

Design and Prototyping of a Biomimetic Serpentine Robot

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Abstract

Objectives: In this study, a mechanism for a biomimetic serpentine robot is designed and tested. **Methods/Analysis:** A field survey was conducted to notice various parameters of snakes like their locomotion patterns, sizes, shape, speed, etc. Based on the observations and other important design considerations a mechanism was designed consisting of components analogous to that of snake's anatomy. As the prototype would consist of abundant segments, analysis and simulation of a single segment was performed to validate the mechanism. After validation, the prototype was manufactured, controlled and tested. **Findings:** Although, there had been snake robots developed in the past, none of bot could depict the natural curve of snake's locomotion. The bots are modular i.e. consists of abundant modules connected to each other by rigid rotating joints which disallows them to perform the perfect curve of snake. **Novelty/Improvement:** The mechanism developed in this study overcomes the drawbacks of previous models and hence is able to depict the serpenoid curve with maximum accuracy providing a real life curve of snake. The first prototype is cheap to manufacture and further improvement could really prove promising hypothesis.

Keywords: Biomimetics, Serpenoid Curve, Serpentine Robot

1. Introduction

Biomimetics is the imitation of the models, systems, and elements in nature for the purpose of analysing and solving complex human problems. It means mimicking biology or nature. Organisms in nature have evolved over millions of years constantly improving their abilities to survive, grow and hunt. This has made them a great source of superior design and engineering intelligence. It involves the understanding of biological functions, structures and principles of various organisms found in nature which could guide us to imitate and produce useful designs and processes. It can also be described as the intersection of biology and technology.

The very first idea of bio mimicry came into existence when man was astonished by the flying ability of birds. Man tried to depict it by targeting at the wings of the

flying species which was an obvious choice. Since then, many inventions have been made using Biomimetics.

One of the promising examples of bio mimicry is a 'snake robot'. Researchers have attempted successfully to depict the propagation pattern of a snake by using its many internal degrees of freedom to move into tight spaces or non human friendly spaces at the time of crisis or even for surveillance. They have evolved to adapt locomotion to different environmental conditions with different propagation patterns. An example of snake propagation is shown in the Figure1.

Section 1 of this paper introduces the concept of Biomimetics and also proves snake to be a fine option for bio mimicry. Section 2 consists of research and conclusions of numerous existing mechanism and models of snake robot. The final Section incorporates the design considerations, validation, the working and the physics behind the working of the developed mechanism.

2. Literature Review

Qualitative research on snake's locomotion was first given in^{1,2} the initial developments of the snakelike robots were executed in 70s by Hirose group of investigators. They performed analysis of limbless motions experimental data and suggested mathematical description of the snake's instant form. The curve shown in Figure 2 is called as "serpenoid curve" and was used for snakelike robot's control assignment².

Here, $s=0$ is the starting point of the curve and corresponds to the first point P on the left side of the curve. The parameter α is the angle of the body at point O relative to the travelling direction called as the winding angle, and L is the length of the curve in one cycle of the curve.

The very first model named ACM-III shown in Figure 3 was invented in the year 1972 which was successful in demonstrating the world's first serpentine motion by using the same locomotion principle as that of a real snake². In 1995, a self-contained version of this snake robot was build, and named ACM-R1².

The ACM series was followed by a model capable of 3-dimensional (3-D) motion, ACM-R2². This model was further developed to form ACM-R3 shown in Figure 4 in

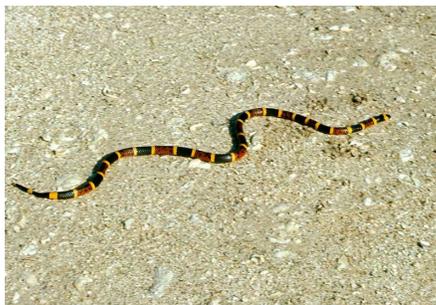


Figure 1. A Coral snake propagating on a rough terrain.

