Biomimetic design of an underwater robot inspired to the cownose ray

Giovanni Bianchi
Dipartimento di meccanica
Politecnico di Milano
Milano, Italy
giovanni.bianchi@polimi.it

Simone Cinquemani
Dipartimento di meccanica
Politecnico di Milano
Milano, Italy
simone.cinquemani@polimi.it

***Abstract*—This paper shows the design of an underwater autonomous robot. The challenges of this activity are mainly linked to motion design and to energy efficiency. Therefore, a bioinspired approach has been used. Batoid fishes swim moving their pectoral fins, they produce a wave travelling in the direction opposite to their motion, pushing water backwards and gaining thrust as a consequence of momentum conservation. The motion of the fin has been studied and reproduced with a series of articulated mechanisms. In this work the optimization of the mechanism's geometry is described and the experimental results on the reconstructed fin are presented.**

***Index Terms*—Bioinspired, robot, fish, manta, swimming**

I. Introduction

The design of autonomous underwater vehicles (AUV) is one of the most promising fields of application of bioinspired engineering. AUVs can be employed for environmental monitoring, search and rescue or marine life observation, tasks that require great endurance and high maneuverability [1]. Batoid fishes, i.e. stingrays and mantas, swim by moving their large pectoral fins and generate a force by producing a travelling wave that pushes water in a direction opposite to their motion. This kind of locomotion can be identified as undulatory, if more than half wave is present on the fin, or oscillatory otherwise. Undulatory swimming is characteristic of small species which need great maneuverability, whereas oscillatory swimming is distinctive of fish swimming at high speed [2]. The cownose ray (*Rhinoptera Bonasus*) is a median size fish which combines these capabilities, therefore it is taken as source of inspiration for the development of a robot mimicking its locomotion. There are already projects that study the design of different robots inspired by this marine species. [3]–[7] What essentially makes the design of the robot presented in this paper different is the choice of the motors actuating the fin: they have a continuous rotation of 360° at constant speed.

II. Mechanical design

The mechanisms actuating the fins have been designed aiming at accurately reproducing the fin deformation, which is responsible for thrust generation. Since the number of waves per body length is about 0.4, a wave propagation can be obtained with just three mechanisms for each fin. They are positioned near the head, in the center and near the tail, and each of them is actuated independently by a servomotor. The kinematics of the mechanisms is designed minimizing the distance between the position of the mechanism and the correspondent fin section for every instant of the periodic oscillation. The deformed configuration of the fin has been derived from the observation of biologists. [8]

The optimization method used to define the length of the links minimizes the residual area resulting from the superposition of the ideal target curve, obtained from the cownose ray locomotion, and the actual curve, drawn by the control points, as shown in Fig. 1. The transformation of a continuous rotation of the motor into an alternate rotation of the first link has been obtained with a four-bar linkage, whose kinematic synthesis has been carried out with an analogous optimization process. All the parts composing the mechanism have been obtained by 3D printing. The tail is composed of two parts actuated by two servomotors and it acts as a rudder to correct pitching rotation during maneuvers.

The shape of the fin is obtained through the reconstruction of a curve that follows the real fish profile [9]. The cownose ray's pectoral fin can be approximated to a series of air-foil shapes with gradient changes from mid-body to the fin tip. The largest profile is used for the central body of the robot and it contains the main components such as motors, supports and all the electronic components. It is rigid and made with additive

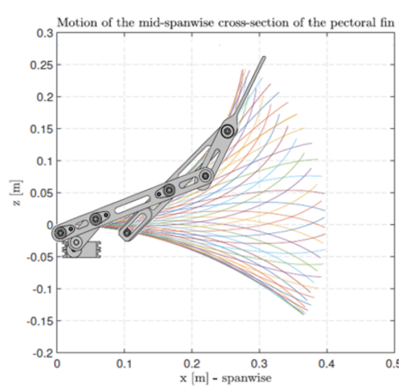

Fig. 1. Superimposition of the central section of the cownose ray fin and the mechanism of the bioinspired robot

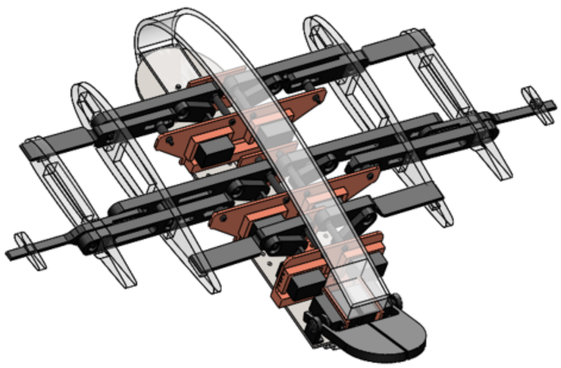

Fig. 2. CAD assembly of the robot without the external coating

manufacturing technology. Conversely, the air-foil profiles in the mid-span and at the tip are manufactured using liquid silicone and 3D printed molds, so that they are flexible and they maintain their shape despite the phase shift between the three mechanisms. The final assembly is presented in figure 2.

