Design of a bioinspired ray robot with flexible fins

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ABSTRACT

This paper presents the design and construction of a biomimetic swimming robot inspired by the locomotion of rays. These fishes move by flapping their pectoral fins and creating a wave that moves in the opposite direction to the direction of motion, pushing the water back and giving the fish a propulsive force due to momentum conservation. The robot's fins are molded from silicone rubber and moved by a servo motor that drives a mechanism inside the leading edge of each fin. The traveling wave, mimicking the movement of the fin, is passively generated by the flexibility of the rubber itself. The robot is also equipped with a tail that acts as a rudder, helpful in performing maneuvers. The rigid central body of the robot is the housing for motors, electronics, and batteries.

Keywords: Bioinspired robot, Swimming, Batoid fishes, Cownose Ray, Flexible fins

1. INTRODUCTION

One field in which nature outperforms current technology is fish swimming because its efficiency, maneuverability, and noise are far better than typical propellers. These advantages are mainly due to the propulsion mechanism, making thrust generation possible with small energy dissipation. Nowadays, the interest in autonomous underwater vehicles is in constant increase following the emerging needs of underwater exploration and environmental monitoring.[1]

Mantas and rays, which belong to the order of batoid fishes, propel themselves by flapping their large pectoral fins with a movement featured by a wave traveling from the fish's head to its tail that pushes water backward so that the fish gains thrust as a consequence of momentum conservation.[2,3] This kind of locomotion can be classified as oscillatory if less than a half-wave is present on the fin or undulatory otherwise. Oscillatory locomotion is typical of fishes swimming at high speed in pelagic environments, whereas undulatory swimming is distinctive of small species which live in closed environments and need great maneuverability.[4]

Batoid fishes have inspired the design of several underwater robots,[1] and some of them are briefly described in the following paragraph.

The robot object of this paper takes inspiration from the cownose ray, which has a diamond-shaped body, and large triangular fins, which perform a complex movement composed of two waves traveling along the fin in two different directions: a longitudinal wave responsible for thrust generation, and a lateral wave generated by the flexibility of the fin. The challenge of mimicking the flapping movement of the manta ray's pectoral fin has been solved in different ways, with different complexity and accuracy.

A solution applied in some robots is to have the fin moved by three independent ribs. Each rib is actuated by a mechanism that performs the desired movement to replicate the fin curvature, while the phase gap between each rib movement creates the wave along the traveling direction. This kind of solution has been applied in the biomimetic robots developed by Chi et al.,[5] and by Cai et al.[6]

A simpler solution to achieving the movement of the fin is the one adopted for the robots developed by Ma et al.,[7] by Zhang et al.,[8] and by Festo.[9] They have only two motors for each fin: one controls the upside-down flapping movement, while the other drives the twisting rotation of the fin. The combination of these two movements replicates the wave propagation along the fin for an oscillatory swimming strategy, which is featured by a small

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wavenumber.
Finally, the simplest possible solution is to control each fin with just one actuator, achieving a traveling wave exploiting the passive deformation of the fin. A robot using this principle has been developed by Cai et al.;[10] the fins of the robot are made of a thin membrane of silicone rubber with a rigid leading edge made of fiberboard. Another robot of this kind has been developed by Chew et al.[11] This robot's fins are PVC films with uniform thickness attached to the robot base only at the leading edge, where they are connected to servomotors. Conversely, the fin root is not connected to the central body, and it is free to oscillate.

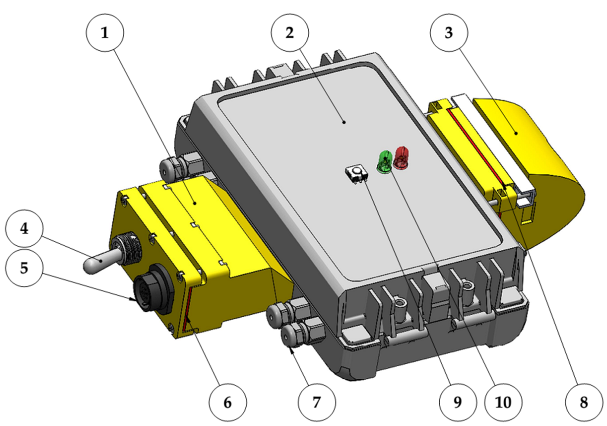
The robot object of this research belongs to this last category, having very flexible fins actuated by a single servomotor and passively generating a traveling wave.

