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PROPULSION ANALYSIS OF A CARANGIFORM FISH ROBOT

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Abstract. *At this paper is presented a study of the carangiform robot fish propulsion. A review of recent papers is presented at the introduction. Several works all around the world are devoted to this research subject. At this paper the well-known sinusoidal gait is implemented at the hardware through a numerical algorithm. Some solutions for the gait control to define trajectories in a plane are discussed. The mechanical structure of the biomimetic robot is inspired on the class of carangiform fishes, like the tuna. The attitude measurement and control and the electronic circuits needed to control the robot and to supervise the whole system are presented. The sensors needed to obtain autonomous movement control and power supply are also analyzed. At the end of the work it is presented the future steps of this research, where the forces acting at the tail will be considered at the propulsion algorithm.*

Keywords: *Robot Fish, Biomimetic Robot, gait control*

1. INTRODUCTION

Several recent works describes biomimetic robots and its applications. Bioinspired robotic structures may be used since that some engineering solutions presented at nature are also applied at some kind of our needs. The robot configurations for underwater needs, flight applications or unstructured terrain movement are providing several good solutions for innovative development.

Several kinds of legged robot are being designed. With two, four or six legs kinematic and dynamics problems related to equilibrium, force feedback, position sensing or artificial vision applications are also studied. Bachega et al. (2010, 2011 e 2012) describe aspects of hexapod legged robot designed at Instituto Federal de São Paulo (IFSP). A FPGA is used to implement the robot kinematics and a set of strain gauges were attached to the legs to measure the forces at each link. It will be necessary to solve the force feedback needs. At Totaki et al. (2010) the same system was developed, but using a Digital Signal Controller (DSC). At these works several important developments were done. The embedded processor is different at each work, The design of mechanical structure and its needs helped to develop a Computer Aided Design procedure that is being used in recent works. The sensors developed at Bachega et al. (2012) are being used to develop the force analysis of other robots under development at IFSP. The legged robots present some different design skills from that presented by others biomimetic robots, like the fish robot, but several similar challenges have to be solved.

Underwater robots with fish like shape are being studied in recent works. Some research related to underwater bioinspired robots are devoted to fish like robots. This kind of solution for propulsion underwater have some advantages over that commonly used by other underwater machines. The biologically inspired fish robot may have several structures, called: angilliform, carangiform, subcarangiform and ostraciiform or thunniform. This classification is related essentially to the ratio of the tail length and the width of the fish body. Greater is this value, it is rated as angiliform and if this indices is lower, the fish is rated as ostraciiform.

ZHAO et al. (2011) present a design of a cow-nosed ray and a finite element analysis is developed to obtain a structural optimization. At this paper is presented the swimming number (S_w), commonly used to evaluate the performance of the designed robotic fish. Parameswaran and Selvin (2011) describes a complete ostraciiform robotic fish platform composed by servomotors, battery, microcontroller, sensors and aa internal pump system used to control the deep of swimming. Some ideas presented at this paper were used at the carangiform fish robot described at this paper. The main characteristic is the mechanical solution to attach the servomotors to each link. Chowdhury et al. (2011) present an open loop control of a carangiform fish robot. The robot was designed using CAD construction in Solidworks and 3D motion simulations in MATLAB VRML. The kinematic study was performed and the simulation results were presented. Some design tool presented at this paper also were used at the design developed at IFSP.

YU et al. (2004) studied a four-link biomimetic robotic fish like the one presented at this work. At that research a radio-controlled oscillating foil was built and the swimming speed was adjusted according the modulation applied to the joints. The kinematics related to the motion control task was developed using a PID algorithm and a hybrid control strategy. The undulatory motion presented at this work was used as one of the propulsion kinematic solution for the prototype adopted at this work. The same researchers developed several other works at the following years using the same structure (YU et al. 2005, 2007, 2008, 2011). At these other works some advances were introduced, like pectoral fins, improvements at hydrodynamic models, experimental validation of the proposed models, maneuver issues analysis

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of the multilink biomimetic robotic fish. Other recent works concern about the dynamic propulsion and maneuvering problem. WEN et al.(2012) proposes an experimental approach very similar to that studied at this paper. At that work, thrust efficiency was analysed and a energy optimum set of operation points was determined for propulsion kinematic control.

