Lappa: A new type of robot for underwater non-magnetic and complex hull cleaning*

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Abstract— **This paper is concerned with the design and implementation of a new concept of robot to clean the underwater sections of ship hulls without using any magnetic attachment. The use of this type of robots on a regular basis to preserve a clean hull, usually when ships are in port or anchored, will improve the efficiency of the ships and will permit a reduction in the use of chemicals that are harmful to the environment to prevent the growth of marine life on the hull. The main contribution of the robot described in this paper is that it is a completely novel design that through an appropriate morphology solves the problems that arise when moving along hulls, including changing planes, negotiating appendices, portholes, corners, and other elements. It thus provides a basis for completely autonomous operation. The design and implementation of the robot is described and some simulations and tests in real environments are presented.**

I. INTRODUCTION

Hull cleaning is a very important operation in ship maintenance. As time passes, ship hulls are invaded by barnacles, algae and other marine life. This is what is usually called biofouling and it leads to two perverse effects. On one hand, it can end up reducing vessel speed by up to 10%, and according to some statistics it may result in a 30% to 40% fuel consumption increase in order to counter the drag these organisms produce. To reduce or delay this effect, most ship hulls are painted with different types of antifouling paints that contain biocides in the form of different substances, such as the now illegal Tributyltin (TBT). These paints and biocides have been found to be contaminants with a strong impact on marine life as the toxic paint disseminates copper and other heavy metals into the underwater environment affecting the organisms that live there.

Even when these antifouling substances are used, ships need to undergo cleaning operations at regular intervals, both for removing fouling that was not avoided by the paint and to remove the paint itself (which has around a 5 year effective lifespan) through blasting operations that produce large amounts of toxic waste in addition to the very high cost of the process. According to [1] the US navy spends over 500 million dollars annually to prevent and treat fouling.

In the last few years, some authors, such as [1], [2] have proposed robotic solutions to the fouling problem. The main idea behind their contributions is that it is better to stop marine life from colonizing ship hulls than to clean them afterwards. As a consequence, they suggest that it would be much better to continuously (or at least at frequent intervals) clean the hull so that whatever marine life is there has no chance to really fix itself and grow and is thus easy to clean. For this option to be feasible, they propose using robots that clean the ship hulls while they are in port (which in the case of military ships is almost half of their operational life).

In this line, the US Office of Naval Research has presented a ship hull grooming robot, called the Robotic Hull Bio-inspired Underwater Grooming (HULL BUG) tool [1]. This robot attaches itself to the ship hull and proceeds on to cleaning it much in the same way as current robotic vacuum cleaners. It removes the marine biofilm and other marine organisms before they get solidly attached. A series of prototypes of the robot have been tested. However, as the robot is wheeled (in a traditional four wheel configuration) and fixed using suction as a single unit, it cannot go from one surface to another or over fins or other hull appendices. It basically avoids them and concentrates on the areas without obstacles, leaving the rest for human cleaners.

The same approach is followed by researchers participating in the HISMAR European project [2]. They propose the concept of a robot that is magnetically fixed to the hull and uses waterjets to clean the fouling. Its morphology is a little different from [1] and there doesn't seem to be a real implementation of the robot. However, it seems to present the same drawbacks as the HULLBUG.

Finally, as far as we are aware, there is a commercial hull cleaning robot produced by SONARBEAM [3], its SS100 model, which is very similar in concept to the previous two. It is also magnetically attached to the hull and moves over it using silicon wheels in a four-wheel configuration.

As indicated before, hull cleaning is a great concern in the operation of most types of ships and there are many patents and a lot of investment on developing new cleaning methods and equipment, particularly robots. However, not much has been published on this topic in the literature. Apart from a few papers presented in conferences, we have found just one published in a journal [4]. A few papers have been presented in conferences related to the control of this type of robots. An example is the one by Verners, & Sulcs [5]. In this paper a 6-wheel wired remote controlled robot with permanent-magnetic adsorption and magnetic wheels is presented.