The external coating is obtained with two plastic sheets, welded together along the contour. A photo of the robot with its coating is presented in Fig. 3. The robot is $600\,\mathrm{mm}$ long and measures $1200\,\mathrm{mm}$ from fin tip to fin tip.

A. Motor sizing

The dynamics of this system is studied simulating its motion using SimMechanics. The hydrodynamic forces are taken from a CFD analysis. This last provides the pressure distribution on the surface in contact with the fluid, over a period of fin flapping during forward swimming with constant velocity at $1\,\mathrm{m\,s^{-1}}$. The surface of the fin is divided into smaller regions, and the forces and moment acting on each of them are obtained and used to compute torque and power required to motors.

III. Actuation and control of the fins

The motors actuating each mechanism of the fins are Feetech FR5311M-360FB Continuous Rotation motor, they are servomotors capable of 360° rotation, with a position feedback and they are controlled in velocity. The robot is equipped with an MPU-6050 3-axis accelerometer and gyroscope and it can communicate with a Bluetooth module HC-05. The controller is an Arduino Due board, and the system is powered by a 2-cell Li-Po battery.
The actual phase difference between motors is measured and the error is corrected with a PI control logic which accelerates the mechanism in delay and slows the mechanism in advance. During forward swimming the wave travels in the same direction in both fins, so they generate an equal forward thrust; whereas, if the wave travels in opposite direction in each fin, they generate equal and opposite forces, creating a torque and making the robot turn. The control logic used for turns is the same as for forward motion, but the reference is calculated reversing the sign of the phase shift on one of the two fins.

Fig. 3. Bioinspired robot

IV. Conclusion

The development of a bioinspired swimming robot has been presented from the conceptual design to simulation and control. Through optimization of the kinematics the fin deformation has been reproduced and the capability of motors to actuate the mechanisms in the desired fashion has been verified with a multibody simulation. The control algorithms for the principal gaits of the fin have been implemented and tested. The obtained results in the experimental tests are encouraging and they are preliminary to the development of a fully autonomous robot, which could be used to investigate the advantages of batoid fish locomotion.

References

[1] R. Salazar, V. Fuentes, and A. Abdelkefi, "Classification of biological and bioinspired aquatic systems: A review," *Ocean Engineering*, vol. 148, pp. 75–114, 2018.

[2] L. Rosemberger, "Pectoral fin locomotion in batoid fishes: Undulation versus oscillation," *The Journal of Experimental Biology*, vol. 204, pp. 379–394, 2001.

[3] J. Gao, S. Bi, Y. Xu, and C. Liu, "Development and design of a robotic manta ray featuring flexible pectoral fins," in *Proceedings of the 2007 IEEE International Conference on Robotics and Biomimetics*, 2007, pp. 519–523.

[4] C. Niu, L. Zhang, S. Bi, and Y. Cai, "Development and depth control of a robotic fish mimicking cownose ray," in *Proceedings of the 2012 IEEE International Conference on Robotics and Biomimetics*, 2012, pp. 814–818.

[5] Y. Cai, S. Bi, L. Zhang, and J. Gao, "Design of a robotic fish propelled by oscillating flexible pectoral foils," in *The 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2009, pp. 2138–2142.

[6] W. Chi and K. Low, "Review and fin structure design for robotic manta ray (roman iv)," *Journal of Robotics and Mechatronics*, vol. 24, no. 4, pp. 621–628, 2012.

[7] Y. Cai, S. Bi, G. Li, H. Hildre, and H. Zhang, "From natural complexity to biomimetic simplification. the realization of bionic fish inspired by the cownose ray," *IEEE Robotics & Automation Magazine*, 2018.

[8] R. Russo, S. Blemker, F. Fish, and H. Bart-Smith, "Biomechanical model of batoid (skates and rays) pectoral fins predicts the influence of skeletal structure on fin kinematics: implications for bio-inspired design," *Bioinspiration & Biomimetics*, vol. 10, 2015.

[9] Y. Cai, S. Bi, and L. Zhang, "Design and implication of a bionic pectoral fin imitating cow-nosed ray," in *The 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2010, pp. 3525–3529.