WANG et al. (2011) developed a dynamic model for a carangiform fish and analysed several individual effects of tail beat bias, frequency, amplitude on the attack angle. XU and NIU (2011) presented a Lagrangian formulation to obtain the dynamics of the fish model considering kinematics constraints of an anguilliform robotic fish, that consists of N links and N−1 joints, and the driving forces are the torques applied to the joints.

2. DESIGN DESCRIPTION

At the present work a four-link biomimetic fish with a carangiform structure named *Tucuazul I* (Fig. 1) was designed and built. Several experimental essays were developed at a water tank where the propulsion forces and maneuver issues analysis were performed through the use of a test facility. The forces generated along the tests, when the robot fish movement was generated were measured through the use of a set of strain gauge sensors attached to a vertical bar.

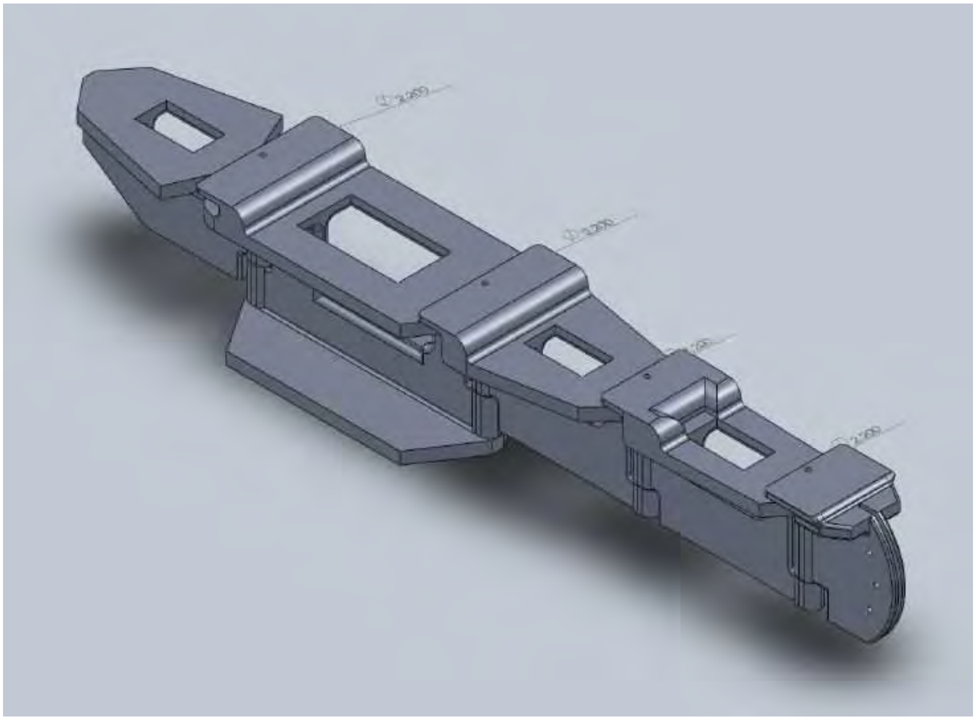

Figure 1. CAD Design of *Tucuazul I*

The present development is part of a long term project that have as its principal aim to obtain a complete autonomous carangiform fish robot. At this moment the system have several parts developed, like its mechanical structure, the servomotor control system, the kinematic control system designed to obtain the straight propulsion force and the maneuverable structure with sensors disposed to measure the propulsion forces.

The test facility used to analyze the forces produced by the robot fish gait are measured through the use of a strain gauge based system. At Fig. 2 it is presented a lateral view of the system. The strain gauge attached to the vertical bar was chosen to measure the propulsion force and the torsion force. These forces are measured through the use of a full bridge structure and the voltage generated was measured directly at the acquisition board. To use the facility it was necessary to proceed with a calibration procedure. After that the graphs generated could be adjusted to present the data in International System unit.

