Design of a swimming snake robot

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ABSTRACT

This paper presents the design and realization of a bioinspired snake robot that can move on the water surface. This robot mimics the locomotion strategies of anguilliform fishes such as eels and lampreys, which have a thin, long, cylindrical body and whose movement resembles the crawling of a snake. An autonomous underwater vehicle with such a shape can pass through narrow crevices and reach places inaccessible to other swimming robots. Moreover, this locomotion entails a high energy efficiency and outstanding agility in maneuvers. The body of the bioinspired robot consists of a modular structure in which each module contains a battery, the electronic board, and a servo motor that drives the following module. The head of the robot has a different shape as it contains a camera and an ultrasonic sensor used to detect obstacles. In addition to the design of the robot, this paper also describes the implementation of the kinematic model.

Keywords: Bioinspired robot, Snake robot, Aquatic snake, Modular robot

1. INTRODUCTION

The locomotion of snakes has inspired researchers and engineers for decades because they can move on unstructured terrains and reach places inaccessible to other vehicles thanks to their elongated shape. Snakes exhibit different locomotion strategies, and some of them can also swim.

Their swimming strategy is similar to anguilliform locomotion, characteristic of eels and lampreys and other aquatic animals with long, slender, and highly flexible bodies. Their movement is undulatory, as they generate on their body a wave that propagates from the head to the tail, and thrust is generated because the surrounding water is pushed backward by this kind of motion. A wavelength shorter than the body length ensures that all lateral forces are always balanced, but it also implies that the wave propagation velocity is small. Thus, these animals swim rather slowly, not exceeding 0.3m/s. Nevertheless, several migratory animals, like many species of eels, adopt this type of locomotion, suggesting that its energy efficiency must be high to allow such a long endurance. Furthermore, these animals are extremely agile, being capable of turning with a small curvature and even swimming backward.[1]

The flexibility of their body is due to the high number of vertebrae (> 100), and it can be reproduced in bioinspired robots using a modular structure of actuators and joints, similar to the structure of crawling snake robots. An example of a robot of this kind is Amphibot. It is a modular robot in which every module is a box containing an actuator for the neighboring module. This robot is inspired by aquatic snakes, and it floats on the water surface. Its swimming velocity is comparable to a human's, and it can perform rapid and agile maneuvers. Moreover, it is an amphibious robot as it can also crawl on land, exploiting the same principles as terrestrial snake robots.[2] A similar robot is the Mamba, whose modules contain two actuators so that the robot can perform 3D movements. In addition, this robot is equipped with force contact sensors, making it able to measure environment contact forces, useful to perform complex underwater operations.[3] Another amphibious robot of this kind is Snakey, designed for surface swimming. The motion strategy of this robot is inspired by the sidewinding of snakes, and it is powered and controlled through a cable.[4]

This work aims to develop a swimming snake robot that moves on the water surface, exploiting the advantages of snake locomotion. This robot is modular, and each module is actuated with a servomotor. The head module is different from the others because it also contains a camera and an ultrasonic sensor for obstacle detection. The paper is organized as follows: in section 2, the mechanical design of the robot is described; in section 3, the kinematic model is presented; and, finally, section 5 is dedicated to the conclusion.

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2. MECHANICAL DESIGN

The robot's body is made of eight identical rigid modules and a larger module for its head so that the robot has in total 8 DOFs, accurately approximating the serpentine curve. The robot is modular, and other identical modules can be added to increase its length. All the elements are connected by a rotational joint actuated by a servomotor. The dimensions of each body module are 140 mm x 56.5mm x 97 mm, whereas those of the head module are 190mm x 78 mm x 116mm; thus, the total length of the robot is 1.310m. The density of the robot is lower than the water density so that it floats on the water surface, with half of its body submerged. The robot is covered with a welded polyethylene cylinder which makes it waterproof.

2.1 Head module

The head module hosts all the sensors needed to inspect the environment and the electronics used to communicate with the user. Hence, it is larger than the other modules, and it is equipped with more computational power. The head module does not contain any motor, and it is moved by the motor present in the first module of the snake's body. In Figure 1 it is possible to see an exploded view of the CAD model of the head module.

