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Design and implementation of a biological inspired swimming robot

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Abstract. This paper describes the design and development of a bio-inspired swimming robot, intended for inspections purposes. The main goal of this work was the development and implementation of a first prototype of a robot with locomotion similar to a biological fish. For that purpose, it was first performed a study concerning fish swimming, in order to understand how they move. In parallel, a study was conducted on swimming robots already developed to examine their locomotion modes. With this background knowledge it was designed a prototype, that was latter implemented. After the prototype development there were performed several locomotion tests. Several experiments revealed that the robot was able to swim with stability and keeping the programmed direction.

Keywords: robotics; swimming; biological inspiration; biomimetics

1. Introduction

There is currently a great interest in the development and use of aquatic vehicles in the oceanographic observation, search and rescue, cleaning, and in purely sport competitions. However, there is still few research in this subject, being an area with potential for future growth.

On the other hand, one line of research and development in robotics that has received increased attention in recent years is the development of biologically inspired robots.

Whether robots that use legs, wings or fins as a means to implement locomotion, the idea is to acquire knowledge of biological beings, whose evolution took place over millions of years, and utilize the knowledge thus acquired to implement the same methods of locomotion (or at least use the biologically inspiration) on the machines. It is believed that in this way we are able to develop machines with capabilities similar to those of biological beings in terms of locomotion capacity and energy efficiency (Manoonpong *et al*. 2014).

Bearing these ideas in mind, in this paper is presented the development of a bio-inspired

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swimming robot, i.e., a robot whose movement is based on the waving motion of the fins (in a similar way to a fish). This robot is seen as a first prototype of a series of biological inspired swimming robots, whose final purpose is their use for inspections purposes. One of the main objectives of this prototype was to realize what are the main difficulties that have to be overcome while developing this type of vehicles, and what are the most important aspects to be considered in order to have an efficient and effective locomotion on water.

The rest of the paper is organized as follows. Section 2 describes previous studies on robotics for the aquatic environment. Section 3 presents the architecture adopted for the developed prototype and the used components. In Section 4 is described the implementation of the robot and on Section 5 are presented the experimental results gathered from distinct tests performed with the robot on different sites. Finally, in Section 6 are discussed the main results obtained and are presented the main conclusions of the developed work and some ideas for future developments.

2. Studies of robotics in the aquatic field

Fishes are vertebrate aquatic animals (about 95 % of the 25000 species usually designated as fishes possess bony skeletons), which swim through the water mostly with the help of fins, and breathing through its gills. In the breathing process the water enters through the fish mouth continuously, goes through the gills and ends up being expelled through the lateral parts of the head. Fishes are cold-blooded animals, meaning that their body temperature varies according to the surrounding environment. In general fishes possess the temperature of the environment in which they are inserted (Moyle and Cech 2004).

The locomotion is ensured through muscular contractions which propagate along the entire body, from the head to the tail, and give the arched flanks a wavy movement, pushing them back against the water (the waves come to an end in the tail fin, and the oscillatory movements increase the impulse) (Sfakiotakis *et al.* 1999). The musculature of the fishes' body is segmented, which allows its wavy movements. The fins of a bony fish obey primarily to objects of orientation and balance. The different fins of fishes are displayed and labelled in Fig. 1 (TODW 2014). The unpaired fins, dorsal and anal, arranged throughout the superior and ventral profile respectively, act as keels, avoiding lateral oscillations for the fish. The tail fin, or tail, operates giving the locomotion a certain gentleness. The chest ones, localized behind the gill openings, allow the fish to change its direction abruptly. The pelvic ones, placed under the chest, perform mostly braking functions (Moyle and Cech 2004).

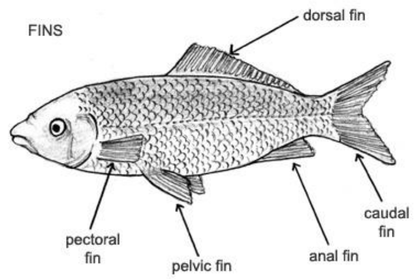


Fig. 1 Definition of terms: fish's fins

In the last years some prototypes of swimming robots have been developed (Hu *et al.* 2006, Giguere *et al.* 2006, Guo *et al.* 2006, Suzumori *et al.* 2007, Hu *et al.* 2008, Xinxiong and Yawei 2012, Choi *et al.* 2012, Robotic-Fish.net 2014, Kruusmaa *et al.* 2014). A swimming robot consists of a vehicle capable of moving in the water, at the surface or submerged, through determined body aiding movements or body appendices (typically from biological inspiration, such as fins and/or tails). On the opposite, other aquatic robots move both on the surface and submerged, without the need of auxiliary movements, with its propulsion usually being assured through mechanic propellers.

