A Screw-less Solution for Snake-like Robot Assembly and Sensor Integration

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***Abstract*— Assembly or repair of snake-like robots are often time consuming and low efficiency. This paper presents a novel approach for module improvement that can efficiently integrate sensors, micro-controllers and batteries into the snake-like robot, without needing of any tools. The implementation is built upon the GZ-I module—an open frame structure with only servo motor involved. Based on the sliding mechanism, an intermediate module accommodating two infrared sensors, one force sensor, one battery and one micro-controller, together with a terminal module used for mounting infrared sensor at each end of the snake-like robot is designed. Thus, screw-less assembling a snake-like robot can be achieved. In addition, a circuit board is developed for the micro-controller and peripherals connection. A master-slave software framework taking advantage of wireless communication capability of the micro-controller is implemented, enabling remote control/monitoring of the snake-like robot. Through a case study of sidewinding locomotion , the screw-less solution is proven to be applicable on the snake-like robot.**

***Index Terms*— Snake-like robot, screw-less connection, sliding mechanism, sensor integration.**

I. Introduction

Snake-like robots that inherit the features of biological snakes, including distributed body mass, low center of gravity and versatile locomotive patterns, have gained great attention for decades [1]. Their slim mechanism, with a redundant design in a modular manner, not only offers significant benefits in complex environments where traditional robots with appendages such as wheels or legs may fail to traverse, but also, guarantees the robustness of the robotic system—even for the failure of some of the actuators [2].

From the literature, the movement of snake-like robots depends on their configurations, as well as auxiliary equipment. There are three categories of snake-like locomotion, i.e., undulation using passive wheels [3], [4], self-propulsion with powered wheels/treads [5], [6], and pure body undulation [7]–[9]. Through these diverse of prototypes, it is evident that the design of snake-like robots evolutes towards more flexible motion mode, from planar movement to 3D gaits. A modular design in conjunction with a pitch-yaw configuration is found to be flexible enough to realize different gaits, including sidewinding, turning, rolling and rotating [8], [9].

Modularization, taking advantage of identical modules and its lower design cost, is a popular way used for designing snake-like robots. In general, a simple module consists of an actuator and a frame to hold it, producing $180°$ rotation in one degree of freedom (DOF) [7]–[11]. Higher DOF can also be achieved within one module at the expense of a more complicated structure with more components involved [12]. Depending on the control architecture, e.g., in a distributed implementation manner, a micro-controller may be integrated into the module for control purpose. Based on that, the module can further be equipped with on-board sensors, such as accelerometer, gyroscope and force/torque sensors, for a better perception of environment and sophisticated reaction [13], [14]. The module structure becomes complex with integration of multiple sensors. A tradeoff between module size and the number of sensors must be balanced, so as to achieve a compact design while possessing enough perceptual ability.

In order to assemble modules into a snake-like robot, screws, bolts and nuts are needed to secure the connection between modules. If there is no independent battery, wires must go through each module for power transmission. In addition, there will be more wires if communication between modules is taken into account. Therefore, assembly of a modularized snake-like robot requires extra tools and patience, and is not as easy as putting a plug into a socket. Similarly, replacing components for the snake-like robot is also tough. Nothing is more annoying than dissembling and reassembling any components for the robot. Some attempts have been made to ease the problem to some extent. For example, Krupke et al. use magnets for module connecting [15]. Although the method works, it is still not efficient enough to assemble a modularized snake-like robot, especially in terms of the wires, the screws and the sensors.

Our on-going project aims to develop a new snake-like modular robot that is simple to be reproduced via fast

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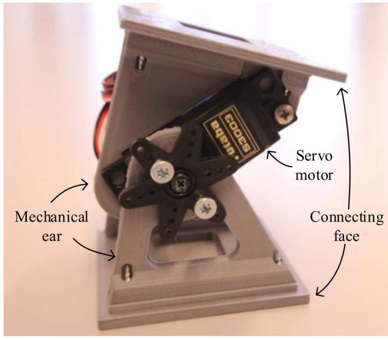


Fig. 1. 3D printed GZ-I module.

