Serpentine Robot: An overview of Current Status & Prospect

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Abstract

Robots that mimic the natural motions of animals have long been of interest in science and engineering. The primary engineering interest in such robots is in having them conduct tasks that require complicated locomotion and cognition. Designating an outdoor mobile robot is more challenging work than the indoor mobile robot because it has the capability of operation at all weather condition and terrains. In case of Serpentine Robots it's more difficult to control its motion and path. Crawling movement as a motive mode seen in nature of some animals such as snakes. Serpentine robots are slender, multi-segmented vehicles designed to provide greater mobility than conventional wheeled or tracked robots but speed is a limitation. Serpentine robots are thus ideally suited for urban search and rescue, military intelligence gathering, and for surveillance and inspection tasks in hazardous and hard-to-reach environments. Serpentine robots designed by inspiration from nature and snake's crawling motion, is regarded as a crawling robots. The aim is to establish serpentine motions on a snake robot without appendages, limbs or wheels. Serpentine robots may be limbless or with limbs. Though various works have been done in this field, very few of them are based on a limbless system. It will be particularly challenging to simulate motion on a limbless system. The paper describes the different features of serpentine robots and summarizes the developments in the world.

This paper is organized in the following manner:

Interesting Biological aspects of snake is described in Section-1 which also includes its physical characteristics and associated research work in this direction. Locomotion studies and various types of locomotion are described in Section-2. Design aspects are discussed in Section-4. Section-5 is for discussion and conclusion.

Keywords: Serpentine, robots (SR), rectilinear motion, locomotion, gaits, degree of freedom

1 Introduction

1.1 Biology of a Snake

The important source of inspiration for researcher to developing mathematical models and control mechanism for snake robot is the physiology of snakes and caterpillars. Therefore it is necessary to provide some description about the biology of a snake because understanding the snake physiology is an important step for developing a snake robot model. A short description about physical characteristics of a snake, snake skeleton and skin are given below.

1.1.1 Physical Characteristics

Skeleton: The skeleton of a snake often consists of at least 130 vertebrae, and can exceed 400 vertebrae. 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). A large total bend of the 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 body.

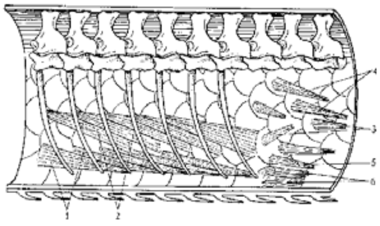


Fig. 1: Snake anatomy

Skin: A snake skin consists of a scaly integument that protects the animal from abrasion and prevents water loss. The integument on the snake's back and sides is thinner than that of the belly. Scales on the back and sides are more numerous than belly scales and are either smooth or keeled with noticeable ridges. Belly scales, also referred to as scutes, are thick and large, and are commonly arranged in narrow strips that extend from one side of the belly to the other. Snake scales are dry and highly polished with a coefficient of friction of between 0.3 and 0.4. The skin, to which the scales are attached, is highly elastic [1]. A snake anatomy is shown in fig.1.

1.2 Serpentine Robots

Serpentine robots are made by interconnecting components called module. Modules can include electronic components, motors/actuators, processors, etc. Modules are connected by joints, which considering the deployment of modules toward each other can have two DOF. Articulation of robot body has facilitated the increase or decrease in body length and assembly of components [2]. High level of DOF increases the power and controllability of the robot [3]. The short transverse and altitude of the robot has made it possible to move in narrow routs such as pipes and also has provided it with camouflage ability. There are no balance or stability problems in such a robot. By stabilizing the robot's end component, it can be used as a manipulator with high DOF [4]. The drive in such a robot is not a wheel or other similar components, but it is possible to motivate it by using a number of angular drives and creating coupling at joints [5]. In controlling the robot movement, it is possible to determine the robot's path by controlling its head in a way such that other components follow it [6]. Serpentine robots designed by inspiration from nature and movement of snakes, were made for first time by Hirose [7]. Serpentine robots' applications include mine detecting [8], inspection of oil and gas pipes [9], submarine inspection, bridge inspection, surgery [10], assistant robot [11] and identification operations in battlefields.

A lot of work has been done on the construction of snake-like robots with elegant and flexible motion, which can move in two or three dimensions [12, 13, 14]. Usually, these robots have many degrees of freedom in order to achieve the flexibility of the real snake and their motion is periodic. Snake-like robots can move in rugged, sandy, terrestrial environments such as rough or muddy terrains, where wheeled mechanisms are not effective.

