Simulation and Experimental Study of the Direction Control Based on the Torque Compensation of a Snake Robot

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**Abstract.** Because the direction goals of the snake robot are different in applications, e.g. the target point and target path, the direction control of the snake robot is a challenging problem. In this paper, the direction of the snake robot which is controlled by the passive creeping control method is discussed. A new direction control method which is based on the torque compensation is proposed. The direction control method set a universal direction goal for all the applications. The torque of the head joint which leads the locomotion direction is adjusted by the torque compensation. The compensated torque decreases the angle between the direction of the body axis and the expected direction by the exponential decay function. In simulation, the trajectory and the angle describe the process of direction adjustment. The error analysis proves the validity and adaptability of the proposed direction control method. Also the validity of the proposed method is proved by the experiment which is based on the virtual/physical mixed experimental system.

**Introduction**

A biological snake with hundreds of joints can perform various locomotion gaits [1]. The various locomotion gaits give the biological snake ability to adapt to the various environments, e.g. desert and tree. The great locomotion capability and environment adaptability attract the researchers’ attention. The snake robot is developed by imitating the body structure and movement form of the biological snake [2-7]. The snake robot will be used to work in the environment where human and the limbs animal cannot arrive, such as the deep-space detection, disaster rescue and so on.

The present researches on the snake robot mostly concentrate on the control algorithmic of the basis movement, while it is short of the further study on the some problems in the snake robot’s application. The direction control is one of the most important questions in the application, but it is difficult to control the locomotion direction of the snake robot because of the multiple-joint and specific movement form. The existing direction control method can be divided into the following three categories: 1) the sinusoidal angle control method [8-10], which control the locomotion direction of the snake robot by transforming the expected direction into the parameter of the joint angle, the typical methods are amplitude adjustment method and phase adjustment method, etc. 2) central pattern generator [11, 12], CPG, which transforms the expected direction into the parameter...
of the CPG. 3) The energy-based passive creeping [13]. In this control method, there is a parameter, only used to change the movement direction. The above algorithms can change the movement direction of the snake robot, while the relationship between the expect movement direction and the parameter of the control method is fixed or unfixed, so the direction control parameter is difficult to be computed. The reason for the above drawback can be summarized that the expected direction cannot be directly used for control parameter.

We have proposed a passive creeping control method which is based on the energy balance. In this paper, a direction control algorithm based on the passive creeping control method is proposed. The locomotion direction is controlled by additional torque compensation. The decay function of the torque compensation decreases the angle between the body axis and the expected direction. When the body axis is equal to the expected direction, the function of the torque compensation will disappear.

The contents of the paper are arranged as follow: firstly, a universal goal of the direction control is proposed. A detailed introduction on the direction control method is expressed in the secondly section. Thirdly, the validity and adaptability of the proposed direction control method are proved by the results of the simulation. Fourthly, the experiment analysis is shown. Lastly, we will give a summary.

The universal goal of the direction control

The direction goal of applications. The snake robot can be applied in the deep space exploration and disaster rescue. The different part of the snake robot is wanted to reach the target point in the different applications, for example, in some situations, to observe the status of the target point, the head is needed to reach the target point; in other situations, when the snake robot is an operation, the tear is controlled to reach the target point. In addition, when the path is limited, the goal of the locomotion is not only to reach the target point, but also to move along the expected path.

Because the body of the snake robot follows the trajectory of the head, so the above direction targets are summarized into one class in this paper: whether the locomotion goal is a target point or an expected trajectory, whether the head or the body part is controlled to reach the target, the goal of the snake robot’s locomotion is that the head of the snake robot reach the expected point which is the point on the expected trajectory or the target point.

The direction goal of the direction control method. The definitions of the two most important parameters of the direction control in this paper are expressed as follow:

Definition 1: The expected direction means the direction from the center of the head link to the expected point which is the point on the expected trajectory or the target point, and the expected direction is shown in Fig.1.

Definition 2: There are two points that the coordination of the head when the head joint is zero in one period, expressed as $P, O$. The direction of the snake robot’s body axis means the direction from the first point $P$ to the second point $O$, and the direction of the snake robot’s body axis is shown in Fig.1.