Summarizing, all of the robots that have been developed for underwater hull cleaning are based on a wheeled configuration that in most cases is magnetically attached to

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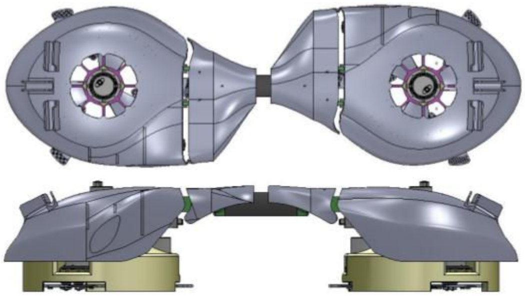

Fig. 1. Robot architecture

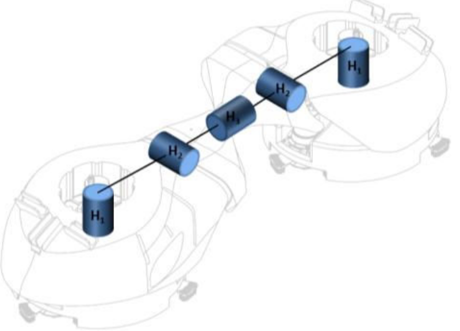

Fig. 2. Robot hinges

the hull. This is fine for many ships that have metal hulls to which these units can be fixed and that present few appendices and obstructions to the motion of these robots. The problem is that there are many ships that have nonmagnetic hulls (fiberglass, aluminum, etc…) and that present many appendices on these hulls, such as fins, full keels and fin keels. In fact, smaller ships usually present a ratio of these types of appendices to unobstructed areas that is much higher than larger ships. Some other boats present sudden changes in their surfaces, as is the case of flat or V bottom ships. In these cases a more appropriate approach in terms of the morphology must be sought and a different attachment mechanism proposed.

This is the objective of the work presented here. We have addressed the design of 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. This robot is principally, but not exclusively, aimed at cleaning sailing and sport boat hulls. To this end we propose a completely unconventional morphology and actuation for the robot that is quite intelligent in terms of being adapted to the environment in which it will operate and that with a very low number of actuating elements is able to cover all of the needs in this environment.

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 of any material, whether magnetic or non-magnetic. It has also been considered that these surfaces can be flat or curved and may display sudden changes in their orientation. The robot should be able to fix itself and move over these surfaces overcoming any obstacles present. It should also be able to move to a different working surface by passing over the edges dividing both surfaces even in cases presenting large slope changes, as in the case of full or fin keels. The robot should also remain stable in whatever position and orientation it may be placed. For that purpose, it has been designed to achieve almost neutral buoyancy avoiding preferential orientations.

The description of the robot is divided into the following five sub-sections that reflect different aspects of its design.

A. *Mechanical design*

In order to have a device that can go over or around an edge and change from one working plane to another of different slope, the robot (Fig. 1) has two identical modules capable of fixing individually to the surface. These two modules are joined together by a rigid arm, articulated at its ends. The details of the kinematics are shown in Fig. 2, which depicts the six hinge joints of the robot (H1, H2, and H3).

Each module consists of two parts: a suction chamber and an upper housing. They can rotate concentrically with respect to each other (H1). The rotation is achieved by the action of a DC gear motor which rotates at 500 rpm acting on a worm gear with a 1:180 reduction. The advantage of using a worm gear is that it enables a large reduction in one step while blocking the relative rotation when the motor is not operating.

The linking of the modules to the rigid arm is performed on the housing of each module by means of a double articulation that allows two different relative rotational motions between the connecting arm and each of the modules. The first one (H2) is a rotation in the plane perpendicular to the base-plane of the module and coincident with the geometric centers of each module. The other one (H3) is a rotation around the axis of the arm. These degrees of freedom allow the robot to adapt perfectly to the different types of boat hull surfaces and, in addition, to overcome sudden changes of plane or boat surfaces.

The rotation of the upper housing of a module that is fixed to the hull surface transmits a translational motion to the other module through the arm, forcing it to describe a circular trajectory that is concentric to that of the first module. Fixing and turning each module alternatively achieves the displacement of the robot.

The main characteristics of the robot are shown in Table I.

B. *Attachment System*

The robot must be able to attach itself to any magnetic or non-magnetic surface. Consequently, we have opted for an arrangement combining thruster forces and negative differential pressure. Other options, such as the use of suction cups or thrusters, have been discarded after performing different tests and determining that they were less appropriate. If we use suction cups, in case of an adhesion failure, the robot would not be able to return to the surface it was working on. In the case of using thrusters the adhesion force of the module to the surface would be insufficient for the same power. To achieve the necessary suction each module has a DC geared motor connected to a propeller. This propeller rotates at 500 rpm within the suction chamber causing a pressure differential between the inside of the suction chamber and the outside.