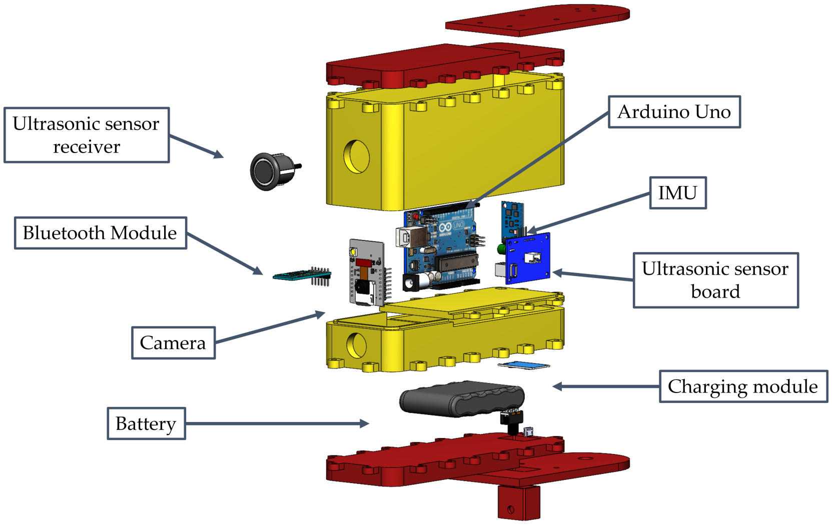


Figure 1: Robot's head

The components of the head module are:

- **Electronic board**: The electronic board used for the head module is Arduino Uno, which elaborates the inputs given by the user and the measurements of the sensors and communicates to the other modules with an I^2C protocol all the data required to generate the swimming pattern.
- **Bluetooth module**: The HM-05 Bluetooth module transmits data to the user.
- **Inertial Measurement Unit**: The IMU used in this project is the IMU-9250, which includes a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis magnetometer.
- **Ultrasonic sensor**: By using an ultrasonic sensor, the robot is capable of detecting the distance of an obstacle by observing the time an echo of the emitted signal takes to return to the sensor itself. The ultrasonic sensor JSN-S4RT is waterproof, and its range of operation is from 20cm to 70cm.
- **Camera**: The camera of the snake robot is OV7670. The visual feedback provided by the camera is sent to the external user with Bluetooth, making it possible to remote control the robot.

- **Battery**: The battery is NiMH with 5 cells providing 6V and with a capacity of 2000 mAh.
- **Voltage regulator**: A voltage regulator is necessary to avoid damage to the battery while recharging it.

All the components are stored inside a 3D-printed ABS box.

2.2 Body modules

The body modules are responsible for generating the traveling wave that propels the robot forward. They are actuated, as each of them contains a servomotor which moves the preceding module. They follow the commands received from the head module.

An exploded view of the CAD model of the body modules is shown in Figure 2.

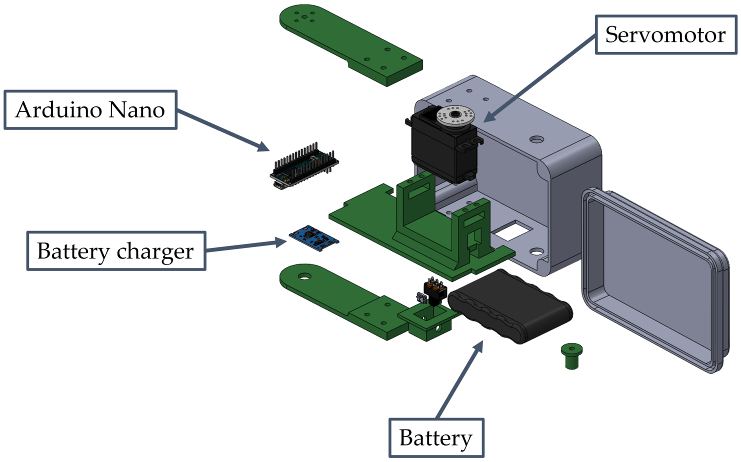


Figure 2: Robot's module

The components of the head module are:

