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Design and Construction of an AUV Robot Type ROV

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Abstract: The present research shows in detail the design and implementation of an aquatic robot type ROV. The design of the robot was primarily developed with the monitoring of seas and rivers having a social focus in the fight against climate change and control of optimum water conditions. In this way, the objective of the project is focused on the design and implementation of an aquatic robot suitable for underwater exploration in order to improve its stability performance and achieving an efficient exploration result. With the proposed design, it was possible for the robot to navigate on the surface and at a certain depth making it possible to emerge and submerge. The vehicle receives and sends data via. wireless communication to a base station this station is designed to be portable (via. Smartphone) or fixed (base computer). The robot has a structure composed of six flaps with which the direction is determined and two submerged propellers which generate the propulsion of the robot characterizing it as a robot suitable for exploration.

Key words: Aquatic vehicles, robotics, mechatronics design, portable, structure, exploration

INTRODUCTION

The field of mobile robotics has evolved in such a way that it has been able to expand the frontiers that were previously unexplored due to the advances and the appearance of the autonomous vehicles this has contributed to improve the functions in the terrestrial, aerial and aquatic constructing areas of research of great importance for engineering. The massive use of robotic applications and equipment symbolizes one of the areas that represent the future where a vision of robotics is specifically focused on the aquatic area.

At present, underwater operations are of great importance in many cases the means of work presents big difficulties and risks for the man (Ollero, 2001; Gros *et al*., 1995), besides the complexities that must require the development of the task as the precision and the use of large tools. With the advancement of technologies, it has been generated that the treatment of these tasks is reduced, since, they appear the remotely operated aquatic vehicles better known as ROV (Robert and Wernli, 2007; Meinecke, 2011).

The ROV vehicles have been implemented in a variety of applications such as coral exploration (German *et al*., 2008), pipeline inspection (Yoerger *et al*., 2007), ship inspection (Acosta and Calvo, 2008), offshore constructions and installations for oil and gas exploration (Negahdaripour and Firoozfam, 2006), operations Military (Brown *et al*., 2011; Rudnick, 2012), among other applications.

The present research aims to design an aquatic assisted robot giving the operator the possibility to occupy tasks as supervision and at the moment of detecting an error in the movement of the robot can define the path to follow. For the implementation of the design is considered parameters such as mass, centre of gravity, inertia and the characteristic properties of aquatic vehicles.

Taking into account the above described the development of this document initially presents the mechanical design of the aquatic robot after this, we proceed to demonstrate finite element analysis of the system. Finally, we show the prototype implemented and the results and conclusions.

MATERIALS AND METHODS

Mechanical robot design: The mechanical design was proposed for the development of a system with the ability to submerge and move within an aquatic environment. In order to construct the movement direction mechanism, it was started by the attachment of six flaps to the structure of the robot and for the displacement of it, two turbines were incorporated with their respective propellers (Fig. 1) with the configuration of the flap was searched the improvement of performance in water also to opens the possibility of redesigning some parts of the robot to configure it as a robot for terrestrial exploration.

To develop a model that comply the requirements of movement direction, movement in an aquatic environment

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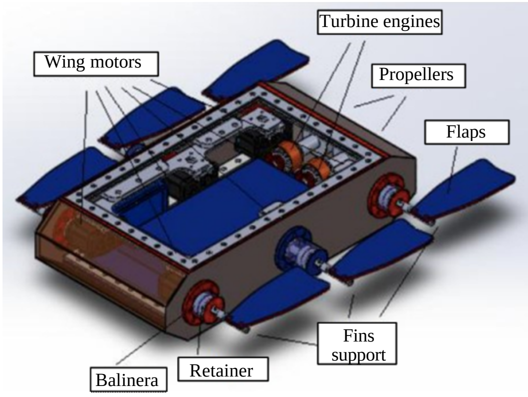

Fig. 1: Proposed system design

and integration of sensors for monitoring, communication and location, a mechanical system implemented in Solid Works® was developed where the pieces that were modelled are related in the following form:

- Turbine support
- Short flap support
- Large flaps support
- Structure aquatic vehicle

The wing supports consist of a ball bearing and a commercial mechanical retainer assembled with a motor by a mechanical coupling (Fig. 2a). This assembly is capable of producing the movements of the flaps that define the direction of the aquatic robot within the water. In the same way, the assembly of the long flap support is constituted by the same mechanical system whereas the chamber where the retainer and the ball bearing are housed is longer (Fig. 2b).