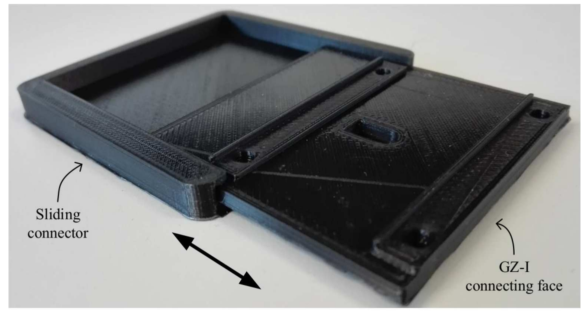


Fig. 2. 3D printed sliding connector.

TABLE I
SPECIFICATION OF INTEGRATED COMPONENTS IN ONE MODULE

Component	Size	Range	Number
Circuit board	58.4 × 44.5 × 20.0 mm	—	1
LiPo battery	45.0 × 34.5 × 6.2 mm	3.7V/2000mAh	1
Infrared sensor	29.5 × 13.0 × 13.5 mm	4∼30 cm	2∼3
Force sensor	16.0 × 40.0 × 0.4 mm	0.1∼10 kg	1

prototyping, and is easy to configure and add sensors. In this paper, we focus on developing a valid method to simplify the procedure of module connection and sensor integration. The contribution of the paper lies in two aspects. First, a screw-less solution is proposed that modules with such characteristics could be easily produced, put together and taken apart with a minimal number of tools. Second, a real snake-like robot has been implemented to verify the effectiveness of the proposed method.

The rest of the paper is organized as follows. Section II describes the system requirements of the snake-like robot. In Section III, 3D model design for an intermediate component and a terminal component based on a slide mechanism is presented in detail. Section IV introduces the hardware and the software realization. Experiment results are shown in Section V, which is followed by conclusion and future work.

II. DESIGN GOALS

Developing a snake-like robot from scratch or based on off-the-shelf modules is a trade-off that one must consider at the beginning. On the one hand, starting from the scratch will free the mind for mechanical design and enable the customization of all the components. The downside is time consuming. On the other hand, if the development is based on certain existing model, time used for module design can be reduced but constraints for further integration may raise later on.

In this project, we take the latter alternative, i.e. choosing an existing model as the basis and then expanding its function. The GZ-I module [8], which is an improved version of Y1 module designed by Gonzalez-Gomez et. al [10], features low-cost and simple structure and is thus considered a suitable choice for our project. Through 3D-printing, rapid prototyping of GZ-I is feasible, as shown in Fig. 1. The printed module is stiff enough to support the servo motor rotation and collision on the ground.

As the design goals, improvements will be made based on the GZ-I module towards:

1) easy to plug-in/out other modules;
2) easy to mount/dis-mount sensors;
3) as less wire connection as possible between modules.

Following the last item, GZ-I will be expanded to be equipped with an onboard battery, forming a self-powered module. Moreover, wireless device will be added on the module. Thus, no wires will be needed between the modules. A circuit board including the controller and peripheral connection is considered to add into the module. The initial attempt will also integrate two types of sensors, i.e., the infrared sensor and the force sensor for collision avoidance and gait stability analysis. Table I lists the specification of all the components that will be added onto the GZ-I module.

III. SCREW-LESS SOLUTION ON GZ-I MODULE

A. Sliding mechanism

Sliding doors have been used for centuries. They are often found at mall entrances, cars and elevators. The sliding mechanism is beneficial to save space, because there is almost no room required when opening the door. More importantly, the mechanism is secure, since the door cannot be lifted out of its track.

Inspired by this, a 3D printing connector is developed, as shown in Fig. 2. The sliding connector can be nested on the connecting face of GZ-I, and use the material's strength and flexibility to hold the part in place. Because the sliding direction and the rotating axis of the servo motor is perpendicular, the connector is prevented from sliding out of the GZ-I module. The same mechanism will be used for module connection and sensor integration, as seen in Section III-B.