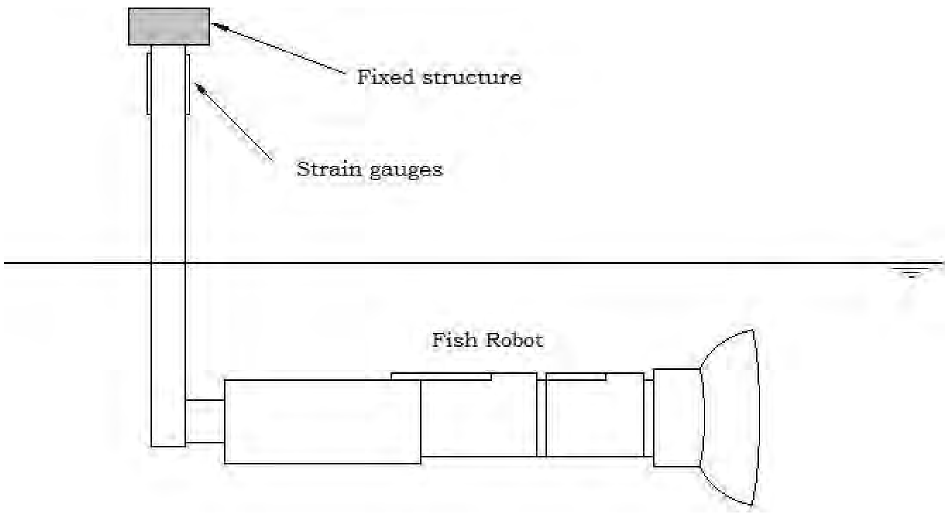

Figure 2. Test facility to study propulsion forces of *Tucuazul I*

Several tests may be done with this facility. Some of that are presented at this paper. One question to be solved is about the relation between the frequency of the movement and the propulsion force. Other parameters are also important to obtain a better propulsion force, like the amplitude of the tail movement or the number of links used to build it. At Fi. 3 is presented a picture of the strain gauges at the bar and the acquisition board used to measure the forces.

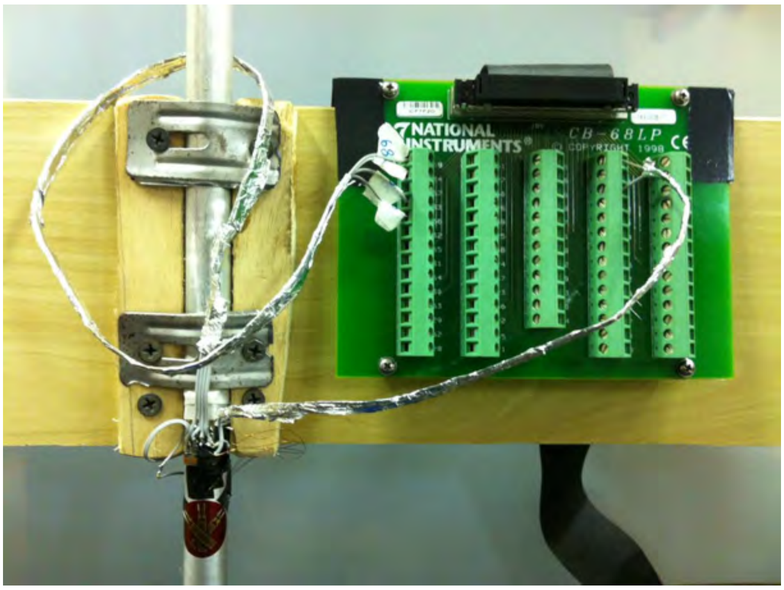

Figure 4. Acquisition board and strain gages at the bar (left)

3. STUDY OF ROBOT FISH KINEMATICS

According to Sfakiotakis (1999) the fishes that use their own bodies to swim (under body and/or caudal fin - BCF) can be classified into four different modes of locomotion: anguilliform, subcarangiform, carangiform and thunniform, as show in the Fig. 5. The subject of this study is the carangiform type, this one moves only its posterior half body.

