Development and Experiment of a Snake-like Robot Composed of Modularized Isomorphic Joints

Haomiao Wang, Hongtao Wang, Wenfu Xu*, *Senior, IEEE*, Zonggao Mu

***Abstract*— A snake-like robot is a hyper-redundant robot. It has flexible movement ability and high stability with low center of gravity. It is very suitable for environment detection in the rugged road or narrow space. This paper develops a snake-like robot with 10 degrees of freedoms (DOFs). Its joints are arranged as the structure of "Roll-Pitch-Roll-Pitch-….", where "Roll" and "Pitch" respectively denote a Roll and Pitch joint. Each joint is designed as the same modularized unit, which can be used as a "Roll" or "Pitch" joint. Such design decreases the cost of development and enhances the flexibility of applications. Furthermore, the kinematics equation of this robot is derived and the movement ability is analyzed. Inspired by the biological behavior of a real snake, we plan several typical gaits for the snake-like robot, including peristalsis, rolling and Serpenoid curve gaits. We also develop the embedded controller based on the ARM processor and uc/os-ii real-time operation system. The gait planning algorithms are programmed using C language and realized in the embedded processor. At last, typical cases are experimented. The experiment results show that the developed robot has high mobility and flexibility.**

Keywords—Snake-like Robot; Hyper-redundant Manipulator; Bionic Robot; Bio-inspired Robot

I. Introduction

With the development of science and technology, planetary surface exploration is becoming the research focus of main aerospace organizations of the world. Because of high danger, challenge and cost for manned-exploring on a planetary surface, mobile robots are considered as the best choice for un-manned exploration. However, the environment of the planet's surface is very complex and un-structured. The surface is rugged. There are a lot of obstacles with different material, shapes and dimensions. Furthermore, some interesting sites to be explored are very narrow. Snake robots have many advantages over other types of mobile robots on exploring complex environment.

Snake-like robots are a class of hyper-redundant mechanisms consisting of multiple links connected through joints. They are chained together in series. The small cross-section and many degrees of freedoms make them suited to explore confined spaces such as rugged road, narrow holes, and collapsed buildings.

The snake robots have been researched for several decades. Early empirical and analytical studies of snake locomotion were reported by Gray in the 1940s. Hirose developed the world's first snake robot in 1972 [1]. In the last 20 years, the literatures on snake robots have flourished enormously with numerous proposed approaches for modelling, development, and control of these mechanisms. Professor Hirose and his group developed a series of snake-like robots, within which ACM-R7 (Active Cord Mechanism) was the most famous one. It consists of ball-shaped joint modules connected in a serial chain. It has two features: 1) The exterior surface is smoother and the corresponding friction is smaller; 2) It is mounted by a contact force sensing system [1, 2] so the dynamic performance was largely improved by the controller. Besides, they proposed a path following planner that enables snake robots to track straight paths [1, 3]. Hirose also defined the serpenoid-curve, which made a snake robot moving like a real snake [1]. Professor Howie Choset and his group developed some modular snake robots for different applications [4, 5, 6, 7]. They also proposed an architecture for a robust, capable, and reliable modular snake which can be used as a research platform to verify the key algorithms[8]. His research group, as well as others [9], developed and implemented the movement gaits that can traverse a variety of terrains, including flat ground and pipes. They also demonstrated the use of snake robots to navigate pipe networks that are not able to be traversed with traditional wheeled robots [10]. Professor Ma Shugen and his group developed a unit named MUU for a snake-like robot and reconfigurable robots. This MUU has 3 DOFs, among which the pitch and yaw DOFs are driven by a differential mechanism. There are many configurations that the MUUs can form as a snake-like robot, a car-like robot, a three-unit vehicle and a four-wheeled vehicle, and so on [11, 12, 13]. Mamba developed the snake-like robot with multiple same joints, whose surface is mounted with passive wheel for increasing the lateral friction during movement; what is more, the snake robot has the capacity of the perception of the external environment [14]. Howie Choset developed the Unified Snake robot which is composed by 16 joints [15], it has a very abundant form of movement [16]. The robot can easily across the obstacle which is less than half length of the body height. Ye Changlong developed the tour's second-generation bionic robot, the single joint has three degrees of freedom (Pitch, Yaw and Roll) to avoid the singularity effectively, which greatly enhances the athletic ability and adapt to the environment [17].

