Design of a Snake Robot to exhibit Rectilinear Motion On Floor and Inside Pipes

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Abstract

In this paper we present a novel 3 DOF joint mechanism for a snake robot which makes the segment to turn, lift and extend. Using these degrees of freedom, the robot is made to exhibit rectilinear motion on floor and inside pipes. A simple wall press mechanism is used at the center of each segment which helps it to climb pipes. The design of the snake robot using this joint mechanism is explained in detail. The experiments were conducted where the snake robot moved on a flat surface, horizontally inside a pipe and also vertically from top to bottom inside a pipe.

1 Introduction

A snake is a versatile animal which can adapt its body structure with changing environment and hence, exhibits complex motion patterns. A snake robot which can replicate the motions of a real snake has many applications in real life. For instance, they can be used for fire fighting, exploring damaged buildings, traveling through pipes during maintenance activities, moving over cluttered environments and also under water [1]. The making of a snake robot has a hardware design challenge as one has to create joint actuating mechanisms that has compliance [2] with minimum number of links. Therefore in this paper we focused on creating one such joint mechanism.

1.1 Rectilinear motion

Rectilinear motion is exhibited by thick snakes like boas where they move approximately in a straight line [3]. Although it is a slow form of locomotion [2], it is needed while the robot moves in confined regions and inside straight pipes. It is exhibited in a snake robot by stretching and pulling the alternate segments. Since the length of the snake robot needs to increase and decrease while stretching and pulling, there needs to be some compliance in the joint mechanism. Therefore in this paper we have created a cam based joint mechanism using a spring-mass system which has compliance since it can expand and contract.

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1.2 A survey of snake robots exhibiting rectilinear motion

There are many snake robots in the literature that exhibit rectilinear motion. They can be divided into two categories (1) Snake robots that exhibit only rectilinear motion (2) Snake robots that exhibit rectilinear motion along with other motions. The snake robots made by Hopkin $.et.al$ [4] and Spranklin $.et.al$ [5] come under the first category. The snake robots made by Primerano $.et.al$ [6] and Sugita $.et.al$ [7] come under the second category. Further the rectilinear motion can be demonstrated in one of two forms as mentioned in [8]. (1) By propagating vertical waves (2) By expansion and contraction. The snake robots done by Kotay $.et.al$ [9] and Dowling [10] navigate by propagating vertical waves. On the other hand, the snake robots made by Sugita $.et.al$ [7] and Yeo $.et.al$ [11] navigate by expansion and contraction of segments.

1.3 Theoretical works done in the past

Many works on modelling of snake robots for rectilinear motion based on the spring-mass system have been done in the past [12] [13]. Some of the works are limited to simulation [14] [12]. The kinematic and dynamic analysis of the two mass system has been done in the literature which can be referred to in [15]. Having studied these works, we have experimentally verified the rectilinear motion in a snake robot using the spring-mass system.

1.4 Our contribution

In our work, we create a compliant joint mechanism for a snake robot which makes it move on the floor and also inside pipes. Springs are compliant in nature and are hence used as a part of the joint mechanism. The snake robot exhibits on floor motion by propagating vertical waves and in-pipe motion by expansion and contraction of segments. Hence this leads to a new category of snake robots that exhibit rectilinear motion apart from the two kinds as mentioned in [8]. The joint mechanism is shown in Figure 1 (b). Extension springs are used to connect the two cuboid shaped segments of the snake robot. While moving on floor, the two cam-like structures at the bottom of the segments are made to actuate so that vertical waves are generated. This causes the snake robot to exhibit rectilinear motion on floors. During in-pipe motion, the segments are made to extend and contract by the rotation of all the four cam-like structures located in the four corners of the square cross section in the segment. The segments are held in position inside the pipe using the wall press mechanism that induces friction. The fabricated snake robot can be seen in Figure 1 (a). A video of the snake robot can be seen on the following link (Video of the Snake Robot)

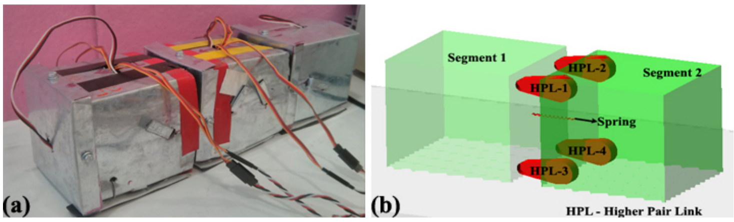


Figure 1: (a) The fabricated snake robot based on the spring-mass system (b) The joint mechanism with four sets of disk cam-like structure called as HPL.

2 Notations and defined symbols used

The various parameters of the snake robot are represented using the notations and symbols in Table 1.

