

Design and implementation of a snake-like robot with biomimetic 2-D gaits

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ABSTRACT

For the purposes of field explorations and rescues, this research designed and implemented a simple snake-like robot that can move in narrow space and various terrains. The frame of the robot was constructed by modular segments. Each segment consisted interlocked rings, connecting rods and servo-motors that enabled the robot to bend and oscillate the body and imitate the 2-D gaits of snakes. We used Motoduino module, Bluetooth, servo-motors and wireless micro-camera to activate the robot. In order to cut down the cost, the robot's skeleton and mechanical components were designed by 3-D printing using PLA material. The weight of the robot is about 960g and the size is 79cm×14cm×9cm. The maximum speed and the radius of gyration are about 16cm/sec and 21cm, respectively.

Keywords: Biomimetic robot, Modular robot, Snake robot, and Motoduino.

1. INTRODUCTION

Snake-like robots are always applied to special environments like narrow spaces, uneven terrains or rubbles. Therefore, many snake-like robots are designed to be thin, serpentine, and flexible. The real snakes bend their bodies sideways and use friction to generate propulsion force. In order to imitate the gaits of snakes, various designs and implementations of snake robots were studied. Li et al. (2020) proposed the double-body car-snake hybrid transformable robot that can be switched between car-shaped and snake-shaped modes to adapt its posture to meet the requirements of environments. Many snake robots were designed as modular assemblies. If active wheels or crawlers are attached to the modules, each module can be operated like a trailer (Tanaka and Tanaka, 2015; Tanaka and Matsuno, 2014) (<https://technews.tw/>). The locomotions of each modular segment can be controlled individually and the robot can be drove from head-segment to tail-segment. In order to enable the robot to climb smooth obstacles and handle versatile motions, Singh et al. (2018) made the modular segment to be spherical shape. Some studies focused to make the robot be able to execute various gaits, like rolling, climbing on a pole, lateral undulation sidewinding, or crawling as caterpillars (Dalu and Dalu, 2019). The snake robot presented by Xue et al. (2020) was additionally attached a gripper on its head to enhance the robot's functions. Shi et al. (2016) designed a planar modular snake robot that was attached with passive wheels at the bottom of modular segments. Each modular parts of the planar snake robot were connected with servo actuation joints, and this structure can generate the imitation of serpentine locomotions. Additionally, several papers investigated the elastic material used to develop the snake robots. Snake-like and soft-bodied robots (Ta et al., 2018; Qin et al., 2018) made from soft material or mixed materials of different friction-coefficients, presented great adaptability to the environments. Some snake robots were also applied to special scenarios, like inspecting in pipelines (Selvarajan et al., 2019) or exploring underwater (Huang et al., 2019). Kamegawa et al. (2004) and Tanaka and Matsuno, (2014) designed the snake robots that can move on one plane to the other, raise the robot's

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head, or move in 3-D environments well.

Based on previous research we can observe that in order to imitate the serpentine gaits of snakes, many snake robots were developed by modular segments. The modular parts can be controlled individually or interlocked to each other. The advantages of modular structures are that can increase the degree of freedoms and also make repairs easy. However, to design a feasible modular structure should integrate versatile technologies and the mechanical design is complex usually. When 3-D gaits or trajectory-tracking are considered, the mathematical analysis of motion control will become very complicated, too. Therefore, in this paper, we designed a simple mechanical structure for modular segments. Each segment was constructed with 4 PLA rings. These PLA rings were connected serially by brads or latches, and drove by connecting rods and servo-motors easily. The servo-motors embedded in the robot's backbone were used to curve the body and generate a little extra propulsion. The head-segment of the robot was attached with 4 active wheels that was the major source of propulsion. Bluetooth module and wireless camera enabled the robot to be controlled remotely and feedback the instant images of environments. In this research, we paid attention to implement a snake-like robot that can execute fundamental tasks of explorations and perform 2-D biomimetic locomotions. Trajectory-tracking and 3-D gaits were not investigated in this paper. This article is organized as follows- section 2, details the skeleton design of the robot. The robot's performance is described in section 3. Section 4 is the summary.

