Improvement of Winding Gait for Snake Robot

Wenyu Xiao¹, Wu Wei¹ and Yong Gao¹,*
¹School of Automation Science and Engineering, South China University of Technology, Guangzhou, China
*Corresponding author e-mail: andygao_scut@163.com

Abstract. In order to solve the problem that the image information is difficult to handle due to the swing of the snake robot’s head during its serpentine locomotion, this paper improves the control function of the general winding gait for the orthogonal joint-connected snake-like robot, and the useful image information is obtained by reducing the swing of the camera-mounted snake's head based on the improved function. Combining the Sigmoid function with the general function to control the rotation of the yaw joints and applying the Gaussian function to the pitch joints to lift the snake head off the ground, this new control function presented in this paper not only enables the joints to rotate smoothly, but also decreases the swing range of the snake head. Additionally, it can also fasten the robot's movement. Experiments based on MATLAB and GAZEBO platform demonstrate the superiority and effectiveness of the improved winding gait.

1. Introduction
Snake robot, a typical bionic robot with strong stability and high robustness, is inspired by biological snakes. Because of snake robot’s multi-degree of freedom and low center of gravity, it has many advantages, such as high stability, adaptability and flexibility. Nowadays, snake robot has been widely used in complex environments such as topographic survey, disaster relief and so on [1].

Since Professor Hirose of Tokyo University of Science and Technology developed the first snake robot in 1972 [2], domestic and overseas scholars have done lots of research on the kinematics model, dynamics model and control method of snake robot by using the serpoid curve proposed by Hirose. With the idea of using curve to fit control function [3], snake robot gradually plays an important role in three-dimensional space and complex environment [4]. In order to achieve the self-perception and self-adaptation of robots to the environment, visual sensors are essential. However, because the snake robot uses sinusoidal-like curve to move forward, the information acquired by the visual sensor will swing violently, which makes it difficult to analyze and match quickly. In this regard, Johana Florez et al. proposed a digital image stabilization algorithm for snake robot [5], which makes the images coherent and stable by motion estimation and inter-frame compensation of the collected images.

However, limited by the control function of the robot and the basic image obtained, the video information still suffers from some problems after processing, such as large field of vision, difficulty in identifying and locating the object, and so on. ChiKit Au adds compensation control function to optimize the relative angle between the head and the body of the snake robot, and make the visual field of the camera stable [6]. But the process of obtaining the optimal parameters of robot’s head compensation function by this method is complex, and compensation for a single joint of snake will destroy the overall coherence of the robot.
In order to solve the above problems, this paper proposes an improved winding gait control function based on the experimental platform of a snake robot with orthogonal joints. We combine Sigmoid function with general control function of yaw joint to ensure smooth rotation of all joints, significantly reducing the swing amplitude of the snake head. In addition, the Gaussian function is applied to the pitch joint control function to lift the snake head slightly to reduce the friction resistance with the ground. Based on the improved joint control function proposed in this paper, the snake robot can obtain more stable image information in the process of fast forward, which provides a theoretical basis for the realization of autonomous positioning and navigation of the robot.

2. Structure Design and Modelling of Snake Robot

2.1. Structure Design

After observing and comparing various snake robot at home and abroad, there are four main joint connection modes of robot: parallel connection, P-R connection, orthogonal connection and universal connection. Considering the versatility, simplicity and other performance and requirements, the joints of the snake robot designed in this paper adopt the orthogonal connection mode. Every two orthogonal joints are combined to generate a unit which can achieve pitch and yaw rotation. A high redundancy structure, composed by all units, enables the snake body to move in a three-dimensional space through coordinated rotation of the orthogonal joints. The orthogonal joint structure is shown in Figure 1.

![Figure 1. Snake robot's unit.](image)

The whole snake robot consists of 8 units, namely 16 joints. Each joint module is composed by a rounded connecting rod (the grey part in Figure 1) and a U-shaped swing arm (the blue part in Figure 1). The structure design of the U-shaped swing arm can make the joint rotate at least 180 degrees, which can reduce the collision and the snake body weight. Each connecting rod is encapsulated with a driving steering gear. The rotation axes of adjacent joints are perpendicular to each other (yellow straight lines in Figure 1), which enables the robot to perform pitch-yaw-pitch-yaw motion in turn. Combining these motions can generate a variety of gaits.