- **Electronic board**: The electronic board used for the head module is Arduino Nano which receives the commands from the head modules and performs feedback control of the servomotor position.
- **Servomotor**: The used servomotors are continuous rotation FeeTech FB5311M-360 motors. They are equipped with an in-built encoder; hence, they provide position feedback, which allows implementing control on the angular position. Their maximum angular speed is 50 rpm, and their stall torque is 1.5 Nm.
- **Battery**: The battery is the same as for the head module, a NiMH with 5 cells providing 6V and with a capacity of 2000 mAh.
- **Voltage regulator**: As for the head module, a voltage regulator is necessary to avoid damage to the battery while recharging it.

The box containing all the components is an IP68 standard box.

The assembly of the robot can be seen in Figure 3. Each module is mounted flipped with respect to the previous to increase the maximum turning angle, which is equal to ±60°.

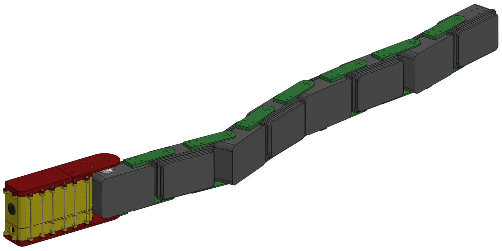
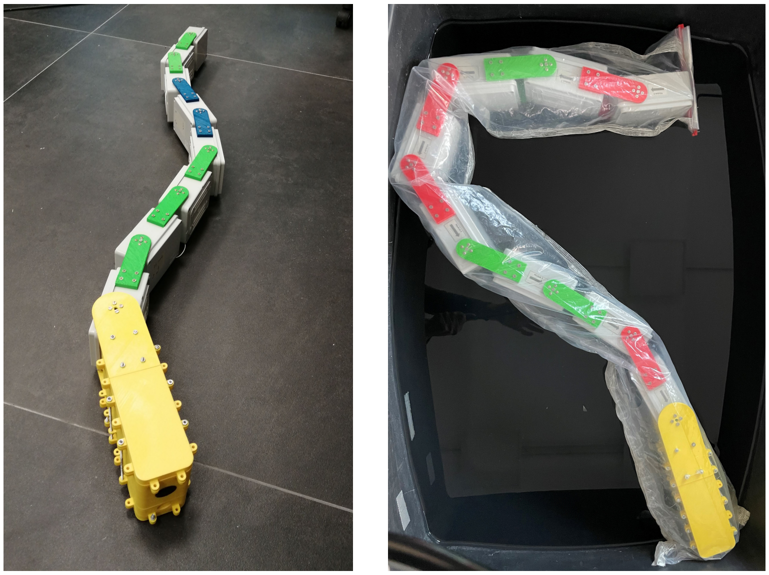


Figure 3: Snake robot CAD model

The robot has been assembled, and, in Figure 4, it is shown on the ground and inside a water tank.



(a) Snake robot on the ground (b) Snake robot in a water tank

Figure 4: Assembled snake robot

3. ROBOT KINEMATICS

The control algorithm aims to recreate the swimming gait for straight motion and turning maneuvers.