2. DESIGN AND IMPLEMENTATION OF THE SNAKE-LIKE ROBOT

2.1 Electrical Actuation

The electrical devices utilized in this snake-like robot included Motoduino module, Arduino function extended module, Bluetooth, servo-motors, wireless camera, LEDs, and lithium batteries. The items are listed in Table 1.

As the Bluetooth module received the instructions from mobile phones, Motoduino module sent the driving signals to the corresponding motors to activate the robot. Four

servo-motors were embedded inside the backbone of the robot to bend the body and generate the serpentine or curly gaits. The remaining servo-motors were attached with Mecanum wheels which offered the major propulsion for robot. Additionally, the wireless micro-camera mounted on the robot's head provided the instant monitoring of the environments. The feedback images were helpful to regulate the robot's routes.

Table 1. The electrical devices used in the proposed robot

Components	Part number	Pieces
Servo-motors	MG90S	8
Arduino module	Motoduino U1	1
Function module	S4A IO board	1
Bluetooth module	HC-06	1
Wireless micro-camera	Microcase-v8	1
LEDs	Red LEDs	2
Batteries	Lithium battery	3

2.2 Mechanical Structure

We used computer aided program to design the mechanical components. The most mechanical components like rings, latches, tenons, connecting rods, head and tails were produced by 3-D printing due to the considerations of costs and accessibility.

1. The Robot's Skeleton

The major skeleton of the snake-like robot was developed by modular segments. Each segment consisted 4 rings, one servo-motor and one connecting rod. As shown in Fig. 1(a), we designed the rings of 3 sizes that were marked as (A), (B) and (C). These rings can be incorporated each other by brads or latches.

The servo-motor was embedded in ring-A. The bear of motor was joined with a connecting rod (as shown in Fig. 1(b)) that was linked to the following second and third rings with a latch (as shown in Fig. 1(c)). Fig. 2(a) describes the structure of a servo-motor and a connecting rod fixed in the ring-A. Fig. 2(c) shows the structure of a segment that consisted of ring-A, ring-C and 2 rings-B. In order to differentiate the placements of 2 rings-B, ring-B was

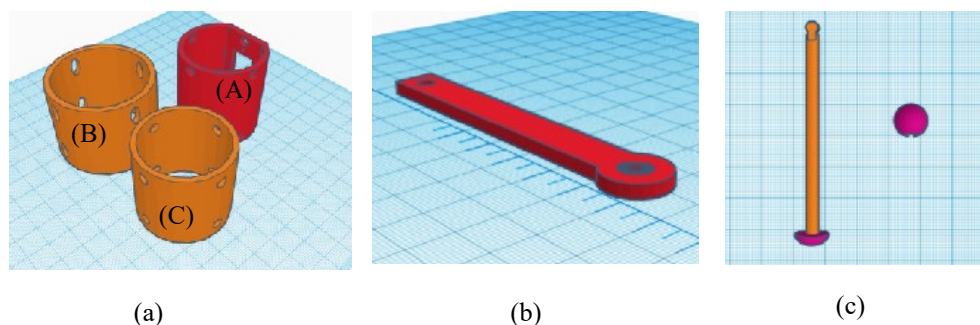


Fig. 1. 3-D models of (a) the rings of different sizes (b) connecting rod and (c) latch