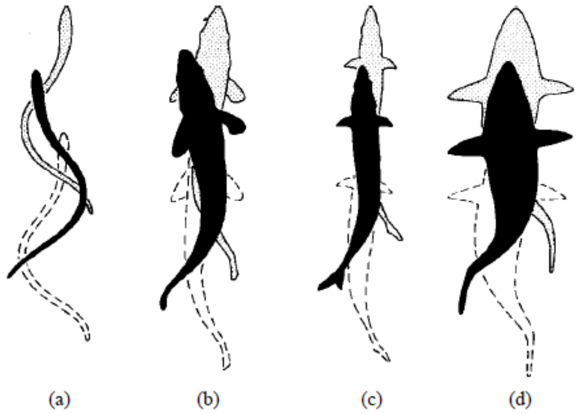

Figure 5. Fish classification due the locomotion mode. (a) Anguiliform, (b) subcarangiform, (c) carangiform and (d) thunniform. (Sfakiotakis, 1999)

3.1 Mathematical model simulations

The Eq. (1) is the mathematical model which represents the thrust motion of a carangiform fish (Barret, 1996).

$$y_{body}(x,t) = (c_1 x + c_2 x^2)[sin(kx + \omega t)] \tag{1}$$

It is a sinusoidal function which amplitude is modulated by a quadratic function, where y_{body} is the position in the transverse axis of the posterior portion, according to the position x in the main axis and a certain time t (Fig. 6). The parameters c_1 and c_2 might be adjusted due to the amplitude of the tail motion. The parameter k is responsible for the number of tail waves, ω is related with the rear motion speed.

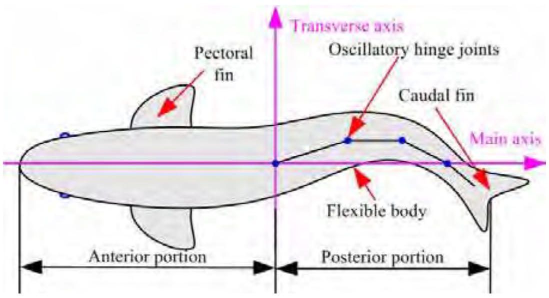

Figure 6. Tail positioning. (Yu, 2005)

To obtain the joint position at any time along the movement of the robot fish it was developed a MATLAB program that used the mathematics model of swimming fish kinematics described by Eq. 1. Using this result it is possible to calculate the angle associated to each servomotor attached to each joint. These position calculations have some parameters associated, like the length of each link. At Fig. 7 is presented the resultant function obtained through Eq. 1 with a superposed set of links that represent the position of each link and joint of the robot fish tail.

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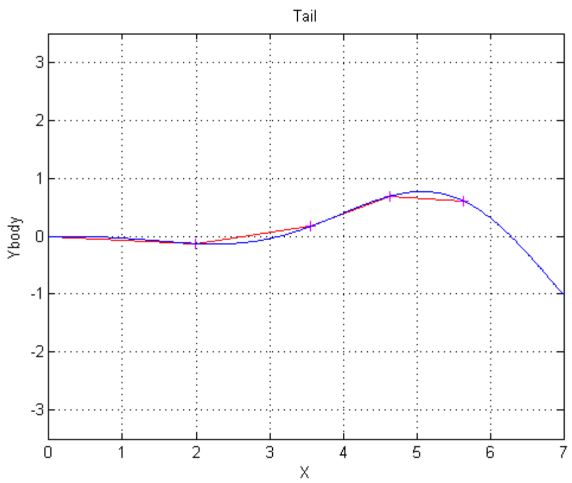

Figure 7. Positioning of the joints.

At Fig. 8 is presented the angle of each joint along the propulsion movement described by Eq. 1. It is possible to see that the curves may be approximated by trigonometric functions. Each function have its own amplitude and phase, but all the functions have the same frequency. It is also possible to observe that how far from the head of the robot is the link, greater is it amplitude. At this joint of the robot tail the form of the curve is not a pure senoidal function and it have harmonics associated.

