Serpentine Robot Locomotion: Implementation through Simulation

Atanu Maity [#1], S. Majumder [#2], S. Ghosh[#3]
[1,2] Central Mechanical Engineering Research Institute (CSIR), Durgapur, India
[3] National Institute of Technology, Durgapur, India

Abstract—Machine locomotion using wheels, tracks or legs is common where as generating locomotion in a limbless, wheelless system is more challenging. Wheeled locomotion and legged locomotion have already been studied by many researchers in detail. On the contrary the limbless locomotion has drawn very limited degree of interest. In limbless locomotion (of a serpent) the cyclic changes in the body shape allow it to locomote. This paper considers the development of a hyper redundant un-tethered serpentine robot for implementation of various serpentine and non serpentine gaits. A highly optimized 3D model of the robot was prepared and exported to CAE environment for kinematic and dynamic analysis. Parameters so obtained through simulation were implemented on the robot for demonstration of serpentine locomotion.

Keywords: Serpentine Robot Locomotion, Hyper redundant, Mobile Robot.

I. INTRODUCTION

The first qualitative research on biologically inspired serpentine robot was done by Hirose [1]. Early works of Burdick and Chirikjian on hyper redundant robot are worth mentioning [2]. Since then many multi segmented articulated serpentine robots have been attempted by researchers for implementation of crawling gaits. Design of a serpentine robot is principally guided by gait implementation philosophy. Some of them use wheels, tracks, legs or other means for locomotion while others rely solely on body undulation. In most of the cases the segments are connected with revolute joints, but prismatic joints [3] are also employed. These joints may be active or passive. In general, revolute joints were considered for yaw and pitch, however a few models were also developed using roll DOF [4][5].

Locomotion of a serpent is due to cyclic changes in the body shapes (gaits). These body shapes most often can be simulated by two body waves on two orthogonal planes passing through snake's body. Again these body waves are functions of joint orientations in case of an articulated serpentine robot. Mathematical models of the joint orientations were verified in simulation environment before implementing them into the physical prototype. Moreover, the parameters of the mathematical model were fine tuned in simulation for optimal gait performance.

II. SERPENTINE ROBOT

CSERP-X is an experimental serpentine robot developed at CMERI (CSIR) for experimentation with serpentine gaits and locomotion [6].

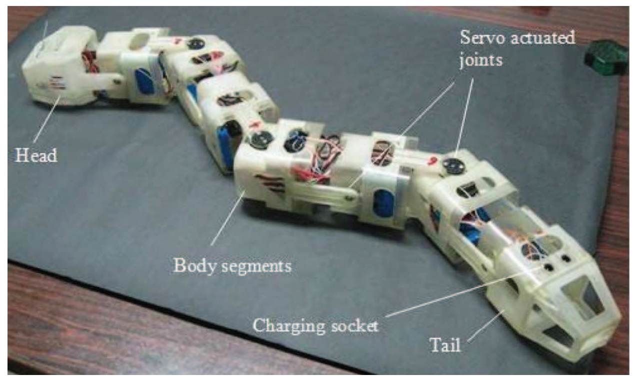

Fig. 1. Experimental serpentine robot CSERP-X [6]

There are six body segments, one head and one tail. Body segments are identical in shape and size. Head and tail segment are slightly different. Head segment houses some sensors and the tail houses a few other components, for example, battery charging point and

Overall length	807 mm
Number of Segments	8
Number of joint actuators	7 R/C servos
Joint actuator torque	9 kg-cm
Joint to joint	96 mm
Segment cross section	70 mm x 70 mm
Overall weight (Including battery)	1.26 kg
Obstacle detection	IR based
On board micro controller	PIC 16F84A
Power source:	
Servo actuators	6x4500mAh@6V
μ-controller and other electronics	4500mAh@6V
Camera, video transmitter & light	9V

LED indicator.

TABLE I: A BRIEF SPECIFICATION OF CSERP-X

Overall system has 7 DOF with seven joints actuated by seven R/C servo actuators. The adjacent actuators of the robot are perpendicular to each other and each joint has angular freedom of ±90°. Joint pitch on any plane is 192 mm. Four of the joints actuators have horizontal axes and three have vertical axes. Some gaits utilize all four sides of body segments. The segment cross section was chosen as squire so that the robot shows uniformity in all state of its gait. Variation in dorsal and ventral shape would lead to anomalous behaviour in various stages of those gaits which utilize all the four faces of the body segment such as *lateral roll*. The overall weight of the system includes servos, battery, electronics, cabling and weight of the body segments. If the robot is sleeved with a skin, total volume is about 3675 cm^3 and the overall robot density 0.34 g/cm^3.

