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Obstacle Avoidance of Snake Robot by Switching Control Constraint

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Abstract: In this paper, we propose an obstacle avoidance strategy for the autonomous locomotion control of a snake robot with passive wheels. By using a general pass planning method for the head position control, it will be a complicated problem and the robot will have to take a circuitous path because any parts of the robot (from head to tail) must avoid contact with the obstacle. Our strategy is transformation of a periodic undulate gliding form for the robot to keep go straight without any collision with the obstacle. It is actualized by switching a control constraint imposed on the head of the robot. In this paper, we denote the detail of our strategy and investigate the effectiveness of our strategy by numerical simulations.

Keywords: snake-like robot, obstacle avoidance, control constraint

1 INTRODUCTION

As a control strategy of the n-link snake robot with passive wheel, Mita and Prautsch et al [1] proposed an autonomous locomotion control of the head's position based on Lyapnov function method. They also proposed another control strategy which restricts the motion of the snake robot to some kind of a serpenoid curve to minimize the energy needed for motion of the snake robot. The serpenoid curve has proposed by Hirose [2], he is a pioneer of the field of the snake robot, to describe the undulation of natural snakes. This is based on an assumption that natural snakes have developed an efficient way of creeping. As other approaches, Hoshi et al [3] proposed an autonomous control strategy with consideration of the dynamic manipulability. Sato et al [4] proposed a method that they removed passive wheels of some links, and introduce the shape controllable points in the snake robot's body.

Considering the autonomous locomotion control of the snake-like robot in real environment, obstacle avoidance is one of the important tasks. However, there are few reports about it. Therefore, in this paper, the obstacle avoidance is considered under following assumptions; a snake robot is going straight, this robot consists of some rigid links with passive wheels, there is one obstacle in the direction of forward movement of the robot, and the length of robot is long enough for the width and depth of the obstacle. For above assumption, a general path planning method for the head position control will be figured out immediately. However, the path must be designed to that any parts of the robot (from head to tail) avoid contact with the obstacle. Therefore, the path planning will be complicated problem and robot will have to take a circuitous path. Moreover, if the robot must go straight through the area where is narrow width, enclosed with walls (for example, pipe line or air duct) and assigned one obstacle, the robot might not be able to pass the area without any touch with the obstacle or walls.

For these problems, we propose a different approach of the obstacle avoidance. Note that the robot moves with periodic undulant gliding form. If the length of robot is long enough for the width and depth of the obstacle, and the amplitude and cycle length of the gliding form can be chosen appropriately when the snake robot closes the distance from the obstacle, the robot will be able to keep go straight without any collision with the obstacle. To control the snake locomotion with an arbitrary gliding form, we introduce zeroing method [1]. It constrains the motion of the snake robot to an arbitrary serpenoid curve. This constraint is imposed on the first link of the robot. The serpenoid curve can be calculated by numerical integration and the snake robot traces the curve exactly. Therefore, switching the control constraint, the gliding form is transformed and the snake robot traces the changed serpenoid curve. In this paper, we denote the detail of our strategy and investigate the effectiveness of our strategy by numerical simulations.

2 Dynamic model of the Snake Robot

In this research, we deal with the dynamical model of the snake-like robot consisting of n-links as shown in Figure 1. Length $2l$ and weight m are the same for each link and distribution of the weight is assumed to be uniform. Therefore, the COM (center of mass) of each link is placed at the middle of the link. (x, y) is the position of the head in $x-y$ coordinates on a ground. For each link, (x_i, y_i) and θ_i $(i=1,...,n)$ represent the position of its COM and absolute angle measured clockwise from y axis. $p_i (i=1,...,n-1)$ is the relative angle which is controlled by input torques $u \in R^{n-1}$.