2. MECHANICAL DESIGN

The design of the robot is independent of the design of the fins, as each pectoral fin is moved by one servomotor placed in the front part of the robot, and the motor shaft is accessible to make it easy to change the fins. This design allows using the robot as a test bench for experiments on the efficiency of different fins in future research. Furthermore, the robot is equipped with two caudal fins, whose role is to control the pitch rotation of the robot, guaranteeing stability during the flapping of the pectoral fins. The caudal fins are actuated independently by two servomotors.
The robot is neutrally buoyant, as its mass is balanced by adding or removing ballasts.

2.1 Central body

The robot's core is room for all the electronic components, so it is entirely waterproof. It is composed of a central waterproof box, with attached two 3D-printed extensions. In the rear part are placed the power switch and a connector that allows charging the battery and communicating with the microcontroller via USB. The front extension contains the camera, and it is the only part of the core visible when the robot is assembled. Finally, a button and two LEDs are on the top of the box to monitor the robot state. The robot's core is shown in Figure 1.

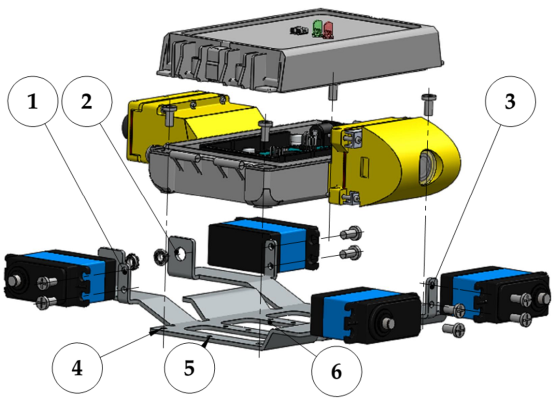


1	Rear extension
2	Central box
3	Front extension
4	Power switch
5	Connector
6	Rear gasket
7	IP68 Cable gland
8	Front Gasket
9	Button
10	LEDs

Figure 1: Robot's core

The central box is a waterproof box made of ABS plastic, and its dimensions have been selected to contain the Arduino Due as fit as possible. The chassis is formed by a 2mm thick aluminum sheet, appropriately cut and bent. A series of threaded holes allows the mounting of the other components on it. The two flaps, centered with respect to the symmetry axis of the chassis, offer support to the front and rear extensions of the core. They preserve the gluing of the extensions and prevent water leakage inside the core. Four other flaps, two in the front and two in the back, are designed to mount the motors. They create the necessary offset to align the motors to the robot's horizontal plane of symmetry. Each motor lies on the flat part and is fixed to the additional thin

flap with two screws. Two more vertical flaps with a hole are present in the rear part, where the bearings of the caudal fins are mounted.
The robot's components assembled on the chassis are presented in Figure 2.



1	Rear motor mounting holes
2	Caudal fin bearings holes
3	Front motor mounting holes
4	Central box mounting holes
5	Cover mounting holes
6	Extra holes for ballast

Figure 2: Robot's assembly without fins

The external part of the robot influences both the appearance of the robot and its interaction with the fluid. The cownose ray's body can be well approximated by an airfoil profile, and following the profile analysis by Cai et al.,[6] a NACA 0020 profile has been adopted for the robot's central body. This profile remains constant for the whole robot width.

The airfoil profile is divided into two parts: the cover, fixed to the central box, and the caudal fins, that can move. The rigid structure that forms the cover is composed of two symmetric shells that can be removed by sliding them sideways. The caudal fins' geometry follows the end of the NACA 0020 profile, and they can rotate up to 20° upward and 75° downward, as they are limited by the interference between the fin and the shell.