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

The proposed system permits achieving a significant level of adhesion in cases where separation between the module and the surface occurs. Fig. 3 shows the binding force achieved as a function of separation. Moreover, in case of total loss of adhesion of both modules, the propellers operate as thrusters, allowing the robot to return to the surface. A rubber strip has been added along the periphery and in the lower parts of the suction chambers to increase friction with the surface of the boat, minimizing possible slippage during robot motion.

C. Actuation

It can be gleaned from the description provided in previous sections that the robot is underactuated. While the rotation between the upper housing and the suction chamber is driven by a geared motor the remaining degrees of freedom do not have any actuator. To prevent 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.

It is possible to control the separation between the module and the surface using the geared DC motor responsible for carrying out the suction. This motor together with the propeller attached to it works as a thruster when the module is separated from the hull surface. By controlling the rotation direction and the power of the motor, the module can approach or move away from the surface.

D. Cleaning System

The cleaning process is carried out 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 housed under the suction chamber (Fig. 4). However, depending on the type of treatment to be carried out these brushes may be exchanged for other cleaning tools.

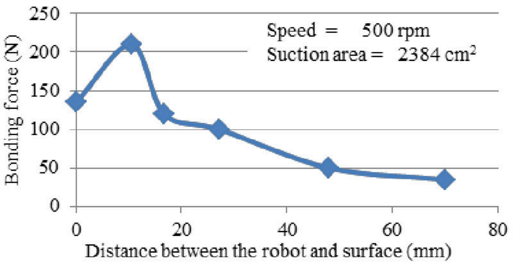

Fig. 3. Force as function of the distance to the surface.

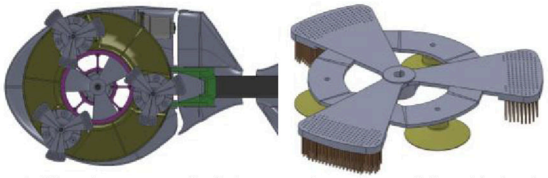

Fig. 4. Cleaning system: Left, bottom view of a module with the three cleaning tools. Right, detail of the cleaning tool.

E. Sensors and control

As in the end the robot must operate in a semi-autonomous manner without supervision, it is necessary to include enough sensors to be able to provide the kinematic state of the robot as well as information on whether the suction elements are fixed or not. Thus, the design provides for sensors that measure the rotation of each joint (encoders) as well differential pressure sensors that check whether the pressure inside each suction chamber is lower than outside. The latter permit knowing the fixation state of a module.

The orientation of the robot can be obtained through a set of accelerometers in each module and the depth at which it is operating from an absolute pressure sensor located on the connecting arm. These two additional sensors provide extra information to estimate the position and orientation of the robot on the hull. Finally the design provides for the use of local environment sensing elements such as whiskers, sonars or even cameras that allow the robot to negotiate immediate obstacles and the operators to know what is going on.

As the robot has to be powered by an external power supply, it requires a tether to a base station. In addition, this tether also handles communications and allowing an operator or an external computer to control the robot from the surface.

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 ultrasonic systems are commonly employed in AUV's and ROV's [6], this is the type of approach we are contemplating in the next version of 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 using a Simatic S7-300 PLC, 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 for on line human control.

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, in this section we will describe how this structure allows it to achieve this objective by explaining the steps it follows in of these operations.

A. Moving over or cleaning a surface

Fig. 5.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 and turns the upper housing (2). Then 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. 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 going over obstacles can be seen in Fig. 5.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 itself 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. 5.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 this point, 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 on the initial working surface is released and the other rotates to separate it from the surface. Finally, the torsion bar rotates the module to 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. 5.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 point 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. KINEMATIC ANALYSIS

From a more formal point of view, this section deals with the kinematics of the robot. The robot motion is achieved by alternating a series of basic movements which consist in fixing one of the modules while moving the other. The equivalent kinematic model of these basic movements of the robot is shown in Fig. 6. In this model, the suction chamber on the left is fixed to the surface and we provide the kinematics for the rest of the robot.