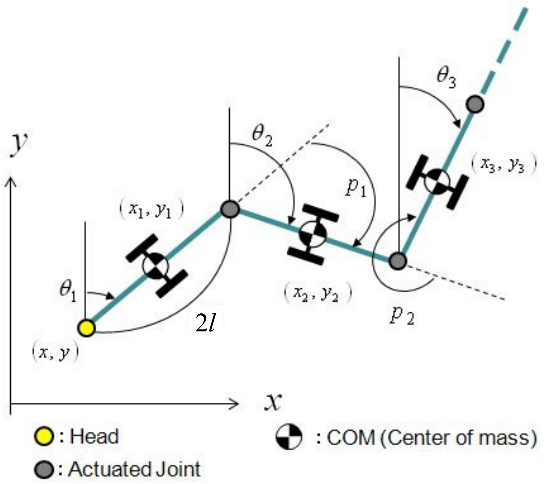


Fig. 1. n-link model of the snake robot

Each link has a passive wheel at the middle which does not slip in direction perpendicular to the body. From the condition, the equation of motion of the snake-like robot can be written as

$$\tilde{M}(\theta)\ddot{w} + \tilde{C}(\theta, \dot{\theta})\dot{w} + \tilde{D}(\theta)\dot{w} = F^T(\theta)Eu$$
$$w = \begin{bmatrix} x \\ y \end{bmatrix}, \theta = \begin{bmatrix} \theta_1 \\ \vdots \\ \theta_n \end{bmatrix} \qquad (1)$$

where $\tilde{M}$, $\tilde{C}$ and $\tilde{D}$ are matrices which are relevant to inertia, centrifugal force and friction, respectively. $E \in R^{n \times n-1}$ is a matrix satisfying $\theta = Ep$. F is a matrix which expresses the velocity constraint of each links is as $\dot{\theta} = F(\theta)\dot{w}$. In our research, we use another reduced order model using a different set of coordinate in order to control the robot motion with an arbitrary gliding form. Rewriting Eq.(1) with respect to the absolute angle of the 1st link θ_1 and the length of the trace of the 1st link η_1, the following system is obtained.

$$\bar{M}\begin{bmatrix} l\ddot{\theta}_1 \\ \ddot{\eta}_1 \end{bmatrix} + \bar{C}\begin{bmatrix} l\dot{\theta}_1 \\ \dot{\eta}_1 \end{bmatrix} + \bar{D}\begin{bmatrix} l\dot{\theta}_1 \\ \dot{\eta}_1 \end{bmatrix} = GF^T Eu \qquad (2)$$

Where, G is a transformation matrix, and $\bar{M}$, $\bar{C}$ and $\bar{D}$ are transformed matrices from $\tilde{M}$, $\tilde{C}$ and $\tilde{D}$ by the change of coordinate, respectively. The detail of the derivation of Eq. (1) or Eq (2) is introduced in [1].

3 Obstacle avoidance strategy

Here, let consider an obstacle avoidance problem for the snake robot modeled as Fig.1 under following assumptions; a snake robot is going straight, there is one obstacle in the direction of forward movement of the robot, and the length of robot is long enough for the width and depth of the obstacle. In the case, a general path planning method for the head position control will be figured out immediately. However, the path must be designed to that any parts of the robot (from head to tail) avoid contact with the obstacle as shown in Figure 2. Therefore, the path planning will be complicated problem and robot will have to take a circuitous path.

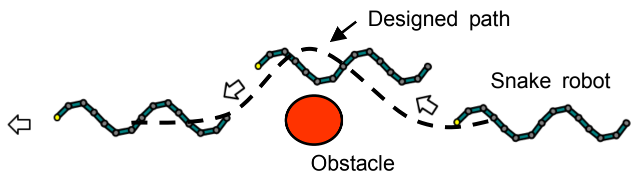


Fig. 2. Obstacle avoidance by the path planning

Moreover, as shown in Figure 3, the robot must go straight through the area where is narrow width, enclosed with walls (for example, pipe line or air duct) and assigned one obstacle, the robot might not be able to pass the area without any touch with the obstacle or walls.