2.2 Fins

The fin's profile is taken from literature, and it has been obtained by overlapping some reference points on the image of a real cownose ray's fin.[10] The cross-section of the fin is taken from literature too,[12] and a biomimetic profile has been selected, which generates up to 80% thrust more than an airfoil profile. This biomimetic profile appears thicker in the initial and middle section of the fin, near the leading edge, while becomes thinner in the rear part, arriving at the trailing edge almost flat. By combining the external contour and the cross-section, it is possible to obtain the external surface of the fin shown in Figure 3.

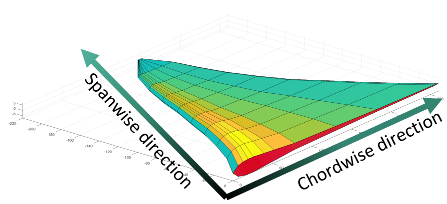


Figure 3: External surface of the fin

The fin is made of silicone rubber, and the leading edge is made stiffer by adding a stick mounted on the motor bracket. Two different rigid sticks have been designed and tested: one made of aluminum and another made of aluminum and PVC.

The thrust is generated by the interaction between the flexible fins and the fluid, which would be extremely complex to simulate since it would require the coupled use of Computational Fluid Dynamics (CFD) with Finite

Element Analysis (FEA). Therefore, a simplified approach has been used to understand if the designed fins deform in the desired way when moved in the water. The followed approach is based on the existence of a constant ratio between the natural frequencies of a body in the water and the natural frequencies in empty space[13] called Λ and defined as:

$$\Lambda = \frac{frequency\ of\ mode\ in\ water}{frequency\ of\ mode}. \tag{1}$$

Under the hypothesis of undamped motion, the natural frequency can be written as:

$$f = \frac{1}{2\pi}\sqrt{\frac{k_m}{m_m}}, \tag{2}$$

where k_m and m_m are the modal stiffness and modal mass of the considered vibration mode. Since the stiffness of the fin does not change, substituting Equation 2 into Equation 3, the frequency reduction ratio can be expressed as:

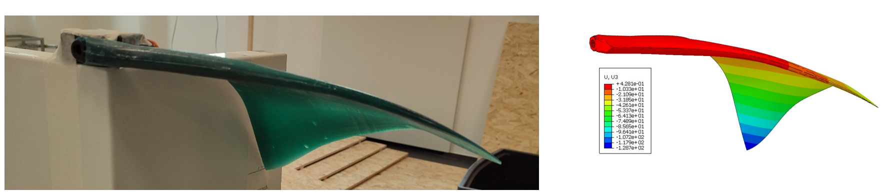
$$\Lambda = \sqrt{\frac{m_m}{m_m + m_w}}, \tag{3}$$

where m_w is the added mass of water that contributes to the vibration mode increasing the inertia force acting on the fin. This ratio is shown to be variable with the frequency mode: it is around 0.6 for the fundamental and tends to 1 as the harmonic number increase, whereas the mode shapes inside and outside water are quite similar.[13]

Hence, it is possible to study the vibration modes of the fin without water and then calculate the natural frequencies of these modes in water using this reduction ratio Λ.
The study of vibration modes has been carried out using the FEA software Abaqus, and the geometries of the fin, the sticks, and the bracket are imported from the CAD model. The bracket has been considered a rigid body because its deformability is negligible with respect to the other parts.
The density of the used silicone rubber is 1170 kg/m^3, and it is straightforward to measure, as the volume of the fin is known from the CAD. Conversely, in order to measure the Young modulus E, a deflection measure of the fin under the gravity load has been carried out, and the results have been compared with an FEA simulation.
A first guess of the Young modulus is obtained from the shore hardness using the following empirical relationship:[14]