I. SIMULATION

The design process is iterative in nature and involves simulation in CAE environment [7]. If a design does not work in simulation, most likely it will fail on implementation. A highly optimized 3D model of the robot was prepared and exported to CAE environment for kinematic and dynamic analysis. The study of animal locomotion is typically considered to be a sub-field of biomechanics. Gray used pegs to measure serpentine reaction forces [8][9]. Hirose used strain gauges and supports to measure force in snake locomotion [1]. Biomechanics of scale and muscle in *rectilinear* mode of snake locomotion was studied in [10].

A. Integration Technique

CAE solvers use numerical methods to solve dynamic simulation problems. The solution of the motion of mechanical systems is governed by differential equations arising from mechanics principles and the solution is carried out by numerical integration. While many numerical integration methods exist, the Kutta-Merson integration technique [11], which is considered to be fairly accurate, was used. At each integration step, the solver checks its computation results to see if the model satisfies the error bounds. Reducing time step substantially reduces error. Maximum time step for all our simulations was chosen to be 0.001s; however, the solver was allowed to refine it on the run to remain within error bounds.

B. Geometry

The simulation model of the serpentine robot was made using basic 3D model data used for the design of the experimental system. To reduce computational load the simulation model was made much simpler as compared to the actual design of the serpentine robot which is further depicted in Fig. 2. While doing so, special attention was given to the overall shape and size and other critical dimensions. As the ACIS geometries were needed for the simulation environment, it converts curves and curved geometries with a set of polygons or planar surfaces (faceting). Optimized geometry was carefully prepared to get better simulation performance without sacrificing realistic simulation results.

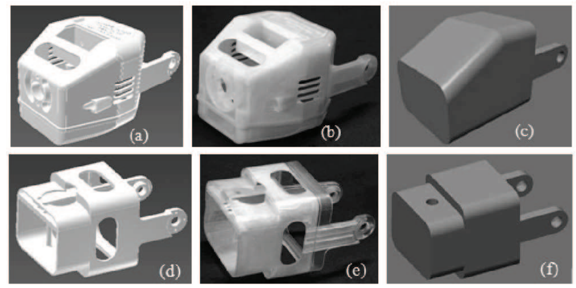

Fig. 2. The head segment of the experimental serpentine robot (a) as designed, (b) as built, and (c) as prepared for simulation environment and the body segment of the snake robot (d) as designed, (e) as built, and (f) as prepared for simulation environment.

C. Friction

Friction plays a very important role in locomotion simulation. To achieve meaningful locomotion sometimes directional friction helps to a great extent. A biological snake enjoys certain advantages as far as directional friction is concerned.

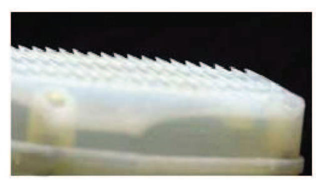

Fig. 3. Sawtooth corrugation on the head and tail segment of the experimental serpentine robot

This is also termed as frictional anisotropy. Particular orientation and overlap of serpentine scales contributes to achieve directional friction and by virtue of this a snake can easily slide forward than sidewise. On a serpentine robot it can be achieved in many ways. Many serpentine robots use wheels to utilize this directional property. For example, Snakey [2], SR-2 [12] and ACM series robots [13][14][15] use wheels to achieve low forward friction and high lateral friction. However, in simulation environment it has to be modeled. For example in case of Inchworm locomotion the dynamic coefficient of friction (μ) was modeled as:

IF (velocity of *Tail* w.r.t. *Surface* is negative) THEN μ = 0.8 ELSE μ = 0.5 IF (velocity of *Head* w.r.t. *Surface* is negative) THEN μ = 0.8 ELSE μ = 0.5

In general a value of 0.5 was considered for all other purpose. To impart directional friction sawtooth corrugation on the bottom surface of the Head and Tail segment of the experimental serpentine robot was provided (Fig. 3b).