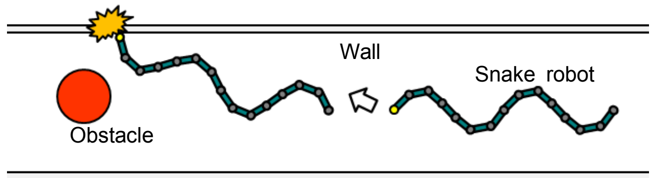


Fig. 3. Obstacle avoidance in the narrow width space

For these problems, if the robot can move with a periodic undulate gliding form, and the amplitude and cycle length of the gliding form can be chosen appropriately when the snake robot closes the distance from the obstacle, the robot will be able to keep go straight without any collision with the obstacle. Furthermore the robot will be able to pass the narrow width space without any touch with the obstacle or walls (See Figure 4).

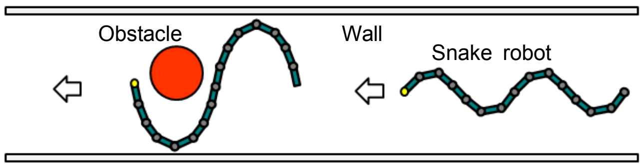


Fig. 4. Obstacle avoidance changing the gliding form

To control the snake locomotion with an arbitrary gliding form, we introduce zeroing method [1]. It constrains the motion of the snake robot to an arbitrary serpenoid curve.

3.1 Serpenoid Curve

The serpenoid curve has proposed by Hirose [2] to describe the undulation of natural snakes. An arbitrary curve can be described by its length η and the direction angle $\theta(\eta)$, as shown in Fig.5.

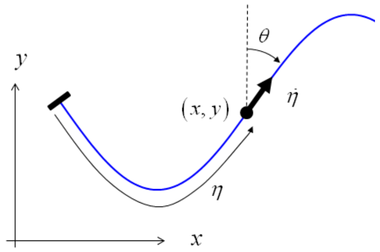


Fig. 5. Length and direction angle of a curve

Following Hirose[2], the serpenoid curve is defined as

$$\frac{dx}{d\eta} = \sin(w\sin(k\eta)), \frac{dy}{d\eta} = \cos(w\sin(k\eta)) \tag{3}$$

From this definition and relations $dx = \sin\theta d\eta$, $dy = \cos\theta d\eta$, it can be see that

$$\theta = w\sin(k\eta) = w\sin\left(\frac{\pi}{2L}\eta\right). \tag{4}$$

Therefore, the serpenoid function is a curve whose direction angle varies sinusoidally along the distance and shape of the curve depends on the w or k . Where, w is a maximum angle of gliding form and L is body length of 1/4 cycle of gliding form. The position of any point on the curve is obtained by integrating (3).

3.2 Restrict motion to the serpenoid curve

To restrict the motion of the robot to an arbitrary serpenoid curve, we use zeroing method [1]. For the control constraint to the serpenoid curve (4) and distance control with a reference distance along the curve γ expressed as

$$\begin{aligned} F_1 &= l\theta_1 - lw\sin(k\eta_1) = 0 \\ F_2 &= \eta_1 - \gamma = 0 \end{aligned}, \tag{5}$$

following differential equations are defined.

$$\begin{aligned} &\ddot{F}_1 + \alpha\dot{F}_1 + \beta F_1 = 0 \\ &\ddot{\eta}_1 + \vartheta\dot{\eta}_1 + \xi(\eta_1 - \gamma) = 0 \end{aligned} \tag{6}$$

where,

$$\begin{aligned} &\dot{F}_1 = l\dot{\theta}_1 - lwk\cos(k\eta_1)\dot{\eta}_1 \\ &\ddot{F}_2 = l\ddot{\theta}_1 - lwk\cos(k\eta_1)\ddot{\eta}_1 + lwk^2\sin(k\eta_1)\dot{\eta}_1^2 \end{aligned} \tag{7}$$

and $\alpha, \beta, \vartheta, \xi$ are positive coefficients. Define a nonsingular transformation matrix

$$P = \begin{bmatrix} 1 & -lwk\cos(k\eta_1) \\ 0 & 1 \end{bmatrix} \tag{8}$$

and multiply the vector $\begin{bmatrix} l\ddot{\theta}_1 \\ \ddot{\eta}_1 \end{bmatrix}$ by P from the left to get

$$P\begin{bmatrix} l\ddot{\theta}_1 \\ \ddot{\eta}_1 \end{bmatrix} = \begin{bmatrix} l\ddot{\theta}_1 - lwk\cos(k\eta_1)\ddot{\eta}_1 \\ \ddot{\eta}_1 \end{bmatrix} := K. \tag{9}$$

