional Development Funds under grants GRC 2013-050 and redTEIC network (R2014/037)

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