Proceedings of the 2nd International Conference on Mechatronics and Smart Systems
DOI: 10.54254/2755-2721/78/20240420

A review of locomotion of snake robots

Pu Huang[1,3,4], Wenyue Huang[2,5]

[1]Knowledge-First Empowerment Academy, Shanghai, China
[2]Shanghai Experimental School Cambridge International Education, Shanghai, China
[3]Corresponding author

[4]879571168@qq.com
[5]M13777407020@163.com

Abstract. In this review paper, we demonstrate the high structural flexibility and motion diversity of snake robots, which are important indicators to measure the performance of the mechanism. And animals in nature, especially reptiles, often have a high degree of flexibility and a variety of modes of movement in order to be able to shift through various terrains. Thus, making a robot with excellent performance, a bionic robot is a suitable choice. Currently, we have reviewed the state of the act in the snake-like machine. In the end, we conclude that with the simplicity of design and practice, it can be designed easily with unique constructures to complete modes of locomotion. Furthermore, we also provide the perspectives of future work.

Keywords: Locomotion, Gait, Snake Robots Structure, Revolute Joint

1. Introduction

Biological snake locomotion can reach rescue work in some sudden incidents that occur in nature for a unique way of moving because the snakes lack limbs and they can push their simple body through diverse environments, such as narrow spaces and gaps of branches. Those harsh and tricky natural environments make it hard for humans to act. This review paper makes some contributions to help people in improving resource efficiency and to greatly reduce the government's resource costs. It will be possible for more and more human beings trapped in accidents to be treated in a limited time. These serpentine rescue robots comprise several same segments assembled with a two-way, corresponding degree of freedom, which ensures the freedom of the mechanism and improves the efficiency of searching for jobs used in dangerous situations. A modern snake-like machine needs several steps to achieve its goal, including a specific structure, building a local map, serpentine gaits of the rescue robot, and sensor-based online path planning. At the end of this review paper, expand to another part of the motion model to change the appearance matching to the movement mode of the serpentine machine. As a lot of catastrophes happen naturally and have attracted people's attention, scientists have invented a mechanism that assembles alive snakes to improve the efficiency of looking for living beings that suffered natural disasters. Such robots are beneficial for rescue teams seeking persons who are not found, and then more and more human beings can get treatments. The mortality can be reduced a lot. Reviewing this paper about the snake can give students more motivation to involve robotic areas to create practical and emulation models, which can provide help for some difficult missions. Society can adopt these vivid

DOI: 10.54254/2755-2721/78/20240420

robots to perfect some drawbacks of each sphere. The paper reviews a whole system of mechanisms. Several papers have indicated various aspects of snake robot locomotion for people to fully understand how it works. Ismet et al explored the principle of dynamics during moving [1]. Kristin et al. conducted controllability and stability of planer snake robot locomotion [2]. Mariko et al. studied the approach to motion design for complicated pipes [3]. Tatsuya et al. researched motion in a helical way [4]. F. Matsuno and H. Sato indicated tracking control [5]. C. Wright et al. showed the design of each plate of snake robots [6]. P. Prautsch and T. Mita explored the control and gait of snake robots [7]. I. Erkmen et al. presented the utilization of rescue [8]. Liu, Jindong, et al. put forward the mode of motion in the strict environment [9]. Liljebäck, P. et al claimed modeling and implementation of snake robots [10]. We organize the remainder of the review paper. Section II provides the prototype mechanism and control of snake robots as well as motion planning. Section III shows the challenges of robotic fields.

2. Core Principles

In this section, we cover summaries of the core principles that ground the overall knowledge of snake robots. We intend to show the archetype at first and then contain how it controls the move. In the end, planning motion is another important procedure.

2.1. Development of Prototype Mechanism

The multisensor-based online path planning of a serpentine robot can search for living beings during some natural disasters. These serpentine rescue robots consist of several uniform segments assembled through a two-way, several degrees of freedom (DOF) which can be calculated by the Kutzbach criterion. These a kind of robots include an ultrasound sensor which is good at detecting the hinders, and thermal imagers are located in the first segment (their first segment). As shown in Fig. 1.