The assembly corresponding to the support of the turbines consists of two chambers composed of 4 ball bearings and two central axes where an oil film is housed inside which restricts the passage of water to the interior of the robot structure. At one end of the plants the propellers are coupled and the other Brushless motors which define the speed at which the robot moves in an aquatic environment. The dimensions of the shell and flap are given in Table 1, the latter being the same for all flap.

The measurements used for the construction of the shell were based on the dimensions of the mechanical and electronic components that would be shipped in the structure, so that, the design was not oversized. In comparison to other aquatic robots having a smaller design in its dimensions it allows to cover a greater range

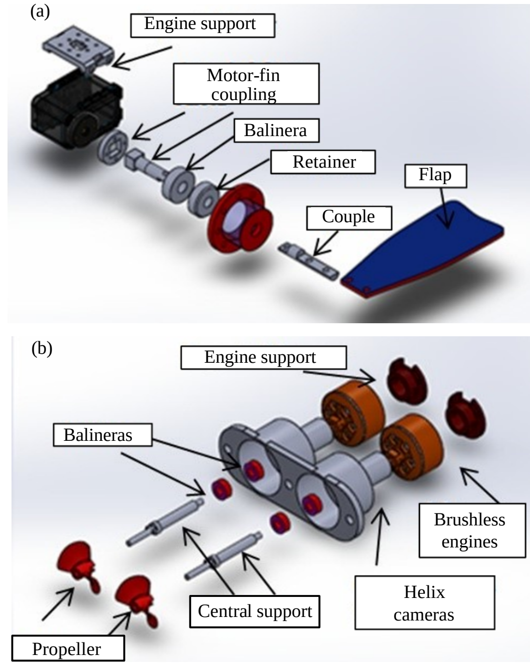

Fig. 2: Turbine support assembly: a) Short/long flap support assembly and b) Turbine support assembly

Tabla 1: Prototype dimensions

Piece	Length (mm)	Width (mm)	Height (mm)
Case	350	180	80
Flap	115	50	3

of exploration which does not prevent that this prototype cannot get to have the same functions of a robot with a much more robust design.

The proposed design of the flaps was generated from the measurements of the structure in addition from the study on the physiology of the fins of the fish considering the total area of the fin had to be sufficient to be able to propel the robot in any of the established destination.

Structure of robot: The structure is designed to put the motors, batteries, mechanical system, submerge system and emerge in the water also electronic and control circuits. For the construction of the structure was used an acrylic material because it is light and easy to work in addition other mechanical properties suitable for the application required for more detail of this information can be observed by Garcia (2000).

To perform the design is essential the theme of flotation additionally to submerge and move both inside and on the surface of the water. For this a hydrodynamic

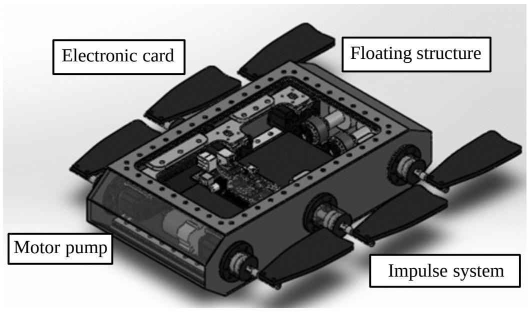

Fig. 3: Structure of robot

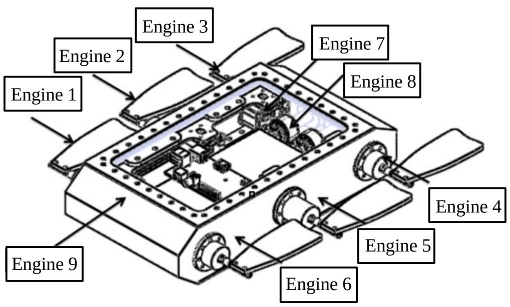

Fig. 4: Motor nomenclature

structure was designed that reduced the water resistance, facilitating the movement and control in an aquatic environment (Fig. 3).

Actuators: The aquatic robot is composed of 9 motors, each with a specific function (Fig. 4). The motors 1-6 are responsible for directing the movement of the robot, either to the interior or on the surface of the water. The function of the motors 7 and 8 allow the agile movement of the aquatic robot within the water. The motor 9 is a water pump to have the ability to submerge or to emerge it is responsible for filling the tank.