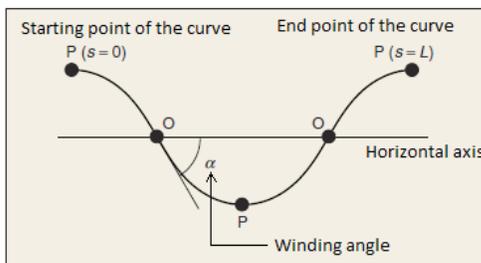


Figure 2. Serpenoid Curve used for analysis of serpentine motion.

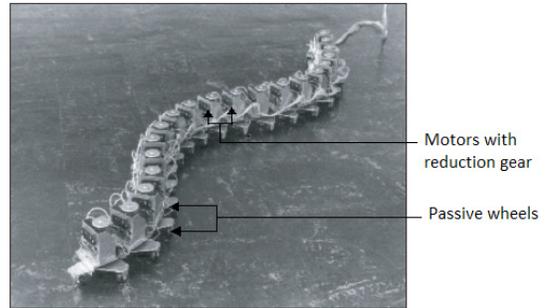


Figure 3. The first modular snake bot ACM-III.

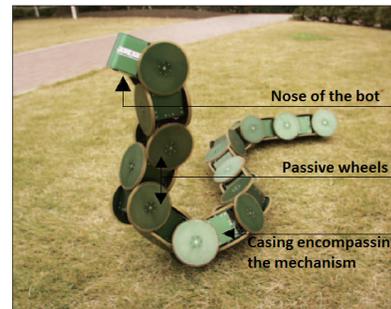


Figure 4. ACM-R3.

the year 2001, which had advanced functioning and could perform more propagation patterns in a very authentic manner².

ACM-R5 developed in 2001 was the first amphibious snake bot². It could propagate on land as well as swim in water. The level of sophistication in design as well as in working of a snake robot has been increased in last few decades. Analysing various mechanisms of various snake robots presents us the development in this field. Every model has got its own strength and flaws. The very first snake robot (ACM-III) was a wheeled bot which looked like a train like model. It could just propagate in only one locomotion pattern without carrying any end effectors. ACM-R3 developed by Hirose had a different layout of the module. Big passive wheels encompassing the internal mechanism as well as allowing to slide leading to smooth movement at any position. It didn't really look like a snake and mainly was wheeled. Stevens Institute of technology developed a snake robot of abundant modules which was simple and cheap³. The latest and the most sophisticated limbless snake bot was developed recently at CMU⁴. They micro-engineered their way out of all the flaws there could possibly be. They used many electronic components each having specific purpose and that too with perfection. It could perform way more gaits than any other snake robot.

In spite of all these advantages, it was a costly robot as well as high maintenance. It was wired too. Gavin Miller developed a bot with most accurate snake movement in the year 1999. But again, it was a wheeled bot.

3. Design and Validation

In Section 2, different types of snake robots as well as their working mechanisms used for depicting snake's motion and their flaws are explained. It is quite clear that a working model of any snake robot should be embedded with pitch and yaw mechanisms in order to depict snake's locomotion with an acceptable efficiency. Many researchers and developers were able to depict the locomotion with a robotic similarity with an error of not creating a perfect sine curve during propagation of the model. In case of wheeled snake robots the curve can be achieved easily but it won't be bio mimicry in true sense as it won't be any good than a normal wheeled train-like robot.

The main objective of this paper is to achieve similar locomotion as that of a biological snake's. Snakes are believed to make certain curves while propagating which actually helps in providing frictional force necessary for protruding forward. Figure 5 clearly shows the difference in the curves made while propagating by a robotic snake and a real snake.

In order to overcome this drawback it is necessary to provide a more muscular movement for the propagation i.e. to trace the serpenoid curve with maximum accuracy. This can be done by properly studying the anatomy of the snake and by developing a design considering the limb placement of a biological snake. Biology of snake says that even though a snake is considered to be utterly flexible, it has numerous bones. Snakes have between 200-400 vertebrae with as many ribs attached. That is what makes them so flexible and helps them to move in random manner.



Figure 5. Difference between the curves made while propagating by a snake robot and a real snake.

