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Coordinated Gait Control of Snake Like Robot Based on Electromechanical Tracking

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Abstract

In order to improve the stability of snake-like robot in unknown environment. The coordinated control method of snake like robot gait based on electromechanical tracking is proposed. The motion angles of each joint are designed according to the actual needs. The desired motion curve is designed based on the curve discretization. The coordinated control design of all kinds of gait is completed by discretization. The snake is realized by electromechanical tracking combined with the control system with TwinCAT soft PLC as the main control unit Gait coordination control of the robot. The experimental results show that the proposed method has good control effect on the snake like robot prototype's winding gait and plane rolling gait, and the overall performance and control stability are good. It has certain reference value for the improvement and perfection of snake like robot in the future.

Keywords: Snake Like Robot; Kinematics Analysis; Discretization; Gait Coordination Control.

1. Introduction

The small size and flexible movement of snake-like robot make it competent for search and rescue work, and search and rescue personnel can enter the place where it is easy to collapse to search [1, 2]. In toxic environment, pipeline detection, bridge detection, nuclear power station radiation inspection and other occasions, snake like robots carry cameras and detection equipment to replace people to enter these high-risk or difficult to reach occasions, and assist human beings to successfully complete the specified tasks [3]. The snake-like robot has the characteristics of high degree of freedom redundancy, unfixed base and forward power provided by friction force with the ground or contact force with the surrounding environment. It brings variety of motion forms, but also brings great difficulty to its dynamic modeling and motion control mode.

On the research of snake-like robot, some scholars have begun to study it gradually. Berthet-Rayne et al. focused on the real-time remote operation and control of redundant snake like robot for minimally invasive surgery under the master-slave structure [3]. Based on the mapping between DOF of master robot and redundant slave robot, six different control methods are proposed. Through simulation and user research, the proposed method performs better in terms of visualization, real-time performance and total consumption, but there is still room for improvement in control stability; Kano et al. proposed a decentralized control scheme for snake like robot based on Tegotae [4], which is a Japanese concept describing the matching degree of perception response and expected value. In this study, a snake like robot is developed. The experimental results show that the proposed control scheme can generate multi-functional gait patterns without changing any parameters, such as scaffold based movement on irregular terrain and Concerto movement in narrow channels, but the robustness of the method still has room for improvement; Ryo et al. studied the trajectory tracking problem of planar snake like robot without lateral constraint [5]. The reference trajectory of the head position and the orientation of the connecting rod 1 are given, and the torque control is determined to reduce the tracking error. The performance of the controller is tested through a large number of simulations. The robustness of actuator failure is studied. It is assumed that one of the actuators is damaged and the corresponding joint becomes passive. As a more realistic situation, some states are not easy to obtain from the sensor readings and need to be estimated by the observer. The performance of the closed-loop system with observer is verified by simulation [5]. This method has good control performance, but it has higher requirements for the collection of external environment information.

On this basis, this paper proposes a coordinated control method of snake like robot gait based on electromechanical tracking. The method of curve discretization is used to design the gait of snake like robot. The coordinated control of snake like robot gait is realized by electromechanical tracking combined with software design. The effectiveness of the proposed method is verified by experiments.

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1.1. Gait design of snake like robot

1.1.1. Serpenoid curve and its discretization

The symbols used in this paper are shown in Table 1.

Table 1. Corresponding interpretation of symbols

K_n	the number of propagation waves formed by the snake like robot
L	the overall length of the snake like robot
s_p	the length of the snake and the robot along the curve
s	the arc length
n	the number of joints
φ	the angle of positive direction turning anticlockwise to the connecting rod direction
α	the amplitude of joint angle
β	the phase difference between adjacent joints
γ	the control parameter of motion direction
ω	angular velocity
θ_{even}	the horizontal joint function of the snake like robot
θ_{odd}	the vertical motion joint function of the snake like robot
A	the amplitude of the joint motion
t	the joint motion frequency
κ	the curvature of the curve
τ	the torsion of the curve
e_1	the unit tangent vector
e_2	the principal normal vector
e_3	the secondary normal vector

Serpenoid curve is a curve that imitates the plane motion of snakes in nature [6]. When the snake moves, it is equivalent to serpenoid curve and propagates in the plane. Serpenoid curve is defined by curvature equation [7]:

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

where K_n is the number of propagation waves formed by the snake like robot; L is the overall length of the snake like robot; s_p is the length of the snake and the robot along the curve. The curvature equation is decomposed in two directions, x and y, in rectangular coordinate system:

$$\begin{cases} x(s) = \int_0^s \cos(a\cos(\alpha) + c\alpha)d\alpha \\ y(s) = \int_0^s \sin(a\cos(\alpha) + c\alpha)d\alpha \end{cases} \tag{2}$$

The point (x (s), y (s)) is the coordinate point along the direction from the starting point to the arc length s. a determines the amplitude of the curve motion, b determines the number of periodic waveforms in the unit length, and c determines the direction of the curve.