Major work has been done in 3D animal modeling. A 3D animal model and its texture mapping can be computed using images captured from specific views and a predefined animal model. This methodology has been applied successfully in snake, lizard and goat 3D model construction [15]. Miller [16] simulates muscle contractions of snakes and worms by animating spring tensions. Realistic snake movement depends on the mode of locomotion used by the snake. When snakes encounter different environments, they are remarkably adept at changing their pattern of movement so that they can propel themselves effectively. Gray [17] provides a good review of his earlier papers, some of which emphasized modeling, while others made direct observations of snake movement. In [18] the first quantitative kinematic analysis of the major modes of terrestrial snake locomotion using lateral bending of the vertebral column to generate propulsive forces is presented. In [19] the muscular basis and propulsive mechanism of terrestrial lateral undulation in gopher snakes are examined using patch electrodes. The snake mass center trajectory depends mainly on the snake orientation. Thus, depending on exactly how periodic motion is defined, most of the modes of snake locomotion involve some sort of periodic motion or repetitive pattern. During concertina locomotion, snakes moving at a steady speed periodically (at regular time intervals) stop, although the pattern of left and right movement is highly variable.

Some works discussed below which were done in various universities and Research institutes. Summarization of these works will help us to understand various techniques for simulation of a biological motion in an artificial system.

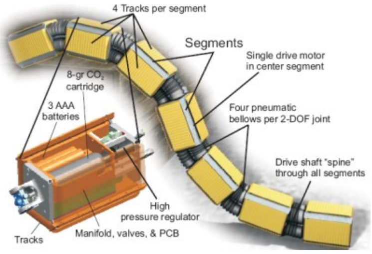


Fig. 11: Snake robot developed at University of Michigan

1.2.1 University of Michigan

A virtually unstoppable "snakebot" developed by a University of Michigan team resembles a high-tech slinky as it climbs pipes and stairs, rolls over rough terrain and spans wide gaps to reach the other side. The 26-pound robot developed at the U-M College of Engineering is called OmniTread. It moves by rolling, log-style, or by lifting its head or tail, inchworm-like, and muscling itself forward. The robot's unique tread design prevents it from stalling on rough ground. The snake-shaped serpentine robot is propelled along by moving treads that cover 80 percent of its body. These treads prevent the snake robot from stalling or becoming stuck on rough terrain because the treads propel the robot forward like a tire touching a road. A human operator controls the snake robot via a joystick and umbilical cord, which provides electric power and sends commands to specially designed software. The *OmniTread* is divided into five box-shaped segments connected through the middle by a long drive shaft spine that drives the tracks of all segments as shown in fig.11. Bellows in the joints connecting the sections inflate or deflate to make the robot turn or lift the segments. The bellows provide enough torque for the *OmniTread* to lift the two fronts or rear segments to climb objects.

1.2.2 Drexel University

The serpentine robot design and developed at the Drexel University as shown in fig.12 is having the capabilities of crossing gaps of up to 8 inches and can move at a speed of 4 in/sec. The segments are modular and can be added or removed. It is able to execute straight line gait. Each segment has two appendages which help it to move.

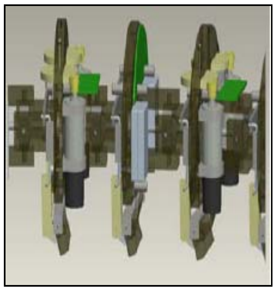


Fig. 12: Robot developed at Drexel University

1.2.3 Carnegie Mellon University

The 3-ft-long robotic snake made of 16 modules, all connected by simple hinge joints and tethered to a hand-held controller as shown in fig.13. The

Fig. 13: Robot developed at Carnegie Mellon University

robots are versatile with heads that come equipped with seeing-eye cameras featuring LED spotlights. When dressed in customizable skins, the snakes can even swim underwater. It can gain access to almost anything, whether it is getting into a house, climbing up a tree or getting to the top of a flagpole. The idea behind the snakes is to create a robot able to adapt and transfigure itself under a variety of circumstances. The snakes will need to be able to respond to unknown conditions during underground searches or power-plant turbine inspections.

2 Locomotion

It is very important to study how snakes locomote and how a snake robot can be made to locomote. Some basic forms of locomotion are – Limbless, Limbed, Flapping and Rolling. Limbed Locomotion can be of two-legged, four-legged or multi-legged.