D. Kinematic Model

Fig. 4 may be referred for better understanding of kinematic structure of the robot. Drawing similarity with ISO8855 convention the axes were defined, which dictates that X-axis pointing straight forward, the Y-axis to the left and the Z-axis pointing upwards. The rotational degrees of freedom with respect to the axes are denoted with φ (roll), θ (pitch) and ψ (yaw) respectively. The body segments are named as: Head – B1 – B2 – B3 – B4 – B5 – B6 – Tail. Each segment (link) is joined with the adjacent one with the help of a revolute joint. There are seven revolute joints altogether for the eight links. The H-Plane (for yaw) and V-Plane (for pitch) are the same as *dextro-sinistral* and *dorso-ventral* planes of a biological serpent respectively.

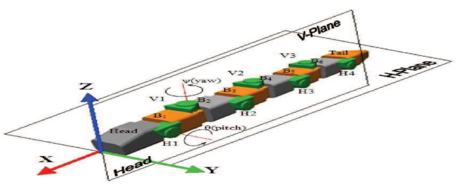

Fig. 4. Kinematic model of the experimental serpentine robot showing coordinate system and naming convention of segments and joint constraints (green)

Each revolute joint has a play of 0° to 180° and in straight configuration they are at 90°. For a biological snake the range of movement between each joint is limited to between 10° and 20° for rotation from side to side (yaw), and to a few degrees of rotation when moving up and down (pitch) [16]. A large total bend of snake body is still possible because of the high number of vertebrae. A very small rotation (roll) is also possible around the direction along the snake's body. The experimental serpentine robot does not have any roll freedom as it does not contribute significantly in gait generation.

Locomotion of the serpentine robot was achieved with the generation of body waves by the sinusoidal actuation of joints. Two separate sets of sinusoidal actuators were used to simulate waves on both horizontal and vertical plane:

$$\psi_i = D_\Psi + A_\Psi \sin(2\pi t / T_\psi + \alpha_0 - (i-1).\delta\alpha); \quad i = 1 \text{ to } 3 \qquad (1)$$

Pitch,

$$\theta_j = D_\theta + A_\theta \sin(2\pi t / T_\theta + \beta_0 - (j-1).\delta\beta); \quad j = 1 \text{ to } 4 \qquad (2)$$

These two orthogonal sinusoids are parametric to joint position and time dependent. They are made structurally similar for easy deployment and they are deployed in piecewise manner and termed as *Joint Orientation Functions* or JOFs.

Here D, A and T are offset, amplitude and period of joint oscillation respectively. The suffix θ and ψ denotes parameters of horizontal and vertical joints respectively. Vertical sinusoid contributes to the lift and proper ground interaction which is essential for this robot to propel. The parameters α_0 and $\delta\alpha$ are initial phase (epoch) and phase lag of H-Plane JOFs. Similarly β_0 and $\delta\beta$ represents the same for the V-Plane JOFs. 'i' and 'j' are the joint positions numbered from the head side on their respective planes. All the seven revolute joints are constrained with JOFs and considering spatial orientation of the robot, four of which have axes on the horizontal plane (viz. H1, H2, H3 and H4) and three of them have axes on vertical plane (V1, V2, and V3) as shown in the Fig. 4.

E. CAE Environment

Various studies were carried out to make the serpentine model locomote in simulation environment.

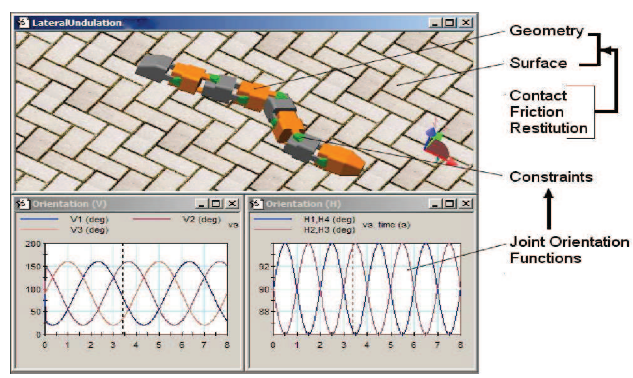

Fig. 5. Experimentation with gaits in simulation environment. The joint constraints are actuated with joint orientation functions to produce desired locomotion. Contact, friction and restitution were modelled between the surface and the simulation geometry

There is one-is-to-one correspondence between the experimental serpentine robot and the simulation model of the robot as the model geometry was prepared in line with actual robot. In the Fig. 5 the joint locations shown in green are constrained with the mathematical model of the robot kinematics. As such all the joint constraints are made responsive to corresponding *joint orientation functions* and mathematical model used for gait implementation was verified in simulation environment prior to deployment on the robot.