2.2. Kinematics Model

The forward kinematics model plays an essential role in the serial snake robot. It is helpful to describe the robot’s position and posture in three-dimensional space and lays the foundation for the research of target positioning and navigation. In the kinematics analysis of robot, the commonly used kinematics methods are D-H method [7] and screw theory [8]. In this paper, the kinematics model of the snake robot with orthogonal joints is established based on D-H method.

![Figure 2. D-H modeling of snake robot with orthogonal joints.](image)

The base coordinate system \(\{O_0\}\), the end coordinate system \(\{O_n\}\) and the joint coordinate system \(\{O_i\}\) \((i = 1, 2, \ldots, n - 1)\) of the snake robot are shown in Figure 2, and the corresponding D-H parameters are shown in Table 1.
Table 1. D-H Parameter Table of Serpentine Robot with Orthogonal Joints.

| Coordinate system | Joint variables | Offset of link | Length of link | Twist angle of link |
|-------------------|-----------------|---------------|---------------|--------------------|
| 1-2               | $\theta_1$      | 0             | $L$           | $\pi/2$            |
| 2-3               | $\theta_2$      | 0             | $L$           | $\pi/2$            |
| \ldots            | \ldots          | \ldots        | \ldots        | \ldots             |
| (n-1)-n           | $\theta_{n-1}$  | 0             | $L$           | $\pi/2$            |

According to the D-H parameter table and the transformation rules of adjacent coordinate systems, the homogeneous transformation matrix of $\{O_{n+1}\}$ system of snake robot relative to $\{O_n\}$ system is obtained as follows.

$$nT_{n+1} = \begin{bmatrix} \cos \theta_n & 0 & \sin \theta_n & L \cdot \cos \theta_n \\ \sin \theta_n & 0 & -\cos \theta_n & L \cdot \sin \theta_n \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad \text{and} \quad 0T_1 = \begin{bmatrix} 1 & 0 & 0 & l_0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (1)$$

In equation (1), $l_0$ denotes the distance from snake head to joint 1, and $L$ denotes the length of each connecting rod.

Thus, the total transformation of the end coordinate system of the snake robot with respect to the base coordinate system is as follows:

$$0T_n = 0T_1 \cdot 1T_2 \cdot 2T_3 \ldots \cdot (n-1)T_n. \quad (2)$$

So according to the total transformation of D-H parameters, it is in the form of homogeneous matrix multiplication. Taking the snake robot of five modules as an example, the D-H modelling method is implemented and simplified. The following results can be obtained:

$$\begin{bmatrix} C_1(S_{24} + C_{234}) + C_4 S_{13} & C_{12} S_3 - C_3 S_1 & S_{134} - C_1(C_4 S_2 - C_{23} S_4) & p_x \\ S_1(S_{24} + C_{234}) - C_{14} S_3 & C_{13} + C_2 S_{13} & -C_3 S_{34} - S_1(C_4 S_2 - C_{23} S_4) & p_y \\ C_{34} S_2 - C_2 S_4 & S_{23} & C_{24} + C_{3} S_{24} & p_z \end{bmatrix}, \quad (3)$$

Among them, $C_i \triangleq \cos \theta_i$, $S_i \triangleq \sin \theta_i$, $C_{ijk} \triangleq \cos \theta_i \cdot \cos \theta_j \cdot \cos \theta_k$, $S_{ijk} \triangleq \sin \theta_i \cdot \sin \theta_j \cdot \sin \theta_k$, and

$$\begin{cases} p_x = l_0 + L[S_1(S_3 + S_3 C_4) + C_1(1 + C_2 + C_{23} + C_{234} + S_{24})], \\ p_y = L[-C_1(S_3 + S_3 C_4) + S_1(1 + C_2 + C_{23} + C_{234} + S_{24})], \\ p_z = L[S_2(1 + C_3 + C_{34}) - C_2 S_{4}]. \end{cases} \quad (4)$$

Through the above steps, the three-dimensional kinematics model of the snake robot with orthogonal joints is established. Besides, the relative position and attitude of each joint module relative to the basic coordinates can be determined uniquely.