In this paper, we develop a snake-like robot prototype with homogeneous joints for complex environment exploration. It is composed of 10 modular joints. Then, we derive the kinematics equations using the standard modeling concept. Based on the analysis of a real snake movement forms, we plan the typical gaits, including peristalsis gait, rolling gait and Serpenoid curve gait for the snake-like robot. We also develop

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the embedded controller based on the ARM processors and uc/os-ii real-time operation system. The gait planning algorithms are programmed using C language and realized in the embedded processor. At last, the movement on different road environments is verified by several experiments. The robot and its key algorithms are then tested and evaluated from practical experiments.

II. Configuration and Mechanical Design

A. Function Requirements

To meet the needs of space exploration, a snake-like robot is required to have the following functions:

(1) Movement function: a snake-like robot should have different movement forms, in order to adapt to different environments. It can use different motion forms to finish the mission.

(2) Remote control function: a snake-like robot needs to be controlled from remote distance. When it executes a given mission, the operator can monitor it from remote site.

(3) Obstacle avoidance function: to ensure that the mission be completed successfully, a snake-like robot should have the capacity to cross obstacle. Then it can get through a certain obstacles when it execute mission.

(4) Environmental adaptability: when a snake-like robot executes missions, it should have certain environmental adaptability, in order to ensure that the robot can adapt to complex environment.

B. Performance Requirements

The performance requirements of the snake-like robot are as follows:

(1) Light weight: the overall weight of the robot (including the mechanical structure, control circuit, sensor module, and so on) should be less than 3 kg;

(2) The radial is less than or equal to 20 mm. The overall length is less than 0.8 m;

(3) Payload mass: The robot can carry a payload whose mass is larger than 2kg under 1 g (1g=9.8kg/m^2). .

C. The Configurations and its Modularized Joint

The snake-like robot is composed of 10 modularized joints; each joint has one degree of freedom. The rotation vectors of adjacent joints are perpendicular. The layout of all the joints are shown in figure 1.

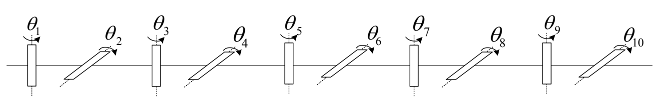

Fig. 1 Layout of the snake-like robot

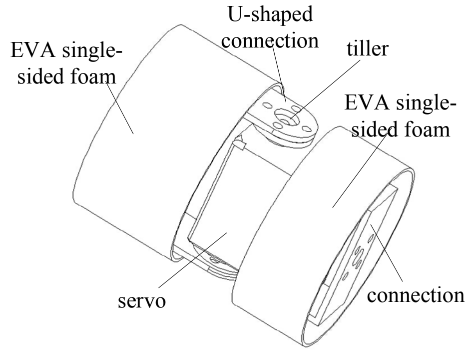

Fig. 2 Modular joint with single degree of freedom

Each joint is driven by a servo motor. Based on the theoretical analytical, the driving torque is determined. Then, we choose RDS3109 biaxial servo motor for the snake-like robot. Its torque is 15 kg/cm. It operate smoothly with low noise and high linearity. The controllable angle range of the servo is 180 degree; it can rotate 360 degrees when the power is turn off. The output terminal of the motor is connected with a u-shape connection frame, and the end of the servo is connected with the connection by a bolt. The external surface of the joint is packaged by the EVA single-sided foam, which is used to improve the frictional force between the robot and the ground. It can enhance the motion capacity of the snake-like robot. The 3D design of the modular joint is shown in figure 2. And, figure 3 is the three-dimensional diagram of the assembled snake-like robot, which is named HITSZ-Snake I because it is developed by the group of Harbin Institute of Technology Shenzhen Graduate School (HITSZ). The parameters of the designed robot is shown in Table I. The parameters of the servo motor is listed in Table II.