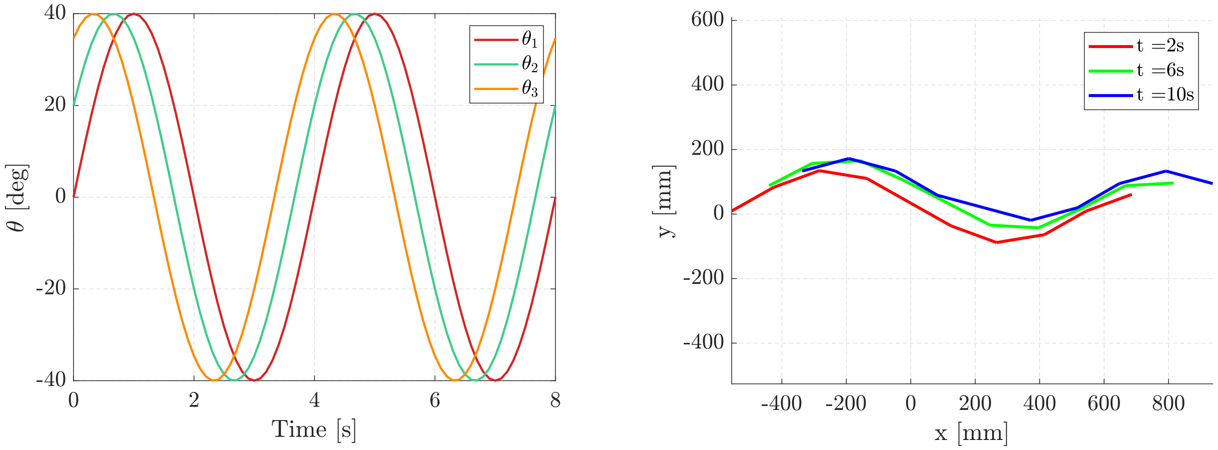
3.1 Straight swimming

Two different swimming strategies have been implemented to achieve forward swimming: lateral undulation and anguilliform motion.

Lateral undulation is also known as serpentine movement, it is inspired by snake's movements and it is the most used gait in both terrestrial and underwater snake robots.[5] This gait consists in passing a traveling wave along the body of the robot, which is obtained by actuating the links with a sinusoidal motion with a constant phase delay:

$$\theta_n = A \sin(n\phi - \omega t) \tag{1}$$

where A represents the amplitude of the movement, n is the link's number, and ϕ is the phase shift between each module and the previous one. Changing the sign of ϕ makes it possible to reverse the traveling wave direction and swim backward. In Figure 5a the relative angles of each link are presented, and, in Figure 5b, successive instants of lateral undulation of the snake robot are shown.



(a) Angles between links
(b) Snake robot during lateral undulation

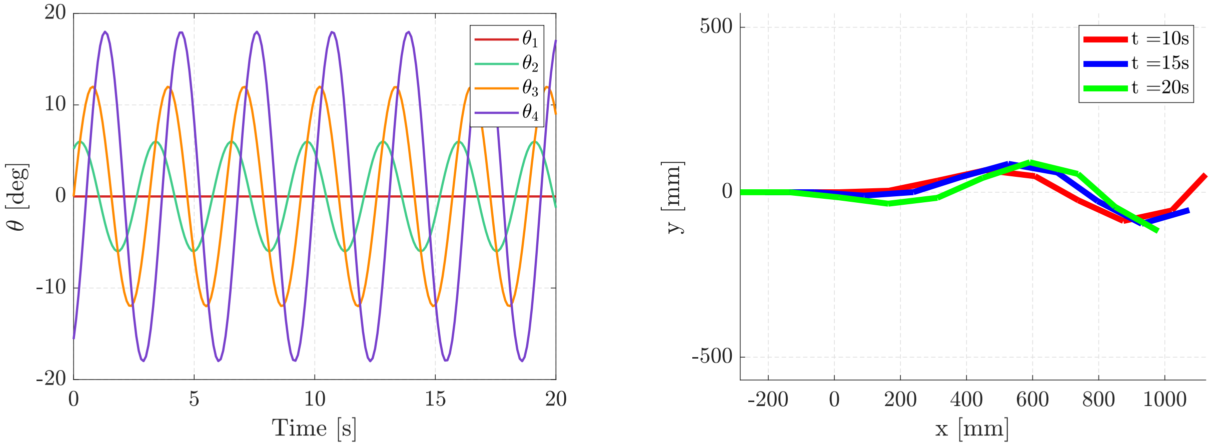
Figure 5: Lateral undulation

The position of each segment of the robot can be expressed as a function of the curvilinear abscissa as:[5]

$$\begin{cases} x(s) = \displaystyle\int_0^s \cos\left(\arccos\left(b\sigma\right) + c\sigma\right) \mathrm{d}\sigma \\ y(s) = \displaystyle\int_0^s \sin\left(\arccos\left(b\sigma\right) + c\sigma\right) \mathrm{d}\sigma \end{cases} \tag{2}$$