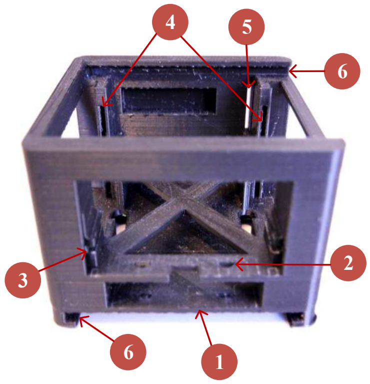
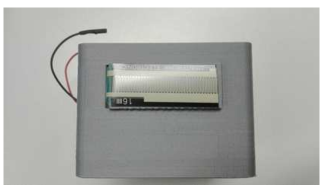
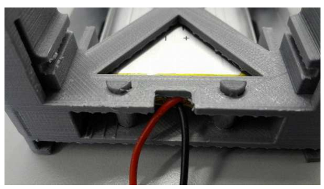


Fig. 3. Intermediate module. ① Battery housing; ② Battery holding hole; ③ Circuit board slot; ④ Infrared sensor slot; ⑤ Force sensor connection interface; ⑥ GZ-I sliding connector.



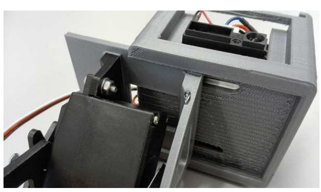
(a) Force sensor installation



(b) Battery installation

(c) Circuit board installation

(d) Infrared sensor installation



(e) GZ-I module connection

Fig. 4. Intermediate module assembly.

B. Intermediate module

Considering that the GZ-I module is an open frame structure, it is not wise to add the sensors and the battery on the module directly, as it violates its simple structure principle. Therefore, an intermediate module is proposed, taking the following aspects into account:

- battery housing;
- circuit board housing;
- sensor holding;
- GZ-I connecting.

The intermediate module is $66 \times 66 \times 49$ mm in size and can be printed as one fully part, as shown in Fig. 3. It is worth noting that the current version of the intermediate module only supports pitch-yaw connection of GZ-I modules, as depicted by ⑥ in Fig. 3.

Fig. 4a illustrates that the force sensor is glued on the back wall of the intermediate module, and its wire can go through ⑤ in Fig. 3 to connect to the controller. The battery box for the LiPo battery is designed in a way so that it could easily be inserted in and taken out. This is the only part of the intermediate module that does not directly uses the materials strength and flexibility to secure its position. Note that two holding pins are inserted into the two holding holes to fix the battery in its place, as seen in Fig. 4b. The circuit board can slide into the two horizontal slots on the left and right side of the faces until it touches the back face, as shown in Fig. 4c. The infrared sensors use the same principle to secure themselves. Vertical slots are designed so that the parts of the infrared sensor that are normally used to put a bolt through, can slide into the slots, as illustrated in Fig. 4d. In Fig. 4e, the sliding mechanism to secure the intermediate with the GZ-I module is presented. Notice that since the rotating axis of the GZ-I module and the sliding direction are orthogonal, the gravity will prevent the module from sliding out.

C. Terminal module

The terminal module is special designed for mounting sensors such as infrared sensors and cameras at each ends, enabling the snake-like robot to perceive along its body length direction. For current prototype development, only infrared sensors are considered to be added on the terminal module.

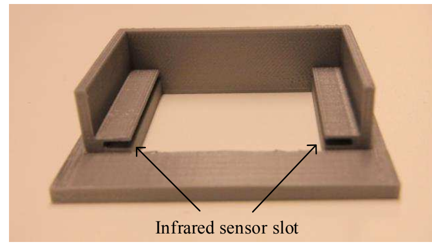


Fig. 5. Terminal module for head/tail infrared sensor mounting.

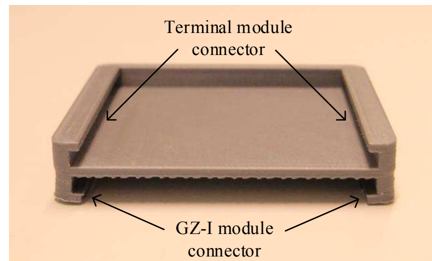


Fig. 6. Auxiliary module for connection between the GZ-I module and the terminal module.