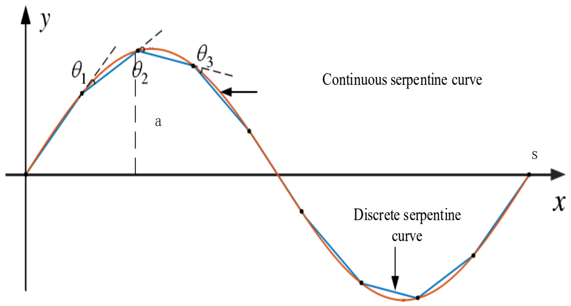


Figure 1. Discretization of serpentine curve

As shown in Figure 1, the discrete serpentine curve is approximately simulated as a continuous serpentine curve by discretization. Since the snake-like robot is a series of rigid joints with fixed length, it can not move continuously according to the serpenoid curve [8]. It is necessary to discretize the serpentine curve by segments, and the length of each segment is the length of a single joint of the robot. The overall length of the snake like robot is L. If the robot is divided into n segments according to the number of joints, the length of each segment is L/n, that is, the length of the joint module of the snake like robot. The length along the robot body from the initial point of the snake like robot to the i joint point is$s_i = iL/n$, i = 0, 1, …, n. The discrete diagram of serpentine curve is shown in Figure 1. The discrete points (x (s), y (s)) on the serpentine curve after discretization. the position of joints, can be expressed as follows:

$$\begin{aligned} x_i &= \sum_{k=1}^{i}\frac{L}{n}\cos[a\cos(\frac{kb}{n}) + \frac{kc}{n}] \\ y_i &= \sum_{k=1}^{i}\frac{L}{n}\sin[a\cos(\frac{kb}{n}) + \frac{kc}{n}] \end{aligned} \tag{3}$$

Mark the connecting rod between each position point as i, and define the angle of x positive direction turning anticlockwise to the i-th connecting rod direction as $\varphi_i, i = 1,2,...n$, then Equation (4) can be obtained:

$$\tan\varphi_i \frac{\sum_{k=1}^{i}\frac{L}{n}\cos[a\cos(\frac{kb}{n}) + \frac{kc}{n}]}{\sum_{k=1}^{i}\frac{L}{n}\sin[a\cos(\frac{kb}{n}) + \frac{kc}{n}]} = \tan[s\cos(\frac{ib}{n}) + \frac{ic}{n}] \tag{4}$$

The angle between the connecting rod and the moving direction can be obtained as follows:

$$\varphi_i = [s\cos(\frac{ib}{n}) + \frac{ic}{n}] \tag{5}$$

When analyzing the gait of the robot and making joint control, the angle between the extension lines of adjacent connecting rods is applied in practice θ_i :

$$\theta_i = \varphi_i - \varphi_{i+1} = \alpha\sin(i\beta + \frac{\beta}{2}) + \gamma \tag{6}$$

where, $\alpha = 2a\sin\frac{b}{2n}$ represents the amplitude of joint angle, $\beta = \frac{b}{2n}$ represents the phase difference between adjacent joints, and $\gamma = -\frac{c}{n}$ represents the control parameter of motion direction.

When the discrete serpentine curve propagates forward at angular velocity ω , it can be expressed as follows:

$$\varphi_i = \alpha\cos(\omega t + \frac{ib}{n}) + \frac{ic}{n} \tag{7}$$

From Equation (6) and Equation (7), it can be seen that the value of ω affects the change speed of φ_i, thus affecting the speed of the snake like robot. By changing the parameters *a, b, c* in the curve, the snake-like robot can move in different directions and at different speeds. For the snake like robot with orthogonal joints, only odd joints move in 2D planar meandering motion, and the initial angle of each joint can be any value. As long as the phase difference of adjacent odd joints is β , the winding motion can be guaranteed:

$$\begin{aligned} \theta_{even} &= A\cos(\omega t + (i-1)\beta), i = 1,3,5,.. \\ \theta_{odd} &= 0, i = 2,4,6,... \end{aligned} \tag{8}$$

where, θ_{even} is the horizontal joint function of the snake like robot; θ_{odd} is the vertical motion joint function of the snake like robot; *A* is the amplitude of the joint motion; *t* is the joint motion frequency; β is the adjacent joint phase.