The direction goal in the application is transformed into the goal of the control algorithm as shown in Fig.1. $a$ is the absolute value of the angle between the expected direction and the link direction of the snake robot. Due to ‘S’ shape of the locomotion trajectory, $a$ is continuously change, $a_1 \leq a \leq a_2$ in one period, where $a_1, a_2$ are two values of $a$ when the head joint of the snake robot is zero in one period. When the direction of the body axis is not equal to the expected direction, $a_1 < a_2$. When the direction of the body axis is equal to the expected direction, $a_1 = a_2$. In this paper, the goal of the proposed direction controller is $a_1 = a_2$ after the torque compensation.
The direction control method

The retrospect of the passive creeping method which is based on the energy balance. The snake robot has \( n \) links and \( n-1 \) joints, \( \dot{\mathbf{q}} = (\dot{q}_1, \dot{q}_2, \ldots, \dot{q}_{n-1}), \mathbf{q} = (q_1, q_2, \ldots, q_{n-1}) \) are the angle and angular velocity respectively. The main content of this section is the retrospect of the passive creeping method which we have proposed. The research process of the control method is along with the process of the energy balance.

Firstly, in the stage of the energy supply, Because the energy supply directly affects the movement of the snake robot, to adapt to the environment, the energy supply must cater for the energy demand, so we can obtain the relation as follow:

\[
\dot{\tau} = \dot{E} - \dot{P}_d. \tag{1}
\]

Where:
1) \( \dot{E} \) is the kinetic energy change rate, means movement demand;
2) \( \dot{P}_d \) is the energy dissipation rate.

Secondly, in the stage of the energy distribution, an optimal distribution of the energy source is proposed as follow: a given \( \dot{\tau} \), \( \sum_{i=1}^{n-1} \tau_i^2 \) is minimum. According to the conditional extreme value method, we get the optimal torque as follow:

\[
\tau_i = \frac{(\dot{E} - \dot{P}_d)\dot{q}_i}{\sum_{i=1}^{n-1} \dot{q}_i^2} \quad i = 1, 2, \cdots, n-1. \tag{2}
\]

Finally, in the stage of the energy transfer, the snake robot, simulating the movement characteristic of the biological snake that the head leads the locomotion direction and the body follows the movement of the head by dynamic transfer, can reduce the energy dissipation.

To take the above three stages into consideration. The passive creeping method is proposed and described as follow:

\[
\tau_a = I \cdot a \cdot K \cdot [\ddot{q}_d + k_d(\dot{q}_d - \dot{q}_0) + k_p(q_d - q_0)]. \tag{3}
\]

\[
\tau_j = K \cdot (q_{j-1} - q_j) \quad j = 2, 3, \cdots, n-1. \tag{4}
\]

Where:
1) \( I \) is the moment of inertia of the head module about the head joint axis[13];
2) \( a \) is a control parameter;
3) \( q_d \) is the reference angle.
\[ K = \frac{n \cdot v \cdot (\bar{E} - P_d)}{L \cdot \sum_{i=1}^{n-1} \dot{q}_i^2} \]  

(5)

\[ \dot{q}_i = \frac{1}{L} \sum_{j=1}^{n-1} q_j \]  

(6)

\[ \tau_s = \tau_i \]  

(7)

\[ \bar{\tau} = I \cdot \alpha \cdot K \cdot \delta. \]  

(8)

\[ \delta = (\rho \cdot e^{-c \cdot a} - 1) q_d. \]  

(9)

K is the amplitude of the joint torque, which is changed by the environment and movement demand;

1) \( v \) is the linear velocity of the head;
2) \( L \) is the length of the snake robot.

In the above mentioned control method, the reference angle \( q_d \) is only used to stimulate the continuously swing of the snake robot’s head, and the snake robot cannot fully follow the reference angle, the follow degree is adjusted by \( K \). From the above analysis, the locomotion direction is uncontrollable. In this paper, to control the locomotion direction of the snake robot which is controlled by the above passive creeping method, the torque compensation is added to the above torque to utilize the direction controllability of the snake robot.

The direction control which is based on the torque compensation. The passive creeping method Eq.3 and Eq.4 show that the head of the snake robot leads the locomotion direction and the body follows the head. To control the direction of the snake robot, we propose the following control method.