A field survey was done to observe various snakes to discover various parameters like locomotion pattern, size, length, mobility, etc. Figure 6 shows the various snakes observed. The observations indicated that different snakes propagate in different manner at different speeds. Heavy snakes protrude slowly making a larger radius of curvature whereas lean snakes move faster making a smaller radius of curvature. The difference is due to the reason of generating sufficient magnitude of frictional force which changes according to the shape and size of a particular snake. They had certain scales on their skin which could provide resistance when felt from one side and provide smoothness when felt from the opposite side. This is also an anatomy to be considered while designing the prototype.

The mechanism developed is based on achieving following objectives-

- More than 90 % depiction of the serpenoid curve
- Ability to perform as many gaits as possible
- Components housing
- Retaining the unique capabilities of the serpentine
- Size and shape minimization
- Weight
- Speed and agility

In order to match the body composition of snake, a series of circular aluminium discs 0.0075 m thick and 0.08 m in diameter acting as ribs shown in the Figure 7 are held together with the help of a Polyurethane rod of diameter 0.01 m passing through the centre of each disc which acts as the vertebral column or the backbone. Such discs are



Figure 6. Snakes observed at field survey.

joined in succession being 0.05 m apart. Polyurethane being a flexible material, the proposed snake robot has got a flexible backbone analogous to the backbone of the biological snake. Considering the Polyurethane rod as the origin, the discs have got four holes of diameter 0.005 m each, individual hole being at a distance of 0.035 m from the origin on both the positive and negative sides of the mutually perpendicular axes within the plane of the disc.

A series of 4 discs as described in Figure 3.3 makes a segment and such multiple segments make the prototype. With the intention of providing motion to a single segment flexible strings are to be passed through each hole of the discs placed one after another as shown in the Figure 8.

The strings passing through the right and left holes are supposed to provide the yaw motion while the strings passing through the upper and lower holes are supposed to provide pitch motion to the snake robot. In a single segment, if the last disc is kept stationary and the string passing through the right holes of consecutive discs is pulled keeping other strings unfastened, the segment tends to bend towards right side with respect to its normal position.

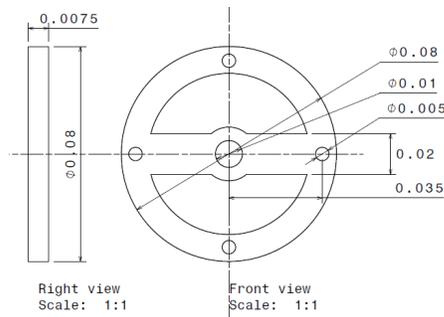


Figure 7. Dimensions in m of a single disc used in the proposed mechanism of the snake robot.

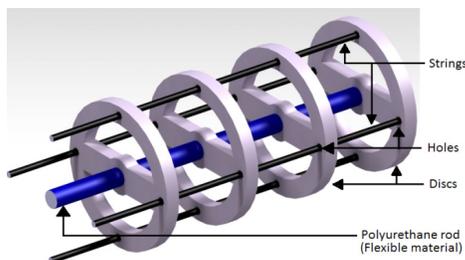


Figure 8. Arrangement of the components of the proposed mechanism of the snake robot.

At the start, the discs are held together in a straight line due to the stiffness of the polyurethane rod. Polyurethane has got good elongation and recovery properties. It provides stiffness at mean position as well as provides the required flexibility for forming the curve. The string when pulled, the tension formed in the string applies a pull force on the first disc where the other end of the string is tied. If we observe that particular disc we can find that an external force is being applied on one end of the disc in axial direction while the diagonally opposite end of that disc has no force acting on it in any direction. This unbalanced force motivates the rotation of the disc about its planar axis which is restricted by the polyurethane rod. As an external unbalanced force is experienced by the polyurethane rod, the inertia is disturbed and hence the rod bends towards the direction of pull force generated. Basically the force transfer takes place between first and last disc and the in between discs acts as skeleton and restrictors.