I. LOCOMOTION

Various serpentine and non serpentine locomotion gaits as categorised in Fig. 6 were simulated and implemented. These gaits were not only inspired by snakes but can also be extended to mimic other interesting gaits such as caterpillar, inchworm and tail flapping of fish for example.

For all locomotion types the *basic joint orientation function* remains same while their parameter changes. These parameters are genetic imprints that determine what gait the robot performs. The value of the parameters as presented in this paper are optimal and can be further adjusted or fine tuned depending upon serpentine robot design, actuator characteristics and environmental parameters.

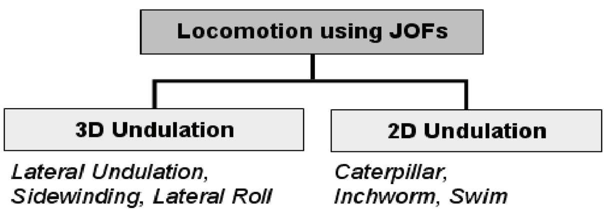

Fig. 6. Various serpentine robot locomotion types simulated and implemented.

These issues have been critically examined through experimental serpentine robot specially designed and extensively used to compare various gaits generated through simulation. Due to space constraint only *Lateral Undulation* and *Caterpillar* locomotion are presented here as cases of study. However, [17] may be referred for locomotion videos related to the project.

A. *Lateral Undulation*

It is a continuous sliding motion achieved by swinging the body segments sidewise i.e. on H-Plane. For values of $\delta\alpha \in (0,180)$ the body wave travels from rear to front as in the case of *caterpillar* locomotion. For values of 0 and 180° the body wave is stationary. On the H-Plane undulation a phase difference of 240° suggest that the body wave moves from front to rear. It may be noted that V-Plane undulation is a stationary wave with $\delta\beta$ =180° which creates two alternating pairs of ground support points.

TABLE II

JOF PARAMETERS FOR LATERAL UNDULATION LOCOMOTION

ψ - Functions				θ - Functions			
A_ψ	T_ψ	α	$\delta\alpha$	A_θ	T_θ	β_0	$\delta\beta$
70°	4	0	240°	4°	2	120°	180°

A slight undulation on the V-Plane (±4°) is provided to simulate proper ground reaction which will help it to propel forward. This undulation can be used to simulate 'sinus lift', a term coined by Hirose [1] where the lateral extremities of the serpentine body get lifted above the ground at high speed of locomotion. For straight heading the offset parameter ($D\psi$) is set at 90°.

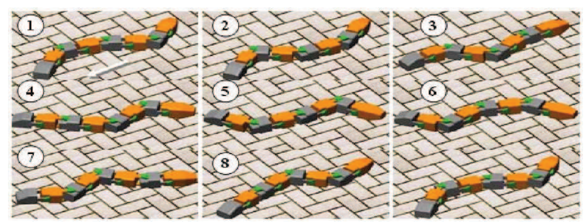

Fig. 7. Simulation of gaits for lateral undulation locomotion

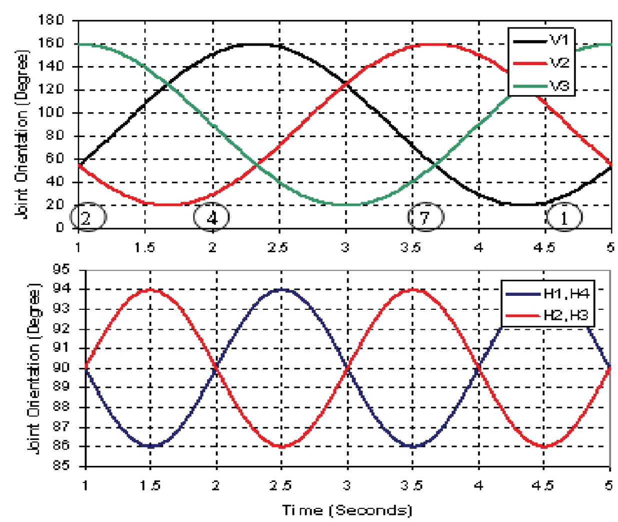

Fig. 8. JOF Plots for H-Plane undulation (top) and that of V-Plane undulation (bottom)

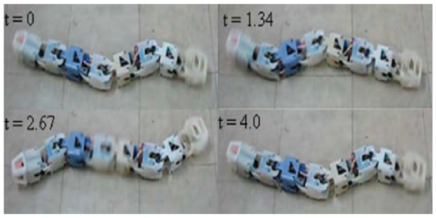

Fig. 9. Sequence showing gaits of lateral undulation locomotion at different times

B. Caterpillar

In this mode of locomotion pure sinusoidal wave travels through the length of the body on the V-Plane. The direction of motion of this wave is from rear to front while the robot moves forward.