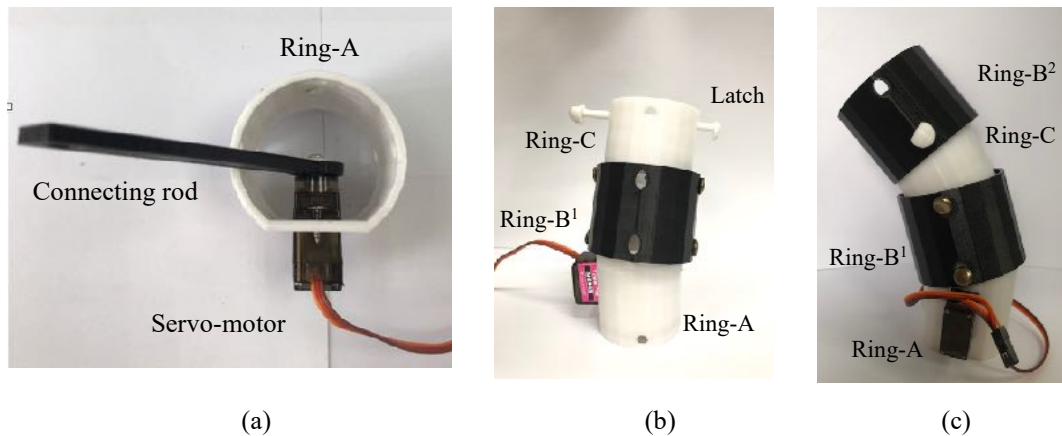


Fig. 2. (a) The motor embedded in ring-A and joined with a connecting rod (b) Assembly of the motor, rings-A-B¹-C, and latch (c) The structure of a segment

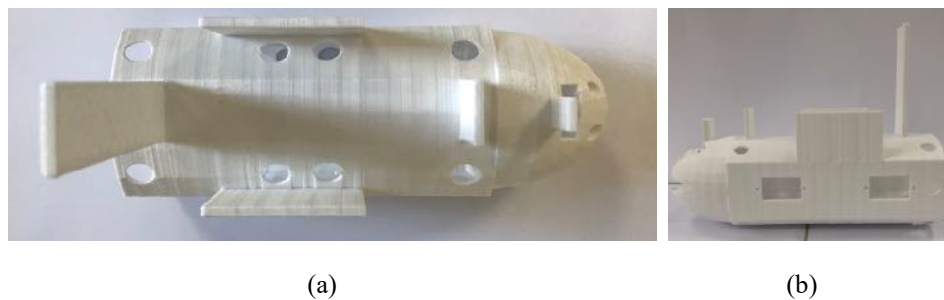


Fig. 3. The structure of the robot's head-segment in (a) top-view, and (b) side-view

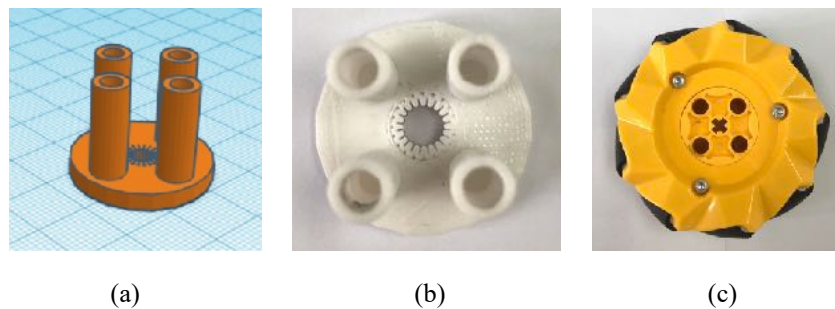


Fig. 4. (a) The 3-D model of tenon (b) The appearance of tenon (c) Mecanum wheels

marked with the superscripts of 1 or 2. In each segment, the rings were assembled in order of A-B¹-C-B². Rings-(A and B¹) and rings-(B¹ and C) were joined by brads (as shown in Fig. 2(b)), and rings-(C and B²) was joined by a latch.

The diameters of rings-B were larger than rings-A's and rings-C's diameters. Each ring was designed to have 8 holes on its side that were used to connect each other by brads or latches. Hence, the rings can be overlapped with each other but they were not close-fitting. When the motor rotated, the connecting rod associated with the rings-(C and B²) were swung flexibly. Then, the ring-A of the succeeding segment can be directly connected to the ring-B² of the previous segment, and so on for the next segments. There were totally 4 modular segments to develop the robot's body. When the

robot moves, the body of the robot can be stretched or contracted slightly. That makes the necessary radius of gyration decrease. It is an important characteristic when a robot moves in a restrict space.