The control method of head joint:

\[ \tau_{s0} = I \cdot \alpha \cdot K \cdot [\dot{q}_d + k_d (\dot{q}_d - \dot{q}_0) + k_p (q_d - q_0) + \delta]. \]  

(6)

The control method of body joint:

\[ \tau_{si} = \tau_i. \]  

(7)

According to Eq.6 and Eq.3, we can get

\[ \bar{\tau} = I \cdot \alpha \cdot K \cdot \delta. \]  

(8)

Where \( \bar{\tau} \) is called the torque compensation. \( \dot{q}_i \) is the input power, where \( \tau_s = (\tau_{s1} \tau_{s2} \cdots \tau_{s(n-1)}) \).

The change of the input power brings the change of the rotational energy; the change of the rotational energy brings the change of the direction of the head link, so the trajectory of the snake robot is ‘S’ shape. The symmetrical changes of \( \dot{q}_s \) can keep the direction of the locomotion unchanged in one period; on the contrary, the asymmetrical changes of \( \dot{q}_s \) will change the direction of the snake robot’s locomotion in one period. Utilizing the above mentioned effect on the direction, \( \delta \) is set as follow:

\[ \delta = (\rho \cdot e^{-c \cdot a} - 1) q_d. \]  

(9)

Where \( \rho \) and \( c \) are constants, The two constants adjust the speed of the exponential decay by adjusting the effect on the torque of the difference between \( a_1 \) and \( a_2 \). The two constants are set empirically. How the torque compensation \( \bar{\tau} \) controls the direction of the locomotion is described as follow. From Fig.1 (a), in the beginning of the locomotion, the direction of the body axis is not equal to the expected direction, expressed as \( a_i < a_i \). According to the performance of the exponential function as shown in Fig.2, the relation \( e^{c \cdot a_i} - e^{c \cdot (a_i - \Delta a)} > e^{c \cdot a_2} - e^{c \cdot (a_2 - \Delta a)} \) can be got. When \( a = a_i \), the change rate of \( \delta \) is less than \( \delta \) of \( a = a_i \), the asymmetrical changes of \( \delta \) bring the asymmetrical changes of \( \tau_s \). The asymmetry will be continuously decreased by the exponential decay function \( \delta \), and the asymmetry will change into symmetry at \( a = a_i \) which means that the direction of the body axis is equal to the expected direction.
Simulation analysis

The simulation platform is ODE (Open dynamic engine)[14], and the simulation parameters are shown in Table 1.

Table 1 The basic parameters in simulations

| Parameter               | Symbol | Value |
|-------------------------|--------|-------|
| Number of real units    | \( n \) | 10.0  |
| Length of the \( i \) th unit | \( l_i \) | 0.08m |
| Mass of the \( i \) th unit | \( m_i \) | 0.5kg |
| Inertia of the \( i \)th unit | \( I_i^b \) | \( 0.27\times10^{-3}\) kg\( \cdot \)m\(^2\) |
| Time Step of simulation | \( T \) | 0.01s |
| Reference angle         | \( x_d^a \) | \( 0.5\sin(2t + \pi/2) \) rad |
| Control parameter 1     | \( a \) | 10.0  |
| Control parameter 2     | \( k_d \) | 1.0   |
| Control parameter 3     | \( k_p \) | 1.0   |
| Reference energy        | \( E_{\text{ref}} \) | 0.5   |
| Direction parameter 1   | \( \rho \) | 1.0   |
| Direction parameter 2   | \( c \) | 1.0   |

Let each real unit be of the same length, mass and inertia respectively.

The validity of the direction control method. To demonstrate the validity of the proposed method, the trajectory of the snake robot is shown in Fig. 3. In Fig. 3, the locomotion of the snake robot is start from the point (0, 0). The target point of the locomotion in Fig. 3 (a) is (6,-6). The target point of the locomotion in Fig. 3 (b) is (6,-6) too, but the trajectory is limited by the expected path which is marked by a line. Fig. 4 shows the changes of \( a \) which correspond to the locomotion in Fig. 3. In Fig. 4 (a), \( a_1 \neq a_2 \) at the beginning of the locomotion can be known; after adjusting, \( a_1 = a_2 \), so the body axis is equal to the expected direction. Due to the change of the given path, \( a \) of locomotion in Fig. 3 (b) will sharply change when the path is changing. From Fig. 3 and Fig. 4, it is known that the snake robot can be close to the target point by adjusting \( a \).
The trajectory of the snake robot locomotion