2.1 Robot Tuna

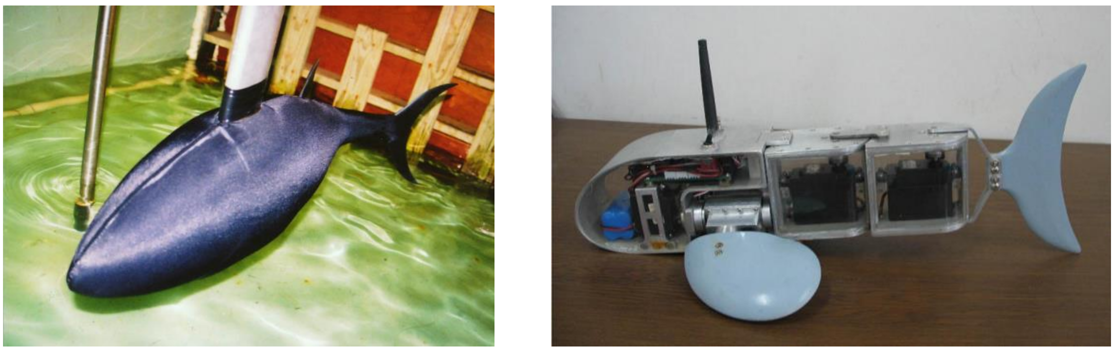
The robot Tuna, developed in the MIT in 1994 and depicted in Fig. 2(a), was constructed in order to look like a small tuna fish, being the first robot fish that propels its flexible body and executes oscillatory movements (Barrett *et al.* 1996). It is controlled by six sensors, which are placed in several locations of its body.

Gathering a set of sophisticated components, allowing locomotion close to the biological one, this robot possesses the ability of free and autonomous movement. The structure of the robot consists in a rigid aluminium surface.

Engineers associated to the MIT developed the first version of the robot, being its first tests performed in a pool. The conclusion was that, thanks to its physical components, this project could reach its main goal, which consists in possessing a dynamic body that has the ability of imitating a biological tuna fish. The dynamic shape of a tuna fish was never measured rigorously, therefore there is no exact definition.

The experiences settled on two phases. The first phase was the analysis of the controllers, sensors and the performance of the software when it comes to the motion of the Tuna robot in a dock. This first phase was crucial to assess the movement capacity. The second phase consisted on a basic set of locomotion movements, in which the Tuna robot basically moved with variable amplitude which crossed over the entire body. The goal was to verify the entire system, in order to check the stability of the movements.

In conclusion, it was verified that the robot performance depended on several aspects, in which its hardiness and technical characteristics predominate. Despite all the obstacles, the goals of the project were reached.



(a) (b)

Fig. 2 Tuna robot (a) and reconfigurable robot fish (b)

2.2 Reconfigurable robot fish

Another example of a biological inspired swimming robot its the machine presented in Fig. 2(b) (Hu *et al.* 2007). The head of this robot is built in aluminium, with two transparent coverages set in the robot skeleton, being noticeable that the head module is constituted by several electronic components. The wireless antenna, the tight switch and the plug to charge the battery are fixed in the upper part of the robot. The inside of the head has enough space to put the battery and all the electronic components in. Two servomotors are placed symmetrically in the top and its hubs are directly connected to the rotating hubs which allow the rotation of the fins. The outer casing of the chest membranes includes a half cylinder and a piece shaped like a cube, which are screwed with tight rings between them. The servomotor is placed in the inside of the half cylinder cavity and the rotating hub is connected to the servomotor hubs through a fencing structure in the cube-shaped module. The modules of the chest fins are symmetrically placed and, simultaneously, capable of two movements: the rotation upon hubs and through the rotation of the chest fin.

This robot was designed for a free locomotion, and it incorporates microcontrollers and wireless communication. It is equipped with four Ni-Cd rechargeable batteries of 2500 mAh, with capacity of one hour of autonomy. The locomotion of the robot is processed through a AT9SAM7A3 microcontroller. The controller establishes the wireless connection through a UART port. A ADXL202 accelerometer is used to measure the acceleration movements. The functioning of the servomotor depends on the PWM signal generated by the microcontroller. Other interfaces such as USB ports, CAN bus, I2C bus and Analog Digital Converter (ADC) could be used in future efforts (Hu *et al.* 2007).