Table 1: Notations used in the paper

Symbol	Description
L_c	Effective cam length
θ_i	Angle made by the segment with the X axis
x_i, y_i	Initial position of the CM of a segment
X_i, Y_i	Initial position of the CM of a segment from the origin
X_f, Y_f	Final position of the CM of a segment from the origin
X, Y, Z	Displacement of the segment in x,y axis
$\dot{X}$,$\dot{Y}$	Velocity of the segment in x,y axis
$\ddot{X}$,$\ddot{Y}$	Acceleration of the segment in x,y axis

3 Synthesis of the joint mechanism

The joint mechanism proposed here is used to make the snake robot exhibit rectilinear motion when it moves over floor and inside pipes. The synthesis of the mechanism is done in order to find out the possible ways in which the four cam like structures can be rotated to obtain the desired output. The type synthesis and dimensional synthesis are done and presented in this section.

3.1 Type synthesis

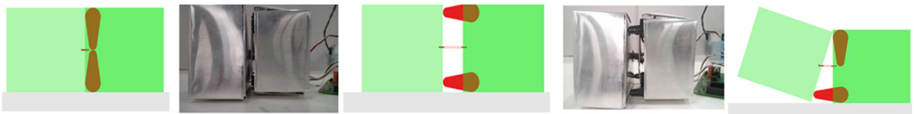
The type synthesis is the definition of proper type of mechanism best suited to solve the problem [16]. In this case, the problem is to make the snake robot exhibit rectilinear motion on floor and inside pipes. This is made possible by suitably rotating four disk cam-like structures in the joint mechanism. The proposed joint mechanism is shown in Figure 1 (b) and the type synthesis of the rectilinear motion is done in the following section for on-floor and in-pipe motion.

3.1.1 Rectilinear motion for on-floor motion

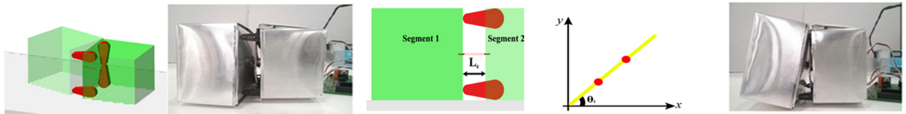
While moving on floor, the snake robot has to lift and push its segment forward. It is shown in Figure 2(c). It is done by rotating to and fro the two cam-like structures at the bottom of the joint mechanism. The rest two cam-like structures at the top are kept idle. The rubber linings at the bottom induces anisotropic friction and helps in the propulsion of the snake robot.

3.1.2 Rectilinear motion for in-pipe motion

To achieve this motion in our snake robot, all the four disk cam-like structures of the joint mechanism rotate simultaneously to and fro. This makes the segment in front to move forward. The extension and contraction of the joint mechanism is shown in Figure 2(a and b). The links, as shown in Figure 3(b) project out of the segments in the snake robot and provides stability while moving inside vertical pipes.



(a) Contraction (b) Extension (c) Lift up



(d) Turn (e) Linear Distance Moved (f)

Figure 2: (a) Initial position of the joint mechanism (b) Extension motion exhibited during in-pipe motion (c) Lift and extension motion exhibited during on-floor motion (d) The segment of the snake robot making a turn by actuating the cam like segments on the sides (e) The linear distance L_c moved by the segment 1 during extension motion (f) Representation of the snake robot on a 2D plane

3.2 Dimensional Synthesis

It is the way to determine the proportions of lengths of the link necessary to accomplish the desired motions [16]. The distance moved forward during the rectilinear motion depends on the length of the cam like structures. This parameter plays a vital role during the kinematic analysis of the snake robot that is dealt with in the Section 5.

Linear distance moved by the segment during rectilinear motion: If the lengths of the four disk cam-like structure are increased or decreased, the forward distance moved by the segments is also increased or decreased respectively. The length of the cam like structure is determined based on the size of the segment. It has to be less than half the height of the segment so that when all the four are contracted, they fit inside the segment. The maximum linear distance LD moved by the first segment during rectilinear motion is equal to the effective length L_c of the disk cam-like structure. It is represented in Figure 2 (e).

$$LD = L_c \tag{1}$$

4 Mechanical design of the snake-like robot

The snake robot consists of segments, joint mechanism and friction inducing mechanism. The details of them are explained in this section.

4.1 Segments of the snake robot

The segments of the snake robot are considered as masses and the joints between the segments are considered as springs which are expanded and contracted using the four cam like structures.

4.2 Joint mechanism

The joint mechanism is used to connect the segments of the snake robot. It is shown in Figure 1 (b). The cuboid shaped segments are connected to each other using an extension spring. There are four cam-like structures in the corners of the segment which rotates to and fro for a certain angle. This makes the segments extend and contract while moving inside vertical pipes. The extended state of the joint mechanism can be seen in Figure 3(c).