The same mechanism is applied to bend the segment towards left, upside and downside just by changing the string to pull. Bending left side and right side provides the yaw motion and bending upwards and downwards provide the pitch motion to the segment of the bot. Such segments with the proposed bending mechanism are to be arranged in series to form the working prototype of the proposed snake robot. Such a motion of a single segment is shown in Figure 9 by a simulation done in MSC Adams Software.

The main factors while considering the dimensions of the discs were subsystem housing and manoeuvrability. As the design suggests actuation of the strings for providing the required movement, actuators are supposed to be installed within the casing. Also the prototype must be able to manoeuvre through tight spaces as per the application. The effective diameter of the disc was a compromise between these two factors. To confirm this assumption

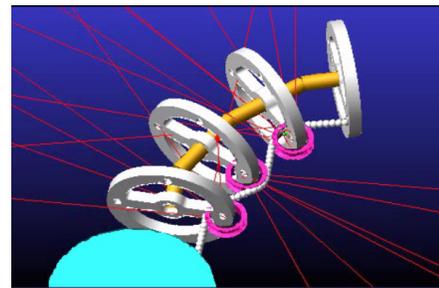


Figure 9. Simulation of bending motion of a single segment done in MSC Adams software.

of effective diameter i.e. 0.08 m and thickness 0.075 m, a crude prototype was manufactured and trail tested for the conditions similar to working conditions for its ability to trace the curve. The offset is selected considering the effective diameter of the disc and the magnitude of pull force generated.

While propagating, snakes are known to generate certain curves to apply force and friction for protruding forward or in any desired direction. The bent segments are supposed to accomplish such curves and hence help in propagation of the snake robot.

Figure 10 shows the superimposition of the result of simulation of the designed mechanism on the serpenoid curve. It is clearly seen that the designed mechanism satisfies about 90–95 % of the radius of curvature of the serpenoid curve and hence is a valid mechanism. The number of discs in a single segment has an impact on the accuracy of tracing the radius of curvature in a serpenoid curve and also the response time. Four discs were found to be most excellent choice for formation of a single segment because it traced the radius with maximum accuracy of 90–95 % with less response time. Also a four disc segment can trace the serpenoid curve with less number of segments. Less than four discs segment would require more segments and more than four discs segment would compromise the response time.

As explained in Section 1, snakes move forward using principles of weight distribution and frictional resistance. It is known as 'sinus lifting'. Along with these principles, minor elongation and compression of its body is also responsible for its movement. In order to achieve the sinus lifting, both the yaw and pitch motions are performed at a certain acceptable degree. The timing as well as the precision of the yaw and pitch angle is necessary for proper propagation in desired direction.

As stated earlier, a segment has to be powered by some mechanism. For that purpose four micro servomotors along with suitable battery are installed in the last disc of

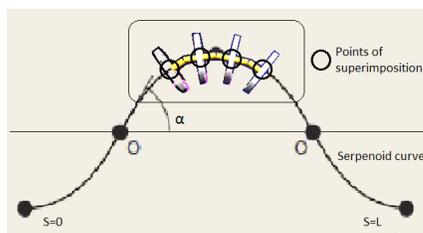


Figure 10. Superimposition of result of simulation and the serpenoid curve.

each segment in a casing. One motor for each string and a pair each for performing yaw and pitch motion. A pulley of certain diameter is fixed on the output shaft of the servomotors. One end of the string is tied to the pulley and another end is tied to the first disc in a way shown in Figure 8. The strings are pre wound on the pulley for maintaining the initial tension required in the strings to hold up at normal position. To perform yaw motion, the motors controlling right and left strings should be actuated. For bending towards right direction, the motor controlling the string passing through right side holes starts winding up the string on the pulley and at the same time the motor controlling the string passing through left side holes starts unwinding the string from its pulley. This provides the proper actuation for bending of the segment, in this case, towards right side. The same actuation method is used to bend the segment towards left, upside and downside just by proper winding and unwinding of the respective strings on and from the pulleys of the respective motors.

For correct winding and unwinding of the strings, the angular displacement and angular speed of the motor has to be controlled with great accuracy which will lead to proper bending and proper curve formation.

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