$$S = 100\ \text{erf}\left(3.186\ 10^{-4}\sqrt{E}\right) \tag{4}$$

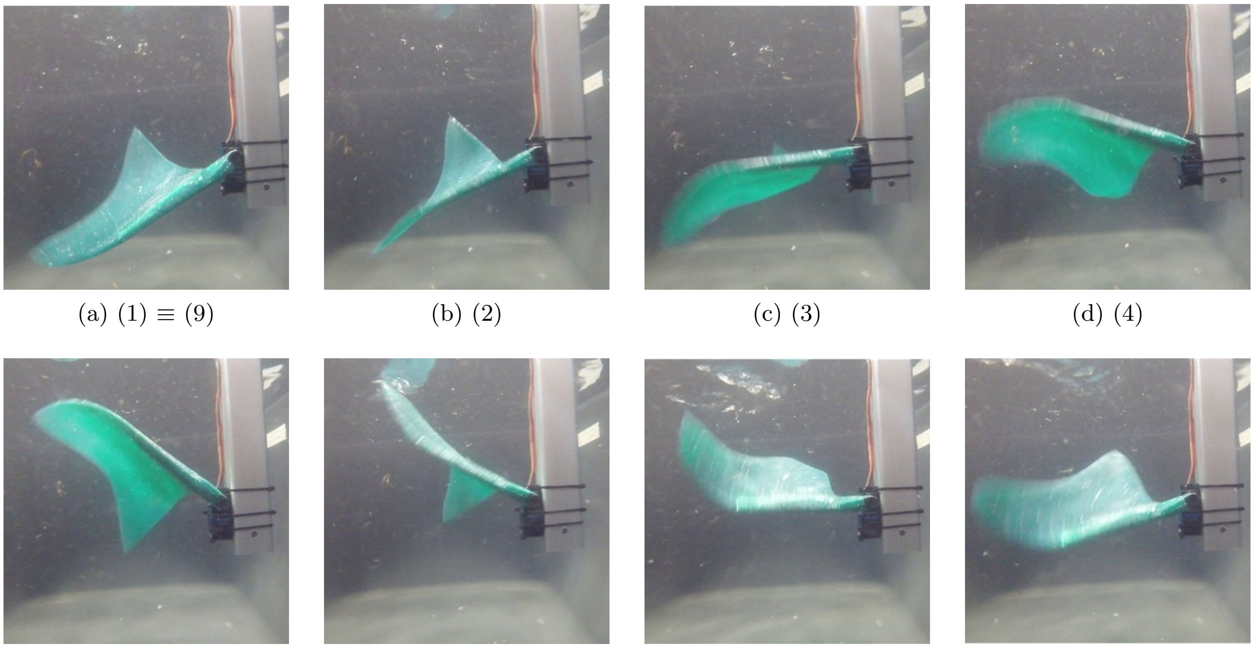
Having a shore hardness of 45, on the scale A, the resulting Young modulus E is 1.76 MPa. The comparison between the experimental and numerical fin deflections is shown in Figure 4, where it is possible to appreciate that the difference between the two is negligible, as the experimental deflection is 123.7mm, whereas the simulated deflection is 128.7mm. This means that the stiffness of the fin can be computed using the Young modulus $E = 1.76$MPa. The natural frequency of the first mode of the fin, resulting from the FEM analysis, is 1.35 Hz.



(a) Experimental (b) Numerical

Figure 4: Comparison between experimental and numerically computed fin deflections

The underwater behavior of the fin is observed in a small tank, and an aluminum structure holds the fin and the motor inside the tank. The motor performs a sinusoidal movement of 45°, and, in Figure 5, the corresponding movement of the fin is shown.