Fig. 3 The trajectory of the snake robot in the ODE

(a) The trajectory of the snake robot locomotion  (b) The trajectory of the trajectory is limited

(a) The change of the locomotion of Fig. 2(a)  (b) The change of the locomotion of Fig. 2(b)

Fig. 4 The absolute value of $a$ of the locomotion in Fig. 2

(a) The $a$ change of the locomotion of Fig. 2(a)  (b) The $a$ change of the locomotion of Fig. 2(b)

The environment adaptability of the direction control method. The snake robot which is controlled by the passive creeping has great locomotion capability and environment adaptability, so the direction control is demanded to adapt to the different environments. Fig. 5 shows the error between the snake robot and the target point when the snake robot is in 49 different environments that the tangential friction coefficient changes from 0.003 to 0.021 with the 0.003 interval, and the

Fig. 5 The error between the snake robot and the target point when the snake robot in different environments with the different tangential friction coefficient and the different normal friction coefficient.
normal friction coefficient changes from 0.2 to 0.5 with the 0.05 interval. The start point of all the 
locomotion is (0,0), and the target point is (6,-6). The error is equal to \( \sqrt{(x-x_t)^2 + (y-y_t)^2} \), where  
\((x, y)\) is the coordinate of the snake robot’s head, and \((x_t, y_t)\) is the target point. From the errors 
in Fig.5, we can know the snake robot can reach the target point with little error. The results  
demonstrate that snake robot which is controlled by the proposed direction control method has great 
environment adaptability. The snake robot can reach the target point, while the error is inevitable.  
The reasons for the error is summarized as follow: 1) the ‘S’ shape of the snake robot’s locomotion.  
2) The passive creeping is generated by inputting torque, displacing the angle planed in advance.

**Experiment research**

**Experiment bench.** The experiment of direction control adopts the mixed virtual/physical  
experiment which is proposed in the energy-based passive creeping [15]. The experimental bench  
mainly consists of a host computer which is used to simulation, an Optotrak Certus motion optical  
motion capture system which is used to capture the date of the snake robot’s locomotion, and a  
snake robot. The environment is the rough rubber that the normal friction coefficient is 0.612±0.047  
and the tangential friction coefficient is 0.042±0.012 [15]. The target point is marked by the white  
and circinal marker as shown in Fig.6.

![Fig.6 Experiment system of the proposed direction control](image)

The experiment flow is described as follow. The coordination of the target point can be  
measured before the experiment or can be measured by the optical measure system captures. In this  
paper, only to prove the validity of the proposed method, the first method of the target point  
measure is chosen. The optical measure system captures the kinematic and angle information of the  
real snake-like robot in real time. The coordination of the target point and the kinematic data are fed  
back to the host computer by the Optotrak API. The target point and the kinematic data input the  
controller of the virtual snake robot in simulation, and joints’ angles of the snake robot are  
transmitted to motor of the real snake robot based on RS-232.
Experiment results. The snake robot starts movement from the 50\textsuperscript{th} second as shown in the first picture of Fig.7. From the figure, in the beginning of the creeping, the snake robot cost about 25 seconds to adapt to the environment and adjust the head direction. After adjusting, the snake robot can precisely reach the target point. From Fig.8, we can known the distance between the head of the snake robot and the target on X axis and Y axis reach zero nearly at the same time. From Fig.7 and Fig.8, we get the result that the snake robot can reach the target point.

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Conclusion

According to the universal direction goal which is proposed in the paper, a direction control method which is based on the passive creeping is proposed. A new torque as compensation is added to the original torque. The torques as the input parameters control the joints; the head joint angle is changed by the changed torque; the direction is changed by the changed joint angle. The exponential function of the compensation torque controls the snake robot to reach the target direction. The simulation results demonstrate the validity and adaptability of the direction controller, and prove the direction of the passive creeping which is based on the energy balance can be controllable. The experience results further demonstrate the validity of the proposed direction control algorithm.
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