1.1.2. Spine curve and discretization

When the snake-like robot is required to move in three dimensions according to the desired trajectory, a three-dimensional spine curve can be designed according to the motion constraints of the surrounding environment and the snake body [9, 10], and then the motion planning is carried out by discretizing the spine curve. According to the knowledge in differential geometry and based on FrenetSerret frame [11], a three-dimensional spine curve can be designed, as shown in Equation (9):

$$\begin{cases} \dfrac{dc}{ds} = e_1 \\ \dfrac{de_1}{ds} = \kappa(s)e_2 \\ \dfrac{de_2}{ds} = \kappa(s)e_1 + \tau(s)e_3 \\ \dfrac{de_3}{ds} = -\tau(s)e_2 \end{cases} \tag{9}$$

where κ is the curvature of the curve and τ is the torsion of the curve. The shape of the curve can be determined by the two. $c\{x(s), y(s), z(s)\}$are the coordinates of point *s* on the curve, $\{e_1, e_2, e_3\}$ are orthogonal coordinate systems, e_1 represents the unit tangent vector at point *s*, e_2 represents the principal normal vector, e_3 represents the secondary normal vector at point *s*.

The joint configuration of the snake like robot is a single degree of freedom orthogonal joint, as shown in Figure 2.

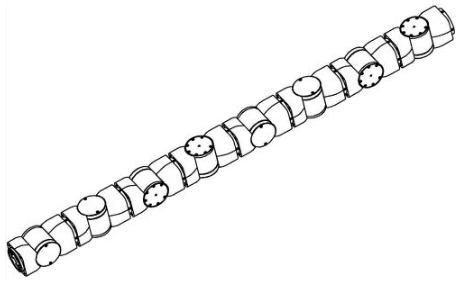


Figure 2. Orthogonal configuration of snake like robot

The Frenet-Serret frame of the spine curve of the snake like robot is shown in Figure 3.

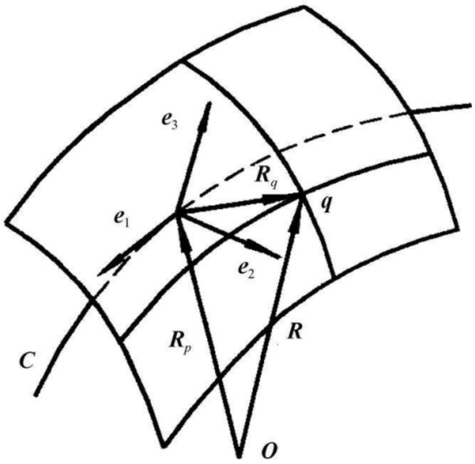
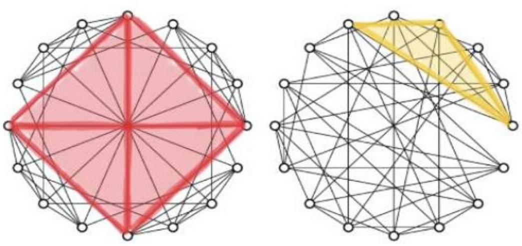


Figure 3. Frenet-Serret frame of spine curve

In order to plan the motion of climbing cylinder for snake-like like robot, it is necessary to design spiral rolling gait to complete the movement of climbing cylinder. Because of the constraint of the cylinder, the trajectory of the snake like robot is designed to be a cylindrical helix, and the spine curve is designed according to the cylindrical helix.

$$\begin{cases} x = r\cos\varphi \\ y = r\sin\varphi \\ z = p\varphi \end{cases} \tag{10}$$

After the design of the spine curve is completed, the spine curve needs to be discretized to calculate the corresponding joint angle. The discretization of planar arc and cylindrical helix is shown in Figure 4.



(a). Discretization of circular arc (b). Discretization of cylindrical helix

Figure 4. The discretization of planar arc and cylindrical helix

The equation of joint angle generated by discretization is as follows:

$$\theta_i = \begin{cases} \int_{s_1}^{s_2} \kappa(s)\sin\varphi, i = 1,3,5,... \\ \int_{s_1}^{s_2} \kappa(s)\cos\varphi, i = 2,4,6,... \end{cases} \quad (11)$$

The gait of planar rolling gait can be obtained as follows:

$$\theta_i = \begin{cases} \frac{2L}{r}\cos(\alpha t), i = 1,3,5,... \\ \frac{2L}{r}\sin(\alpha t), i = 2,4,6,... \end{cases} \quad (12)$$

The gait equation of spiral rolling is as follows:

$$\theta_i = \begin{cases} A\cos(\alpha t + \omega i), i = 1,3,5,... \\ A\sin(\alpha t + \omega i), i = 2,4,6,... \end{cases} \quad (13)$$

2. Design of Control System for Snake Like Robot

When the snake-like robot moves in the complex unknown space, the motion control system is required to have good real-time performance and openness, and can effectively avoid obstacles in the environment [12-14]. The snake like robot needs 15 motors to operate at the same time, and the control system needs strong processing ability. In this paper, the hybrid programming method of C++ and PCL, combined with CAN bus technology [15, 16], realizes the effective control process of gait coordination in the process of snake like robot movement.