4.3 Friction inducing mechanism

The effect of friction played on a snake robot while exhibiting rectilinear motion on three different surfaces (namely dry surface, surface with a layer of oil and surface with a layer of lubricant) was experimentally studied by Virgala $.et.al$ [17]. It is observed that the change in surface did not have much influence on segment motion.

4.3.1 On-floor motion

It is seen during planar motion that the ground friction forces over the segments have to be anisotropic in nature [2]. The anisotropic friction is induced by having rubber linings at the outer edges in the base of the segments. It can be seen in [18] where such linings are given. A similar approach is adopted in our work, where rubber linings are given at the base of the segments. It can be seen in Figure 3 (a).

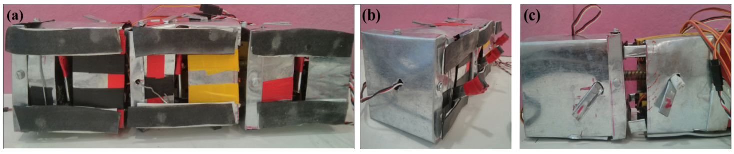


Figure 3: The friction inducing mechanism (a) Rubber linings to induce anisotropic ground friction (b) The projections (links) are used to press against the inner surface of the pipe (c) The HPL are seen extended and the spring is seen in the extended position at the center.

4.3.2 In-pipe motion

There are several ways by which the segments of the snake robot can be made stable inside the pipes while propelling. The wall press mechanism is considered as an efficient one while climbing vertical pipes [19]. The mechanism consists of a simple link attached perpendicular to the axis of rotation of the shaft in a servo motor. It can be seen in Figure 3(b) that each segment has such link projecting outside.

5 Kinematic analysis of the segment motion

In this section, we provide the equations for the displacement, velocity and acceleration of the snake robot while exhibiting rectilinear motion. The rectilinear motion of the segment takes place in two phases. In phase 1, the segment N pushes itself forward by the rotation of the cam-like structures. In phase 2, the segment $N-1$ is pulled forward due to the rotation of the cam-like structures in the opposite direction. The equations derived in this section are limited to phase 1 of the rectilinear motion. These equations can be used to find out the speed with which the snake robot is moving in a particular phase. In Figure 2 (f), the yellow line represents the segments and the red dot represents the joint mechanism. Initial position of the CM of a segment from the origin is given by the equation,

$$X_i = x_i \cos\theta_i ; Y_i = y_i \sin\theta_i \tag{2}$$

Final position of the CM of a segment from the origin after extension of the segment while exhibiting rectilinear motion is given by the equation,

$$X_f = x_i \cos\theta_i \pm L_c \cos\theta_i ; Y_f = y_i \sin\theta_i \pm L_c \sin\theta_i \tag{3}$$

Where the ± sign denotes that the snake robot moves forward or backward respectively.

The displacement of the segment during the forward rectilinear motion (Phase 1) is given by the equation

$$X = L_c \cos\theta_i ; Y = L_c \sin\theta_i \tag{4}$$

The velocity of the segment during rectilinear motion (Phase 1) is given by the equation

$$\dot{X} = -L_c \sin\theta_i . \dot{\theta}_i ; \dot{Y} = L_c \cos\theta_i . \dot{\theta}_i \tag{5}$$

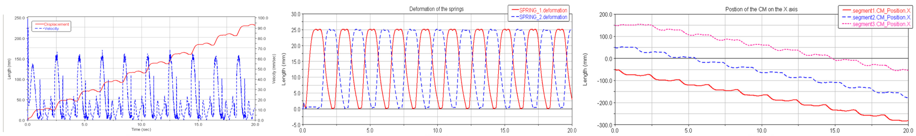
The acceleration of the segment during rectilinear motion (Phase 1) is given by the equation

$$\ddot{X} = -L_c \cos\theta_i . \dot{\theta}_i^2 - L_c \sin\theta_i . \ddot{\theta}_i ; \ddot{Y} = -L_c \sin\theta_i . \dot{\theta}_i^2 + L_c \cos\theta_i . \ddot{\theta}_i \tag{6}$$

6 Simulation and experimental results

6.1 Simulation of the snake robot

A CAD based approach as proposed in [20] was done to simulate the snake robot. The components excluding the spring were considered as rigid body. The properties of the spring were found out by trial and error method. Based on these properties, the spring was chosen in reality. The displacement and velocity curve obtained during on-floor rectilinear motion is as shown in Figure4(a). It can be seen from the figure that there is some pull back effect during the displacement of the segments. It can be prevented by optimizing the spring in future. The deformation of the two springs in the snake robot is plotted against time and is shown in Figure 4(b). The postion of the center marker of the three segments are plotted against time and is shown in Figure 4(c). It was found that the snake robot moved as expected on floor and inside pipe.