Gait is the pattern of movement of the limbs of terrestrial animals during locomotion. Most animals use a variety of gaits in different situations. There are some common gaits namely Walking, Running, trotting, Jumping, leaping, Crawling, Climbing Swimming, Flying etc.

Serpentine gaits are mainly of Crawling type. Crawling gait may be limbed (e.g. lizards) or limbless type. Some of the limbless locomotion is described in the next section. Limbless locomotion gaits that can be successfully simulated in a serpentine robot are Serpentine gaits, Caterpillar gait, Inchworm gait and some Synthetic gaits. These synthetic gaits are non-serpentine in nature but can easily be implemented on an articulated serpentine robot.

2.1 Natural Gaits

2.1.1 Lateral undulation

Lateral undulation is one of the most used snake locomotion technique. In this motion, as shown in fig.2 all parts of the snake body moves with a same speed by sliding contact with the ground. Commonly used by biological snakes, the lateral undulation gait produces propulsion, by simultaneously moving body sections. The sections continuously move from side to side perpendicular to the direction of forward motion. This oscillation, as a directional vector has both a tangential and a normal component relative to the forward direction. The lateral, side-to-side, direction is defined as normal to the forward direction. By assigning a positive, conventional direction to one side and a negative direction to the other, the net result of the lateral oscillation cancels the normal force. The tangential components for both sides are in the same direction, parallel to the direction of forward motion. The tangential forces created by these components drive the body forward. The motion requires three points of contact. Two points for forward pressure and a third for balance. Dependent on sliding friction, lateral undulation is not successful on low friction surfaces. Also, the motion is less effective with shorter body lengths and heavy bodies [20].

As this motion depends on sliding friction between the snake body and ground that is why it is not efficiently use in low friction surface and also it is not so effective for shorter body length and large heavy body snake because may be they don't able to make required curve for their shorter length or for their large heavy body. Wheeled or walking machine needs a static contact but in this motion technique there is no need of static contact. This motion is generated by using sliding or dynamic friction. it is the only snake motion technique where static contact with the ground are not used. The characteristics of this motion make it more efficient on bumped grounds and for long snakes. Maximum speed recorded is 11 km/h by a Black Mamba on a distance of 43 meters.

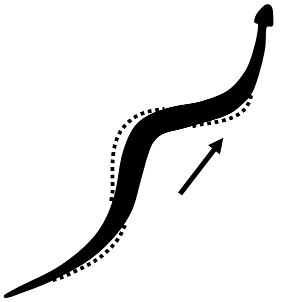


Fig. 2: Lateral undulation

2.1.2 Side Winding:

Side winding is least dependent on friction with the surface. This mode of locomotion technique mainly used by the snakes that are living in the desert (though some non-desert dwellers also use it), where the sand simply gives way under any kind of push. In this motion technique snakes do not progress forward but actually goes sideways as shown in fig.3. A relatively larger amount of energy is expended by attempting this type of motion. This motion is mostly use in low friction ground. In this motion static contact with the ground is needed. Side winding is accomplished by simply lifting all the segments off the ground in sequence. Some snakes can move up to 3 km/h by side-winding motion.

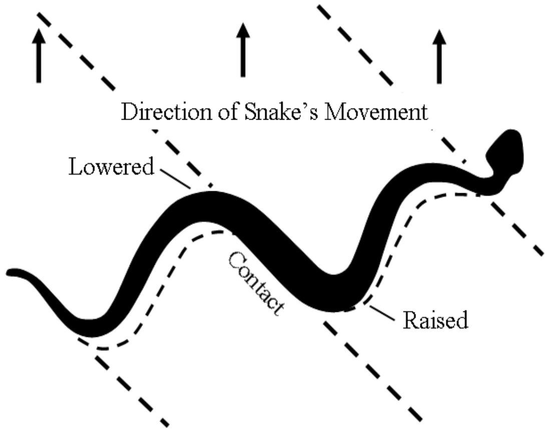


Fig. 3: Side winding

2.1.3 Concertina Progression

Concertina is special types of snake motion unlike the continuous, simultaneous body movements in lateral undulation. The concertina gait uses a progressive, body extension pattern. The body becomes compressed, folded in a posture similar to an accordion. Extending a front section, the snake reaches forward a distance, while the back sections remain stationary as shown in fig.4. The stationary sections provide a foundation for the moving section. The moving sections use the foundation for leverage to extend forward. The extension is undone, as the snake begins to refold its body, by drawing its back section forward. In this phase the front section acts as the foundation, while the back section is in motion. The pattern results in a series, alternating between pushing against a back foundation and pulling against a front foundation. The difference between the static friction and the dynamic friction is the key for this type of gait.

