

Locomotion of Snake Robot through the Pipe

František Trebuňa¹, Ivan Virgala^{2*}, Michal Kelemen², Tomáš Lipták²

¹Department of Applied Mechanics and Mechanical Engineering, Technical University of Košice, Faculty of Mechanical Engineering, Košice, Slovakia

²Department of Mechatronics, Technical University of Košice, Faculty of Mechanical Engineering, Košice, Slovakia

*Corresponding author: ivan.virgala@tuke.sk

Abstract The paper deals with concertina locomotion of snake robot. Mathematical model of robot locomotion is based on locomotion of natural snake. The kinematic model is derived by homogeneous transformation matrices. In the fourth section, the mechanical design of experimental snake robot LocoSnake is introduced. The robot can perform planar motion by means of segments with 2 DOF, one revolute and one prismatic joint. In the following section the simulation of concertina locomotion is done in Matlab. Simulation is compared with experiments and the conclusion are discussed.

Keywords: locomotion, simulation, snake robot

Cite This Article: Ivan Virgala, Michal Kelemen, and Tomáš Lipták, "Locomotion of Snake Robot through the Pipe." *Journal of Automation and Control*, vol. 3, no. 3 (2015): 135-139. doi: 10.12691/automation-3-3-20.

1. Introduction

Locomotion of snake robots is inspired by biological snakes. Only concertina or rectilinear locomotion can be used for inspections tasks in the pipes or channels. However, both locomotion patterns are not very effective, in many cases there is no other option for locomotion. One of the first qualitative research concerning the biological snake was done by J. Gray [1] and H. W. Lissmann [2]. The authors investigated the muscle activity on real snake (boa occidentalis) and their works are often use as basic for this field of research. Next great milestone in this field was work of professor Shiego Hirose. He was an author of the first snake-like robot – ACM III in 1972 [3]. From this point the research on snake robots increased, especially in last two decades.

Sound research and investigation of new approach of concertina locomotion is presented in [4]. The authors dealt with new curve describing concertina locomotion of snake robot. Shape of this curve rise from the shape of snake body during its locomotion. However, snake robot locomotion in this study does not consider real behavior of robot, especially its anchoring to the walls of confined space. In [5] the authors investigated the utilizing anchoring of snake robot in the confined space. In the study there is determined the minimum number of self-locking contact points for concertina locomotion. Next serious contribution to the field of snake robot concertina locomotion is presented in [6]. The authors investigated friction of snake body on the surface. In the paper the video sequences of snake concertina locomotion is showed. On the video sequences can be seen that snake changes its anchoring to the confined space based on confined space width.

Based on previous research our aim established locomotion pattern of snake robot moving in the confined space, what

will be in our case pipe with squared shape. The paper is divided into following sections: at first the sequence of motion of snake robot is introduced. Next is determination of kinematic model of snake robot concertina locomotion. Subsequently, the kinematic model is simulated in software Matlab. At last, the concertina locomotion is verified by experimental snake robot LocoSnake in the pipe with squared shape. The results in the conclusion are discussed.

2. Design of Concertina Locomotion

A snake performs concertina locomotion especially in narrow spaces where it cannot use lateral undulation. This is typically for snakes with small cross-section of their body. Two features are characteristic for concertina locomotion. The first feature consists of anchoring the snake rear by pushing against the walls of confined space while rest of body moves forward. The second feature consists of anchoring front of snake by pushing against the walls of confined space and drawing the snake rear to forward. By repeating of this sequence the snake performs forward locomotion. Anchoring the body of snake can be performed by several shapes of body.

The study of prof. Hu [6] and his team shows the way of snake body anchoring in dependence on diameter of channel.

Above mentioned sequence of locomotion can be in the Figure 1 seen. In this figure the video sequence of biological snake locomotion is shown. In this study the snake moves through the different pipe diameters and ways of its locomotion were observed. From other video sequences in [6] can be seen that the narrower pipe diameter is, the more similar snake locomotion to "concertina" motion is. According to this locomotion (Figure 1) will be designed sequence of locomotion of snake robot consisting of eight identical links, see Figure 2. During locomotion the biological snake uses muscle

activity by which it can reach bending of particular parts to the sides as well as it can reach lengthening and shortening of these parts. From this reason we replace biological snake body by several identical links, which can move to the sides as well as they can lengthen and shorten [9]. For motion to the sides the revolute joint is assumed and for lengthening and shortening the prismatic joint is assumed. Our analysis considers snake robot with eight identical links, but it may be extended by other links.