2.1. Hardware design of control system

In view of the complexity of the snake-like robot's space attitude, a servo control system with TwinCAT software PCL as the center and can bus as the communication bus is constructed. The overall hardware structure of the snake robot control system is shown in Figure 5. It includes industrial PC, EtherCAT coupler, CAN master station, servo driver and servo motor.

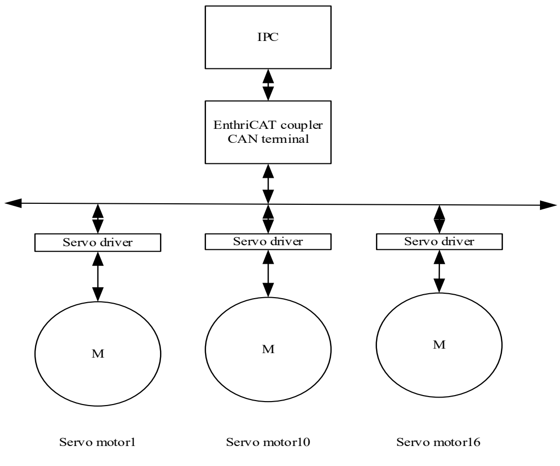


Figure 5 .Hardware structure of snake like robot control system

(1) EtherCAT coupler

EtherCAT coupler is mainly used to convert the transmission message from Ethernet to e-bus signal. A station can be composed of any number of EtherCAT terminal modules and a terminal module of a terminal station. The main parts should be illustrated in Figure 6.

In the control system, it is mainly used to connect the industrial PC and CAN master station, convert some instructions of the upper computer into e-bus signals and send them to the CAN master station, and then send them to the lower actuator, such as servo driver, through the CAN master station.

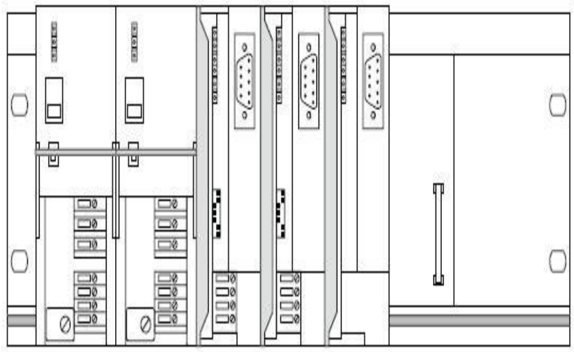


Figure 6. EtherCAT coupler

(2) CAN terminal

El6751 of bechoff company is selected as CAN master station. In EtherCAT network, any CANopen equipment can be integrated through El6751. The equipment itself CAN be used as master station or slave station. In the control system, it mainly realizes the communication function with CAN slave station equipment.

(3) Servo driver

The servo driver is the solowstldigital servo driver of Emlo. The driver is based on DSP and has CANopen interface. It can be used as a slave station in the control network to receive and send signals, so as to control the servo motor. At the same time, the position information on the code disk can be directly fed back to the upper computer. Solowestl servo driver integrates control circuit and drive circuit. It can be programmed by composer, the programming software of Emlo. It can also directly write the program in the upper computer to realize complex control algorithm [17, 18], which makes the motor control more intelligent and digital. In this project, only three servo drivers are used to control three servo motors synchronously to control the motion state of a single joint. In the motion control of snake like robot, position mode is used for parallel control.

2.1.1. Composition of servo system

Servo system is composed of servo driver and servo motor. The control system sends the control command to the servo driver through CAN bus. The servo driver receives the control command and drives the servo motor to move. At the same time, the position pulse received from the encoder is fed back to the control program through CAN bus. Elmo's digital servo driver is in the core position of the whole servo system. It not only has a variety of motion control modes, such as speed, position, return to zero and so on. It can also support complex advanced position interpolation modes, such as PT (Position) speed time interpolation, ECM (Electronic Counter Measure) electronic cam, PVT (Process Verification Test) position time velocity interpolation, etc. At the same time, the CAN bus port of Emlo's digital servo driver is an important part of the whole control network. As a slave station of CAN bus in the control network, it can timely receive control instructions and send feedback information.

In the servo system, the standard three closed loop control system is adopted, including the position loop of the outer loop, the speed loop of the middle loop and the current loop of the innermost loop, as shown in Figure 7.