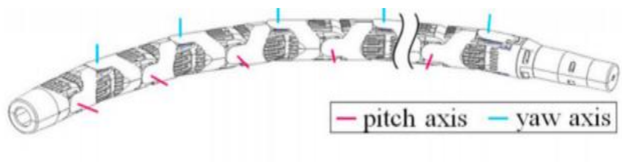

Figure 1. Process of Twisting Locomotion

Also, numerous infrared sensors (IR)are assembled on both sides(left and right) of the robot along the body. Then, a local map will be a token shape in the robot. The modified distance transform (MDT) is the distance transform method ameliorated for the snake-like machine. There are two modifications made to gain the method to move. Firstly, distance transform starts to reckon the surrounding views which are directed towards the intermediate target and do not count sensorial data about barriers. This is goal-oriented planning. Secondly, another modification is to render the original distance transform that integrates IR data that exhibits the obstacles during locomotion. The values of the section are added to the local map. The MDT-based exploratory path planning methodology. Such a machine will move until it finds living beings, and the local map building is needed to help it reach its goal. An ultrasound sensor scans to decide impeders and spare space where the robots can move toward and shape a local map. After discovering ideal intermediate goals, another possible point is found by consideration point. The cost function F(s), which can get the following probable gait s, is defined as F (s) = * C (Xi, Yi)

2.2. Control Strategies

A snake robot mainly consists of many uniform short linkages and revolute joints and each joint is confined by a motor, as shown in Fig. 2 . In order to manipulate a long robot shaped like a snake, there must be a twisting angle of 90 degrees of the axis between every adjacent revolute joint, so that this mechanism can be adjusted to any form we want. There is an interesting point is that why to use revolute joints instead of spherical joints. A 3D spherical joint has 3 degrees of freedom(3 rotations) so it is much difficult be control compared to a revolute joint which has only one degree of freedom. This means we need at least 3 motors and 3 sets of transmission structures to confine the movement of a spherical joint if we want 3 DOFs to be workable. Actually, 2 of the DOFs of a spherical joint can be replaced by two adjacent revolute joints of the prototype and the other one is unnecessary in the practice so far. As shown in Fig. 2. The motors and transmission structures are hidden in the linkage blocks, and easier design makes fewer mistakes, so almost all the prototypes of the snake robots use revolute joints.

Figure 2. The Structure of Three Revolute Joints

Therefore, such a machine with 10 joints has 10 degrees of freedom. One movement of a snake robot is Serpentine meandering, and it allows the robot to move forward like a sine curve. The force of friction between the tangential direction and the perpendicular direction is not the same at any part of the trunk (as seen in Fig. 2). Sinusoidal-driven, the mechanism will move forward along a serpentine curve. The snake can move faster in the even ground with passive wheels. What the right picture of Fig. 2 shows is the relationship between the joint angle and the time of 3 joints, but actually, joints A and B are on the same graph. When the graph of joint A changes, Other graphs of the joint after joint A must be adjusted this, as shown in Fig. 3. Twisting locomotion, We now select a part of the snake, which consists of three links and two revolute joints that is perpendicular to each other .one joint is firstly at a position with an angle of θd degrees (J1), the other one stay at the O degree (L2 and L3). At the moment, L2 and L3 are on the same axis (state 1). When joint J1 counterclockwise and joint J2 clockwise (state 2) are driven simultaneously. The relative Angle at J1 is 0°, and the relative Angle at J2 is θd, and the robot body will be deflected to one side by 90°(state 3), as shown in Fig. 1. The snake has a repetitive mode if every three links and two joins follow the rules above.

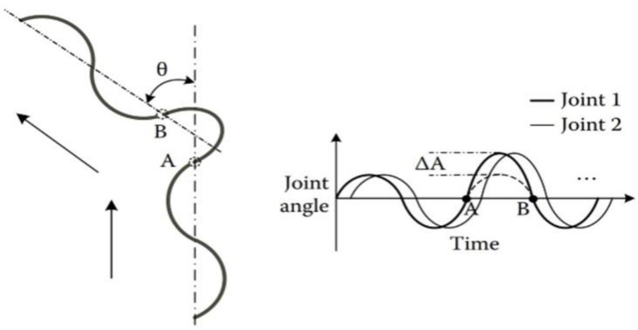

Figure 3. The Serpentine Locomotion and the Twisting Angles.