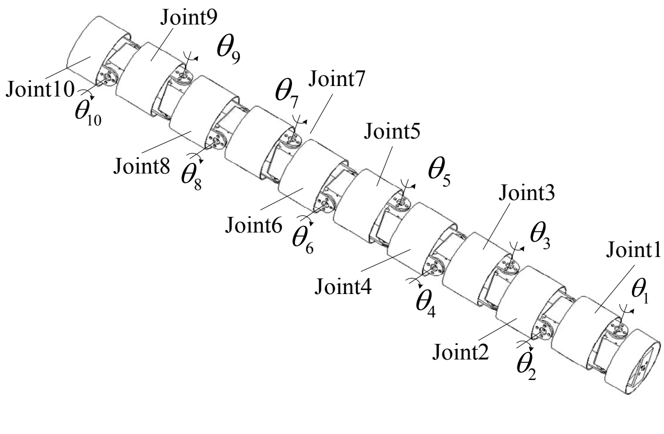

Fig. 3 HITSZ-Snake I

TABLE I PARAMETERS OF SNAKE-LIKE ROBOT

Project	values
Length of single joint (mm)	69
Total length (mm) of the robot	690
Mass of single joint (g)	125
Total mass (g) of the robot	1250
Diameter (without rail, mm)	56
Total DOFs	10

TABLE II PARAMETERS OF THE SERVO MOTOR

Parameter names	**Parameter values**
Mass(g)	60
Working voltage(V)	5-7.2
Working current(mA)	>100
Size(mm)	40×20×40.5
Speed (sec/60° 7.2V)	0.1
Torque(kg/cm)	15

III. KINEMATICS MODELING AND GAIT PLANNING

A. Kinematics Modeling

The Denavit-Hartenberg (D-H) of the snake-like robot (we called it as HITSZ - Snake I) is shown in figure 4. The axes of two adjacent joints Z_i and $Z_{i+1} (i = 0,1,...,9)$ are perpendicular, and the length of each robot joint is l . The corresponding D-H parameters are shown in Table III.

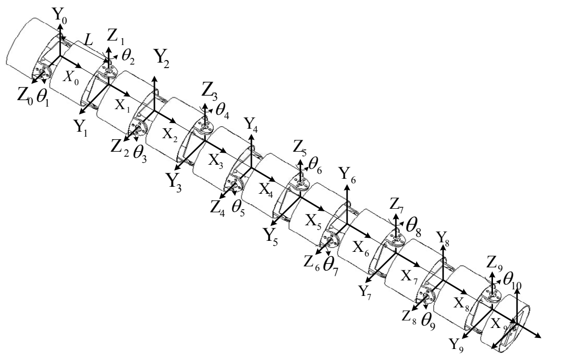

Fig. 4 The D-H coordinate systems of the snake-like robot

TABLE III THE D-HPARAMETERS OF THE SNAKE-LIKE ROBOT

joint	θ_i	a_i	α_i	d_i
1	θ_1	l	0°	0
2	θ_2	l	-90°	0
3	θ_3	l	0°	0
4	θ_4	l	-90°	0
5	θ_5	l	0°	0
6	θ_6	l	-90°	0
7	θ_7	l	0°	0
8	θ_8	l	-90°	0
9	θ_9	l	0°	0
10	θ_{10}	l	-90°	0

B. Serpenoid Gait Planning

Based on long-term observation and research of real snakes' motion, Hirose [1] proposed a curve function named Serpenoid curve to represent the motion of a snake. When a snake is moving, the shape of a snake's body is extremely similar to the Serpenoid curve, shown in Fig.5 .

The shape of a snake is the same as that of a Serpenoid curve spreading in the plane. So, we can fit the Serpenoid curve by the body of the snake-like robot. Then, the movement of a snake-like robot can be realized. Serpenoid curve is shown in Fig.5. It is defined by the following function:

$$\kappa(s) = -\frac{2K_n\pi\alpha_0}{L}\sin(\frac{2K_n\pi}{L}s_p) \tag{1}$$

where, s —— the distance moved along the axial;

K_n ——the number of period;

α_0 ——the initial angle;

L ——the overall length of the snake robot;

s_p ——the length of the robot along the curve.