To calculate the motor some parameters were taken account: the hydrostatic pressure (P) exerted by the water on the robot, the density (ρ) of the water being 1000 kg/m^2 and the depth (h) to which the robot is submerged to 0.5 m:

$$P = \rho gh$$
$$P = 1000\ kg/m^3.9,\ 8\ m/sec^2.0.5\ m = 4.9\ MPa \quad (1)$$

Taking the value of the hydrostatic pressure exerted on the robot is required that the robot speed is 0.02 m/sec and the surface area of the robot is 0.063 m^2, the contact surface is:

$$S = b*a$$
$$s = 0.350\ m*0.180\ m = 0.063\ m^2 \quad (2)$$

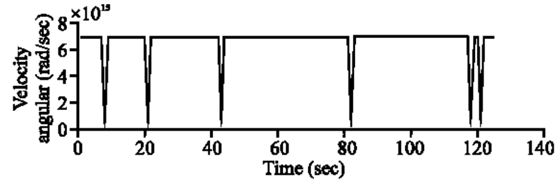

Fig. 5: Dynamixel motor response

Calculating the surface is obtained the force value exerted by the water on the robot according to Eq. 3:

$$F = P*S$$
$$F = 4900\ Pa*0.063\ m^2 = 308.7\ N \quad (3)$$

With this numbers is possible to calculate the torque required for the robot movement which is given by:

$$T = F*d$$
$$T = 308.7\ N*0.02\ m = 6.174\ Nm \quad (4)$$

Knowing the torque needed to move the structure, it is divided between the six motors and you get that each motor must have a torque of 1.029 Nm. In this way the Dynamixel motors are sectioned which comply with the characteristics required by the system because its maximum torque is 1.57 Nm.

For the calculation of motors, the weight of the robot and of the fins were not taken into account, since when inside the water, the total weight of the robot is almost null, due to the force of thrust which must be countered with the force exerted by the robot on the water, so that, it can be kept at a point. This balance is exerted by the system of immersion and emersion in the water. The response of these motors can be observed in Fig. 5 where the behaviour of the motor in relation to the speed over time is observed.

Vehicle locomotion system: For the robot to be able to move on the surface and inside the water is necessary to implement a system that generates movement to the structure or mechanical platform. Therefore, were analyzed the following alternatives found in the literature (Chean, 2007; Fossen, 1994): submerged propellers, fins, fans and sails. In Candy (Cady *et al*., 2013), the advantages and disadvantages of the alternatives of locomotion of the aquatic robots are presented as are presented in Table 2.

According to the above table, it can be analyzed that the most viable options are the propellers submerged by their speed and maneuverability; As well as the fin system, since, they have the characteristic of a good

Table 2: Advantages of vehicle aquatic locomotion

Alternative	Advantages	Disadvantages
Submerged propellers	Speed and maneuverability	Transmission system for motors. Propeller profiles and special angles for each application
Flaps	Easy installation Apply in the depths	Assembly mechanical couplings
Fans	Easy navigation in marshy places	Difficulty turning
	Easy navigation in shallow water	Does not apply in the depths
Sails	Does not require energy	It cannot be submerged in water
	Easy installation	It is affected by drafts Inefficient for the displacement in the water

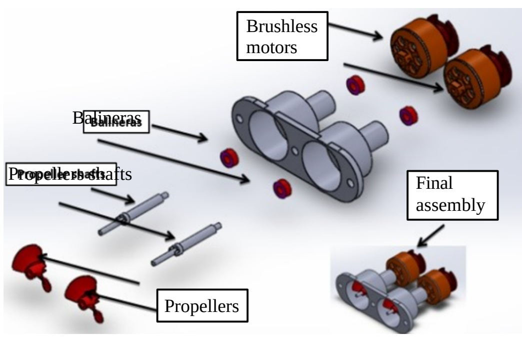

Fig. 6: Exploded view and final assembly of the submerged propeller system

performance in the depths. The other options are discarded because they are not applicable in underwater operations as is required for the operation of the aquatic robot (Franchino *et al*., 2005).

In the same way, in the robot were installed two brushless motors used in aero-modelling this is because they generate a speed of 1500 rpm and when is adapted a pair of propellers each of two blades can be generated the action for the direction of movement In the robot when the two motors are activated simultaneously in the same direction the robot advances in a straight line and if the direction of rotation of one of the motors is reversed, it can turn to the right or to the left as appropriate. Figure 6 shows the final assembly and mechanical components used for the submerged propeller system.