2.3. Genetic Algorithm (GA) for Shape Transitions

When the position of the appropriate phase difference of the joint is For simulating specific movement characteristics of snakes, the impetus is only produced by motors in each joint, which connect two units. The snake-like robot has a variety of motion modes to transform the shape level. To find a motion mode from one shape to another without losing structural stability, a suitable planning method is needed. Genetic Algorithm is a possible way to find the locomotion mode, which has no change in the position of the center of gravity in this section. GA is applied in the trajectory planning for the fixed b bases biped locomotion robots. In this paper, the snake robot has no stational points above the ground on its whole trunk, so the past planning cannot be used directly for the shape transformation planning of the snake machine.

To make the problem simple, assume that the serpentine robot only acts in the vertical plane like 2D. The definition of variables is shown in Fig.4

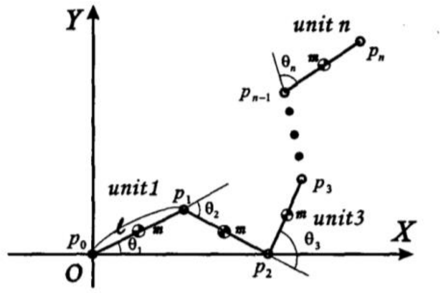

Figure 4. Definition of variables

We make 0 -XY the inertial coordinate system. And place the X-axis on an outdoor environmental surface, assuming it is a flat surface. The robot consists of n units with the same orientation, acting on the XY coordinate system. By definition, the mass and length of the unit are m and 1, respectively. Suppose the last two points on the robot are P0 and Pn, Pi (i= 0,1,2,..., n) is the joint position between unit i and i + 1. Endpoint P0 is touching with the external environment (ground). Let $\theta 1$ be the attitude angle of unit 1 which is relative to O-XY, θi (i= 2,..., n) is the relative angle between Unit 1 and i-1. The transformation that changes the shape from the initial configuration to the discovery one can be divided into k intermediate constructions. The best setting of k configuration sequences is searched by a genetic algorithm, and the shape of the robot is transformed into the optimal configuration sequence. We encode the whole chromosome structure which is as shown in Fig.5. where q_i^j represents The i-th relative joint angle in the i-th configuration sequence. The time interval between each adjacent sequence is not always fixed.

$$\left(\begin{array}{l} \theta_2^0, \theta_3^0, \cdots, \theta_n^0, \theta_2^1, \theta_3^1, \cdots, \theta_n^1, \cdots \\ \quad \cdots, \theta_2^k, \cdots, \theta_n^k, \theta_2^{k+1}, \cdots, \theta_{n-1}^{k+1}, \theta_n^{k+1} \end{array} \right)$$

Figure 5. The equation

The shape of the robot $(\theta_2, \dots, \theta_n)$ can be determined the chromosome structure. However, with respect to the inertial coordinate, the attitude of the robot θ_1 cannot be obtained. To satisfy the three assumptions we introduce, the angel θ_1 needs to be determined.

Assumption 1) The environment the robot is in contact with is flat, and one of the robot's ends is in contact with it.

Assumption 2) The environment is flat. There are more than two points of contact between the environment and the endpoint of the robot.

Assumption 3) No contact point between the environment and the robot.