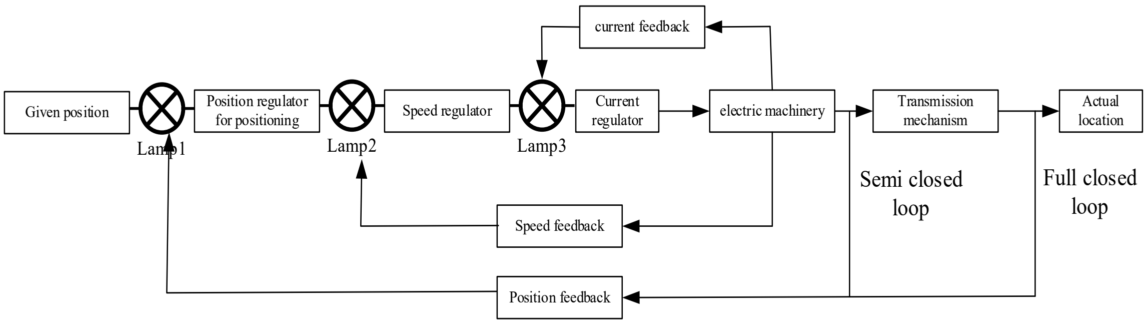


Figure 7. Structure of servo three loop control system

2.2. Software of control system

Combined with the discrete snake like robot gait, the hybrid programming method of C++ and TwinCAT soft PLT is used to integrate the gait coordination algorithm and operation interface in this system, so the interface function of ADS-DLL is selected. The specific process of quoting TcAdsDll is divided into the following parts.

(1) Add TcAdsDll header file

Install TwinCAT in the directory "C: \ TwinCAT \ ADSApi \ TcAdsDll \ Include" and "TcAdsDef.h" in the project file of VC++.

(2) Adding library function TcAdsDll.lib in VC++ Project

Add TcAdsDll.lib to linker input additional dependency in property configuration.

According to the above method, add TcAdsDll.hb, and the specific steps of how to open ads communication port are as follows: Firstly, define port variables and address variables, and then open ads communication port, then different discrete gait data types can be transmitted.

LongnErr,nPort; / / Define the port variables

AmsAddrAddr; / / Define AMS address variable

PAmsAddrpAddr = Addr; / / Define the port address variable

nPort = ADSPortOpen(); / / Open ads communication port

nErr = ADSGetLocalAddress(pAddr); / / Get the local port address

pAddr- > port = 805; / / point the pointer to port 805. The user's port number is defined according to his own definition. The following is the data function that sends the position data in the gait algorithm to the motor in the first section. The function of the position data sent to other motors is similar.

Where paddr is the address of ads device; 0x4020 is the base address, corresponding to the M register address in PLC; 0x00 is the offset address; 0x10 is the offset; FLOAT1-1 is the cache address of received data.

Then, the corresponding variables of FLOAT1-1are compiled in TwinCAT software PCL to save the position data sent and send to the servo driver at the same time, so as to drive the motor to move and realize the control of the snake like robot's gait coordination.

2.3. Development of control program

In the upper computer, the human-computer interaction function is mainly reflected in that it CAN switch different movement gait coordination modes according to different work needs and send them to the lower computer to realize the overall movement of the snake like robot. At the same time, the upper computer can also display the position of each joint in different states and the angle in the overall coordinate system. It can reflect the safety of snake-like robot in real time. There are three main motion modes of snake-like robot. Median mode: The initial state of the snake-like robot is in the neutral state; Follow mode: The head joint of the robot moves first, and then the gait of each joint moves along the path of the head joint; The backward mode: The snake-like robot can return according to its forward path. In the following mode and back mode, the actuator adopts position interpolation motion mode. In the lower computer, various motor running instructions are written by TwinCAT soft PCL program. In the middle mode, the middle position of the rope and lead screw is determined by the return value of the sensor. Under the premise of single motor movement, different movement gait coordination modes of the upper computer are implemented by using the motion function block in the soft PCL. Different modes of gait coordination control are realized by motor motion control, and the gait algorithm process is shown in Figure 8.