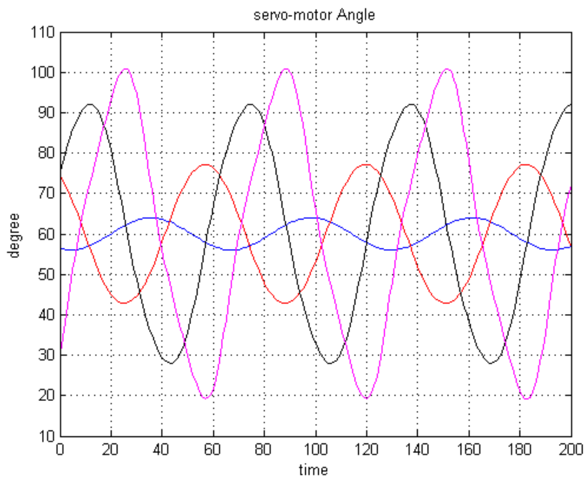

Figure 8. Angle of each link.

3.2 Turning methods

The function of Eq. 1 represents a fish's straight swim motion. For the fish robot be able to turn, it was added a variable v_c with a 3.5 exponent (Eq. 2), at this way, if v_c is other than zero, the sinusoid will oscillate around a curve.

$$y_{body}(x,t) = (c_1 x + c_2 x^2)[sin(kx + \omega t)] + v_c^{3.5} \quad (2)$$

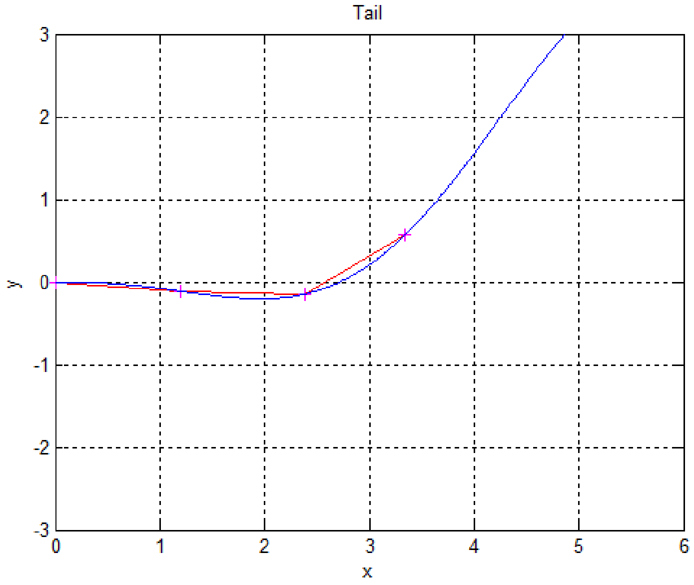

Figure 9. Joints position for a $v_c > 0$.

The Fig. 5 shows the joints position for a v_c greater than zero, in this case the fish will turn clockwise, for counter-clockwise turning, v_c must be less than zero.

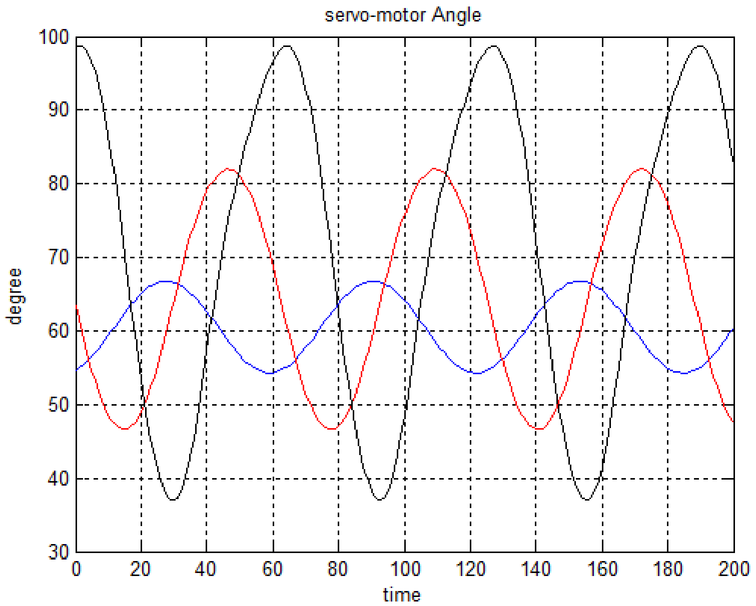

Figure 1. Servo-motor angles for a turning motion.