2. Head-Segment and Tail-Segment

Fig. 3 shows the design of robot's head-segment. Four servo-motors used to drive wheels were embedded inside the head-segment. We also designed a tenon to firmly attach the bear of servo-motor to Mecanum wheels, as shown in Fig. 4. Bluetooth module, function module, lithium batteries, and micro-camera were also laid in the robot's head-segment.

The tail-segment of the robot was designed as a cone, and that was connected to the final segment through a ring-C.

All the mechanical components used in this robot are listed in Table 2.

2.3 Interface of Communications

We utilized Inventor 2 to make the APP interface. Users can remotely control the snake-like robot to move forward, turn left/right, turn around, or swing the body through the APP, as shown in Fig. 5.

Table 2. The mechanical components used in the snake-like robot

Components	Pieces
Rings of robot's body	17
Head-segment	1
Tail-segment	1
Latches	6
Tenons	4
Connecting rods	4
Mecanum wheels	4
Brads	24



Fig. 5. The communication interface in mobile phones

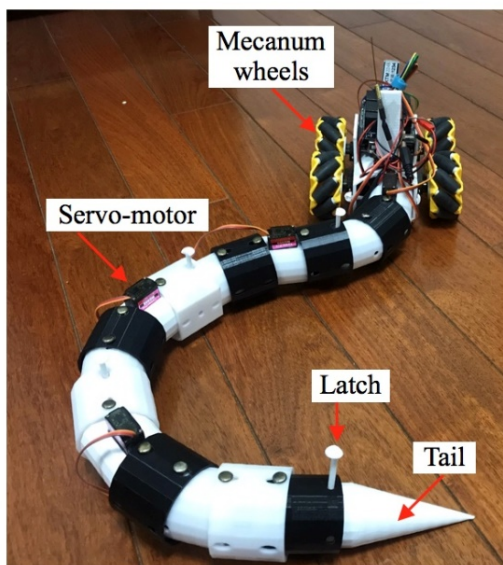


Fig. 6. The electrical devices and mechanical components used in the proposed robot

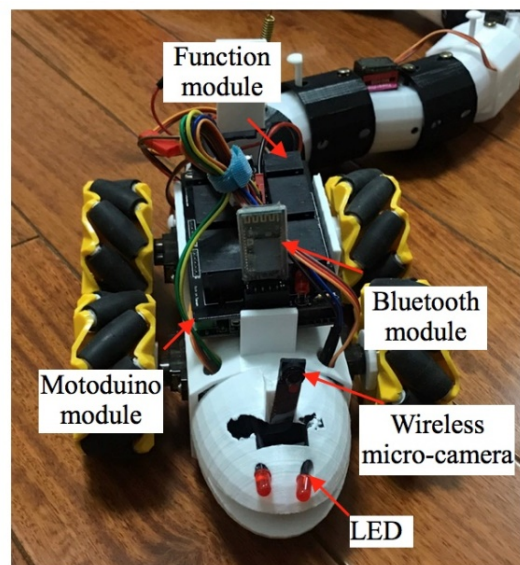
3. THE APPEARANCE AND LOCOMOTIONS OF THE SNAKE-LIKE ROBOT

Fig. 6 shows the electrical devices and mechanical components used in the proposed robot. The appearance of the snake-like robot and the placements of devices are presented in Fig. 7. Users can obtain the feedback images from the robot (as shown in Fig. 8) and accordingly modify the locomotions of robot. The radius of gyration is 21cm and the maximum speed is about 16cm/sec, respectively.

The specifications of the proposed robot are listed in Table 3. We also make the comparisons with the other two snake-like robots. Rollinson's robot was designed to imitate 3-D gaits of snakes. From Table 3, we can observe that the power used to drive the Rollinson's robot is much higher.



(a)



(b)

Fig. 7. (a) The rear-view and (b) the front-view of robot

Similar to our robot, the Zhu's robot was used to mimic 2-D gaits of snakes. The Zhu's robot was developed by the cabin-shape modules and wheels.