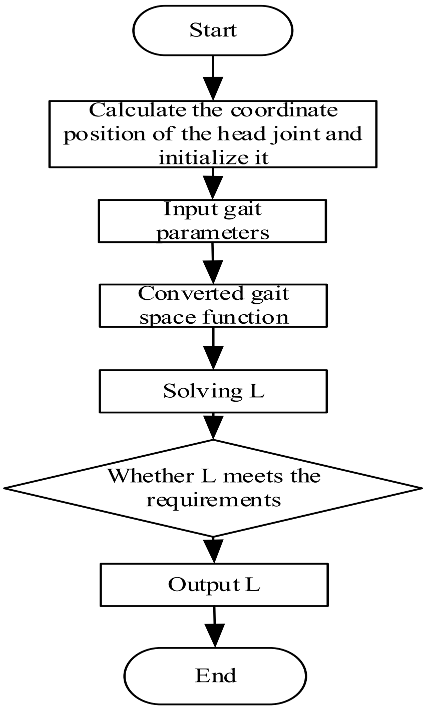


Figure 8. Flow chart of gait algorithm

In this way, the coordinated control of snake-like robot gait based on electromechanical tracking is realized, and the gait selection under environmental conditions is realized through the development of control program.

3. Experiment

In order to verify the effectiveness of the proposed method, the snake-like robot is controlled by a hierarchical control system on the experimental platform. The snake-like robot is made to carry out winding motion and plane rolling experiments, and the sensor data are collected to verify the reliability of the control system.

3.1. Construction of experimental platform

The computing rod and PCB board are installed in the head controller shell, and the camera is fixed at the front end of the head controller. The connection mode between the head controller and the joint is similar to that between the joints. The rear end of the head controller and one end of the joint has external threads. The two are connected through the connecting ring with internal thread, and the circumferential fixation is realized through the positioning pin and the positioning hole. External 28V DC power supply is required, and the power is supplied from the tail. The last joint can filter the power supply and provide current limiting protection, and provide matching resistance for PPSECO communication between joints. The snake like robot is equipped with 8 joints, each joint is distinguished by its own index number. The snake like robot prototype is shown in Figure 9.

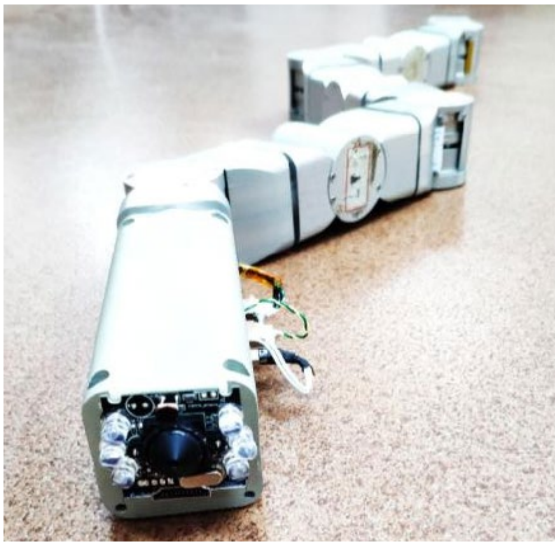


Figure 9. Prototype of snake-like robot

Figure 10 is the experimental platform. The system is composed of upper computer, router, DC power supply and snake like robot. The host computer and the snake robot establish a wireless connection, and the router establishes the local area network. The upper computer interface plays the role of human-computer interaction, which can be used to establish the connection and disconnection relationship with the snake like robot, select the robot's gait, and display the image observed by the snake robot's head in real time, display the sensor data and draw the curve. The DC power supply supplies 28V DC voltage to the snake like robot. According to the collected environmental data, the robot gait is planned and designed, and controlled by electromechanical tracking software.

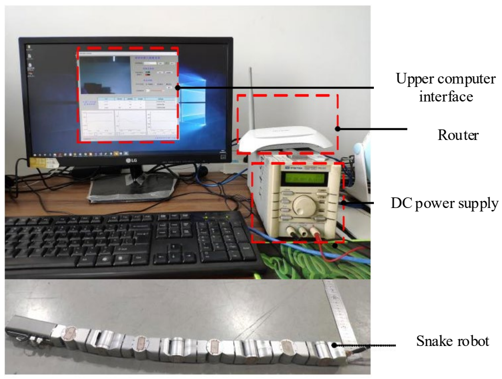


Figure 10. Experimental platform of snake like robot

The three-dimensional motion capture system used in this experiment is composed of eight infrared cameras, which are evenly distributed around the tested joint.

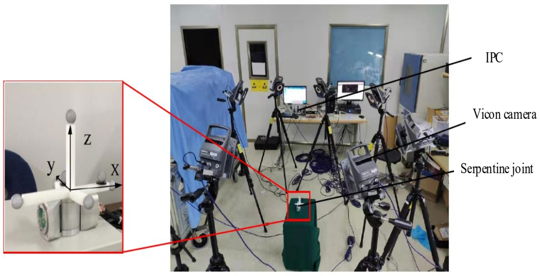


Figure 11. Measurement platform of vicon 3D motion capture system

3.2. Winding gait

Due to the snake like robot's sinuous motion, the whole body plane contacts with the ground, so it is required that the robot and the contact surface have large friction force to provide the motion power, and the normal friction force is greater than the tangential friction force. The surface of cloth with higher roughness is selected for the test. The movement process of the robot is shown in Figure 12, and the collected joint angle position information is shown in Figure 13.