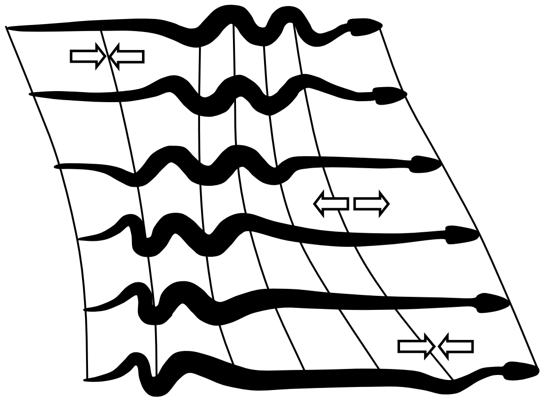


Fig. 4: Concertina progression

2.1.4 Rectilinear

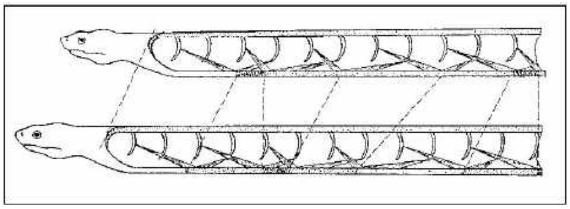


Fig. 5: Rectilinear

In this type of gait the belly muscles shift the skeleton with respect to the skin. Waves of muscular contraction along the body push the whole body forward. Traction to the ground is enabled by belly scales. This gait works with heavy bodies effectively. Rectilinear motion is a slower and creepy in nature. This has shown in fig.5.

2.1.5 Caterpillar Rectilinear Movement

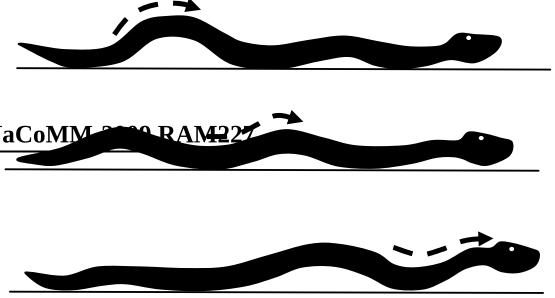


Fig. 6: Caterpillar

A much slower method of movement is caterpillar rectilinear locomotion. This technique also contracts the body into curves, but these waves are much smaller and curve up and down rather than side to side as shown in fig.6. When a snake uses caterpillar movement, the tops of each curve are lifted above the ground as the ventral scales on the bottoms push against the ground, creating a rippling effect similar to how a caterpillar looks when it walks. Both rectilinear and caterpillar rectilinear gaits work on travelling wave principal.

2.1.6 Inchworm Movement

In particular, inchworms (also called loopers) move with a looping movement in which the anterior legs and posterior legs are alternately made fast and released, and thus advancement is obtained by opening the loop as shown in fig.7. The wave remains stationary with respect to the body. In case of serpentine robots without special arrangements to fix itself to the surface, it may be difficult to make a big cantilever. But directional friction may be introduced to make it ratchet forward.

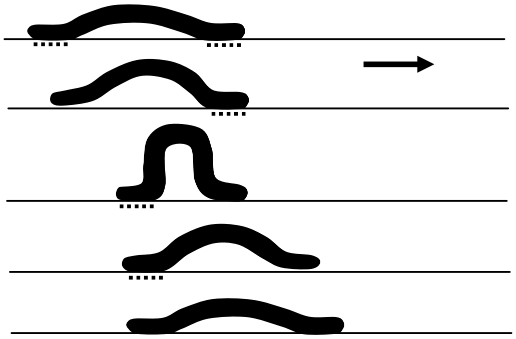


Fig. 7: Inchworm

2.2 Synthetic Gaits

Synthetic gaits are non serpentine in nature but other creatures do perform some of them. These motion types are particularly interesting because they can be easily implemented on a serpentine robot.

2.2.1 Lateral roll

In this type of locomotion generally two waves out of phase generated as shown in fig.8. These are a lateral sine wave and a ventral cosine wave providing oscillating motions about each joint.

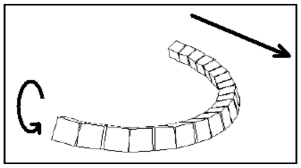


Fig. 8: Lateral Roll

2.2.2 Rolling collar

It’s a variant of Lateral Roll motion where the whole body is curved into a closed or semi-closed loop. This motion can be used to make a serpentine body to climb up a cylindrical surface.