Another of the alternatives selected for the locomotion system is the implementation of fins which were used 3 for each side of the robot for a total of 6 fins corresponding to each engine. This system is useful both for moving on the surface of the water and inside, the movement of the fins allows to direct the robot forward, back, right and left, depending on the commands sent for teleoperation. To assemble the fins with the engine a mechanical system was designed to transmit the rotational

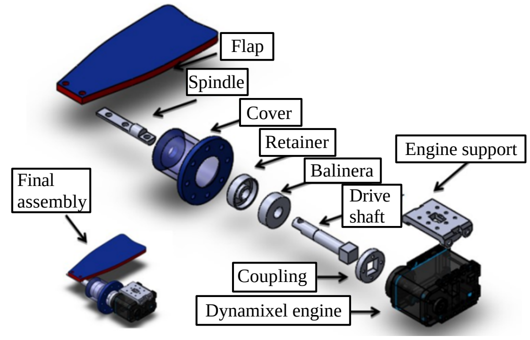

Fig. 7: Exploded view and final assembly of the fins system

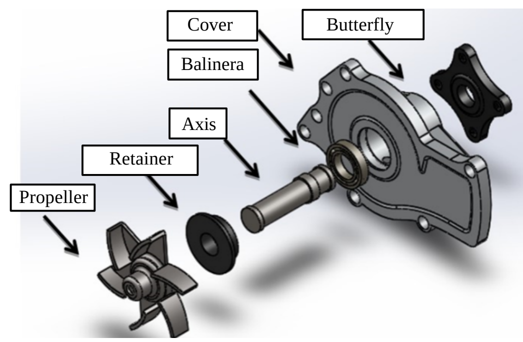

Fig. 8: Components of the water pump

movement generated by the motors to each of the fins. Ball bearing, retainers, shafts and couplings were used (Fig. 7).

Each fin with its respective motor uses a mechanical system composed by an axis that is coupled with the fin and connects it with the motor shaft this is assembled to the motor through a coupling which has in its centre a quadrant that unites perfectly to the motor shaft as shown in the previous figure. The cover, retainer and ball bearing serve to seal and not let the water from the outside to the inside of the robot structure. This sealing system was based on the principle and sealing of a water pump of the engine of a car in which it is sought to ensure a constant circulation of the refrigerant and to make it possible for the cooling system to maintain the thermal equilibrium of the engine. Figure 7 shows the components used by a water pump.

As shown in Fig. 8, the propeller is responsible for circulating the water inside the motor to keep it cool. This rotates thanks to the shaft that connects the butterfly which in turn is assembled with a pulley and a belt that transmits the movement of the engine crankshaft to the water pump. It maintains the adequate pressure, so that, they do not find water leaks in the pump is the retainer

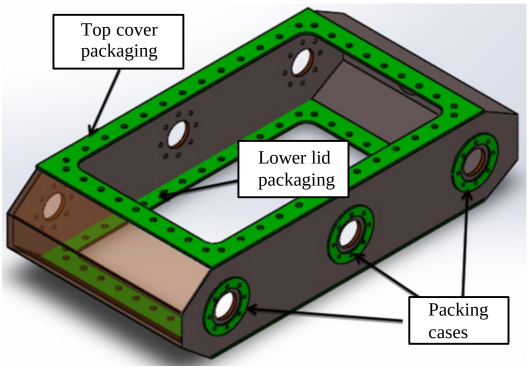

Fig. 9: Location of packing in the structure of the aquatic vehicle

and the ball bearing is used in the mechanism, just as it was implemented in the system of fins to avoid the filtrations of water inside the structure of the robot.

Taking into account the above calculations, it is necessary to calculate the dynamic drag force to compensate for the force exerted by the water on the robot, to calculate it depends on the geometric coefficients of drag that are presented in the following Table 3 (Cengel and Cimbala, 2010):

The drag Force (Fd) is calculated according to the design which is based on a dynamic body and knowing that the relative speed of the robot with water is 0.02 m/s and the reference is 1.029 Nm, it can be calculate according the Eq. 5:

$$\begin{aligned} F_d &= 1/2\rho v^2 C_d A \\ F_d &= 1/2\left(1000\ kg/m^3\right)(0.02\ m/sec)^2(0.04)(0.063\ m^2) \\ F_d &= 0.0126\ N \end{aligned} \quad (5)$$

Therefore, the drag force of each the fin will be 0.0126 N.

Robot sealing system: To avoid leaks inside the structure when immersed in water was used a special rubber type that in the industry is used to make packaging it is known as reinforced thermo-film, to see its features in detail is recommend to review (Wiebe and Brown, 1979). This system was implemented to seal the upper and lower cover of the structure as well as to seal the joint between the ball bearing shell and retainers with the structure of the robot.