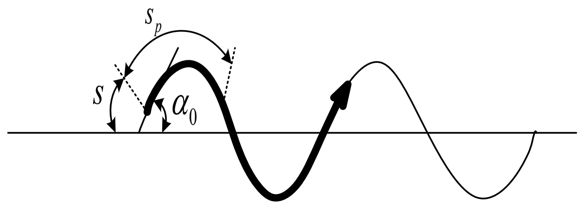

Fig. 5 Serpenoid curve

Assuming that a Serpenoid curve is spreading in the plane, the snake-like robot keep fitting the shape as the curve when it is moving. The snake-like robot's relative joint angle can be obtained by the integration from equation (2). The joints of the snake-like robot are designed in modular structure, and the length of each joint is the same. We can assume that the length of a joint is $l_i = l$, where i is the sequence number of the joint. Hence, the overall length of the snake-like robot is $L = nl$, where, n is the number of joints. Therefore, we can obtain the relative angle of the adjacent joints from the curvature equation by the integral type, i.e.:

$$\begin{aligned}\theta_i(s) &= \int_{s+s_{p_{i-1}}+\frac{1}{2}l}^{s+s_{p_i}+\frac{1}{2}l}\kappa(u)du = \int_{s+(i-1)l+\frac{1}{2}l}^{s+il+\frac{1}{2}l}\kappa(u)du \\ &= -2\alpha_0\sin(\frac{K_n\pi}{n})\sin(\frac{2K_n\pi}{L}s + \frac{2K_n\pi}{n}i) + K_1 l\end{aligned} \tag{2}$$

where, $i = 1,2,\cdots,n-1$, K_1 is the deflective curvature. We can change the direction of the snake-like robot motion by changing the value of K_1 ; is the axial distance of the rear of the snake-like robot moves along the Serpenoid curve.

By the derivative of the joints angles, we can obtained the joint angular velocity $\dot{\theta}$ and angular acceleration $\ddot{\theta}$. $\dot{\theta}$ is the function of s and $\dot{s}$; $\ddot{\theta}$ is the function of s , $\dot{s}$ and $\ddot{s}$. They are written as follows:

$$\dot{\theta}_i(s,\dot{s}) = -\frac{4K_n\pi}{L}\alpha_0\sin(\frac{K_n\pi}{n})\bullet\cos(\frac{2K_n\pi}{L}s + \frac{2K_n\pi}{n}i)\dot{s} \tag{3}$$

$$\begin{aligned}\ddot{\theta}_i(s,\dot{s},\ddot{s}) = &-\frac{4K_n\pi}{L}\alpha_0\sin(\frac{K_n\pi}{n})\bullet\sin(\frac{2K_n\pi}{L}s + \frac{2K_n\pi}{n}i)\dot{s}^2 \\ &\bullet\cos(\frac{2K_n\pi}{L}s + \frac{2K_n\pi}{n}i)\ddot{s} + \frac{8K_n^2\pi^2}{L^2}\alpha_0\sin(\frac{K_n\pi}{n})\end{aligned} \tag{4}$$

where, $\dot{s},\ddot{s}$ are the velocity and the acceleration of the snake-like robot.

Under Cartesian coordinate system, Equation (2) can be represented as:

$$x(s)=\int_0^s \cos(\xi_\sigma)d\sigma \tag{5}$$

$$y(\mathrm{s})=\int_0^s \sin(\xi_\sigma)d\sigma \tag{6}$$

where, $\xi_\sigma = a\cos(b\sigma)+c\sigma$;

a ——a constant, which determines the amplitude of the Serpenoid curve;

b ——a constant, which determines the cycle number of the Serpenoid curve;

c —— a constant, which determines the moving direction of the Serpenoid curve.

A Serpenoid curve is used to emulate a snake's motion curve. When it is spreading forward at a certain speed, its curvature changes continuously. The robot's mechanical structure, however, is composed of modular rigid joints, so the robot body cannot change continuously. Therefore, the Serpenoid curve is discretized into multiple segments. The length of each segment is the same as that of a joint.

