CHAPTER 14

Snake Robot Locomotion in Narrow space: A Review

Raisuddin Khan[1, a], Mitsuru Watanabe[2,b] and Masum Billah[3,c]

[1,2,3]Department of Mechatronics Engineering, Kulliyyah of Engineering, International Islamic University Malaysia, Malaysia
[a]raisuddin@iium.edu.my, [b]nabe@yahoo.com, [c]masum.uia@gmail.com

14.1 Introduction

In snake robot research, one of the most efficient forms of locomotion is the lateral undulation. However, lateral undulation, also known as serpentine locomotion, is ill-suited for narrow spaces, as the body of the snake must assume a certain amount of curvature to propel forward. Other types of motion such as the concertina or rectilinear may be suitable for narrow spaces, but is highly inefficient if the same type of locomotion is used even in open spaces. Though snakes naturally can interchange between the use of serpentine and concertina movement depending on the environment, snake robots based on lateral undulation to date are unable to function satisfactorily in narrow spaces. In this chapter, a brief literature review is done on snake robot locomotion for narrow space navigation.

Before we delve in the prior and current research regarding the topic at hand, it would be wise to take a brief look at snake locomotion in general as it occurs in the natural world. The most prominent structure of the snake is its backbone which is primarily responsible for all of its motions. A typical snake backbone, depending on its species, would consist of anywhere from around 100 to 400 vertebrae [1]. The vertebrae themselves are almost identical except for size which varies only slightly closer to the tail. Each vertebra fits into the other like a ball and socket joint, and is put together with tendons and ligaments such that limited lateral and ventral movements are achieved while almost completely eliminating torsional movement. Maximum lateral movement may vary from 10 to 20 degrees, whereas vertical displacement is only 2 to 3 degrees [2]. Though the angular displacement of each vertebrae is small, together as a linked whole of numerous members, the body of the snake is able to undergo large angular deflections. Using these deflections the snake is able to traverse various environments. As mentioned earlier snakes traverse in four major ways: serpentine, concertina, side-winding, and rectilinear.

Serpentine. Serpentine locomotion, also known as lateral undulation, is the most common mode of movement among snakes, and this is consistent with the fact that it is one of the more efficient forms of progression. In this type of motion, the whole body is moving at once, and all parts of the body slide along the same curved path at the same speed. This is achieved by the propagation of a wave along the body from the front to the rear. The snake remains in constant contact with the ground and may push laterally against obstacles such as stones, branches, or trunks of trees that are stationary with respect to the ground to propel itself forward, as in Figure 1. Interestingly enough, this form of movement does not use static friction between the bottom of the snake and the substrate. This is possible due to the contact points the snake is able to achieve with the ground. A minimum of three push-points are required for the snake to move forward:

two to generate the required forces and third to balance out the forces such that their sum act in the desired direction [3].

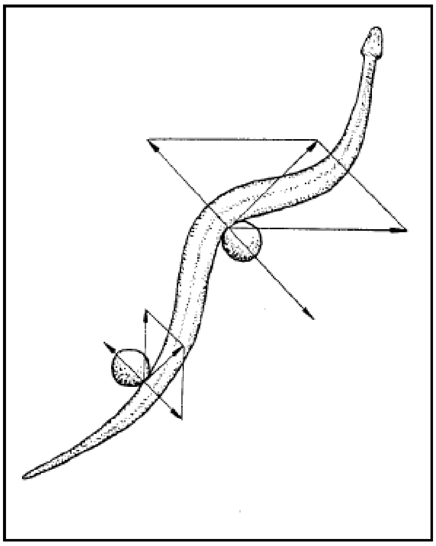

Fig. 1 Lateral Undulation [2]

In the natural world snakes use sliding or dynamic friction rather than static contacts such as bipeds or even wheels, yet this advantage is often difficult to emulate in robotics [2]. The efficiency of this movement depends on two factors: the contour of the ground, and the ration between the length and circumference of the snake. Interestingly enough, the snake is able to move more efficiently on rougher terrains as it uses obstacles on and irregularities in the ground to literally push up against. As for the second factor, it is found that the optimum length to circumference ratio is between 10:1 and 13:1. Speeds of up to 11 km/h have been recorded [4]. This type of locomotion is not effective on smooth, low-friction surfaces and narrow corridors [5].

Concertina. The name for this category of locomotion is derived from a small accordion like instrument known as the “concertina.” Much like the zigzag shaped bag that pumps air into the instrument, the snake also contracts and expands when undergoing this gait. Movement is achieved by first folding up the body, see Figure 2, and then stretching the body starting with its head. The tail end remains folded and stationary until the head has reached its farthest point. The head area then folds up and pulls the tail area to assume the folded position again. This is repeated to allow the snake to move forward.