The advantages of studying the robot Tuna and the reconfigurable robot fish consisted in analysing the construction and the work principle of these machines to increase the level of knowledge regarding swimming robots.

3. Architecture and used components

This section details the developed architecture and the used components, with the goal of implementing the biologically inspired swimming robot, possessing a stable and directional locomotion, without abruptly altering its movement direction.

In order to achieve these goals, the structure, materials and dimensions of the robot were initially analysed. The structure of the robot should consist on a structure comparable to that of a biological fish. The materials to be used could be acrylic glass, steel, nylon and rubber, among others. However, it should be a material that would allow its usage and molding in an accessible way, and that would guarantee a perfect insulation. Among the already mentioned solutions, the choice was the acrylic with a thickness of 2 mm since it possesses the mentioned characteristics, and is an affordable material.

The propulsion of the robot is obtained through its two chest fins. The tail fin contributes to the orientation of the robot. For the motion of the fins it was necessary to use motors. Initially were analysed the possible type of motors to be used, namely servomotors, DC motors, step motors, among others. Servomotors were selected due to its characteristics, being used three units: two for the movement of the chest fins and one for the movement of the tail fin. These servomotors have a weight of 14.7 g each one and a torque of 2.5 kg.cm. In order to control the heading a compass was used, with 0.5 degrees of resolution, which communicates directly with the control board to control the robot direction. It was decided to use the Arduino in this project, but it was also considered the usage of the Atmega16. An RF module was used to allow the wireless communication with the robot, making possible its control. All of these equipments are electrically fed by a battery with capacity of 2800 mAh, 12 V, while the servomotors are powered from another battery with capacity of 1200 mAh, 6 V. Lead batteries are used, giving the robot an autonomy of around two and a half hours. The option for these batteries (despite other types with more energy density), was also justified by the need to increase the ballast of the robot, lower its mass centre and, finally, also allowed to make the project more economic.

4. Implementation

This section presents the implementation of the robot physical structure, which was idealized with the purpose of resembling a biological fish as much as possible.

4.1 Robot body

The design of the robot was initiated by studying the dimensions it should possess, based on the equipments that it should carry on board (its dimensions and weight). In a second phase, was analysed the shape that it should present, with the purpose of reducing the drag of the water to its movements. Between the several shapes that the robot could adopt, the fusiform format was chosen (meaning a long body with its extremities narrower than the central zone). This format allows the reduction of the friction between the robot's body and the water and presents a compromise regarding the easiness of implementation. Due to some difficulties in producing this form, it was adopted the form depicted in Fig. 3(a). For executing this shape, an acrylic plaque was used, and by warming it in several zones, it was slowly bent until it reached the intended fusiform format for the robot, with some resemblance to that of a fish, as it can be seen on Fig. 3(a).

After finishing the robot central body structure, was implemented the front part (so called "head"), as it can be seen on Fig. 3(b). To connect the "head" to the robot body structure a glue of high elasticity was used, to make possible uncoupling these two elements, in case it was needed. This glue also prevents water leakages to the inside of the robot body.

The robot body (with the head) has a length of 293 mm, 125 mm of width and 153 mm of height.

(a) (b) (c)

Fig. 3 The robot fusiform structure (a), representation of the robot "head" (b) and the models of fins developed (c)

4.2 Chest fins

The fins are controlled by servomotors and were conceived in order to propel the robot locomotion. Three different pairs of chest fins were conceived and tested with the purpose of evaluating the ones providing better locomotion. These fin models geometries were based on other prototypes already developed and described in the bibliography, and were implemented with the goal of analysing their different behaviours and to try to find the one giving better locomotion results. Fig. 3(c) shows the three conceived fin models, with the third model on the left side, and on the right side the second model (on top) and the first model (below). Concerning the dimensions, the model 2 has 80 mm of length and 53 mm of width.

To connect the chest fins to the servomotors, mechanic shafts were used which are fixed to the motor in one extremity, and in the other extremity to a roller bearing which, itself, is fixed to the robot structure. Four needle roller bearings were applied, two in each chest fin, with the following dimensions: outside diameter of 10 mm and inside diameter of 8 mm. To guarantee a greater stability of the shaft before its rotation, they were fixed to the robot structure in parallel.

In the places in which the inlet of water into the robot acrylic structure was verified, a careful analysis was necessary until full tightness was reached. It was verified, on a first phase, the entrance of water near the motors roller bearings, which implied the use of retainers to eliminate the leakage. The retainer was fixed with its front side having direct contact with the water, guaranteeing the complete isolation of that spot. The retainer includes two sides.