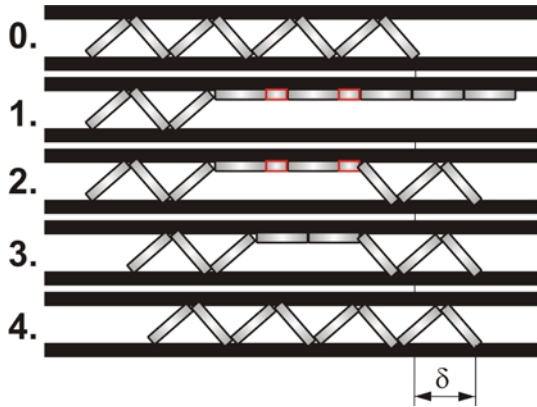


Figure 1. Sequence of snake robot locomotion

In the Figure 1 one locomotion cycle is shown. Three links are considered as static links and other five links move forward. This is the first phase of locomotion cycle. The 4th and 5th links lengthen by means of prismatic joint (red color). In the second phase the front of robot is anchored by pushing the first three links against the walls of pipe. During the third phase the last three links are slightly released in order to 4th and 5th links can be shortened. In the last fourth phase the rest of snake robot body only attract to the front part of the robot. By repeating of these four phases snake robot performs forward locomotion in the pipe.

The letter δ denotes the traveled distance in one locomotion cycle. This distance is dependent on the relation between length of snake robot link and diameter of the pipe.

The pipe diameter is of course important parameter. Locomotion according the Figure 2 can be performed when pipe diameter is lower than length of snake robot link. Locomotion according the Figure 2 would be able with pipe diameter higher than length of snake robot link only when robot has more links. However, snake robots are the robots with many identical links there can be added next links according to requirements.

Description of this locomotion can be expressed by following considerations:

- Pipe has rectangular cross-section
- Pipe diameter is lower than length of snake robot link
- One locomotion cycle consists of four phases. By repeating of these phases the snake robot performs forward locomotion with traveled distance δ during one cycle
- Snake robot uses for its locomotion revolute as well as prismatic joints
- Static links have to push against the walls of pipe with such torque in order to they stay static

For locomotion in the pipe can be used also different locomotion pattern like in [6,7] or [8,9]. The authors used for their study traveling wave locomotion of snake robot.

Uniqueness of our solution is in utilization of revolute as well as prismatic joint in one snake robot link. Snake robot with this kinematic configuration is on one hand more flexible and universal to the changes of environment. On the other hand utilization of prismatic joint in each link is more similar to a biological snake muscle activity. [10]

3. Kinematic Aspect of Concertina Locomotion

The kinematic model describes geometrical aspects of snake robot motion. The model of the investigated snake robot consists of 8 identical links and each of link has 2 degrees of freedom. Each link has one revolute joint and one prismatic joint. Link has length L_i and position of center of gravity CG_i . The reference frame (ground fixed frame) has denotation $O = \{x_0, y_0\}$. The position vector from the reference frame to the origin of particular link is $r_i \in \mathbb{R}^2$, to end of the head link $r_H \in \mathbb{R}^2$ and to origin of rear link $r_R \in \mathbb{R}^2$. The protrusion of particular link by prismatic joint is l_i .

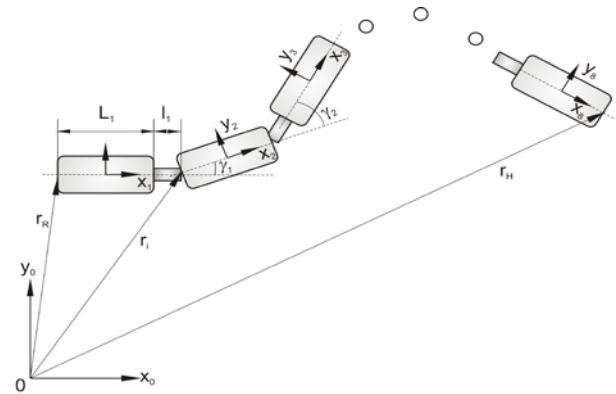


Figure 2. Kinematic aspect of investigated snake robot

Angle between two adjacent links is denoted as γ_i . Considering above mentioned kinematic convention, each link of snake robot is described by homogeneous transformation matrix

$$A_{i-1}^i = \begin{bmatrix} R_{i-1}^i & r_{xi} \\ 0 & r_{yi} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Where R_{i-1}^i presents rotation matrix from coordinate system i to coordinate system $i-1$, r_{xi} and r_{yi} are coordinates of position vector of i -th link. Final transformation matrix from i -th link to the reference frame O is denoted as

$$T_0^i = \prod_{i=1}^n A_{i-1}^i \quad (2)$$

T_0^i represents transformation matrix of i -th link to reference frame O . Position vector of any link can be expressed by multiplication of corresponding transformation matrices according to equation (2). By transformation matrix of last link to reference frame can be also described workspace of snake robot.