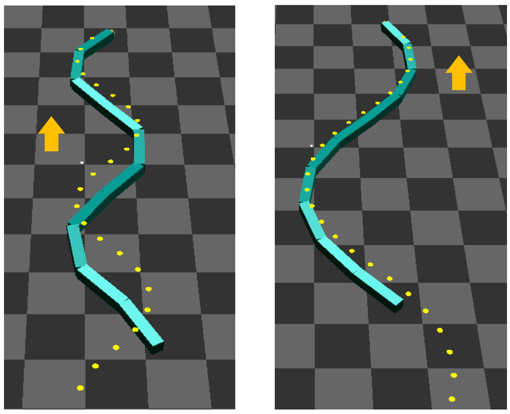
Substituting from (7) and (6) into (9) yields

$$\begin{bmatrix} l\ddot{\theta}_1 \\ \ddot{\eta}_1 \end{bmatrix} = P^{-1}\begin{bmatrix} -lwk^2\sin(k\eta_1)\dot{\eta}_1^2 - \alpha\dot{F}_1 - \beta F_1 \\ -\vartheta\dot{\eta}_1 - \xi(\eta_1 - \gamma) \end{bmatrix} \tag{10}$$

And then, substituting (10) into the system (2), the controller

$$\mathbf{u} = \left(GF^T E\right)^{\dagger}\left[\left(\bar{C} + \bar{D}\right)\begin{bmatrix} l\dot{\theta}_1 \\ \dot{\eta}_1 \end{bmatrix} + \bar{M}P^{-1}K\right] \tag{11}$$

are obtained. This ensure that $F_1 \to 0, F_2 \to 0$.



(a) $4L = 5.0[m]$ (b) $4L = 10.0[m]$

Fig. 6. Simulation of motion of a 10 link snake robot

Figure 6 shows two motions of the snake robot. These simulations are applied the controller (11) to the system (2). The robot has 10 links and each length is 1.0[m], yellow dot-lines denote the serpenoid trace, and the robot go straight to the upper direction. In the left figure (a), parameter w is set $\pi/4$ [rad] and $4L = 5.0[m]$ (It means that the robot moves with two cycle undulate motion). As a result, the robot shows a periodic undulate gliding form. However, the gap between the Serpenoid curve and link position is increased as the distance from the head. On the other hand, in the right figure (b), parameter w is set $\pi/4$ [rad] and $4L = 10.0[m]$. In this case, the gap is very small compared to (a). We simulated various patterns changing w, $4L$, the link length or the number of links. As a result, we confirmed that the number of links is larger or the cycle length of the serpenoid curve is longer, the gap tends to be decreased. Therefore, this control method is useful for the obstacle avoidance if the length of robot is long enough and has appropriate amount of links for the width and depth of the obstacle.

3.3 Switching control constraint

For the snake locomotion, there is an energy-efficient gliding form. Therefore, it is reasonable that under normal conditions, the robot moves with the energy-efficient gliding form, and when the robot confronts the obstacle, the gliding form is transformed to avoid collision with the obstacle. The transformation of the gliding form is actualized by switching the control constraint. Namely, change the values of w or k. However, at the switching point, the angle of the changed serpenoid curve must be coincided with the angle of the former serpenoid curve. If it is omitted, the trace of the 1st link strays far from the serpenoid trace after the switching point as shown in Fig.7.