To fix in place the chest fins to the motor shafts, a nylon accessory was implemented (shown on Fig. 4(a)) which couples the fin to the shaft. This accessory possesses a screw to adjust and fix the fin, allowing its easy replacement in case of need. Fig. 5(a) presents a lateral view of the robot, in which it is possible to observe the chest fin properly inserted in the motor shaft.

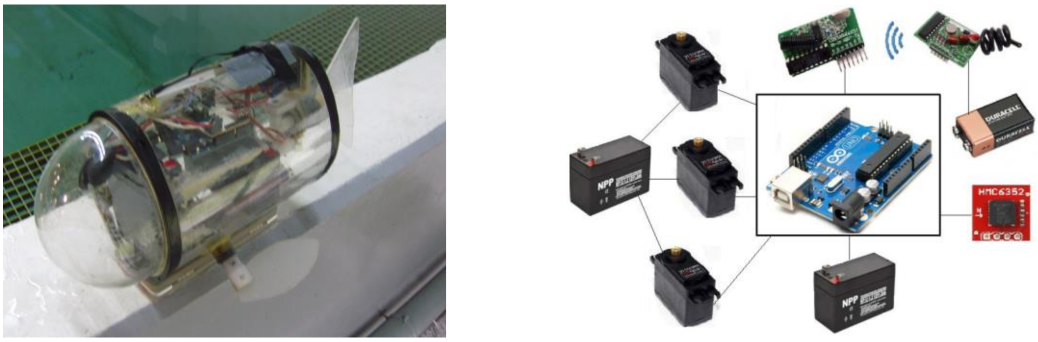
4.3 Tail fin

The tail fin was implemented to aid in the locomotion and orientation of the robot. A mechanism (whose components are in Fig. 4(b)) was developed to perform the movements of the tail fin. Initially the servomotor was horizontally fixed to the robot structure and the propeller was placed too. Afterwards one of the extremities of the propeller was put inside the nylon tube, so that when the servomotor moves the tail fin, on the other extremity of the nylon tube (which crosses the bellows), is moved as well. The tail fins have a height of 170 mm and 82 mm of length.

Once completely assembled, it was verified that the robot possesses a total weight of 2.8 kg and has 415 mm of length, 125 mm of width and 180 mm of height.

(a) (b)

Fig. 4 Representation of the nylon accessory (a) and components of the tail fin mechanism structure (b)



(a) (b)

Fig. 5 Representation of the robot chest fin (a) and control system architecture (b)

4.4 Control of the robot

Concerning the robot control system (depicted in Fig. 5(b)), the emission/ reception through the RF module offers the possibility of turning the robot on/off remotely. This control consists on a digital output which allows the user to turn the robot on/off, becoming more useful because the robot can be turned off in unfavorable situations, in case where it is moving away from the operator.

The communication of the compass with the Arduino is established through the I2C protocol. Through the Serial monitor of the Arduino it was possible to analyse the data sent by the compass, in order to check its proper functioning.

The robot locomotion process is based on a directional locomotion, ideally with no abrupt direction changes, having a stable directional locomotion as its purpose. The robot locomotion possible directions are set to one of the following: North (N) or South (S). This way, every time the robot moves N or S its locomotion is established through the simultaneous work of the two chest fins and the tail fin. In case the robot deviates from the pre-programmed direction of movement, its locomotion gets restricted to the work of only one fin, to try to keep the course it had until that moment, with the following restrictions:

- While the robot is moving N, if it changes the heading to West (W), only the left fin will work;
- While the robot is moving N, if it changes the heading to East (E), only the right fin will work;
- While the robot is moving S, if it changes the heading to W, only the right fin will work;
- While the robot is moving S, if it changes the heading to E, only the left fin will work.

5. Tests performed and results

In order to analyse the robot locomotion were performed tests in three different locations. The first tests were conducted at the LSA tank (14 metres of length and 8 metres of width) and, due to the observed deviations in the compass generated data, were chosen two other locations for performing tests: Espinho City Pool (Piscina Municipal de Espinho Solário Atlântico), and a fiberglass residential pool. Espinho Municipal Pool presents the following dimensions: 60 metres of length and 20 metres of width, and the used fibreglass residential pool has 8 metres of length and 4 metres of width.