Next important issue of snake robot kinematic is expressing of its traveled distance during one locomotion cycle. It is clear that the higher traveled distance of one locomotion cycle will be, the higher average velocity the robot will has. The analysis is based on relation between pipe diameter and length of snake robot link, see Figure 3.

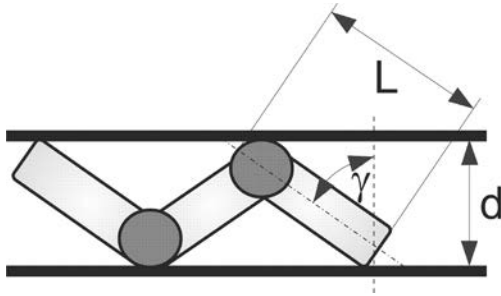


Figure 3. Relation between pipe diameter and length of snake robot link

According to Figure 1 the traveled distance δ can be derived. Let consider that angle between links is the same γ , see Figure 2 – 0th phase. Maximum protrusion of prismatic joint is l (red color), see Figure 1 – 1th phase. By considering all phases we can derive final traveled distance of one locomotion cycle denotes as δ by following relation

$$\delta = 2(L+l) - 2L \sin \left[\arccos \left(\frac{d}{L} \right) \right]. \quad (3)$$

From the equation (3) can be seen, that final traveled distance δ is function of pipe diameter d , length of snake robot link L and maximum protrusion of prismatic joint l . Graphic expression of this relation in the Figure 4 is shown.

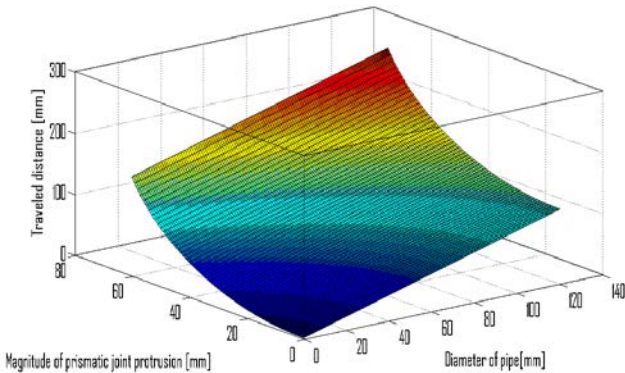


Figure 4. Dependence of traveled distance on changing pipe diameter and prismatic joint protrusion

4. Design of Snake Robot LocoSnake

For our study the experimental snake robot LocoSnake was designed. LocoSnake is of unique kinematic structure not used up to now yet. Each segment of the snake robot consists of two degrees of freedom. The one degree of freedom is represented by the revolute joint with the rotation range of $\pm 90^\circ$ from the zero position. The next degree of freedom is represented by the prismatic joint with the range of 0 to 50 mm. Each end of the segment is equipped with the clutch enabling the connection of other parts and the signal cables and the power source cables transportation.

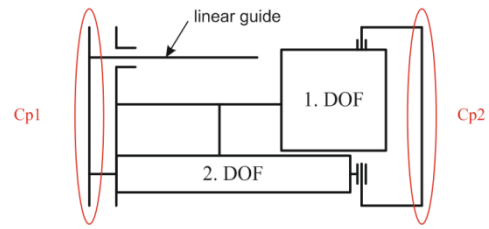


Figure 5. Kinematic configuration of LocoSnake

Based on the kinematic structure the model of snake inspired robot was designed by SolidWorks software, see Figure 6, Figure 7 and Figure 8. However, it was necessary to specify the dimension demands due to the accuracy of the model configuration. The dimensions of the action parts responsible for the segment dimensions were the most important criterion.