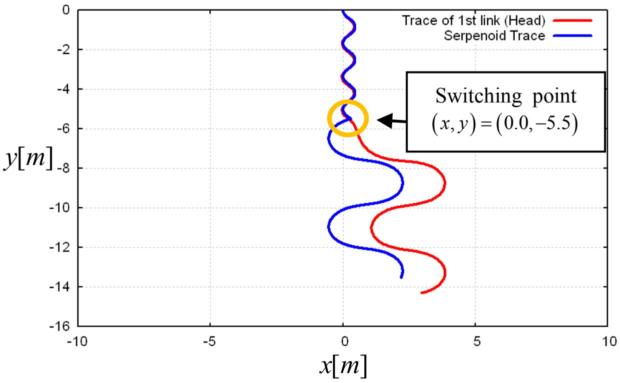


Fig. 7. Simulation result of switching control constraint

Moreover, about the connection of serpenoid functions, two cases are considered as shown in Fig.8. In Case1, the curve is non-smooth and it cause rapid variations of input torques. Therefore, Case2 should be chosen. To achieve the connection as Case2, the serpenoid function after the switching is designed as follows.

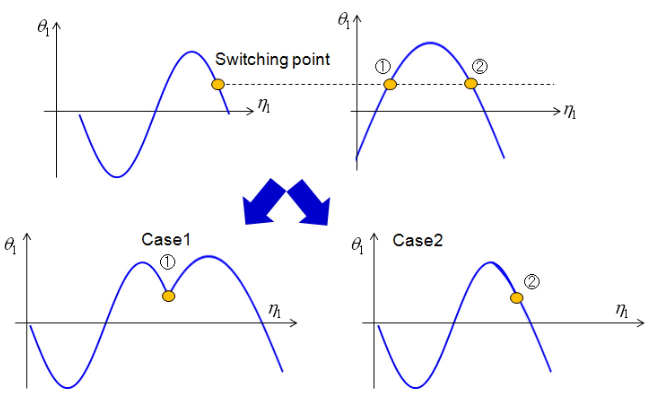


Fig. 8. Connection of the serpenoid function

$$\theta_1(\eta_1)=\begin{cases} w_\beta \sin(k_\beta \eta_1+\phi) & \dot{\theta}_1(\eta_{sw})\ge 0 \\ w_\beta \sin(k_\beta \eta_1+\pi-\phi) & \dot{\theta}_1(\eta_{sw})<0 \end{cases}, \qquad (12)$$
$$\phi = k_\beta \eta_{sw} + \sin^{-1}\left(\frac{\theta_1(\eta_{sw})}{w_\beta}\right)$$

where $w_\beta, k_\beta, L_\beta$ are parameters of the serpenoid function after the switching and η_{sw} is a constant of the length of the trace of the 1st link at the switching point. In Fig.9, it is shown that the trace of the1st link is well coincided with the serpenoid trace after the switching point.

From the result, it is known that designing a serpenoid curve to avoid an obstacle with the proposed technique, the snake robot achieve the obstacle avoidance because the robot can trace the designed trace exactly.

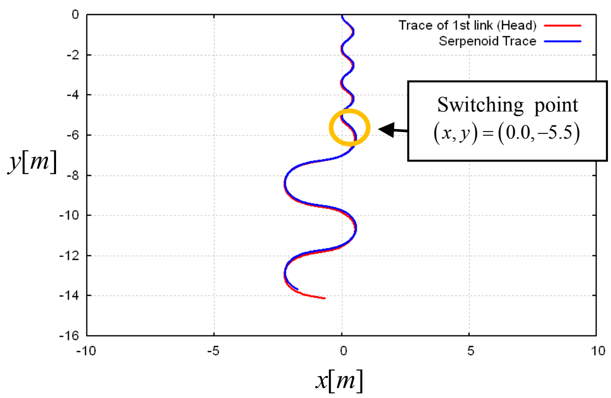


Fig. 9. Simulation result (using serpenoid function (12))

4 CONCLUSION

In this paper, we detailed the obstacle avoidance strategy for the snake robot. By the results of the numerical simulations, we were convinced that the design of the serpenoid curve with the switching control constraint is effective to the obstacle avoidance of the snake robot.

In our future works, we will construct an algorism which designs a serpenoid trace to avoid an obstacle automatically.

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