The suction chambers correspond to points P_0, P_1 (left)

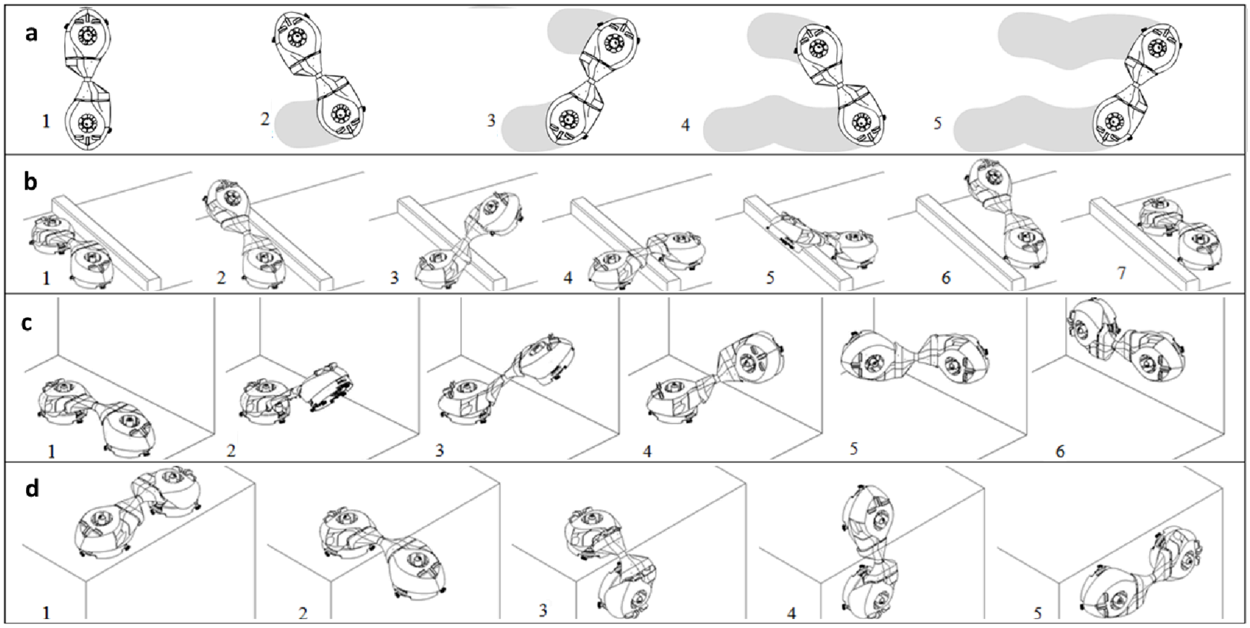

Fig. 5. Maneuvering. a) cleaning surface; b) going over obstacles; c) a 270º change of plane; d) a 90º change of plane.

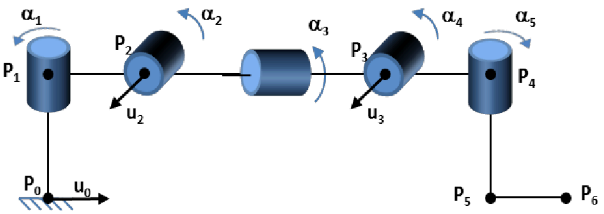

Fig. 6.Kinematic model.

and P_4, P_5, P_6 (right). The $\mathbf{u_0}$ vector defines the orientation of the left chamber. P_0, P_1 and $\mathbf{u_0}$ are known and fixed. The upper housing of the modules are defined by points P_1, P_2 (left) and P_3, P_4 (right), and the rigid arm by P_2 and P_3. Also, it was necessary to define the axis of rotation of the hinge joints H2 ($\mathbf{u_2}$, $\mathbf{u_3}$). Finally, α_i are the angles rotated by the hinges.

In brief, this model has 5 *dof* and it is represented by 26 variables, so we need 21 constraint equations to define it:

$$\left|\overrightarrow{P_iP_{i+1}}\right| - L_{i,i+1} = 0 \ \forall i = 1,2,\ldots,5 \tag{1}$$

$$\overrightarrow{P_iP_{i+1}} \cdot \overrightarrow{P_{i+1}P_{i+2}} = 0 \ \forall i = 0,3,4 \tag{2}$$

$$|\vec{u_i}| - 1 = 0 \ \forall i = 2,3 \tag{3}$$

$$\overrightarrow{P_iP_{i+1}} \cdot \vec{u_j} = 0 \ \forall \begin{cases} j = 2; i = 0,1,2 \\ j = 3; i = 2,3,4 \end{cases} \tag{4}$$

$$\overrightarrow{P_1P_2} \cdot \vec{u_0} - L_{1,2}\cos\alpha_1 = 0 \tag{5}$$

$$\overrightarrow{P_1P_2} \cdot \overrightarrow{P_2P_3} - L_{1,2} \cdot L_{2,3}\cos\alpha_2 = 0 \tag{6}$$

$$\vec{u_2} \cdot \vec{u_3} - \cos\alpha_3 = 0 \tag{7}$$

$$\overrightarrow{P_2P_3} \cdot \overrightarrow{P_3P_4} - L_{2,3} \cdot L_{3,4}\cos\alpha_4 = 0 \tag{8}$$

$$\overrightarrow{P_3P_4} \cdot \overrightarrow{P_5P_6} - L_{3,4} \cdot L_{5,6}\cos\alpha_5 = 0 \tag{9}$$