TABLE II

SPECIFICATION OF THE SNAKE-LIKE ROBOT IN FIG. 7

	Component	GZ-I module	Intermediate module	Terminal module	Auxiliary module	LiPo battery	Infrared sensor	Force sensor
Snake-like robot	Number	5	5	2	1	5	12	5
	Dimension	66 × 66 × 615 mm						
	Weight	950 g						

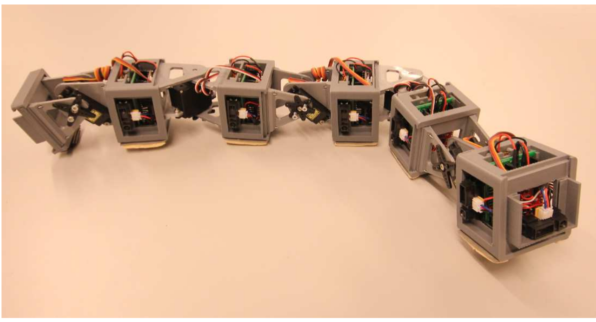


Fig. 7. Screw-less assembly of a snake-like robot.

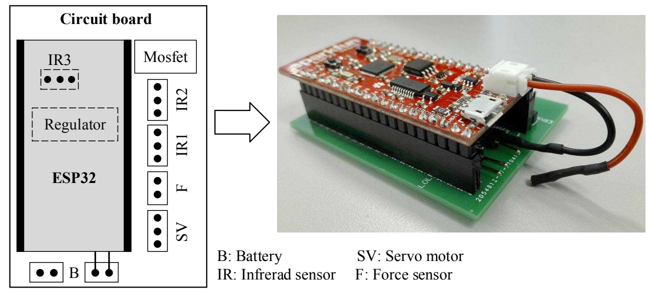


Fig. 8. Circuit board with an ESP32 Thing plugged in.

Fig. 5 shows the terminal module. Again, by using of the sliding mechanism the mounted infrared sensor can be secured on it. In addition, the bottom plate of the terminal module is extended a little bit, so that it can connect to the sliding connector of the intermediate module from ⑥ in Fig. 3.

Because an intermediate module pairs with a GZ-I module, it indicates that after the assembly of a snake-like robot, one end will be an intermediate module and the other end must be a GZ-I module. Considering there are no connectors between the GZ-I module and the terminal module, an auxiliary module is designed to address their connection, as depicted in Fig. 6.

D. Assembly of a snake-like robot

If the controller on the intermediate module is capable of wireless communication, no wires are required between modules. As a result, a snake-like robot can be easily assembled based on the intermediate module, the terminal module and the auxiliary module, without needing any screws, bolts and nuts. Fig. 7 shows a pitch-yaw connected snake-like robot as an example of the screw-less connection result. Its specification is listed in Table II. The snake-like robot will also be used for experimental verification in Section V.

IV. HARDWARE AND SOFTWARE DEVELOPMENT

A. Hardware development

A relative new micro-controller called "ESP32 Thing" [16] is selected as the controller of the system. The reasons lie two twofold. First, it contains the WiFi transceiver to satisfy the requirement of screw-less solution. Second, the ESP32 Thing has rich I/O resources and integrated LiPo battery charger, which means the system has the ability for expansion.

To simply the connection between the ESP32 Thing, the battery and the sensors, a circuit board is developed, as shown in Fig. 8. Its dimension can be seen in Table I. For the battery, there are two groups of pins utilized, one for the ESP32 Thing, and the other for the circuit board and thereby for the sensors and the servo motor attached. Because the ESP32 Thing has a working voltage of 3.3V while the servo motor works at 5.0V, a step-up regulator is used to guarantee the servo motor can generate enough force/torque. In addition, a mosfet is added in the circuit board for energy saving, which enables the infrared sensors only when they are about sensing. This will save up to 60% power consumption.

B. Software development

Considering each ESP32 Thing in the intermediate module contains a Wifi transceiver, it is possible to build up a local area network (LAN) through a router, so that the communication can be made between not only the ESP32 Thing, but also any other devices such as personal computer (PC) and mobile phone that can access the router.