Anguilliform motion is similar to lateral undulation; the only difference is that the snake robot keeps its head oriented in the same direction, while in lateral undulation, the head is moved along with the body as any other module. Anguilliform motion can be achieved by increasing the oscillation amplitude starting from the head. Therefore, Equation 1 is modified as shown in the Equation 3.[6]

$$\theta_n = A\frac{N-n}{N+1}\sin\left(n\phi - \omega t\right) \tag{3}$$



(a) Angles between links
(b) Snake robot during lateral undulation

Figure 6: Anguilliform motion

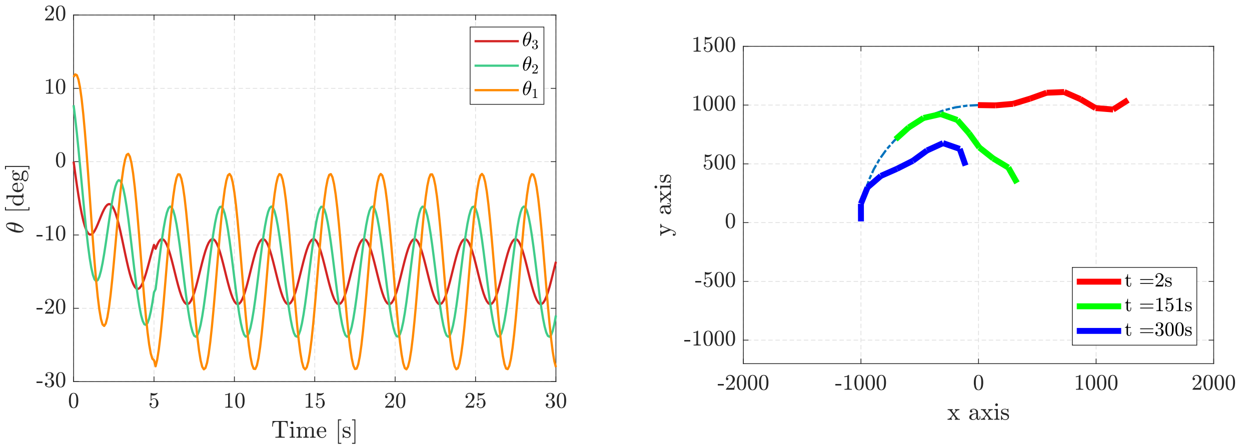
The term $A\frac{N-n}{N+1}$ corresponds to an increasing amplitude from the first joint in the head to the last joint in the tail, and the other quantities are the same as for lateral undulation. In Figure 6a the relative angles of each link are presented, and, in Figure 6b, successive instants of anguilliform motion of the snake robot are shown.

3.2 Turning

The method used to turn the robot is straightforward as it consists of just adding an offset angle to all the joints, as expressed in Equation 4.[5] This technique works for both lateral undulation and anguilliform motion, and here just the results for anguilliform motion are reported.

$$\theta_n = A\frac{N-n}{N+1}\sin\left(n\phi - \omega t\right) + \theta_{offset} \tag{4}$$

The angle θ_{offset} is constant during the whole turning maneuver, and it is set back to zero when the turn has been completed.[5] In Figure 7a the joints angles are shown during a turning maneuver for anguilliform locomotion, and successive instants of the maneuver are plotted in Figure 7b.



(a) Angles between links

(b) Snake robot during turning

Figure 7: Turning maneuver for anguilliform locomotion

It is possible to note that the joint angles are analogous to the angles of straight motion, but there is a constant offset.

4. CONCLUSION

In conclusion, an aquatic modular snake robot has been designed and built. The robot's body is composed of 8 identical modules, which are all actuated, and a head module. The head module hosts a camera and an ultrasonic sensor useful for navigation in the presence of obstacles. The electronic board inside the head generates the motion laws of each joint, and it communicates it to the boards of each module, which are devoted only to the feedback control of the servomotor position.

Finally, a kinematic model for different locomotion strategies has been developed for forward swimming and turning maneuvers.

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