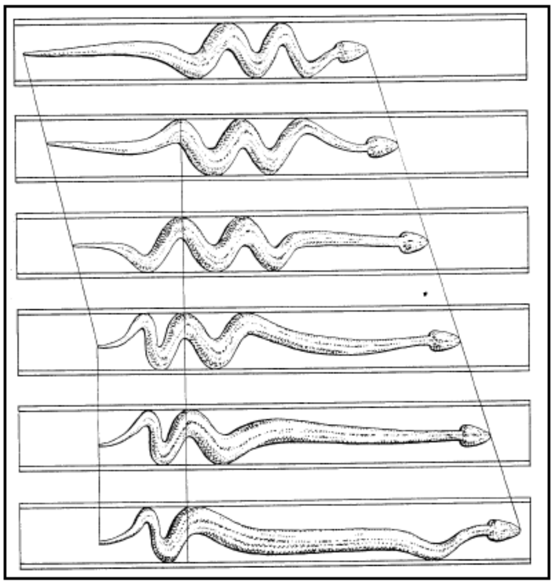

Fig. 2 Concertina Gait [2]

The critical factor in this gait is the difference in friction over different parts of the body due to the difference in static vs. dynamic friction, as well as due to the ability of the snake to lift parts of its body off the ground through sinus-lifting [6]. This gait is used by snakes to traverse confined passages such as tunnels or branches of trees. The gait, however, due to its stop-and-go nature is relatively inefficient and is used by snakes only when the full amplitude of lateral undulation cannot be utilized [7].

Sidewinding. This type of locomotion is perhaps the most poetic of all forms of movement. The snake adopts exaggerated levels of lateral bending to move diagonally across the surface. This is particularly effective on low shear surfaces like sand or loose soil. Only two points are in contact with the ground, Fig. 3, and downward force is applied in such a way as to maximize the rolling friction that is generated.

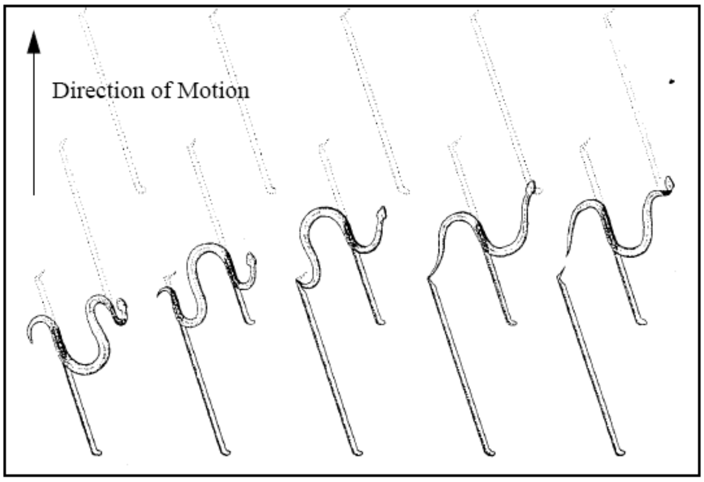

Fig. 3 The Sidewinding Snake [2]

Slippage is thus minimized to the extent that some researchers claim it to be even more efficient than lateral undulation [8]. Sidewinding snakes are found mainly in desert areas where the gait not only aids motion on loose surfaces, but minimizes contact with the ground with reaches scorching temperatures during the day.

Rectilinear. This fourth common gait is used by the species of snake that are too massive to undergo serpentine locomotion, such as anacondas and boa constrictors. The movement is based on the muscle that connects the elastic belly to the ribcage, Fig. 4. The scales on the belly provide the necessary traction, and the snake literally pushes it body mass over its own skin, the skin and scales then bunch up and creep forward, and the body is propelled over the skin again. Though much of the skin surface is in contact with the ground, this creeping motion is rather slower and not as efficient at lateral undulation. However, with this gait, the snake is able to move forward while maintaining a linear configuration, hence the name.

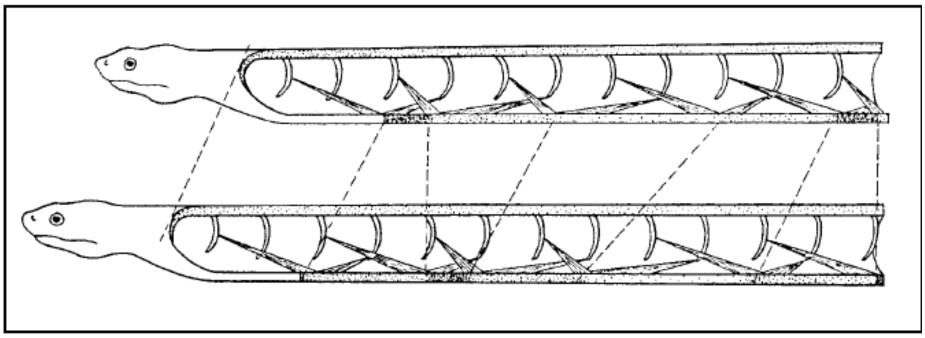

Fig. 4 The Anatomy of Rectilinear Motion [2]