3. Improvement of control function for winding gait

3.1. General function of winding gait

The snake’s winding motion is driven by the friction of scaly skin and irregular obstacles. The snake robot in this paper imitates this method and designs the connecting rod as a shape with tangential stripes. Through coordinated rotation of yaw joint, anisotropic friction can be generated and winding forward can be achieved.

The general function of winding gait is based on the serpenoid curve proposed by Professor Hirose of Tokyo University in Japan [2]. The specific form is as follows:

$$\theta_i = A \cdot \sin(\omega \cdot t + \nu \cdot i) + \varepsilon. \quad (5)$$

Among them, $i$ is the number of joints, $\theta_i$ is the rotation angle of the $i^{th}$ joint, $A$ is the maximum rotation angle of joints, $\omega$ is the angular frequency of the motor, $\nu$ is the angular displacement between adjacent connecting rods, and $\varepsilon$ is the angle displacement of each joint. The general motion pattern of winding gait is shown in Figure 3.
Figure 3. General winding gait in MATLAB.

We use MATLAB and the snake model above to compare the parameters of the general control function of winding gait. The simulation results show that the parameters of the control function have the following effects on the whole gait:

1. For parameter $A$, the larger the value of $A$, the larger the range of the whole snake winding, but the number of peaks will not change.
2. For parameter $\nu$, the larger the value of $\nu$, the larger the winding range and the smaller the number of wave peaks.
3. For parameter $\epsilon$, positive value of $\epsilon$ will cause the snake body to deviate to the right side of the snake head direction, and negative value of $\epsilon$ will cause the snake body to deviate to the left side of the snake head direction.

3.2. Improved function of winding gait

3.2.1. Yaw joint control. Section 3.1 shows that under the control function of general winding gait, the swing amplitude of yaw joint is determined by the value of $A$ and all yaw joints have the same swing amplitude. In order to keep the camera stable during the movement of the robot, the swing amplitude of the snake head should be as small as possible, and the swing amplitude of the middle and rear parts of the snake body should be as large as possible to provide the forward thrust of the robot. For this reason, this paper creatively applies Sigmoid function to decouple the rotating joints, so that the swing amplitude of the robot's head can be controlled to near zero, and the swing amplitude of the rear joints increases gradually, while the swing range behind a certain joint remains constant.

The general expression of Sigmoid function is as follows:

$$S(x) = \frac{1}{1+e^{-x}} \quad (6)$$

In order to control the slope of the Sigmoid curve in the ascending phase and the number of joints whose amplitude changes, the function (7) is improved as follows:

$$S(i) = \frac{1}{1+e^{-k(i-n)}} \quad (7)$$

The parameter $k$ controls the rate of the rising phase of the curve, $n$ is the number of joints expected to be limited, and $i$ is the current joint number.

Combining formula (6) with formula (7), the yaw joint control function of improved winding gait is obtained as follows:

$$\theta_i = \frac{1}{1+e^{-k(i-n)}} \cdot A \cdot \sin(\omega \cdot t + \nu \cdot i) + \epsilon, \text{ if } (i \mod 2) \equiv 0. \quad (8)$$

3.2.2. Pitch joint control. The forward thrust of snake robot comes from the anisotropic friction produced by the swing of yaw joints. Therefore, after applying the new yaw joint control function (8), the swing amplitude of the front part of the robot decreases. The snake head does not provide thrust, but increases friction resistance, which greatly reduces the speed of the robot winding forward. In order to avoid this problem, this paper improves the control function of pitch joints by adopting the Gauss function, the front part of the robot is lifted off the ground and the camera of head is kept parallel to the ground.

The general expression of Sigmoid function is as follows:

$$f(x) = ae^{-(x-b)^2/2c^2} \quad (9)$$
Parameter $a$ is the peak height of the curve. In this experiment, the rotation angle of the steering gear ranges from -0.785 to +0.785, and the stability of the robot will be affected by the height of the snake head from the ground, so $a$ is chosen as 0.5. $b$ is the value of $x$ at the peak of Gaussian curve. Because the pitch joint number is discrete and even, in order to maintain the stability of the robot camera, it is necessary to avoid taking the value at the peak of the curve, so the value of $b$ can be taken as an odd number, here $b$ is set to 1. Parameter $c$ represents the rate of curve rising and falling. In order to minimize the effect of the function on the stability of the robot, the value of $c$ should be as small as possible while not to make other points be 0, here $c$ is set to 0.5. Since the swing direction of the adjacent two pitch joints is opposite, so when the value is given to the joint is positive, the camera of the robot is parallel to the ground. Thus, the control function of the pitch joint used in this paper is as follows.