(a) (1) ≡ (9) (b) (2) (c) (3) (d) (4)

(e) (5) (f) (6) (g) (7) (h) (8)

Figure 5: Underwater movement of the fin

At the end of the leading edge, the fin tip deforms similarly compared to the biological reference. The movement of the fin moves the water backward generating a perceivable thrust force on the aluminum structure. The fin also has some limitations that could be considered for improving it in a future design. The tip of the fin trailing edge does not contribute to thrust generation. It can be observed in frame (2) that it remains up when the stick moves upward and vice versa in the frame (6). In the following frames (3) and (7), the movement of the stick inverts the deformation of the fin base, and, when the stick is steady in the peak position (5) and (9), the tip is again on counter phase. This behavior is caused by the low stiffness of the fin base. The fin does not have enough elastic potential energy to move the water and recover its shape, so it deforms passively under the effect of water resistance. The fin can be improved by increasing the stiffness of the base to move more water and generate more thrust.

2.3 Robot construction

The cover, the caudal fins and the core extensions of the robot are realized by 3D printing, whereas the aluminum structure of the chassis is obtained by laser cutting an aluminum layer 2mm thick. The manufacturing of the fins is performed by casting them in a mold, which is realized by 3D printing, and is composed of two parts with a cavity for the sticks. The assembled robot is shown in Figure 6.

Figure 6: Assembled robot

3. ROBOT COMPONENTS

The electronic board of the robot is Arduino Due, which is featured by high computational power and a large number of input and output pins while remaining economical and simple to program, and the electronic circuit of the robot includes:

- **4 servomotors**: two motors move the pectoral fins, and other two are employed to move the tail. The selected motors are the *TD-8320MG*, which are the smallest available waterproof servomotors. They provide a torque of 2.011Nm when powered at 6V.
- **Battery**: the power source of the robot are two NiMh batteries connected in series. These batteries are suitable for this application because of their small dimensions and their flat shape. Their nominal voltage is 3.7V and their capacity is about 2000 mAh.
- **Inertial Measurement Unit (IMU)**: the IMU is needed to know the position of the robot in 3D space. The chosen module is the GY-MPU9250 , which comprises a 3-axis MEMS gyroscope, a 3-axis MEMS accelerometer and a 3-axis MEMS magnetometer.
- **Camera**: the camera module, at this stage of the prototype, has no role in the control of the swimming maneuvers. Its only scope is recording images from the point of view of the robot. For this reason, the module OV7670 was chosen, which is compatible with Arduino.
- **SD card module**: it is needed to store navigation data since it is impossible to communicate wireless underwater.
- **Wi-Fi module**: the wireless connection is provided by the ESP8266-01 module, programmed with the esp-link firmware, which creates a web server with several features, included a serial console from which is possible to control the Arduino.
- **Ammeter**: The presence of the ammeter is useful to monitor the current delivered by the battery during the testing phase, to control the correct functioning of the batteries and to evaluate the power consumed by the robot.

4. CONCLUSION

The research work presented in this paper describes the design and the manufacturing of a working prototype of a bioinspired underwater vehicle, inspired by the cownose ray, which swims with great efficiency and maneuverability. The main innovative feature of this robot is that it generates thrust thanks to the passive deformation of the fins, which are very flexible as they are made of silicone rubber. This solution is characterized by a high energy efficiency because the desired deformed shape of the fin is passively obtained thanks to the interaction with the surrounding water. Moreover, employing only one servomotor for each fin makes the movement of the

robot simple to control.
The primary purpose of this robot is to assess the capability of flexible fins to generate thrust, and the whole design of the prototype is oriented to assist this function. The robot's main body has limited dimensions to be easy to handle and test in a small swimming pool. The external shape is an airfoil profile to minimize water resistance during swimming. The fins are easy to change, thanks to the accessible motors.
The future developments of this research involve the control of the robot movements and the fin design. The first step to control the robot is to program the caudal fins' movement to stabilize the flapping oscillations. Later, a trajectory following strategy could be developed. This last control could take advantage of the studies on fin thrust generation for a feedforward trajectory generation. The fin design can be both analytical and experimental. The finite element model introduced in this research will be refined and validated by experiments to exploit it for an analytical optimization of fin design. Simultaneously, a test bench for measuring the thrust generated by different fins could be a practical way to analyze how the different parameters of the fin shape influence their performance.

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