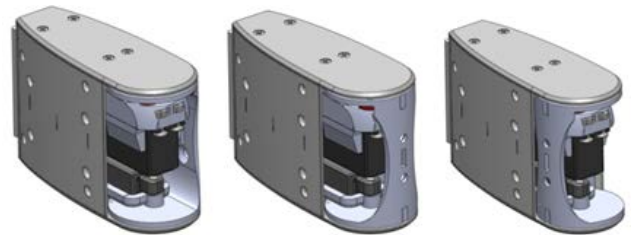


Figure 6. 3D model of LocoSnake link a) +90° b) 0° c) -90°

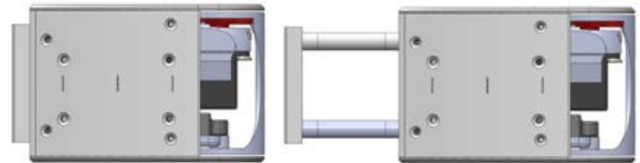


Figure 7. 3D model of LocoSnake link a) 0mm b) 50 mm

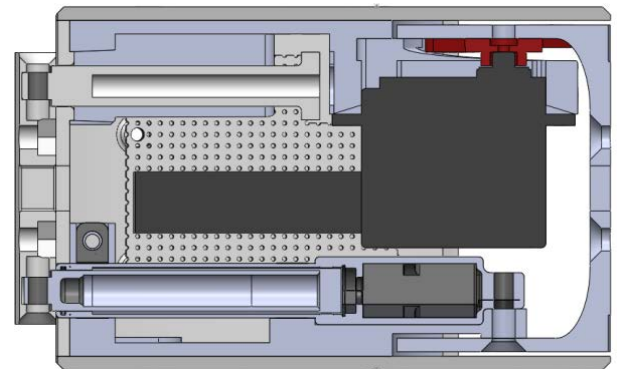


Figure 8. 3D model of LocoSnake link inside

The construction of LocoSnake is designed from parts made by the 3D printer were made. One link of LocoSnake weights 225 g with maximum dimensions: length 130 mm; width 80 mm; height 47 mm.

5. Simulation and Experimental Verification of Concertina Locomotion

In the section two the sequence of concertina locomotion for snake robot was designed and in the section three the direct kinematic model was derived. Based on these two sections the concertina locomotion can be simulated. Simulation is done in software Matlab.

The parameters of the simulation and experiment are: length of link $L_i = 0.13$ m, prismatic protrusion of link is $l_i = 0.05$ m, radius of the pipe (rectangle cross-section) is $d = 0.12$ m, number of links $n = 8$, weight of one link $w = 0.225$ kg.

Used approach is based on transformation matrices, described in the section 3. Actual position and orientation of each link can be obtained in arbitrary time.

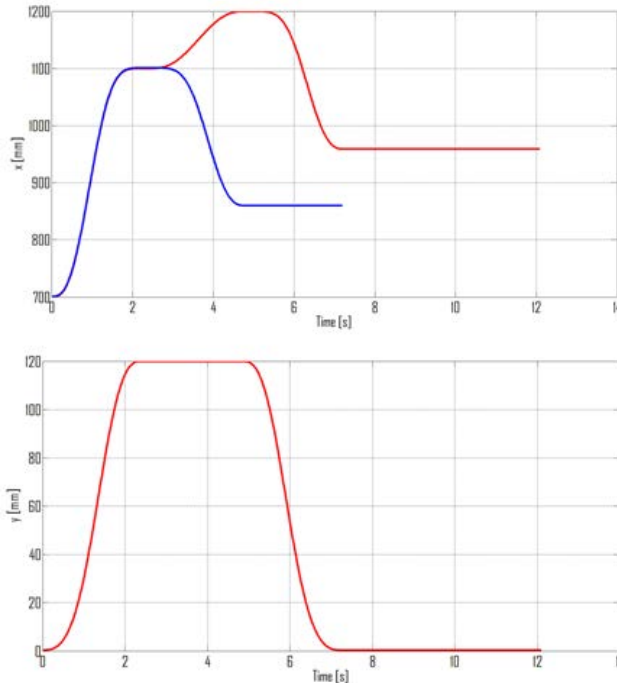


Figure 9. Position of head link during one locomotion cycle

In the Figure 9 the head position in x-axis and y-axis is shown during one locomotion cycle. Red color shows snake robot locomotion using prismatic joints with protrusion 50 mm and blue color shows locomotion without using prismatic joints.

Position of the head link in y-axis changes only in the range 0 – 120 mm, what corresponds with diameter of pipe. Position of the head link in x-axis changes from the initial position 700 mm to 958 mm (red color). Consequently, the final traveled distance of head link using prismatic joints (HLPJ) is 258 mm, what is the distance of one locomotion cycle during concertina locomotion. One locomotion cycle without using prismatic joints (HL) gives 160 mm of traveled distance what makes 98 mm difference between model with prismatic joints and without them. This considerable difference can be seen also in the Figure 5 as well.

While difference of traveled distance between HL and HLPJ is 98 mm, one locomotion cycle of HL is almost twofold faster than HLPJ. Traveled distance of HL can be higher than traveled distance of HLPJ after several cycles. Of course, this hypothesis is only theoretical and it depends on speed and dynamics of real actuators of snake robot. However, this study shows that by means of prismatic joints can be achieved considerably higher traveled distance of one locomotion cycle. By utilization of several prismatic joints (together with adding additional links to robot) this effect increases.