With the help of a laser cutting machine, the various gaskets were formed (Fig. 9) where holes are shown through which screws are passed that adjusts the closing of the parts with the robot structure, guaranteeing the system's tightness.

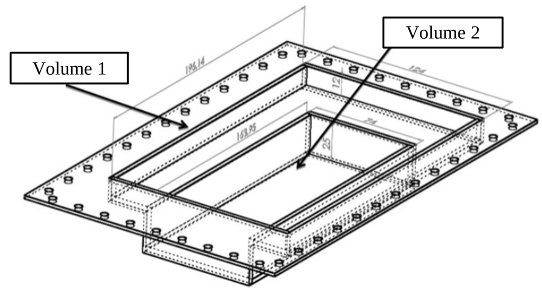

Fig. 10: Sizing of the water storage tank

Table 3: Drive coefficients for different geometric forms

Shapes	Shapes	Drive coefficients
Circular		0.47
Semi-circular		0.42
Triangular		0.50
Cubic		1.05
Cubic-angular		0.80
Long cylinder		0.82
Short cylinder		1.15
Aerodynamic body		0.04
Half aerodynamic body		0.09

Immersion and emersion system: This system is composed of a tank built in acrylic, to store a certain amount of water and to be able to submerge the aquatic robot for it the system counts on a water pump DC of 5 V to 500 mA, to obtain a speed of filling of 1.5 l/min and in turn has the same speed to drain the storage tank to be used for this system.

As shown in Fig. 9, the water storage tank is located in the lower part of the structure, sealed by a lid and its packaging in addition, of its respective screws which guarantees the tightness of the tank. For filling, there is a water pump located on the front of the robot where its main function is to fill and empty the tank arranged for water storage. This allows the robot to dive and emerge from the water.

In order to determine the total volume of the tank, the two different volumes that are evidenced in the Fig. 10. First is calculated the two different volumes then is added to find the total volume and calculate the amount of water that can be stored in the tank. To determine Volume 1 and 2 is used the Eq. 6:

$$V_{12} = l*b*a \quad (6)$$

Replacing the values in Eq. 6 gives:

$$\begin{aligned} V_1 &= 291856{,}32\ mm^3 \\ V_2 &= 303307{,}5\ mm^3 \end{aligned}$$

After finding volumes 1 and 2, the total volume of the storage tank is calculated this corresponds to the sum of the volumes:

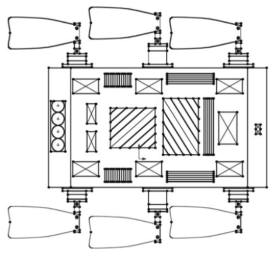

Fig. 11: Internal distribution of the aquatic vehicle

$$V_{Total} = 595163{,}82\ mm^3$$

The total volume found in the tank is approximately 595 mL of water, it is sufficient to counteract the force of thrust that generates the water on the structure and to be able to submerge it completely.

Internal distribution: The location of electronic and mechanical components inside the aquatic robot is very important because some of the cards and integrated circuits are sensitive to the presence of other components such as batteries, motors and high-power cables. Therefore, the structure was constructed (Fig. 11) which contains the circuits, batteries and motors with the characteristic of allowing the easy handling of all the components at the same time.

The accelerometer which is also a digital compass is more isolated from all other electronic-mechanical components, since, its integrated circuit is very sensitive to any magnetic or electric field disturbance.

RESULTS AND DISCUSSION

Analysis of mechanical design by finite elements: With the study of stress analysis can be assessed if the parts can be broken or deformed. This analysis is able to calculate displacements, deformations and tensions in a piece based on the material, constraints and loads. In order to determine if certain mechanical parts supported the loads, a stress analysis software was used by the finite element analysis method to calculate the stress, assuming that the material is isotropic (a material is isotropic if its properties do not vary with the direction) which is defined from the type of study. The pieces selected in this analysis are those that present the most important loads in the system. Such pieces are: body of the prototype (Shell) and supports of the fins. For practical purposes, a load of 50 N. was applied to each of them.

In order to perform the analysis, the material type and its properties such as the Young's modulus, elastic limit, poisson's coefficient and the mass density of each material were taken into account for each piece. Figure 12 shows the results of Von Mise's static voltage analysis. A large deformation is observed because the software simulates the deformation scale in order that the designer can appreciate more clearly the meaning of the deformation.