TABLE III

JOF PARAMETERS FOR CATERPILLAR LOCOMOTION

ψ - Functions				θ - Functions			
A_ψ	T_ψ	α	$\delta\alpha$	A_θ	T_θ	β_0	$\delta\beta$
-	-	-	-	30°	4	0	90°

The serpent moves without sliding any one of the segments on the ground. Vertical servos are not actuated however, their offset values ($D\psi$) can be adjusted to steer the serpentine robot left or right.

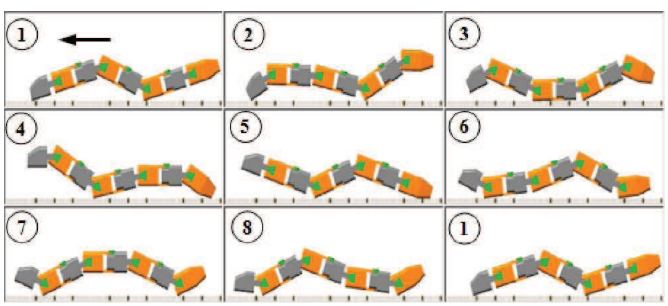

Fig. 10. Simulation of Gaits for Caterpillar locomotion

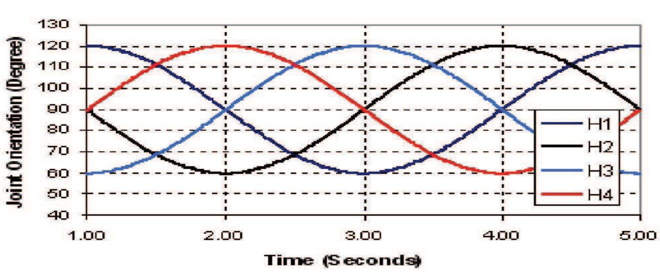

Fig. 11. JOF Plots for V-Plane undulation

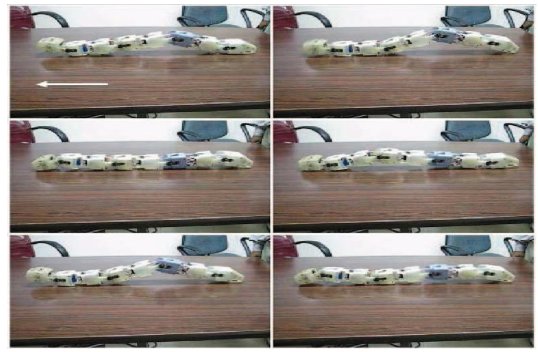

Fig. 13. Sequence showing caterpillar locomotion of the robot

JOF parameters were further adjusted on implementation wherever felt necessary. For the sake of performance comparison all the gaits were simulated with a period of 4 seconds. Again simulation time and real time are different. In simulation environment it takes much longer time to simulate this 4 seconds activity depending upon many factors, for example, simulation time step, computational power. JOF plots are drawn from 1s to 5s. In the first 1s the plots are distorted due to *gait transition*.

I. CONCLUSION

This paper thus presents an approach to gait implementation technique through simulation. Experimentation with serpentine gaits becomes easy and versatile in simulation environment. We can concentrate on a few JOF parameters while experimenting with gaits. JOFs can easily be programmed into a robot's microcontroller having its parameters known through simulation. Moreover it provides with a good insight into the techniques of gait implementation.

However, what conclusion we can draw out of the simulation? How far are they valid? To what extent are they similar to that of a real situation? – are some questions that need to be answered. Simulation results can only be validated through implementation on a physical system. The gait parameters generated through simulation have been successfully tested on the experimental serpentine robot. Due to existence of one-is-to-one correspondence between the simulation model and the experimental serpentine robot, gait experimentation becomes straightforward. Also this approach allows us to implement varieties of gaits on a single design. Any snake robot must have the capability to move within a confined area and traverse all terrains that is not possible by conventional wheeled or walking robots. Though serpentine locomotion has its inherent limitations, snake like robots can have tremendous application potential in surveillance, inspection of pipe lines, search and rescue operation after natural disaster and in many more similar situations.