The proposed snake-like robot can adapt its gaits to various environments. Figs. 9-11 are the dynamic images of different locomotions and each image was recorded at 1-sec intervals. Fig. 9 represents the serpentine gaits and curved body when make the robot to turn. From 0s to 5s, the robot turned its head from the front to the rear, and the head was parallel to its body. Then, from 6s to 11s, the robot turned its head to the front again, and the body of the robot became s-shape. The gaits of moving forward is shown in Fig. 10.

Depends on the requirements of environment, the snake-like robot can be controlled to move with straight body or curved body. This snake-like robot can also imitate snakes to shift sideways. As shown in Fig. 11, the snake-like robot can translate its head to right or left, and also drive its body to shift. Additionally, we applied the robot to various terrains like asphalt road, bricks, or grass to observe the robot's locomotions under different situations (as shown in Fig. 12). We also put the robot into a pipeline to test if the robot can move in the narrow space well. As described in Fig. 13, the snake-like robot can move smoothly in the pipeline.

Table 3. The specifications compared with other snake-like robots

specifications	Rollinson et al. (2014)	Zhu et al. (2017)	The proposed robot
Dimensions	Diameter: 5.1 cm Full Length: 1.174 m Width: ** Height: **	Diameter: ** Full Length: 470 mm Width: 76 mm Height: 79 mm	Diameter: 5 cm Full Length: 790 mm Width: 140 mm Height: 90 mm
Mass	Full Robot: 3.657 kg	Full Robot: 1.6 kg	Full Robot: 0.96 kg
Actuator	Max Torque: 7 N-m Max Speed: 33 RPM	Working Voltage: 6.0V Stalling Torque: 14 kg-cm Max Speed: 0.17s/60degree	Working Voltage: 4.8V/6.0V Stalling Torque: 2kg-cm Max Speed: 0.1s/60degree
Power	48 V Current (resting): 40 mA Current (max): 600 mA	7.4V, 15C	Robot: 7.4V 1850mAh Camera: 3.7V 1850mAh
Communication	100 Mbps Ethernet	ZigBee Wireless Networking	Bluetooth
Sensing	Angular Position and Velocity Output Torque 3-axis Accelerometer 3-axis Gyro Temperature Voltage Current	3-axis Gyroscope 3-axis Accelerometer Temperature Vision	Wireless Micro-camera