The overall length of the snake-like robot is assumed as L. and the snake-like robot was divided into n segment equally, then the length of each segment is $\frac{L}{n}$, namely, it is equal to the length of a joint. The length from the first joint to the i^{th} joint is $\frac{iL}{n}, i=1,2,\cdots n$. Then, equs. (5) and (6) can be represented as:

$$x_i=\sum_{k=1}^{i}\frac{L}{n}\cos\left[a\cos(\frac{kb}{n})+\frac{kc}{n}\right] \tag{7}$$

$$y_i=\sum_{k=1}^{i}\frac{L}{n}\sin\left[a\cos(\frac{kb}{n})+\frac{kc}{n}\right] \tag{8}$$

The point (x_i, y_i) $(i=0,1,2\cdots n)$ is the intersection point of link i and link $i+1$ .It is assuming that the angle between link i and the motion direction of the snake-like robot is ϕ_i $(i=0,1,2\cdots n)$. The following equation can be easily obtained:

$$\tan\phi_i=\frac{y_i-y_{i-1}}{x_i-x_{i-1}}=\frac{\sin\left[a\cos(\frac{ib}{n})+\frac{ic}{n}\right]}{\cos\left[a\cos(\frac{ib}{n})+\frac{ic}{n}\right]}= \tag{9}$$
$$\tan(a\cos(\frac{ib}{n})+\frac{ic}{n}) \quad (i=0,1\cdots n)$$

So, the angle between each link and its motion direction is:

$$\phi_i=a\cos(\frac{ib}{n})+\frac{ic}{n} \tag{10}$$

When we analyze the robot's gait, the angle θ_i between the adjacent joints is important. From equ (10), we can obtain:

$$\theta_i=\phi_i-\phi_{i+1}=\alpha\sin(i\beta+\frac{\beta}{2})+\gamma, i=1,2,3\cdots n \tag{11}$$

where, $\alpha=2a\sin\frac{b}{2n}$ is the amplitude of joint angle;

$\beta=\frac{b}{n}$ is the phase difference between adjacent joints;

$\gamma=-\frac{c}{n}$ is the control parameter of the motion direction.

When the robot travels forward with the angular velocity ω using the Serpenoid curve gait, Equation (11) can be represented as:

$$\phi_i=a\cos(\frac{ib}{n}+\omega\mathrm{t})+\frac{ic}{n}, i=0,1,2\cdots n \tag{12}$$

The angle θ_i can be expressed as follows:

$$\theta_i=\phi_i-\phi_{i+1}=\alpha\sin(\omega\mathrm{t}+(i+\frac{1}{2})\beta)+\gamma, i=1,2,3\cdots n \tag{13}$$

The angle velocity $\dot{\theta}_i$ is then determined by:

$$\dot{\theta}_i=\dot{\phi}_i-\dot{\phi}_{i+1}=\alpha\omega\times\cos(\omega\mathrm{t}+(i+\frac{1}{2})\beta), i=1,2,3\cdots n \tag{14}$$

According to (14), we know that the relative angular velocity can be changed between adjacent joints by changing the value of ω . Thereby we can change the velocity of each link of the snake-like robot to fit the Serpenoid curve. Then the velocity of the snake-like robot's motion will be changed.

The Serpenoid curve can be interpreted as one of the forms of snake-like robot motion. By changing the curve's parameters, i.e. a, b and c, we can get different motion gait with different directions and speed.