We consider the method to determine the attitude angle θ_1. We create a provisional frame of reference O'-xy, and the origin O' r is also one end point p_0 of the robot, the x axis has the same direction as the vector $\overrightarrow{p_0p_1}$, and the y axis is perpendicular to x axis. If the endpoint p_0 slips, 0' is different from the origin 0 of the inertial coordinate frame as shown in Fig.6. (b). By this coordinate, the assumption 1, there is only one contacting point between the environment and the snake robot. And there are straight lines l_i we consider, it passes through p_0 and p_i (i = 1,…,n). Make $\emptyset\ i$ be the intersection angle between the line l_i and the x-axis. And we give the definition that $\theta = \min_i \emptyset i$ in Fig.6. (c). To satisfy both assumption 2 and assumption 3, we rotate the whole robot around p_0 for an angle θ. We can gain the exact attitude angle of unit 1 as $\theta_1 = -\theta$ as shown in Fig.6. (d)

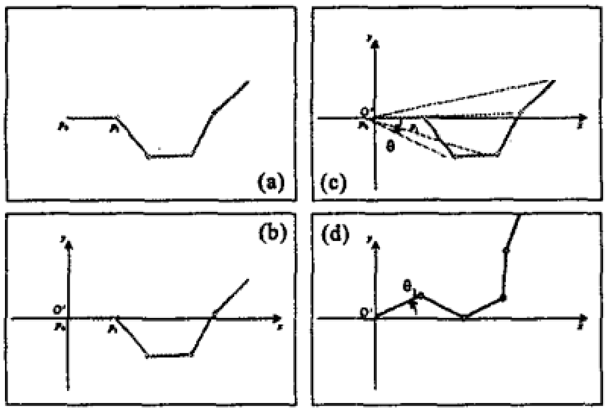

Figure 6. A process of determination of θ_1

The next function V is token as a fitness function in the Genetic Algorithm

$$V = P^h(C_1V_1 + C_2V_2 + C_3V_3) \quad (1)$$

And V_1:stability margin, V_2:smoothness 1, V_3:smoothness 2, P:penalty constant, h:number of counts of penalty shape, C_i weight of $V_i(i = 1,2,3)$.

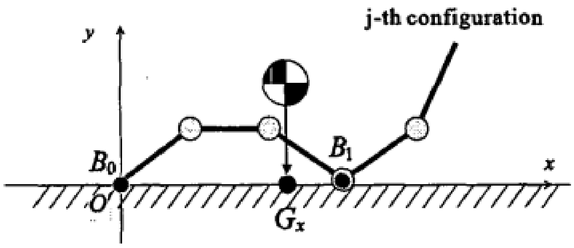

Figure 7. Stability margin

First, we consider V_1. The two points B0 and B1 are in contact with the ground and have two minimum and maximum values respectively. Let $G_x$be the projection of the gravity of the whole robot as shown in Fig.7. The stability margin in the j-th construction is defined as

If $G_x$is placed between$B_0$and B_1

$$\nu^j = min\{|\overline{G_xB_0}|, |\overline{G_xB_1}|\} \quad (2)$$

If not

$$\nu^j = -min\{|\overline{G_xB_0}|, |\overline{G_xB_1}|\} \quad (3)$$

It has a form that ν^j is negative, like a penalty shape. In the process of change, the penalty quantity is set to h, and the stability margin is defined as

$$V_1 = \sum_{J=0}^{k+1} \nu^j \quad (41)$$

In the case $V_1 < 0$ it is determined as$V_1 = 0$.

And we think about V_2 of the smoothness 1. It was referenced to change the layout of the robot from its original appearance to an aim shape. The attitude angel Φ_i^j of i-th unit in the j-th construction is given as

DOI: 10.54254/2755-2721/78/20240420

$$\phi_i^j = \theta_1^j + \cdots + \theta_i^j \tag{5}$$

And d`efine the attitude vector $\emptyset^j$

$$\emptyset^j = [\phi_1^j, \ldots, \phi_i^j] \tag{6}$$

The smoothness 1 as a function of V_2 . In the transition process, the variation of the attitude vectors is formulated as

$$V_2 = \frac{1}{\sum_{j=0}^{K} \left\| \phi^{J^4+1} - \phi^j \right\|^2} \tag{7}$$

Finally, we give an explanation for the smoothness 2. It is expected that the introduction of the smoothness of the change of the position of gravity of the robot obtains the smooth transition, the same as the smoothness 1. The function V_3 of the smoothness 2 is formulated as

$$V_3 \frac{1}{\sum_{j=0}^{k} \{ (x^{j+1} - x^j)^2 + (y^{j+1} - y^j)^2} \tag{8}$$

Where x^j and y^j express the center of the gravity position vector with x component and y component of the whole robot in the j -th configuration.