Von Mises's maximal voltage criterion is based on the theory of shear energy or maximum distortion energy theory. In terms of the principal stresses σ_1-σ_3 the Von Mises stress is expressed as follows in Eq. 7:

$$\sigma_{VM} = \sqrt{\left\{\frac{\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2\right]}{2}\right\}} \quad (7)$$

The theory demonstrates that a ductile material (material that can be deformed, molded, spoil or easily extended) begins to yield at a point when the Von Mises voltage is equal to the tensile stress (property characteristic of each material) as shown in Fig. 13.

In most of cases, the elastic limit is used as the voltage limit. However, the software allows you to use the tensile/breakage voltage limit or set your own voltage limit.

The elastic limit is a property that dependent on temperature. The value of the elastic limit must consider the temperature of the component. The safety factor at one point is calculated from Eq. 8:

$$FoS = \frac{\sigma_{limte}}{\sigma_{VM}} \quad (8)$$

The results of the stress analysis of these parts are shown in Table 4, mass, stress and maximum resulting displacement as well as the safety factor. The latter indicates the maximum permissible load before the material yields and leaves the elastic zone (Elastic limit/maximum permissible load). It can be seen that the shell and the flap supports are able to withstand loads of 50 N without any problem, since, the FDS is in an optimal range for the structural design.

According to the table, the safety factor corresponds to 2.7 which means that the prototype is overrated because it is intended to condition sensors such as cameras, sonars, laser, among others, to strengthen the platform. This implies that the new platform must support totally different conditions to the conditions with which it was designed, since, it is intended to be used as a hybrid platform (aquatic and terrestrial).

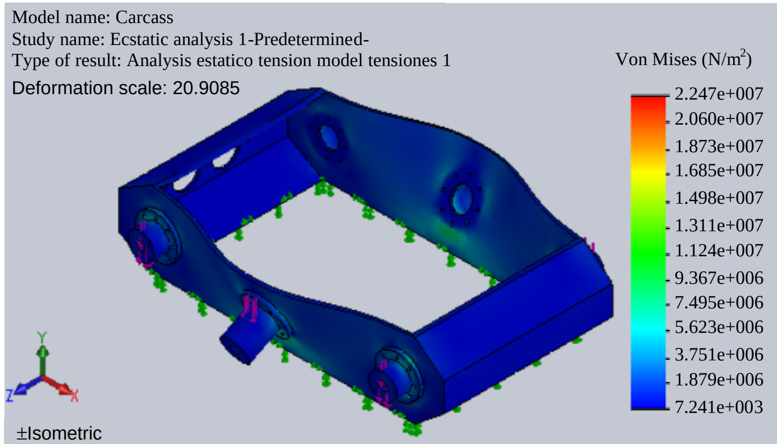

Fig. 12: Tension analysis results by Von Mises

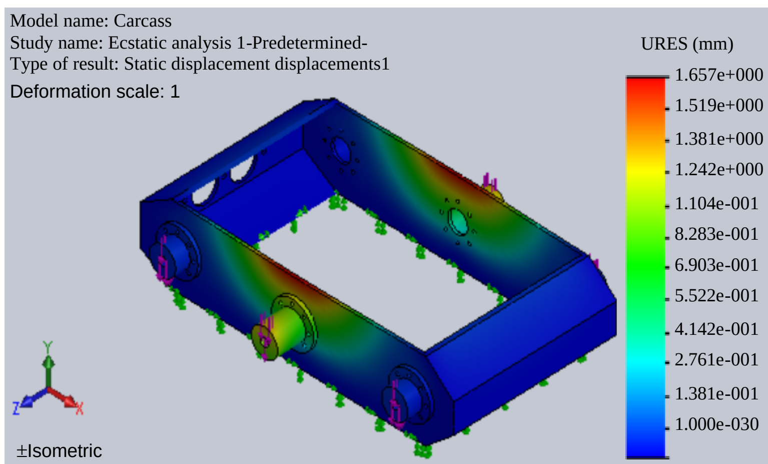

Fig. 13: Results of analysis static displacement of the material

Table 4: Analysis data

Piece	Mass of the piece (gr)	Maximum resulting effort (N/m^2)	Maximum resulting displacement (mm)	The safety factor
Set of components	338.27	2.242 e+7	1.657	2.7

To obtain the force exerted on the robot were calculate the forces on each face and its summation will give us the total of this force. Taking in account the Eq. 1 and 2 obtaining (Table 5):

With this calculation is obtained that the force exerted in each one of the faces and when it is sums them is determined the force on all the robot which is of 617.4 N.

Electronic of project: For the implementation of the control was taken into account the output of the angles of the servomotors, through Arduino Mega as well as the output signal of the brushless motors to which they were implemented a power stage, starting from the technical specifications of the motor. The development board implemented in the project was the Arduino mega because the code is based on C language and its power consumption is very low compared to the BeagleBone, Rasberry Pi or PcDuino boards.