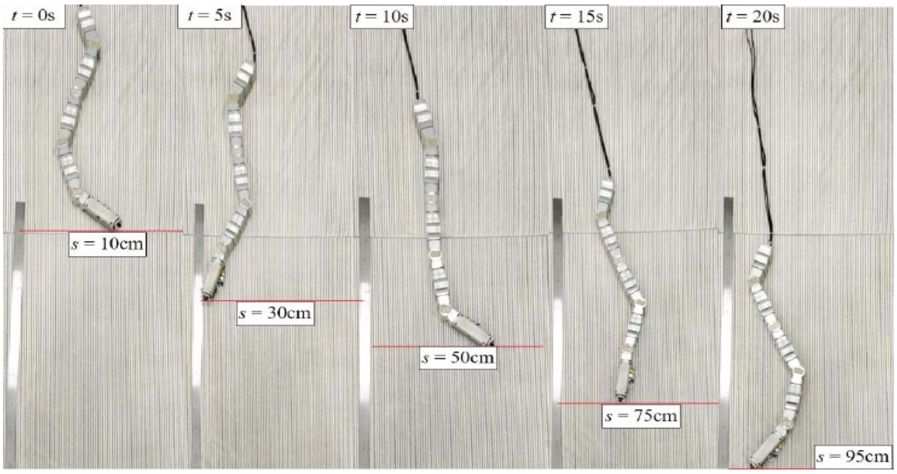


Figure 12. Serpentine robot winding motion

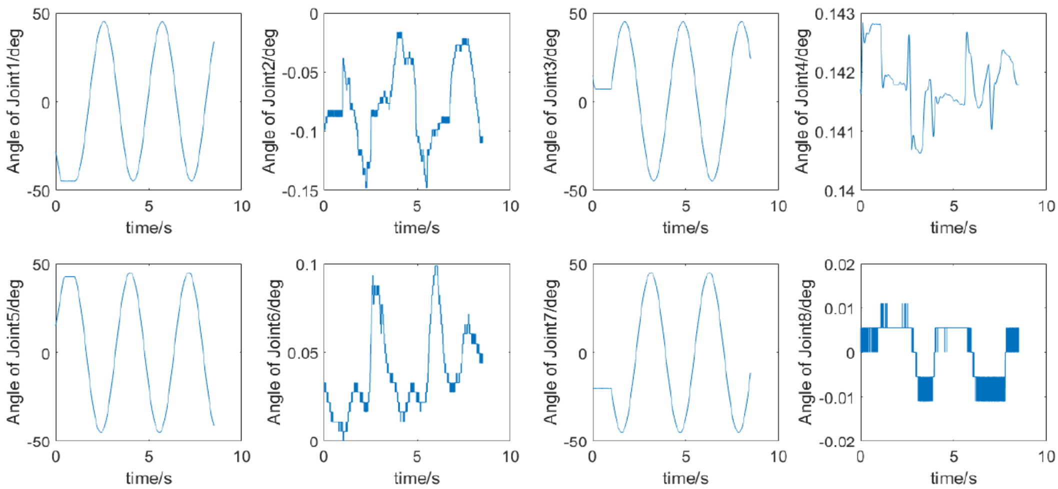


Figure 13. Angle of each joint in winding movement

Experimental results show that the average forward speed of the snake robot controlled by this method is 2.5 m/min. Based on the analysis of Figure 13, it can be seen that there is no sliding surface between the body of the robot and the friction force during the movement, which leads to better movement efficiency and faster movement speed. The results show that this method can effectively realize the coordinated control of robot gait in winding state.

3.3. Plane rolling gait

Take A = 20, ω = 0.5 to carry out the plane rolling gait experiment. The experimental process is the same as that of the winding gait experiment. The motion of each joint is shown in Figure 14. The upper computer reads the sensor data of the joint and saves it. The angle change curve of each joint during the movement process is shown in Figure 15. Take joint 2 as an example, the data of each sensor is shown in Figure 16.