In this project, a control system is developed on a PC and the ESP32 Thing towards the goals including:

- real-time sensor data transmission and collection
- gait generation and parameter adjustment
- advanced control algorithm for adaptive locomotion

Fig. 9 depicts a master/slave structure for data transmission, interaction and control between the master on the PC and the slaves on each ESP32 Thing. The user datagram protocol (UDP) is used taking the communication efficiency into account. The master plays two roles in the system. First,

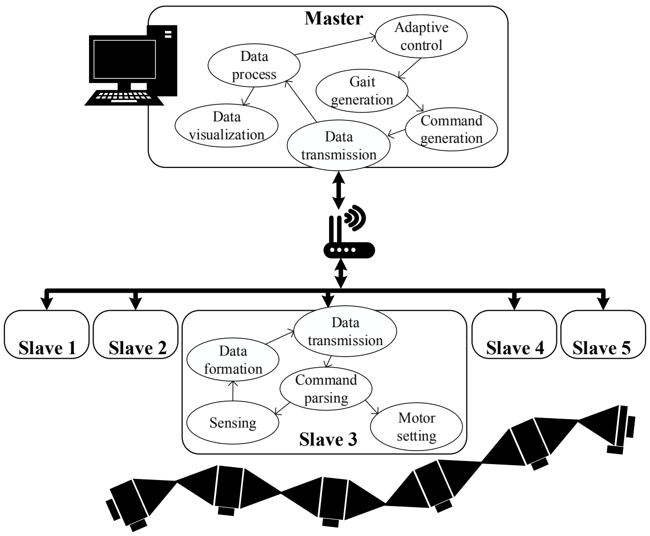


Fig. 9. Control system structure.

it listens to a service port to receive UDP packets which contains sensor data information from the slaves. The data will be parsed for either visualization in a real-time manner or being further filtered to support advanced control algorithms. Second, by comprehensively analyzing the sensor data, a responding gait can be generated, which contains the motor angles for each slave. These motor angles will be coded in a fixed array in a UDP packet and then broadcast out to the whole network.

For the slave side, accordingly, there are two functions implemented on the ESP32 Thing. The first one is to formulate the sensor data in a specific sequence in a UDP packet and send it out once the timer used for regular sensor data transmission is expired. The other function is to parse the broadcast packet from the master to extract the desired motor angle for the corresponding servo motor; then set a proper PWM signal to drive the servo motor to the desired position.

As a result, the control/monitoring of the snake-like robot is able to be performed from the PC. Currently, we have achieved sensor data collection and gait generation for the snake-like robot. The control algorithm for adaptive snake-like locomotion is still under development. Since this part of work is beyond the concern of this paper, we leave it aside and put it as future work.

V. Experiment

An experiment was carried out to investigate the locomotive capability of the assembled snake-like robot, and thus proof the effectiveness of the screw-less solution. The five DOFs snake-like robot (two modules in yaw direction and the other three in pitch direction) shown in Fig. 7 was used as the test-bed of the experiment. The goal of the experiment is to realize sidewinding locomotion on the snake-like robot, while guaranteeing sensor data collection to the PC.

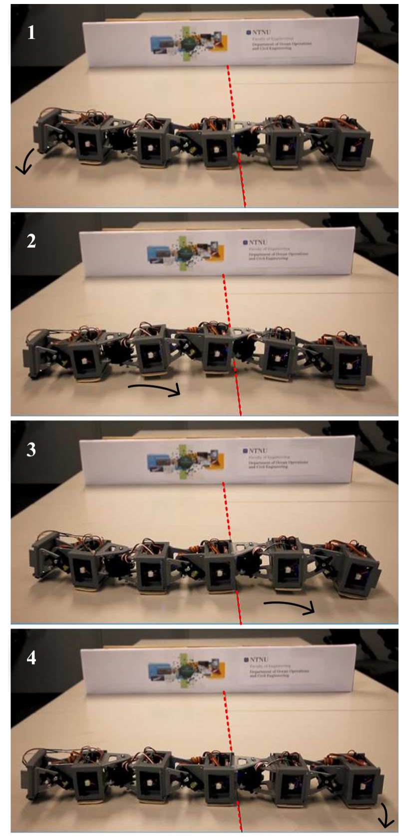


Fig. 10. Snapshots of onsite sidewinding locomotion experiment in one period. The red line is used as a reference for observing displacement.