Table 5: Calculation of the force on the robot

Flat	Hydrostatic Pressure (Pa)	Surface (m^2)	Force (N)
Upper view	4900	0.063	308.7
Bottom view	4900	0.063	308.7
Previuos view 1	4900	0.0072	26.46
Previuos view 2	4900	0.0054	35.28
Previuos view 3	4900	0.0072	26.46
Posterior view 1	4900	0.0072	26.46
Posterior view 2	4900	0.0054	35.28
Posterior view 3	4900	0.0072	26.46
Sumation	-	0.126	617.4

For the communication of the robot with the surface the main technologies of wireless communication adapted

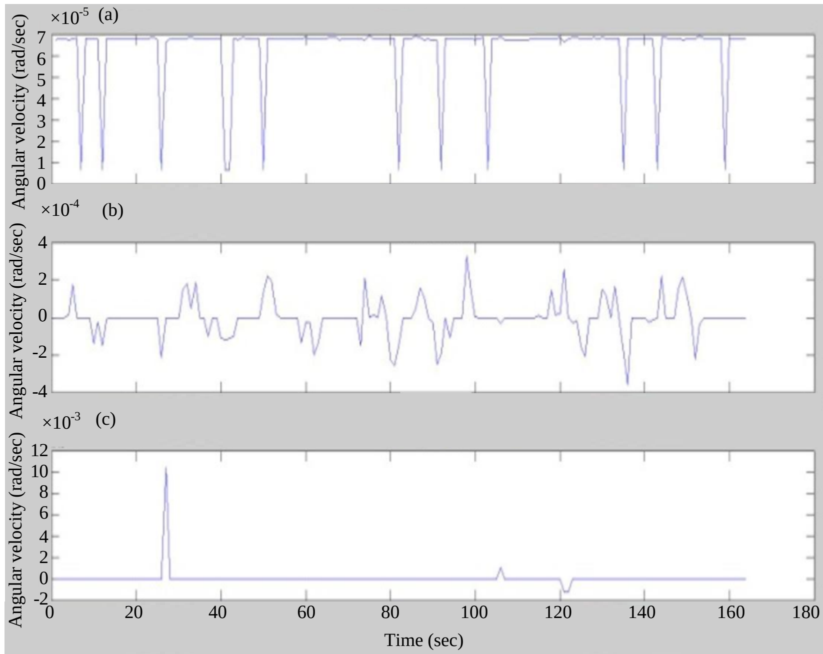

Fig. 14: Curve of response of IMU 9° of freedom; a) Angular velocity on the x-axis; b) Angular velocity on the y-axis; c) Angular velocity on the z-axis

in robotics like Zigbee, Bluetooth and WiFi were studied. The Bluetooth module reaches considerable ranges for the proposed application, its power and transmission speed purchased with the Zigbee and Wi-Fi is adequate. In addition, it has lower power consumption allowing a longer battery life. Therefore, Bluetooth was implemented for wireless communication in this first phase of the robot. Therefore, for the stability module of the robot, the IMU 9° of freedom sensor-MPU-9150 was used which has several characteristics that for the project are suitable and for future works equally as seen in Fig. 14 in the axes where most changes are found in the sensor are in the X and Y axes due to the configuration of the same with respect to the type of disturbances that have to be able to present.

Electronic of project: The aquatic robot prototype that was implemented is a 1:1. For the shell was used acrylic, cutting to the measures specified in the design to cover the edges against the leaks plastic putty was used.

Having the assembled structure checked each part vulnerable to leaks and tested several times by testing the effectiveness of the materials used for the construction thereof. It was preceded with the assembly of the other components of the robot being motors and circuits to do the test in water with the other components. In this way, the construction of the prototype was as

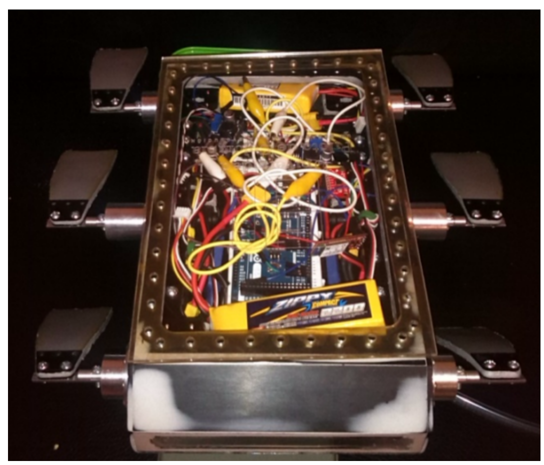

Fig. 15: Aquatic platform assembled

expected in the designs made in Solid Works®. The platform was finished with each of the components and without water filtration problems when tested in an aquatic environment (Fig. 15).