Other Forms of Locomotion. Other forms of locomotion such slide pushing, saltation, burrowing, climbing, and swimming are also mentioned when discussing snake locomotion, but those are only specialized movements used for specific purposes. Some of these modes such as swimming is the same lateral undulation movement used in water. Slide pushing is similar to movement through vibration, where the snake almost violent sends waves through its body. Saltation is just another word for jumping snakes, where the snake would coil up and pounce.

14.2 Snake Robots

The discussion of the natural snakes leads nicely into that of robotic snakes. Snake research really took off during the 1970's and has since been gaining momentum. To date, numerous modeling techniques and prototypes have been developed. It would be unwise to delve on each and every contribution, and hence the focus here should be paid specifically to snake locomotion. Though numerous snake-like structures have been proposed over the years, not all of them are designed as locomotors.

14.3 Research on Snake Locomotion. When it comes to snake robots, the most prominent researcher, and perhaps the pioneer of this field is Hirose. He began his research in the 1970's with Umetani, and has since studied snake locomotion from different aspects and developed several prototypes. He is the first to model accurately the serpentine locomotion and thus formulated his concept of the Active Chord Mechanism (ACM) based on his proposed equation for serpentine curve, dubbed by him as the serpenoid curve. His book [9] on biologically inspired robots, which has now become a mainstay on the bookshelves of many researchers, presents an excellent overview of the research he has conducted over the years. All the prototypes developed by Hirose, however, use passive wheels, and are based on lateral undulation. His contribution, nevertheless, is remarkable.

Research on lateral undulation can be divided into two categories: ones where passive caster wheels are used, such as with Hirose, and ones where such wheels are not added. Another example of the wheeled snake robot is presented by Ma [10], where an alternative to the serpenoid curve is proposed: the serpentine curve. He concluded that robots adopting his serpentine curve where ultimately more efficient than those based on the serpenoid curve. Issues contributing to the efficiency of motion are presented in Saito [11], where it is mentioned that sideways slip must be prevented to maximize efficiency of the forward movement. The proposed scheme is tested on a wheel-less snake robot and a strategy for controlling the parameters for motion is outlined. To this same end, the slippage issue is controlled via the use of passive caster wheels in the work of Ostrowski and Burdick [12], where further developments regarding the configuration of the joint angles are discussed. The wheeled snake robot, much like Hirose's latter models, is used again in the study conducted by Prautsch and Mita [13]. Their work employs a Lyapunov-based approach for controlling the position of the head of the robot. Furthermore, they discuss how the actuator torques may be minimized to reduce the risk of wheel-slip. The issue of wheel-slip is also of concern in the work of Date [14], where the joint reference value are derived from the velocity reference to maintain the certain amount of curvature in the body.

In addition to the problem of efficiency, some groups have experimented with the application of lateral undulation on different environments. Lateral undulation is applyied in climbing a slope in the study of Ma and Tadokoro [15]. The findings state the upper limit of the initial winding angle must be decreased, and the lower limit increased to achieve upward movement on a slope. Other variations include the reliance on physical obstacles to propel the snake forward. The model developed by Shan and Koren [16], is the closest any researcher has come to implementing the concertina movement. In their scheme the links are equipped with solenoids which push against the ground to increase friction when needed. They show that the robot can stay in motion while remaining in contact with the obstacle. Bayraktaroglu and Blazevic [17] adopt a similar approach in their own version of a wheel-less snake robot by utilizing push-points created by pegs to provide the propulsive force while undergoing a modified form of lateral undulation. The push-points in the initial research are activated by linear actuators at both end of the link, while in later prototypes [17], the push-points need no longer be actuated, as sensors are used to find the suitable push-points and adjust the joint angles accordingly. Another approach based on the concertina movement is presented by Chernousko [18]. The snake robot in this case relies on the combination of fast and slow movement, the difference between static and dynamic friction, also known as the stick-slip phase. Motion is achieved so long at the friction in the moving portion is less than the friction on the stationary portion.