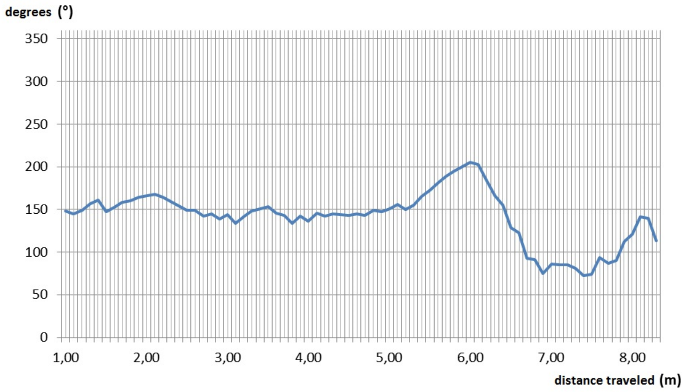


Fig. 6 Data generated by the compass in the tank

5.1 Preliminary tests

The first tests of the prototype consisted on the evaluation of its tightness, floatage and stability. On the first performed test it was noticed that the prototype body was not completely tight, with water entering through the joint of a chest fin and the joint of a tail fin. During this test it was also verified that the prototype presented some lack of stability, with the body being slightly unbalanced on some situations, and more severely on others.

To guarantee the tightness of the prototype it was necessary to replace one of the retainers, and apply some glue on the connection of the bellows which protect the mechanical transmission of the tail fin to the robot body.

To solve the floatage and stability problems it was necessary to incorporate a ballast along the robot length to increase its weight, and deviate its gravity centre to the lower part of the body and, therefore, provide a greater stability to the robot. The used ballast consists on a compact iron cylinder, lined in insulating tape.

5.2 Analysis of the compass behaviour

The behaviour of the compass in the tank was analysed through several experiments, since a digital compass could be affected by the high presence of iron in the interior of the tank walls. After some experiments, reading the data generated by the compass while the robot heading was changed by hand and, later, while the robot was swimming in the tank, it was verified that the compass suffered disturbances, as can be seen in Fig. 6.

After the robot travels approximately 5 metres, in the East-West direction, strong disturbances were verified in the data generated by the compass (Fig. 6). From this point on the compass starts generating unexpected values, and only a fin keeps working in an attempt to redirect the robot. In this situation, some oscillation in the robot body occurs, with the compass possibly suffering increased disturbances.

5.3 Robot locomotion tests

It was verified in the experiments performed at the LSA tank (and later confirmed during the tests at Espinho City Pool) that with fin models 1 and 2, and increasing the cycle time (decreasing the fins speed), the duration of the course (time that the robot takes to complete the course around the tank) increases.

For the execution of the locomotion tests was adopted a movement amplitude of 30° and 45° for the fins, according to the data presented in Table 1 and Table 2, respectively. The data displayed in these tables were registered after several preliminary experiments, and are presented results for different fin models and different cycle times for the fins operation. The deviation is obtained in function of a reference point established in the place of each tests. The deviation is measured taking into account a reference point in both extremities of the sites used for the experiments. The reference point was established at 2.60 metres from the South top of the Espinho City Pool, and for the fiberglass residential pool the width was measured and the centre was defined as the reference point.

5.4 Experiments at Espinho City Pool

One of the purposes of making the experimental tests at Espinho City Pool was the analysis of data generated by the compass. In the initial experimental tests the robot was placed near the wall and it was verified that the compass abruptly changed the generated values, with it being clearly

Table 1 Experimental test results with a movement amplitude of 30° for the fins

Fins	Cycle time (s)	Duration of the course (s)	Deviation (cm)
Model 1	1	84	-131
	1.4	91	-126
	1.8	102	-121
Model 2	1	78	-114
	1.4	82	-106
	1.8	89	-101
Model 3	1	157	178
	1.4	121	162
	1.8	109	132

Table 2 Experimental test results with a movement amplitude of 45° for the fins

Fins	Cycle time (s)	Duration of the course (s)	Deviation (cm)
Model 1	1	74	-143
	1.4	81	-134
	1.8	86	-129
Model 2	1	66	-119
	1.4	73	-111
	1.8	82	-106
Model 3	1	180	244
	1.4	164	228
	1.8	158	206

Table 3 Results obtained in the Espinho City Pool experimental tests

Fins	Cycle time (s)	Duration of the course (s)	Deviation (cm)
Model 2	0.8	376	5
	1	350	-15
	1.4	510	-50

affected by the presence of iron in the walls bounding the pool. To avoid this situation and taking advantage on the fact that the pool possesses a large width, the robot was swerved from the wall, with the compass being verified to work with no disturbance, which enabled the analysis of the robot with no external perturbation. The tests were made along the pool's width, except for the two first metres, that were avoided to prevent interference with the compass.