Immersion and emersion tests were performed to evaluate the robot behavior and without encountering problems with leaks, the test of movement of the platform was carried out, first the tests were developed outside the aquatic environment through the interface in charge of the user to have the interaction of various movements of the

Fig. 16: User interface developed in android

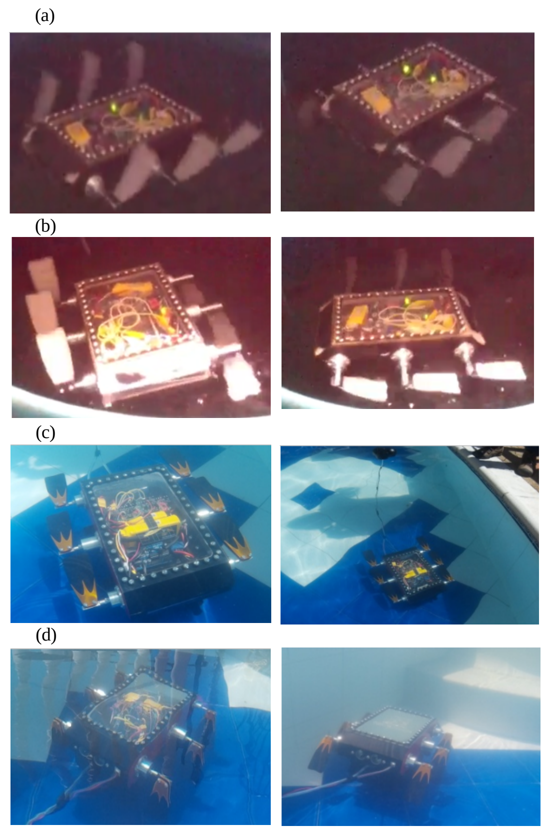

Fig. 17: Behaviours of the robot: a) Forword movement; b) Left and movement; c) Immersion movement and d) Emersion movement

same. For this reason the interface has different movements, thus, not only has a single program for the operation of this but the user can observe more than 9 combinations, verifying the operation of the platform in its entire context (Fig. 16).

From the remote system has of control of the pump by sending commands, for emersion and immersion of the robot. This system not only has the possibility of equitably distributing the introduced water, it also allows to evacuate it in the same way, maintaining the stability in case of disturbances in the water. In the electronic part the turbulence control system was coupled with its respective tests and with this the logic was projected to synchronize the movements of this one and to incorporate it in the user interface.

The commands sent from the interface via. the bluetooth module they are sent to the control board (Arduino mega) to control the movements and other functions that the robot has (Fig. 16).

The stability control code implemented consists of a PI controller based on the Ziegler Nichols Method in which the gains were Kp = 10 and Ki = 2.5 which seeks to minimize the steady error where the feedback from this controller is given by the IMU9150 (accelerometer) module used, so that, the desired values were obtained for the disturbances to be controllable. The accelerometer works based on the three axes (X-Z) and was configured in such a way that, if there was any slope of the stability zero point, it will use the engines for their stabilization, depending on which side the turbulence is (Fig. 17).

CONCLUSION

It can be concluded that the platform comply the requirements of buoyancy, immersion and emersion of the same on the water for this was designed a system that contains a water pump which when is immersing the robot the tank was filled with water to create a counterweight but this was not enough because it did not generate enough pushing force that will counteract the force of pushing the water on the robot, therefore, underneath it is a counterweight which helps to lower the robot.

Having these fully functional systems, each of the limb motors was connected to an Arduino Mega board with which the sequence of the movements was programmed for which two communication platforms were used by means of a Bluetooth module was connected to the board and from an Android application was controlled the basic movements. However, the type of environment the scope of this device was limited, so, it was communicated by means of cable connecting it to the computer from MATLAB® using the GUIDE extension. The platform (Bluetooth) is used for different types of communication, if the module has faults in the communication is backed by another device (RS-232 cable).

The research of this type of platforms allows the exploration of the aquatic robots and on how the project manages to contribute to the research line. The designed platform not only meets the requirements for immersion in aquatic environments and the exploration of these but also is fundamental for the development of terrestrial explorations.

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