2.2.3 Flapping

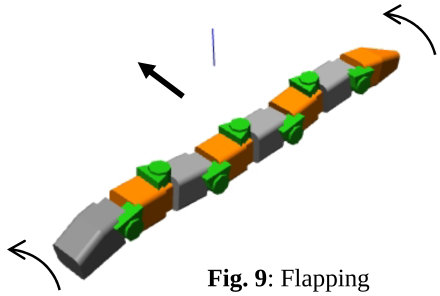


Fig. 9: Flapping

In this mode of locomotion the whole body moves sidewise. Flapping is achieved by in-phase motions of the ends. The ends swing forward, come down in contact with the ground and then lift and drag the center of the body forward a shown in fig.9. This is very much similar to the motions of a swimmer performing butterfly stroke.

2.2.4 Wheel

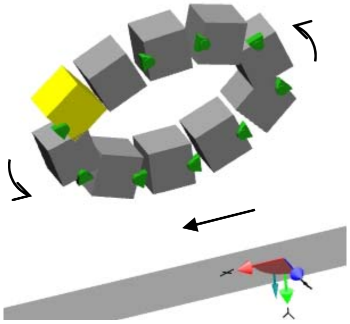


Fig. 10: Wheel

Some caterpillars perform this kind of locomotion in times of emergency. They coil their body in closed loop and roll very quickly as shown in fig.10. The same may be implemented in a serpentine robot by making an elliptical loop and transferring the joint angles to the adjacent joints in a circular fashion.

3 Application & Prospect

Serpentine robots are slender, multi-segmented vehicles designed to provide greater mobility than conventional wheeled or tracked robots. They are thus ideally suited for urban search and rescue, military intelligence gathering, and for surveillance and inspection tasks in hazardous and hard-to-reach environments. Snake-like robots are believed to offer several advantages over conventional wheeled or legged robots like they have low center of gravity, which makes them very stable when moving on inclines. In addition, if a snake-like robots fall over, it may recover by articulating its body in the proper way. Unlike their walking or wheeled counterparts, snake-like robots spread their weight out over a large area, thus exerting less force per unit area over the surface on which they are moving. This means the robots of this class are better suited for moving over loose soil or sand, compared to wheeled and legged robots that are more likely to get stuck in such environments.

3.1 Advantages

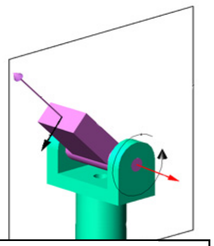
There are many advantages for the serpentine motion of a robot. Some of these are illustrated below:
Terrainability: Snake like robots can traverse rough terrain. They can climb steps whose heights approach.
Traction: Snakes can use almost their full body length to apply forces to the ground.
Efficiency: Low costs of body support, no cost of limb motion.
Size: Small frontal area allows penetration of smaller cross-sectional areas than legged or wheeled vehicles.
Redundancy: Serpentine vehicles consist of many similar segments. The loss of function of some of these may be compensated, though some efficiency may be lost.
Sealing: The surface of a serpentine vehicle is small and does not need to be exposed to the environment in the same way as limbs. This provides advantage to applications in hostile environments.

3.2 Disadvantages

Payload: Transport of materials is difficult until an integral conduit is used.
Degrees of Freedom: A large number of actuators are necessary. This provides problems to motion planning and control.
Thermal Control: The long stretched form of snakes makes thermal control somehow difficult.
Speed: Robot snakes are far slower than their natural counterparts (reaching speeds up to 3.0 m/s) and far slower than wheeled vehicles.

4 Design and Simulation

The main challenge in designing a snake robot is putting actuated joints in a tight volume where we minimize the length and cross sectional areas of the links between the joints. The main concept of any design, as well as many others, is to stack two degree-of-freedom joints on top of each other, forming a snake robot. There are three main designs in practice for these kinds of robots: actuated universal joints, angular swivel joints and angular bevel joints.
Actuated universal joints as shown in fig.14, as the name suggests, the design incorpo-



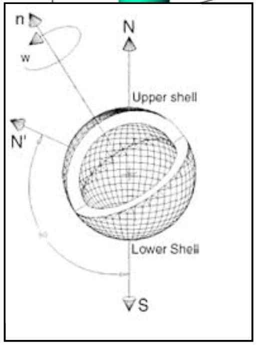


Fig. 15: A typical angular swivel joint

rates a universal joint with two motor to actuate each of the two degrees of freedom of the universal joint.