The experimental tests were made only with the second fin model and with a movement amplitude of 45º, since in the several experiments made in the LSA tank it was seen that this was the most adequate combination for the robot resulting in faster timings. Before the data gathered at the tests, it was concluded that the robot presents an adequate control, with errors inferior to 3% of the travelled distance, given the observed deviation values along the full path. Given the robot favorable performance, in the first experiments, with cycling timings of 1 s and 1.4 s, it was decided to observe the robot behaviour with a timing cycle of 0.8 s, in which a lower deviation was registered, of only 5 cm. It was found that the 1 s cycling time provided the smallest time duration of the path. With a cycling time of 1.4 s a longer time duration of the path was registered, as well as the highest deviation.

Unlike what happened in the tests taking place at the LSA, the robot presented reduced deviations. It is important to highlight that the tests performed at Espinho City Pool took place along a length of 18 metres and only 7 metres at the LSA, with the marked disturbances of the compass in LSA tank becoming notorious.

Comparatively to the experimental tests performed at LSA, in which it was concluded that as the time cycle increased, the course deviation was smaller, in these experiments was verified exactly the opposite (check Table 3). This situation is due to the fact that the compass at Espinho City Pool was working with no disturbance whatsoever and it was establishing an adequate control of the robot path. Slight disturbances that the compass might "feel" due to the oscillation of the robot body, before its correct functioning are perfectly "surpassed", given the fact that most of the values were correct. In LSA tank, it was verified that the compass error was lower when the cycle time increased, due to the lower robot body oscillation, allowing more concise data to be generated, but always with some error due to the high presence of iron in the tank walls, as already mentioned.

6. Conclusions

The biological inspiration evokes plenty of curiosity in the world of robotics, given the interest in developing prototypes that simulate the movements of animals, including human beings.

The developed prototype aims to simulate a fish locomotion and orientation abilities. Initially a study about the locomotion of fishes was made, in order to "copy" the basic principles of locomotion for the prototype to be developed. The following phase consisted on the analysis of the already developed prototypes in order to get conclusions on how the locomotion and control of a swimming robot of biological inspiration is obtained.

In the architecture design phase, the prototype was initially designed at the structure and control system levels. A careful analysis was necessary due to the environment in which the robot would be placed, which right away prevented the consideration of several materials to implement its structure. Even when it came to the architecture of the control, it was necessary to analyse the sensors which could be inserted in the robot, given the impossibility of some sensors to work properly when submerged.

In the implementation of the prototype phase a few problems arose, given the fact that this was the first prototype of this kind to be implemented in ISEP (and, according to the information obtained, also the first nationally) and there was a lack of practical experience in the implementation of systems of this type. The situations which were predicted to need bigger caution were the tightness and stability of the robot.

On the first test of the robot on a tank, the leakage of some water to its interior and a clear lack of balance were immediately verified. To assure the tightness it was necessary to replace one of the retainers, which was not sealing the joint correctly, and apply some glue in the connection of the shaft that protects the mechanic transmission of the tail fin to the rest of the body of the robot. To overcome the stability problem, a ballast was added in the bottom of the robot to increase its weight and provide the necessary stability.

Concerning the control system, it was concluded that the used compass does not provide an acceptable signal in places with high presence of iron and other ferromagnetic materials. However, in places with no disturbances, it allows a quite acceptable control.

Throughout several experimental tests was verified the importance of the chest fins in the locomotion of the robot. It was verified that changing the position of the fin is enough to prevent or allow the locomotion of the robot. In the first tests this situation emerged, with the fins being inserted in several positions which could not make the robot move, even considering the torque that the used motors supply.

Concerning ideas for future developments, it is considered that the developed prototype could be improved through the addition of two (or even four) more chest fins, symmetrically applied in the robot's body. It is estimated that this modification could make possible to greatly lower the temporal duration of the course, given the amount of fins providing traction to the robot. Under consideration is also the improvement of the robot locomotion by developing an articulated body, more similar to the one of real fishes.

The control could also be improved through components/systems that allow reliability in all sorts of tanks, pools, among others. Compasses with a linked correction system, Global Positioning Satellites (GPS), remote control and other sensors/systems are presently under evaluation.

Another idea is to have the batteries charged through the application of solar panels in the immersed part of the robot body, this way increasing its autonomy.

Finally, another development under analysis is the possibility to implement depth control in the robot.

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