Taking the winding motion as the example, we generate different movement gaits by adjusting the curve's parameters. The Simulation analysis are as follows:

The winding motion is similar to the spread of a harmonics wave. According to the simulation analysis, we can get many results. The Serpenoid curve's parameter can determine the amplitude of the motion. The smaller the value of a, the smaller the amplitude of the Serpenoid curve, and the smaller the angle between adjacent joints too. It can make the snake-like robot move difficultly if the amplitude was too small. Due to the confined mechanical structure, the snake-like robot also cannot move with too large amplitude. The reasonable value range of a is $a\in(0,\pi)$. The parameter b of Serpenoid curve determines the period of the curve. If $0\le b\le\pi$, the snake-like curve is smooth, but the waveform is less than a complete period. If $b\ge 3\pi$, the snake-like curve is 1.5 times of the periodic waveform. The reasonable value range of b is $b\in(2\pi,3\pi)$. The parameter c can determine the motion direction of the snake-like robot. If $c\ge 0$, the snake-like curve moves along counterclockwise direction; if $c<0$, the snake curve moves along clockwise direction. Prototype and Experiments

A. The development of snake-like robot prototype

The embedded controller system of the snake-like robot is also developed. The block diagram is shown in figure 9. We choose STM32F103ZET6 for the processor. Its 1st-8th timers (Timer1 - Timer8) are used for controlling the joints of the snake-like robot. The NRF wireless communication module is used for connecting the upper computer with the slave computer of the snake-like robot.

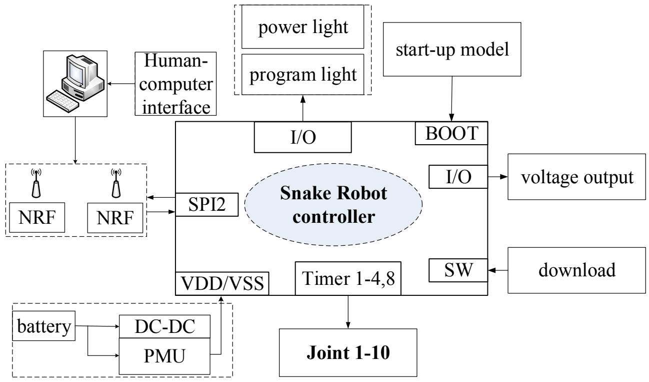

Fig. 9 Embedded controller of the snake-like robot

The prototype, composed of 10 modular joints, of HITSZ-Snake I is shown in figure 10. The radial size is about 56 mm, and the total length is about 690 mm. When it is packaged with a snake-like skin, the appearance is shown as figure 11.

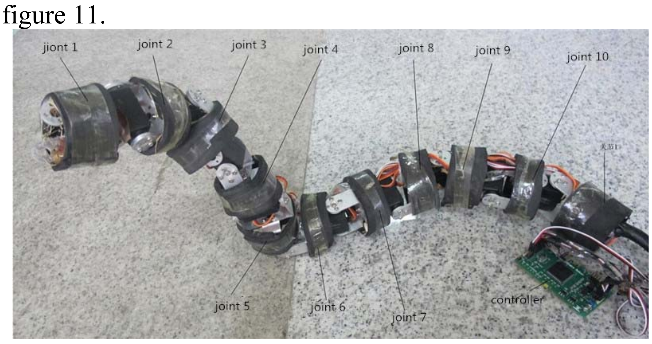

Fig. 10 Prototype of HITSZ-Snake I

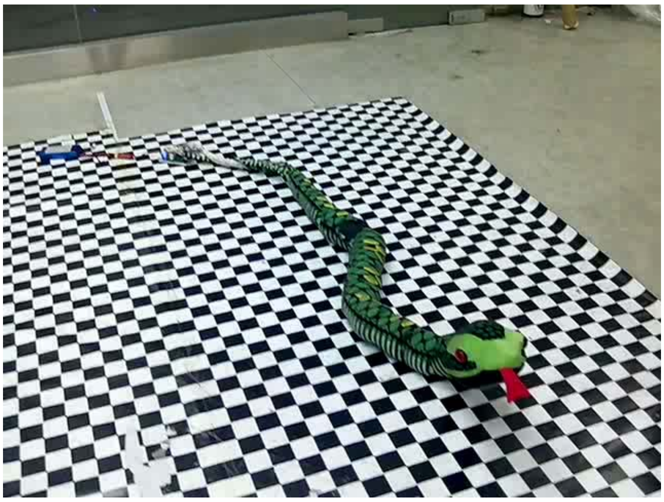

Fig. 11 Prototype of HITSZ-Snake I (with outer package)

B. *The experiments of the snake-like robot prototype*

1) *Experiment with Serpenoid gait on different surface*

a) The motion experiment on the ground

According to the Serpenoid curve discretization method, we can calculate the joint angle of the snake-like robot at different moments. It can be used as the control input. The robot can move by the friction between the lower surface and the ground. The motion experiment on the ground based on the Serpenoid curve gait is shown in figure 12.