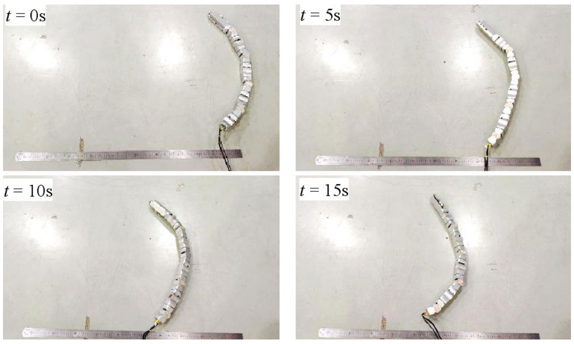


Figure 14. Planar rolling gait of snake like robot

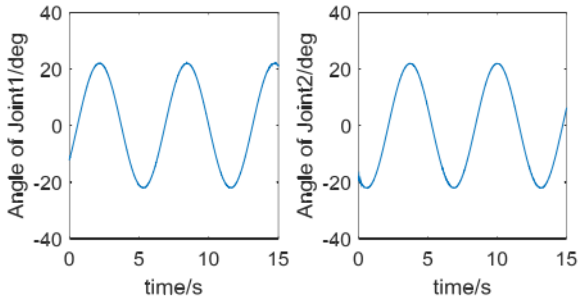


Figure 15. Variation curve of joint angle of snake like robot

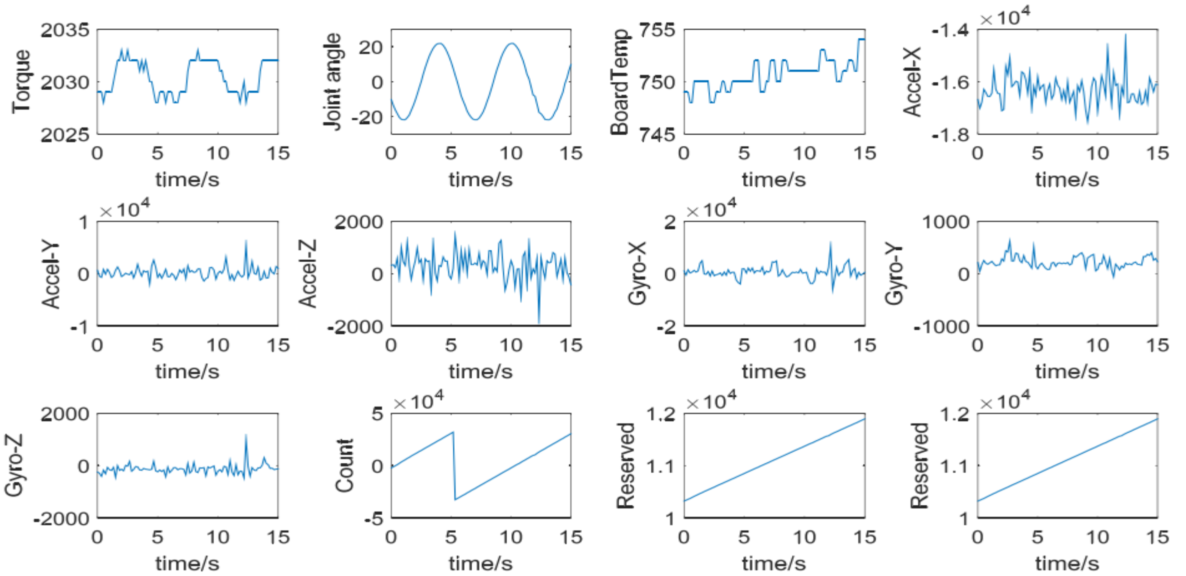


Figure 16. Joint 2 sensor information

It can be seen from the figure 16 that the speed of the snake like robot is positively correlated with the amplitude and period of the trigonometric function of each joint. When the amplitude is 20° and the frequency is the same as that of the meandering motion, the forward speed of the planar rolling gait is about 2.4 m/min, which is faster than that of the meandering motion. The reason is that the normal friction force is far greater than the tangential friction force when the snake-like robot with orthogonal joints is in planar meandering motion, and the friction performance improves the motion effect. The results show that the proposed method is effective and the control effect is stable.

4. Conclusions

In this paper, firstly, the motion planning of the snake like robot is carried out through the curve discretization, and then the coordinated control of the snake like robot gait is realized by the method of mechanical and electrical tracking combined with software design. The online motion control program of the snake like robot is compiled by using PLC and C++ mixed programming. The control system of hybrid programming is more intelligent, and all the work can be completed in a PC. It's more convenient to operate. The prototype of snake like robot is fabricated and assembled, and experiments are carried out to verify the stability and reliability of the proposed control method. The experimental results show that the robot can be controlled to travel at a speed of 2.4 m/min in the plane rolling motion and 2.5 m/min in the snake-like motion. By monitoring the change of each joint angle, it can be found that this method can periodically control the joint rotation, thus realizing the accurate and fast robot travel. In the future research, we can try to optimize the mechanism design of snake like robot to improve the effect of gait coordination control.

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