Equations (1) to (4) define the mechanism and (5) to (9) are the equations to produce the angle of each joint. The last five equations are not valid for α_i values close to 90 degrees. In this case these equations will be substituted by the sine equation. To solve the problem it is necessary solve the following system:

$$\boldsymbol{\Phi}(\boldsymbol{q}) = \boldsymbol{0} \tag{10}$$

where $\boldsymbol{\Phi}$ is the constraint vector, and q the variables vector.

This analysis represents the general case in which the robot has a suction chamber fixed to the surface and the other chamber is free without touching any surface. In the case where the other suction chamber is cleaning (P_5 and P_6 are on the surface) the model becomes a mechanism with only 2 *dof* because a kinematic pair of class III is introduced in the free suction chamber. Therefore, it is necessary to add three more constraint equations. In this case the movement of the robot is controlled by α_1 and α_2.

Another possible case occurs when only one point of the free suction chamber (P_6) touches the surface. Now a kinematic pair of class V is created between this point and the surface reducing the number of *dof* to 4. Therefore, a new constraint equation has to be included.

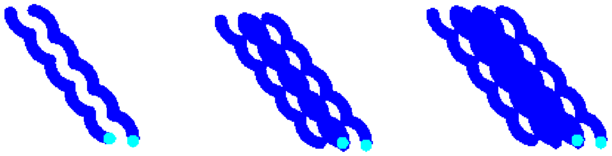

Fig. 7. Cleaning patterns. From left to right: First three passes.

V. SIMULATION OF THE MOVEMENTS NEEDED TO CLEAN A FLAT SURFACE

As a first step to study the complex movements of the robot to completely clean complex hull surfaces assuming a planned (as opposed to random) cleaning strategy, we have studied and improved the motions of the robot to clean a large flat surface. For this purpose we have developed a 2D kinematic simulator that shows the evolution of the surface cleaned by the robot and allows changing the values of the different parameters in order to determine the most appropriate one (the largest cleaned area without patches) for each situation.

In this simulation the rotational velocity of the modules has been set to 0.05 turns/s, the times employed to fix and release a module to 2s and 1s respectively. These values were obtained empirically from the real robot prototype.

Initially, it is assumed that the robot is placed horizontally, one module is then turned a given angle and after that the other module turns the same angle but in the opposite direction. The robot runs this sequence for 75 seconds. Next, the robot completes the same sequence cyclically but starting from different positions. This type of movement is described by two parameters: the angle employed to turn the modules and the incremental distance between the two consecutive starting positions. Small angles generate non-optimum cleaning strategies because they waste a lot of time fixing and unfixing the modules; on the other hand, large angles generate patterns with lots of surface patches that are not cleaned. Similarly, large displacements between consecutive passes do not clean the whole area but small displacements waste time cleaning the same area several times.

Exploring different settings for these two parameters, we obtained the best result to completely clean the maximum area using an angle of 75° and a distance between passes of 1 meter. Fig. 7 shows three patterns of this sequence.

VI. FIRST 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. The tests were performed under manual control accessing the lower level controller through a graphical user interface developed for testing and remote controlled operation.

A typical going over an obstacle operation is displayed in Fig. 8. The movements or the robot have been described previously in section III.B and shown schematically in Fig. 5.b. This type of movement is required to negotiate obstacles present in real ships like fins, full keels and fin keels. To simulate these obstacles, a bar (15cm in height) was placed