(a) (b) (c)

Figure 4: (a) The displacement and velocity plot for the rectilinear motion of a segment (b) The graph shows the deformation of the two springs with respect to time (c) The position (CM) of the three segments of the snake robot with respect to time

6.2 Experimental results

The segments of the snake robot were fabricated using sheet metal. The cam-like structures were actuated by using servo motors. They were controlled using $ArduinoUNO$ micro-controller with $Adafruit$ servo shield. In the three segment snake robot, 11 servo motors were used out of which 8 were used to actuate the 2 joint mechanisms and 3 (one in each segment) were used to actuate the wall press mechanism. The on floor and in-pipe rectilinear motion were carried out and are presented here.

6.2.1 On-floor motion

The rectilinear motion exhibited by the snake robot is shown in Figure 5. It can be seen that the motion takes place in four stages. The Figure 5(a) shows the initial position of the snake robot. In Figure 5(b), it can be seen that the joint mechanism in the segment on the extreme right is actuated and it moves forward. Then the joint mechanism of the middle segment is actuated. At the same time, the other joint mechanism (in the segment at extreme right) begins to contract. It is seen in Figure 5(c). The net effect makes the middle segment to propel forward as shown in Figure 5(d). When the joint mechanism in the middle segment is made to contract, the last segment (on the extreme left) moves forward. This is shown in Figure 5(e). Thus the snake robot has taken a step forward. This sequence is repeated and the snake robot moves forward exhibiting rectilinear motion.

The effect of friction between the base of the segments and the floor plays a vital

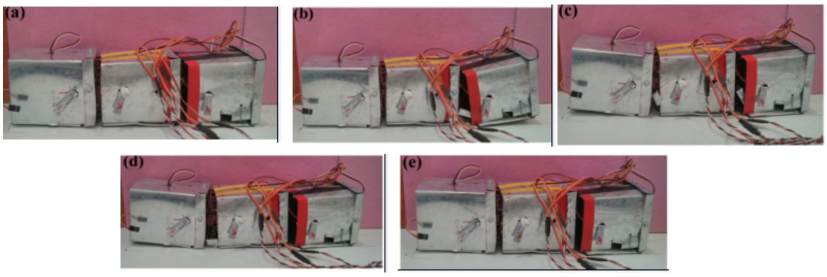


Figure 5: The rectilinear motion exhibited by the snake robot

role during rectilinear motion. The snake robot was initially experimented without the rubber linings at the bottom. It was found that the robot did not propel forward since anisotropic friction was not induced. Then rubber linings were given at the base of the segments as shown in Figure 3(a). Then the robot was able to propel forward as expected. Thus the importance of rubber lining is inferred since it induces anisotropic friction.

6.2.2 In-pipe motion

The snake robot was made to move horizontally and vertically (from top to bottom) inside a transparent acrylic pipe. The four phases involved during the rectilinear motion inside the pipe is shown in Figure 6. The Figure 6(a) shows the initial position of the snake robot inside the vertical pipe. It can be seen that the wall press mechanism is active in all the three segments. This prevents the snake robot from falling. In Figure 6(b) the link of the wall press mechanism at the bottom segment is retracted inside the segment. Then the bottom segment is propelled downward by the four cam-like structures in the middle segment. This is shown in Figure 6(c). Then the link of the wall press mechanism in the bottom segment segment is extended which keeps the bottom segment stable. The link in the middle segment is retracted and the segment is propelled downward. It is due to the extension of the four cam-like structures in top segment and also due to the retraction of the cam-like structures in the middle segment. This is shown in Figure 6(d). During the final phase, the link of the wall press mechanism in the top segment is retracted and the four cam-like structures are also retracted. This makes the top segment to propel downward. This is shown in Figure 6(e).

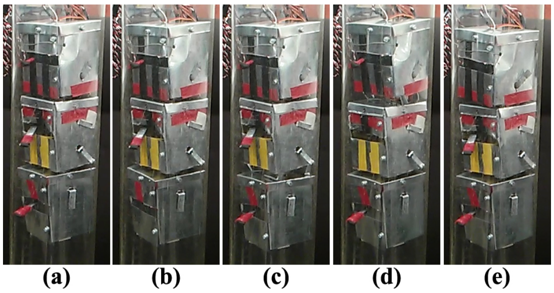

(a) (b) (c) (d) (e)

Figure 6: The fabricated snake robot climbing down the pipe

7 Conclusion and Future works

The future works will be focused on better utilization of the joint mechanism. It can be observed that an additional degree of freedom can be created by rotating only the cam-like structures on the sides (shown in Figure 2 (d)). This can lead to additional gaits like sidewinding and turning. Since the fabricated snake robot was not rigid, the climbing of it from bottom to top was not demonstrated. The motion of the snake robot using this joint mechanism is slow and hence can be used in places where the actual motion of the robot needs to be slow. Some interesting areas where the robot can be used are welding inside pipes and medical applications.

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