Sidewinding is a sideways type of locomotion that is used by snakes when moving on the sandy surfaces of the desert [17]. First, the snake lifts its head off the ground and sets it down a short distance away. Then, the rest of its body follows the path of the head with a constant phase difference. The movement repeats and leaves a series of disconnected sand tracks on the surface.

To replicate the behavior onto the snake-like robot, the control sequence of these modules needs to be considered. Inspired by the central pattern generators (CPG) that is responsible for coordinated pattern of rhythmic activity generation, many CPG-based methods have been proposed and applied on bio-inspired robots for gait generation [18]–[20]. Here, we follow the work [21] and use two groups of sine generators for gait implementation:

$$\begin{cases} \theta_p(i,t) = A_p \cdot sin(\omega t + (i-1)\phi_p/2), \quad i \in \{1,3,5\} \\ \theta_y(i,t) = A_y \cdot sin(\omega t + (i-2)\phi_y/2 + \psi_{py}), \; i \in \{2,4\} \end{cases}$$

where θ is the reference angle for the module joint; A represents the amplitude; ω denotes the angular frequency; ϕ represents the phase difference within one group of the sine generators; and ψ indicates the phase difference between the pitch and the yaw groups of sine generators.

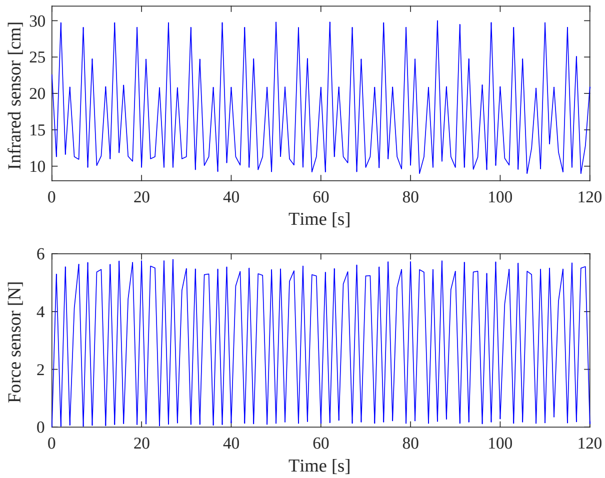


Fig. 11. Raw sensor data from the head module.

Fig. 10 shows the video snapshots for the onsite experiment. The sidewinding locomotion was realized with parameters $A = 15$, $\omega = 2.5$, $phi = 2.1$ and $\psi = 0.2$. Two body waves are presented: one leads to the robot's modules lifting and moving one by one from the head (left) to the tail (right); the other results in lateral movement towards the camera. The raw sensor data was succeeded to be collected. For simplicity, Fig. 11 only depicts the raw data from the front infrared sensor and the force sensor on the head module. The result reveals that the two sources of data are anti-phase, and both of them have a period about 2.5s, which is consistent to the period of the sine generator.

As a result, we conclude the screw-less solution is useful for the snake-like robots and applicable in real applications.

VI. Conclusion

In this paper, we emphasize a screw-less solution that facilitates snake-like robot assembly and sensor integration. Taking the simple GZ-I module as basis, two types of modules are special designed, including the intermediate module for holding sensors, micro-controllers and batteries, and the terminal module for mounting sensors at each end of the robot. Both of them make use of the sliding mechanism to add sensors and connect the GZ-I module, as a result achieving assembling the robot without any tools. A circuit board is developed to connect all the hardware together. Based on that, a software with a master-slave structure is implemented, which enables sensor data collection and the GZ-I module actuation from a remote computer. An onsite experiment about sidewinding locomotion shows the effectiveness of the proposed method.

Future work will focus on improving the intermediate module connector to remove the constraint of pitch-yaw connection for the snake-like robot. Furthermore, we will continue to add more sensors such as accelerometer and gyroscope on the snake-like robot to enhance its perception capability.

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