Then, we consider an instance that in the transformation of the snake-like robot changes from a horizontal and delicate expansion structure to a bridge-like structure like biped locomotion. In the computer simulation, the snake robot is formed by connecting 10 units in a common direction. On a computer, the same simulated shape transition is shown in Fig.8.

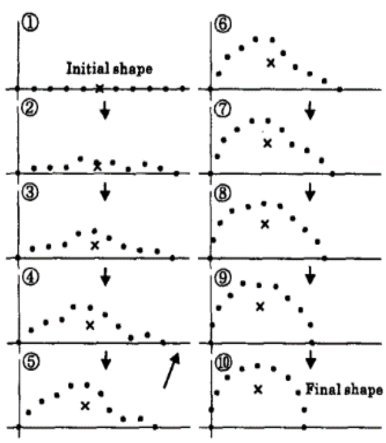

Figure 8. Computer simulation

3. Conclusion

In this paper, we investigated prototype structure and sensor-based path planning. Then we studied the details and theories about twisting locomotion. We considered using a Genetic Algorithm to find the optimal sequences with no loss in structural stability when the snake-like robot changes the mode of locomotion (from the horizon configuration to the bridge configuration). For our further aim, we will do a real model of the snake robot in the example and do a simulation for the model.

References

[1] Eirkmen, I. et al. (2002) 'Snake robots to the rescue!', IEEE Robotics & Automation Magazine, 9(3), pp. 17–25. doi:10.1109/mra.2002.1035210.

[2] Erkmen, A.M. et al. (2002) ‘Controllability and Stability Analysis of Planar Snake Robot Locomotion’, IEEE Robotics & Automation Magazine, 9(3), pp. 17–25. doi:10.1109/mra.2002.1035210.

[3] Matsuno, F., Chatterjee, R. and Kamegawa, T. (2002) ‘Unified Approach to the Motion Design for a Snake Robot Negotiating Complicated Pipe Structures’, IEEE Robotics & Automation Magazine, 9(3), pp. 17–25. doi:10.1109/mra.2002.1035210.

[4] Chatterjee, R. and Kamegawa, T. (2002) ‘Unified Approach to the Motion Design for a Snake Robot Negotiating Complicated Pipe Structures’, Mobile Manipulation Using a Snake Robot in a Helical Gait, 9(3), pp. 17–25. doi:10.1109/mra.2002.1035210.

[5] F. Matsuno and H. Sato, “Trajectory Tracking Control of Snake Robots Based on Dynamic Model,” Proceedings of the 2005 IEEE International Conference on Robotics and Automation, Barcelona, Spain, 2005, pp. 3029-3034, doi: 10.1109/ROBOT.2005.1570575.

[6] C. Wright et al., “Design of a modular snake robot,” 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems, San Diego, CA, USA, 2007, pp. 2609-2614, doi: 10.1109/IROS.2007.4399617.

[7] P. Prautsch and T. Mita, “Control and analysis of the gait of snake robots,” Proceedings of the 1999 IEEE International Conference on Control Applications (Cat. No.99CH36328), Kohala Coast, HI, USA, 1999, pp. 502-507 vol. 1, doi: 10.1109/CCA.1999.806692.

[8] I. Erkmen, A. M. Erkmen, F. Matsuno, R. Chatterjee and T. Kamegawa, “Snake robots to the rescue!,” in IEEE Robotics & Automation Magazine, vol. 9, no. 3, pp. 17-25, Sept. 2002, doi: 10.1109/MRA.2002.1035210.

[9] Liu, Jindong, Tong, Y. and Liu, Jinguo (2021) ‘Review of Snake Robots in Constrained Environments’, Robotics and Autonomous Systems, 141, p. 103785. doi:10.1016/j.robot.2021.103785.

[10] Liljebäck, P. et al. (2012) ‘A review on modelling, implementation, and control of snake robots’, Robotics and Autonomous Systems, 60(1), pp. 29–40. doi:10.1016/j.robot.2011.08.010.