** means the data is not given in the source papers



Fig. 8. The instant images feedback from the robot

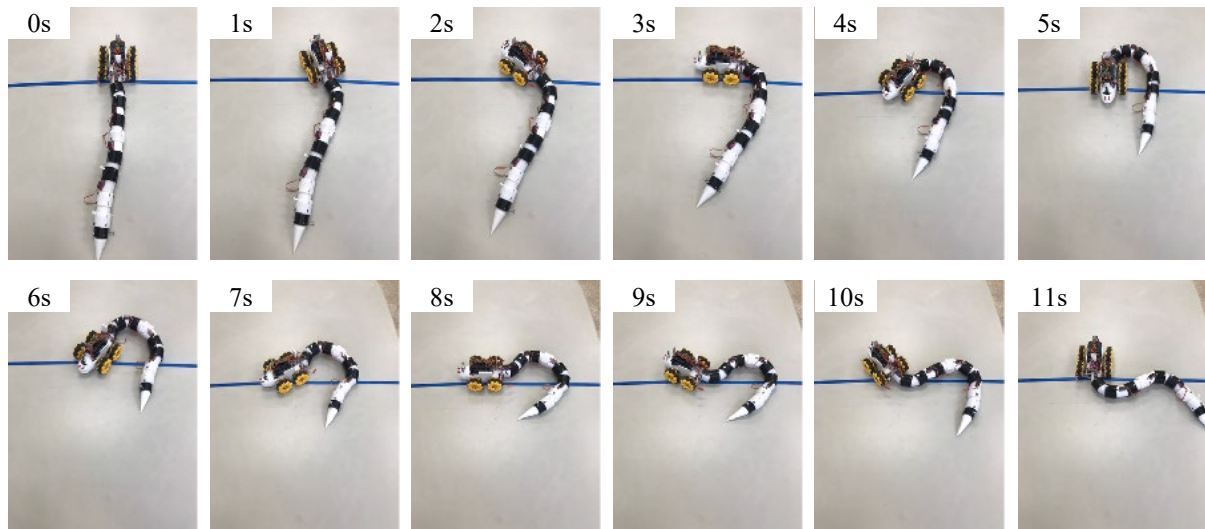


Fig. 9. The gaits of turning and twisting

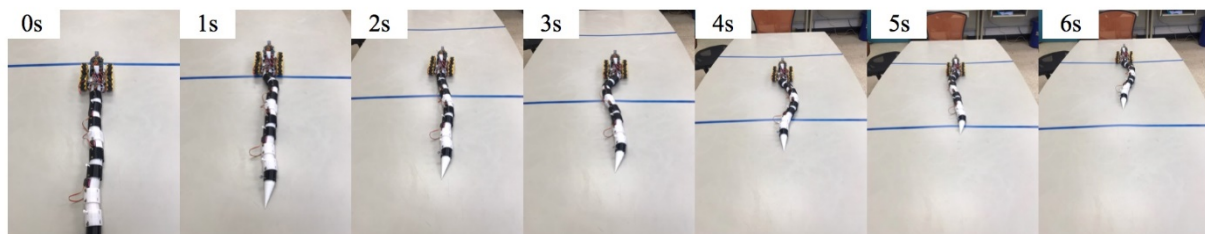


Fig. 10. The dynamic images of the gaits of moving forward

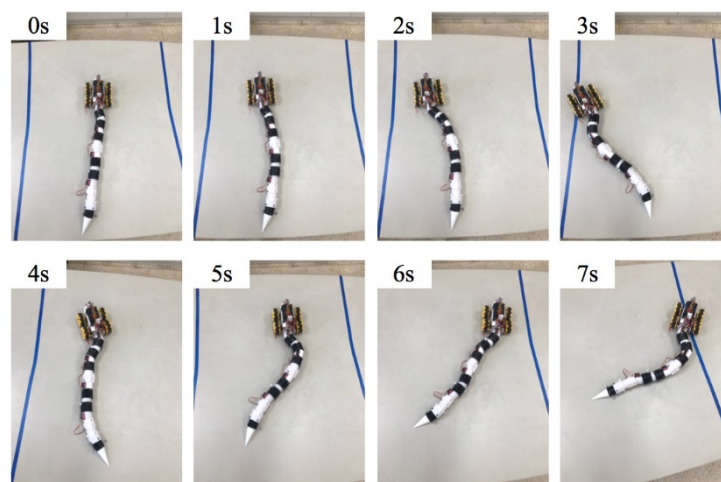


Fig. 11. The gaits of right-left shifting



Fig. 12. The robot's locomotions on various terrains. (left to right: asphalt roads, bricks, grass, and ramps < 30°)



Fig. 13. The snake-like robot moved in a pipeline

4. CONCLUSIONS

This research designed and implemented a snake-like robot with simple mechanical structures. The snake-like robot was constructed by modular segments and each segment can be controlled individually. We utilized 3-D printing to produce the mechanical components we need, and that also makes repairs easy and cut down the cost. This snake-like robot can adapt its gaits and can be applied to many different terrains and scenarios. As demonstrated in experiments, the snake-like robot can imitate the serpentine 2-D locomotions of real snakes, and can also move forward, twist, turn, and shift. The wireless camera mounted on the robot is much helpful for field explorations and observations. The demonstration film of the robot has been uploaded on web and one can watch the film with the URL: <https://www.youtube.com/watch?v=7OoGJBefMcE>.

There are some shortages in the proposed snake-like robot. In our preliminary motivations, this robot was designed for the purpose of low cost and easy implementation with fundamental functions. Therefore, as compare with another snake-like robot, the functionality of the proposed robot is relatively basic and no-frills. The next work is to incorporate more sensors into the robot to enhance its practicality.

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