The second design that evolved was the angular swivel joint as shown in fig.15, which are much more compact two DOF joints. The design is simple: starting with a sphere, then slicing the sphere into two parts such that the slice plane is transversal to the south-north pole axis of the sphere. If one half sphere is rotated with respect to the other the North Pole traverses a cone of revolution. Connecting two adjacent snake bays via a passive universal joint and then by coordinating the rotation of the two spherical cups generate two degrees of freedom.

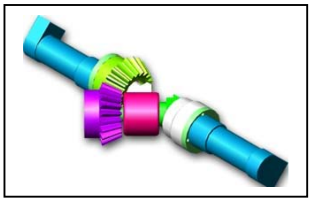


Fig. 16: A typical angular bevel joint

Another design is the angular bevel joints where two mutually perpendicular bevel gears generally used for the degree of freedom as shown in fig.16. The main challenge in this design approach is to make the joint as compact as possible, yet strong enough and with appreciable bending range. One of the main benefits of this design is that you need only one motor to actuate one degree of freedom as opposed to the rest of designs where two motors are used. However, the torques transferred to the motor are relatively larger hence the need of higher reduction. Usually the high reduction is done by using power screws of worm gears hence the slowness of the mechanism.

4.1 Travelling Wave

The simplest locomotion model for serpentine robots is traveling wave, contrary to stationary wave, similar to inchworm motion where the advancing wave remains in the same position with respect to body coordinates. Simple trigonometric sine functions were used to represent the traveling wave on serpentine robots. The nature of these sine functions depend upon offset, amplitude, frequency and phase. Magnitude and frequency are obvious and phase represents the shift of the waveform along the body. Traveling wave modeling is relatively simple but they fail to represent arbitrary time-varying waveforms. Other techniques like Fourier series (approximated to certain terms), Bessel functions, parametric curves, wavelets, body co-ordinate matrices are also used to simulate serpentine locomotion.

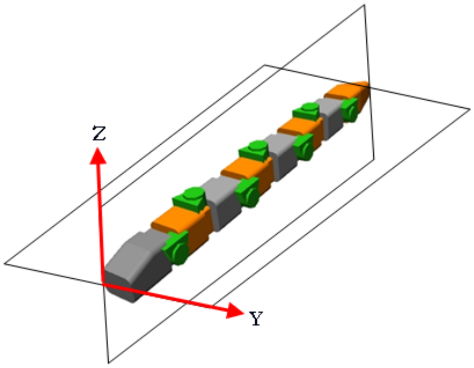


Fig. 17: Analysis Model of a serpentine robot

Analysis of a serpentine robot model is shown in fig.17. In research purpose, it is necessary to assume snakes' undulation as described by a simple traveling wave equation:

- $Y = A_1 + B_1 * \sin(C_1 X + D_1)$
- $Z = A_2 + B_2 * \sin(C_2 X + D_2)$

Where,

A = Offset
B = Amplitude
C = Frequency term
D = Phase

5 Conclusion

Machine locomotion with wheels, tracks or legs are common. Generating locomotion in a limbless, wheel less system is far more difficult. Study of serpentine locomotion helps us a lot in that direction. Snake locomotion techniques are not very easy and are difficult to implement in a mechanical system. Up to this time only a few limbless snake robots have been made with limited locomotion techniques. One of the fundamental issues lies in understanding their locomotion. This paper addresses the limbless serpentine robots that crawl and slither without the use of wheels, legs or any other appendages and only the body motion is used to make it move.

Limbless serpentine robot is a relatively new and upcoming subject in outdoor mobile robot than other types of mobile robot. Biological snakes locomote by their various techniques and their locomotions are generated by some critical biological mechanism. To make a limbless serpentine robot, we have to face lots of problems and we have to overcome lots of real challenges because simulation of a natural mechanism in a man-made device is really a challenging work. But if we able to create a snake like device that could slide, glide and slither could open up many applications in exploration hazardous environments, inspection and medical interventions. A snake robot has the capability to wriggle into confined area and traverse all terrains that will not be possible for our traditional wheeled or walking robots. These robots are more acceptable for its stability, terrain ability, high redundancy and completely sealed mechanism. Snake like robots are generally used in bridge inspection, inspection of pipe systems, minimally invasive surgery, search & rescue, e.g. in collapsed buildings, elephant-trunk-like manipulators etc.

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