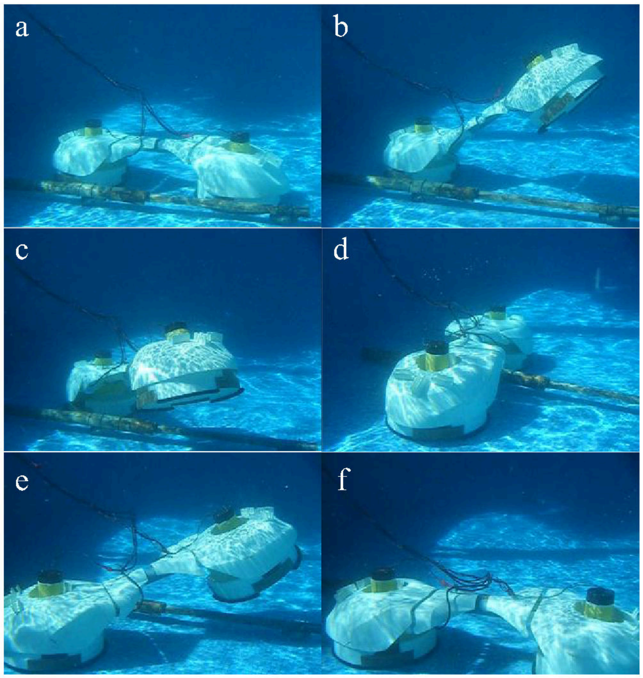

Fig. 8. Maneuver to go over an obstacle.

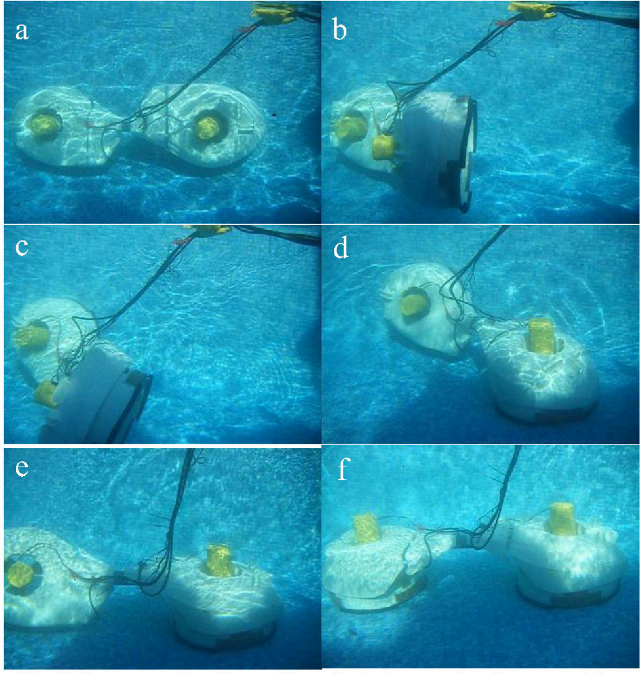

Fig. 9. Sequence of motions of the robot when moving from a working surface to another one oriented 270º from it.

on the floor of the swimming pool. As we can see in the photographs, the robot is able to jump over bigger obstacles.

The next experiment is a more complicated maneuver, a change of plane. The movements in this experiment with the real robot are the same as those displayed in Fig. 5.c, except that here the robot starts from a vertical wall (Fig. 9.a) and finishes on the floor (Fig. 9.f). The robot is easily controlled using the GUI. An intermediate step of the maneuver with the robot fixed to both planes is shown in Fig. 9.d.

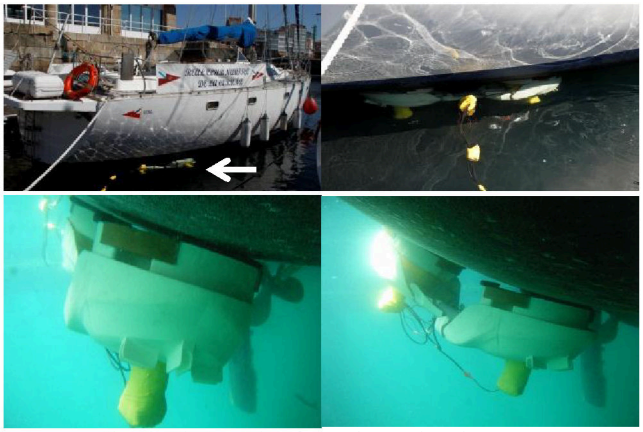

Fig. 10. Photographs of a test in a real environment.

Finally, we are starting to perform some experiments in a real environment. The maneuvers were similar to those presented above and were carried successfully. Fig. 10 displays some pictures of the tests on the real ship. The top part of the figure shows two photographs of the initial position of the robot on the hull (it is the white blob the arrow points to on the left photograph). In the bottom part it is easy to see how the robot is fixed to a convex hull close to the rudder while moving along its bottom part.

VII. CONCLUSIONS

This paper presents the design and operation of an unconventional underwater robot designed for cleaning nonmagnetic and complicated ship hulls. Through an appropriately designed morphology the robot 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. This robot is underactuated, but by adequately using its actuators taking into account its passive spring elements 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.

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