$$\theta_i = 1.5 * e^{-(i-2)^2}, \text{ if } (i \mod 2) = 1. \quad (10)$$

4. Simulation

4.1. Theoretical simulation

In this section, we use the platform of MATLAB and the snake robot model to compare the general winding gait control function with the improved control function. Meanwhile, the parameters in the new control function are modified to compare the effects of different parameters on the shape of the robot, and the appropriate parameters are selected for the following experimental simulation. The experiment verifies the effectiveness of the improved control function theoretically.

As shown in Figure 4, the red curve is the general winding gait control function at a certain time, and the angle values of corresponding numbered joints are obtained at even values. And the blue curve is the improved control function curve. It is obvious that the value range of the general joints of the robot is consistent with the whole. The improved curve function limits the value range of the front part of joints and limits the swing range of the robot head. The theoretical simulation results are consistent with the expected results, which proves the theoretical correctness of the improved control function.

Figure 5 shows the control function curves of four groups of different parameters. It is known that the excessive value of parameter $k$ and parameter $n$ will cause the overall swing amplitude of the robot to be too small and affect the forward speed, while the small values of $k$ and $n$ will affect the smoothness of the whole curve. Considering the factors such as the control function of pitch joints and the stability of the robot, the parameter $k$ is set to 1 and $n$ is set to 3 in the following experimental simulation.

![Figure 4. General and improved function curve of winding gait for yaw joints.](image1)

![Figure 5. Comparison of improved control function parameters.](image2)
4.2. Experimental simulation

In this paper, a snake robot model is established under the environment of ROS and GAZEBO. There are eight units in the model, which are connected by orthogonal method. Meanwhile, the camera is fixed on the head of the robot and parallel to the ground, as shown in Figure 6 below.

![Figure 6. Snake robot model built in GAZEBO.](image)

In the simulation scenario, three cylinders are placed two meters ahead of the head of the snake robot, and the distance between each two cylinders is two meters. Firstly, we use the general control function of meandering gait (5) to simulate the motion of the robot. In the function, the parameter $A$ is set to 1.3, $\omega$ is set to 3, $\nu$ is set to 0.6 and $\varepsilon$ is set to 0. During the motion of the robot, the image information of the snake camera acquired during a swing period is shown in Figure 7 below.

![Figure 7. General winding gait and camera image information.](image)

Obviously, in the course of general winding gait movement, the image obtained by the camera oscillates too much, which makes it difficult for image processing, and even loses the red cylinder in front of it in some viewpoints.

In the same scenario, the improved winding gait formulas (9) and (11) are used to control the motion of the robot. The parameters of the function are consistent with those of the general control function. And the image information of the snake camera acquired is shown in Figure 8 below.

![Figure 8. Improved winding gait and camera image information.](image)

Comparing the two control functions, the improved gait function limits the camera's swing angle of view and greatly increases the stability of the camera. And the red cylinder in front of the camera is always in the field of vision, which greatly improves the availability of basic graphics information.

At the end of the experiment, we compare the forward speed of the robot controlled by two gait functions. Under the general gait function, it takes 1 minute and 8 seconds for the robot to advance 1m, and the speed is 1.47 cm/s. In the same environment, it takes 1 minute and 17 seconds for the robot to advance 1m under the improved gait function control, and its speed can reach 1.3 cm/s. It can be seen that the improved control function has little effect on the forward speed of the whole robot, and the whole robot can move smoothly.
5. Conclusion

This paper focuses on the stability of view angle of camera equipped on the snake-like robot’s head. Based on the general control function, a novel winding gait control function is proposed. The Sigmoid function and Gauss function are applied to control the yaw and pitch joints of orthogonally connected snake robot, respectively. Imitating and comparing the motion process of snake robot under the general control function and the improved control function, the experiments show that snake robot’s camera is more stable under the improved control function, which verifies the validity of the improved gait function and the availability of images.

In this paper, we only improve the gait function of the snake robot and obtain the basic image information. In the following works, it is necessary to apply the image processing and path planning algorithm to achieve the function of locating and tracking specific targets.

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