Although there are several research efforts in this particular field, very few serpentine robots have been successfully demonstrated beyond experimental stage and none of them has any commercial viability till date. This indicates the need for further research in this direction and there is ample scope of improvement in the field of locomotion and control of highly articulated mechanisms.

ACKNOWLEDGMENT

Authors gratefully acknowledge the contribution of all the involved researchers of Central Mechanical Engineering Research Institute (CSIR), Durgapur. The project was funded by Council of Scientific & Industrial Research, New Delhi under XIth Plan Projects.

REFERENCES

[1] Hirose, S., “Biologically Inspired Robots: Snake-Like Locomotors and Manipulators,” Oxford, U.K.: Oxford Univ. Press, 1993.

[2] Burdick, J. W., "Robots That Crawl, Walk, and Slither," Engineering & Science, Summer 1992.

[3] Kimura, H., Hirose, S., “Development of Genbu: Active wheel passive joint articulated mobile robot,” Proceedings of the 2002 IEEE/RSJ Intl Conference on Intelligent Robots and Systems EPFL, Lausanne, Switzerland. October 2002.

[4] Ye, C., Ma, S., Li, B., Liu, H., Wang, H., "Development of a 3D Snake-like Robot: Perambulator-II," Proceedings of the 2007 IEEE International Conference on Mechatronics and Automation, August 5 - 8, 2007, Harbin, China.

[5] Kamegawa, T., Yamasaki, T., Igarashi, H., Matsuno, F., “Development of The Snake-like Rescue Robot "KOHGA"," Proceedings of the 2004 IEEE International Conference on Robotics & Automation, New Orleans, LA April 2004.

[6] Maity, A., Mazumder, S., Ghosh, S., "An Experimental Hyper Redundant Serpentine Robot," 2010 IEEE International Conference on Systems, Man and Cybernetics (SMC-2010), PP. 3180-3185, Oct 10-13, 2010, Istanbul.

[7] MSC.visualNastran 4D 2004, Copyright © 1996-2004. MSC Software, www.vndesktop.com.

[8] Gray, J., “The mechanism of locomotion in snakes,” Journal of Experimental Biology 23, 101-120, Published by Company of Biologists, 1946.

[10] Gray, J., Lissmann, H.W., “The kinetics of locomotion of the grass-snake,” Journal of Experimental Biology 26, 354-367, Published by Company of Biologists, 1950.

[11] Aubin, R., Blazevic, P., Clement, B., Guyvarch, J.P., “Simulation and Design of a Snake-Like Robot Based on a Bio-Inspired Mechanism,” The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, BioRob2006. February 20-22, 2006 Page(s):220- 225.

[12] Fox, L., "Numerical Solutions of Ordinary and Partial Differential Equations," Palo Alto: Addison-Wesley, 1962, pp.24-25.

[13] Wiriyacharoensonthorn, P., Laowattana, S., “Analysis and Design of A Multi-Link Mobile Robot (Serpentine),” IEEE ICIT’02, Bangkok, THAILAND.

[14] HIROSE, S., MORI, M., "Biologically Inspired Snake-like Robots," Proceedings of the 2004 IEEE International Conference on Robotics and Biomimetics, August 22 - 26, 2004, Shenyang, China.

[15] Yamada, H., Mori, M., Hirose, S., “Stabilization of the head of an undulating snake-like robot,” Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems San Diego, CA, USA, Oct 29 - Nov 2, 2007.

[16] Yu, S., Ma, S., Li, B., Wang, Y., “An Amphibious Snake-like Robot: Design and Motion Experiments on Ground and in Water,” Proceedings of the 2009 IEEE International Conference on Information and Automation June 22 -25, 2009, Zhuhai/ Macau, China.

[17] Buchot, R., Ed, Snakes: A Natural History, Sterling Publishing, New York, ISBN 0-8069-0654-5, 224 pp, 1994.

[18] Serpentine Robot, Central Mechanical Engineering Research Institute. http://www.cmeri.res.in/rnd/srlab/srobot.html.