It is observable through the Fig. 6 that the curves still keep the features of a trigonometric function, however the last servo-motors are not oscillating around 60° anymore, the more they are far from the body, more far from 60° they oscillate.

4. EXPERIMENTAL RESULTS

Applying the kinematic solution presented above at different frequencies it was observed that the root mean square of the propulsion force is bigger at higher frequencies. This was the expected result since the higher propulsion velocity of carangiform fishes are observed when there is a high frequency at the tail movement. At the frequency of 1,2Hz it was observed a total propulsion force of 41,9 gf. (Table 1)

At a frequency of 0.6 Hz it was observed that the propulsion force decrease to 16 gf. At the same frequency, but using greater amplitude of motion of the tail, it was observed a propulsion force of 25.6 gf

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Table 1. Summary of experimental results obtained varying frequency and amplitude and analyzing the propulsion force.

Frequency (HZ)	Amplitude Multiply Factor	Propulsion (gf)
0.6	1	16
1,2	1,1	41,9
0,8	1,1	23,5
0,6	1,1	22,2
0,6	1,3	25,4
0,6	1,2	20,1

The experimental facility is presented at Fig. 7. It is possible to see the servomotors, the links and the bar where there was a set of strain gauge sensors.

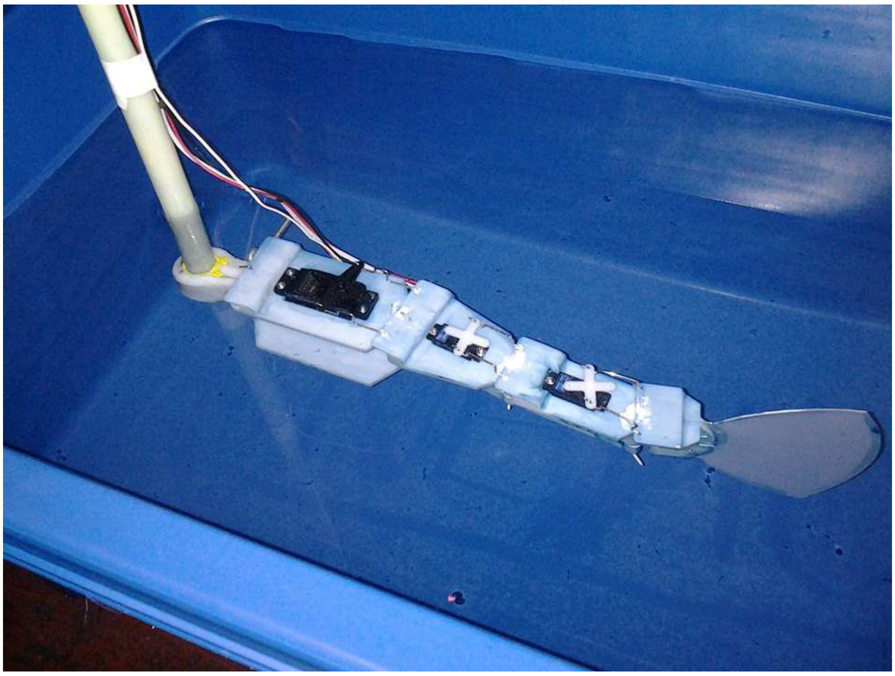

Figure 5. Tucuzul I attached to the vertical bar.

5. CONCLUSIONS

The system proposed to study the propulsion forces was useful to measure and evaluate the relationship between the propulsion force and the frequency and amplitude of the tail movement. The facility may also be used to analyze the torsion force and other parameters of this kind of design. In future works some results relative to this characteristics will be tested and analyzed.

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