The course of entire simulation is animated in Matlab. Particular figures from the simulation are in the Figure 10 shown.

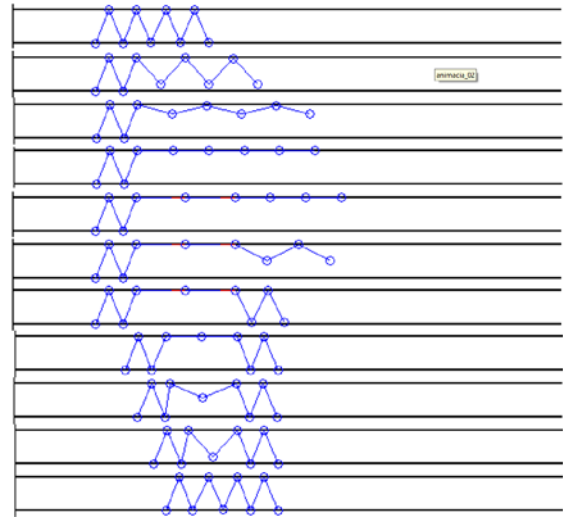


Figure 10. Position of head link during one locomotion cycle

In the Figure 10 only one locomotion cycle is shown. Prismatic joints protrusion is depicted by red color. Visualization only serves for verification purposes of kinematic model which is above mentioned.

Next point of our study is verification of achieved results by experimental analysis. For this purposes have been used snake robot - LocoSnake. Snake robot LocoSnake was designed and built in 2012 at Department of Mechatronics – Technical University of Košice, Slovakia. This robot was designed for experimental purposes of concertina locomotion analysis. Each segment of the robot has 2-DOF, one revolute servomechanism and one prismatic servomechanism. Length and weight of segment are the same like in simulation model. Each servomechanism has its own inner position controller and position of all segments are controlled by 32-bit microcontrollers BasicAtom Pro 28-M, 16 MHz. Supply voltage of the servomechanisms is 6 V DC. The speed of rotation of servomechanism without any load is approximately 60° per 0.2 seconds. Considering other segments as load the speed significantly decreases. The speed of prismatic servomechanism protrusion without any load is 23 mm/s. Considering other segments as load the speed of servomechanism decreases also.

Diameter of pipe is the same like in simulation. In the following shots the concertina locomotion of LocoSnake is shown.



Figure 11. Experiment with snake robot LocoSnake

The Figure 11 shows that LocoSnake can performs concertina locomotion according to computer simulation.

Considering that snake moves from left side to right side, mark the first segment from right side as 1 and the first segment from left side as 8. The most critical point of locomotion is in 2nd and 6th shot, during pushing static segments against walls of pipe. Let consider 2nd shot. Last three segments (6, 7, 8) push against the walls of pipe and this is base for forward motion of other segments. During the experiment there has to be increased the supply of electrical current in order to increasing of revolute joint performance. Next critical point is backlash rising between two adjoining segments what creates not quite pushing the segments against the walls of pipe.

6. Conclusion

A concertina locomotion from the view of biology is introduced. Based on knowledge about locomotion pattern, new pattern of snake robot is designed using revolute and prismatic joints as well. Assuming our locomotion pattern the relation for traveled distance is derived with dependence on diameter of pipe with rectangle cross section, and length of snake robot link. This relation shows signification of using prismatic joint for traveled distance in one locomotion cycle. The direct kinematic model of snake robot is derived using transformation matrix. Kinematic model for simulation in Matlab is used. There were done two simulations. The first with assuming prismatic joints and the second without them. By focusing on traveled distance the difference is considerable. Next, an experiment with snake robot LocoSnake was done.

The main aim of experiment was verification of concertina locomotion in the pipe. The most critical point of experiment was evolving required torque of first static segment (adjoining with first moving segment) in order to other segments can move forward. Next critical point is that junction between two adjoining segments is not too rigid and there arise backlash.

The results of experiment are different from simulation mainly because of differences of kinematic configuration between simulation and real model. Even though, the experiments shows that concertina locomotion is able with snake robot LocoSnake and expose new limitations and

disadvantages of its design. The experiment also shows uniqueness of kinematic configuration using revolute as well as prismatic joints, what is for concertina locomotion significant.

Acknowledgement

The work has been accomplished under the research project APVV-0091-11 financed by the Ministry of Education. This contribution is also the result of the project implementation: Research of modules for intelligent robotic systems (ITMS: 26220220141) supported by the Research & Development Operational Programme funded by the ERDF.

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