Side winding locomotion is presented both by Burdick [19]. The latter takes a more mathematical approach to implementing the gait, while Burdick utilizes 3D motion on a flat surface by curving up the portions that move above the ground and keeping the stationary parts that lie flat on the ground. In the paper present by Tanev [20], a similar side winding gait is achieved without explicit mathematical curves. A genetic programming technique is used to generate the curve. As for rectilinear motion, a prototype actuated with shape memory alloys is shown by Liu and Liao [21]. In addition, to all these attempts at implementing the natural gaits, various types of unique modes of locomotion are also endorsed.

14.4 Conclusion

From the above survey, it becomes clear that, as for the biologically inspired gaits, most have been attempted. Lateral undulation has received a major bulk of attention, while the other modes still have not been studied thoroughly. Though caster wheels and actuated push-points are tried and tested, there seems to be a lack in terms of developing frictional elements based more directly on the scales of snakes. Furthermore, though it is a well-known fact that lateral undulation is not suited for confined spaces, it seems this issue is not further investigated. Unique and even unlikely artificial gaits have been proposed down the years, but again not of them seem to address the ability to traverse confined space. The topic of locomotion in narrow spaces, therefore seems to be an area that has not been examined much.

14.5 References

[1] K. J. Dowling, Limbless Locomotion. Learing to Crawl with a Snake Robot. PhD thesis. Carnegie Mellon University, (1997).

[2] C. Mattison, The Encyclopaedia of Snakes. Cassell Paperbacks. London, (2002).

[3] J. Gray, Animal Locomotion. W.W. Norton Co., (1968).

[4] A. A. Transeth, Modelling and control of snake robots. PhD thesis. Norwegian University of Science and Technology (2007).

[5] C. Gans, Biomechanics: An Approach to Vertebrate Biology. Lippencott, (1974).

[6] S. Hirose and M. Mori, Biologically inspired snake-like robots. In: Proc. IEEE Int. Conf. Robotics and Biomimetics. pp. 1-7, (2004).

[7] M. Walton and B. C. Jayne, The energetic cost of limbless locomotion. Science, Aug 3, pp. 524-527, (1990).

[8] S. M. Secor, B.C. Jayne, and A.C. Bennett, Locomotor performance and energetic cost of sidewinding by the snake crotalus cerastes. J. Exp. Biology, 163, pp. 1-14, (1992).

[9] S. Hirose, Biologically Inspired Robots: Snake-Like Locomotors and Manipulators. Oxford University Press. Oxford, (1993).

[10] S. Ma, Y. Ohmameuda and K. Inoue, Dynamic analysis of 3-dimensional snake robots. In: Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems. pp. 767-772, (2004).

[11] M. Saito, M. Fukaya and T. Iwasaki, Serpentine locomotion with robotic snakes. IEEE Contr. Syst. Mag. 22(1), pp. 64-81, (2002).

[12] J. Ostrowski and J. Burdick, Gait kinematics for a serpentine robot. In: Proc. IEEE Int. Conf. Robotics and Automation. Vol. 2. pp. 1294-1299, (1996).

[13] P. Prautsch and T. Mita, Control and analysis of the gait of snake robots. In: Proc. IEEE Int. Conf. Control Applications. Kohala Coast, HI USA. pp. 502-507, (1999).

[14] H. Date, Y. Hoshi, M. Sampei and N. Shigeki, Locomotion control of a snake robot with constraint force attenuation. In: Proc. American Control Conference. pp. 113-118, (2001).

[15] S. Ma and N. Tadokoro. Analysis of creeping locomotion of a snake-like robot on a slope. Autonomous Robots 20, pp. 15-23, (2006).

[16] Y. Shan and Y. Koren, Design and motion planning of a mechanical snake. IEEE Trans. Syst. Man Cyb. 23(4), pp. 1091-1100, (1993).

[17] Z. Y. Bayraktaroglu, A. Kilicarslan, A. Kazucu, V. Hugel and P. Blazevic, Design and control of biologically inspired wheel-less snake-like robot. In: Proc. IEEE/RAS-EMBS Int. Conf. Biomedical Robotics and Biomechatronics. pp. 1001-1006, (2006).

[18] F. Chernousko, Modelling of snake-like locomotion. Appl. Math. Comput. 164(2), pp. 415-434, (2005).

[19] J. W. Burdick, J. Radford and G. S. Chirikjian, A .sidewinding. locomotion gait for hyper-redundant robots. In: Proc. IEEE Int. Conf. Robotics and Automation. pp. 101-106, (1993).

[20] I. Tanev, T. Ray and A. Buller, Automated evolutionary design, robustness, and adaptation of sidewinding locomotion of a simulated snake-like robot. IEEE Trans. Robot. 21(4), pp. 632-645, (2005).

[21] C. Y. Liu, W. H. Liao, A snake robot using shape memory alloys. In: Proc. IEEE International Conference on Robotics and Biomimetics ROBIO, (2004).