Fig. 12 The motion experiment on the ground

b) The motion experiment on the grass

The motion experiment on the grass based on the Serpenoid curve gait is shown in figure 13. The friction coefficient between the robot and the ground is larger than on the grass condition. The fitting curve at different time can move actuated by the friction between its body and the ground.

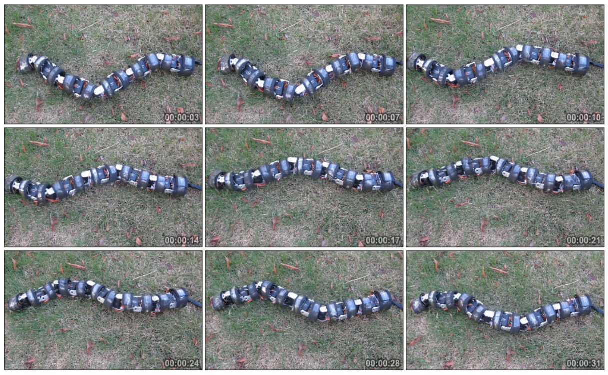

Fig. 13 The motion experiment on grass

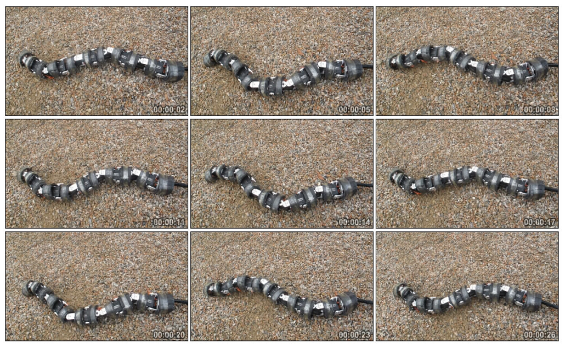

Fig. 14 The motion experiment on the gravel road

c) The motion experiment on the sandy

The motion experiment on the sandy based on the Serpenoid curve gait is shown in figure 14. It can make the robot more fully contact with the soft sand road. In the process of the robot locomotion, the robot contacts with sands continuously. Therefore, it is easy to see that the robot can be actuated by the friction between its body and the sandy road.

2) *Obstacle avoidance experiment*

In the process of movement, the robot can adjust the posture to adapt to the changing environment and cross the obstacles. As long as the friction is large enough, the robot can achieved obstacle cross movement by the contact friction. Experiment results show that the robot can cross the obstacles like rock, roots and grass.

(1) Rock obstacles crossing experiment. The experiment results are shown in figure 15. When the snake-like robot confronts obstacles in his way, the robot can adjust the shape of the body posture to adapt to the obstacle height, and the robot can cross the obstacles.

Fig. 15 Rock obstacles crossing experiment

(2) Grass crossing experiment. The robot has enough contact surface when it moves in the lush grass. The friction between the robot and the ground is large enough, which is better for the robot movement. As is shown in figure 16, the rapid movement has been realized.

Fig. 16 Grass crossing experiment

IV. Conclusion

In this paper, we developed a snake-like robot prototype named HITSZ-Snake I, which has 10 modular joints. Its kinematics equation was then established. Based on it, different gaits are planned. We also developed the embedded controller based on the ARM processors and uc/os-ii real-time operation system. The gait planning algorithms were programmed using C language and realized in the embedded processor. Finally, we established the experiment system. Based on it, the key algorithms were tested and evaluate. Using this robot, we completed typical gait planning and obstacle avoidance experiments in different road conditions. The results show that the snake-like robot meets the desired performance requirements. In the future, we will improve the performance from the following aspects: (1) structure optimization with light and smart material; (2) dynamics control to improve the control performance; (3) autonomous navigation and gait planning.

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