TECHNICAL SCIENCES AND TECHNOLOGIES
UDC 004.896
DOI: 10.25140/2411-5363-2018-4(14)-109-117

Ivan Virgala, Filip Filakovský

CONCERTINA LOCOMOTION OF A SNAKE ROBOT IN THE PIPE

Urgency of the research. *Nowadays robotics and mechatronics come to be mainstream. With development in these areas also grow computing fastidiousness. Since there is significant focus on numerical modeling and algorithmization in kinematic and dynamic modeling. Inspection of the pipes is well-known engineering application. For this application are usually used wheel-based robots. Another approaches are based on biologically inspired mechanisms like inchworm robot. Our study deals with another kind of pipe inspection robot, namely snake robot.*

Target setting. *Modeling and testing of snake robot moving in the pipe for the inspection purposes.*

Actual scientific researches and issues analysis. *Pipe inspection is usually done by wheel-based robots. However, snake robots have great potential to do these applications.*

Uninvestigated parts of general matters defining. *Inspection in section of curved pipes is still the actual point of research.*

The research objective. *In the paper the locomotion pattern of namely snake robot is designed and experimentally verified.*

The statement of basic materials. *This paper investigates the area of numerical modeling in software MATLAB. The paper presents locomotion pattern of snake robot moving in the narrow pipe. Next, kinematic model for robot is derived and motion of robot simulated in the software MATLAB. Subsequently the experiments are done with experimental snake robot LocoSnake. In the conclusion the simulation and experiment results are compared and discussed.*

Conclusions. *The paper introduces concertina locomotion pattern of namely snake robot with numerical modeling as well as experimental verification. The results of experiment are different from simulation mainly because of differences of kinematic configuration between simulation and real model. The experiment also shows uniqueness of kinematic configuration using revolute as well as prismatic joints, what is for concertina locomotion significant.*

Keywords: *concertina; kinematics; locomotion; snake robot.*
Fig.: 8. References: 9.

Introduction. Researcher many years work on biologically inspired mechanisms and robots. One of the first contributions in this research area was done by J. Gray [1] and H. W. Lissmann [2]. Gray and Lissmann have investigated the muscles activity on biological snake. As the first pioneer in designing of snake robot from the view of engineering is considered to be professor Shiego Hirose. He was an author of the first snake robot, namely ACM III[3]. The robot was developed in 1972. From this point the research on snake robots increased, especially in last two decades [9; 10; 11].

An investigation of the new approach of concertina motion is in the paper [4]. The authors dealt with new curve describing concertina locomotion of snake robot.

Shape of this curve rises from the shape of a snake body during its locomotion. In the following research [5] the authors have investigated the utilization of anchoring of a snake robot in the confined space. In the study there is determined the minimum number of self-locking contact points for concertina locomotion. Next contribution to the field of concertina locomotion is [6]. The authors investigated friction between snake body and the surface on which it moves. 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 mentioned researches, our aim is to state the locomotion pattern of a snake robot moving in the confined space. Our study will consider a pipe with a square shape. The paper is divided as follows: 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 square shape. The results in the conclusion are discussed.

Introduction of concertina locomotion. A snake performs concertina locomotion especially in narrow spaces where it cannot use lateral undulation. This is typical for snakes with small body cross-section. 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 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, see Fig. 1.

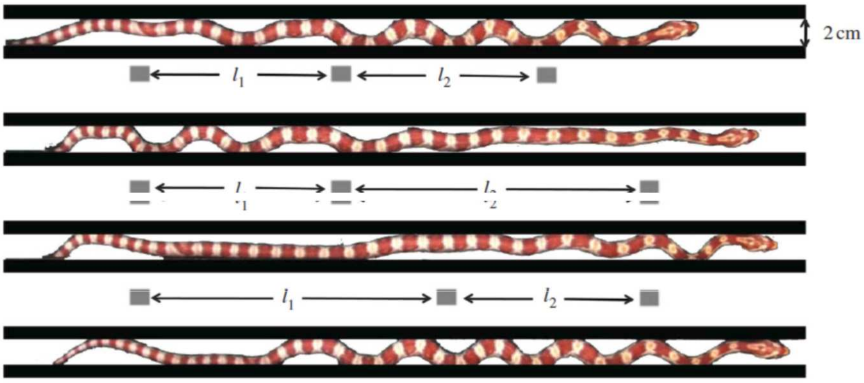

Fig. 1. Video sequence of snake concertina locomotion [6]

Above mentioned sequence of locomotion can be seen in the Fig. 1. 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 than "concertina" motion is. According to this locomotion (Fig. 1) a sequence of locomotion of snake robot consisting of eight identical links will be designed, see Fig. 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.

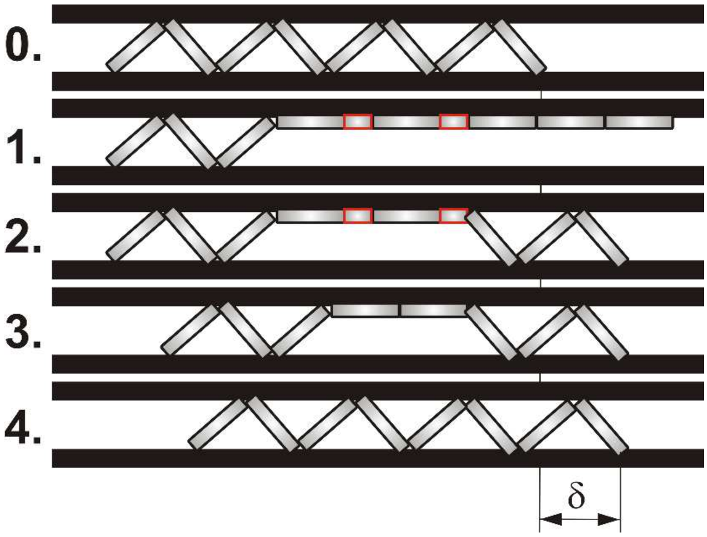

Fig. 2. Sequence of snake robot locomotion

In the Fig. 2 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 faze 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 Fig. 2 can be performed when pipe diameter is lower than length of snake robot link. Locomotion according the Fig. 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 [7] or [8]. 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.

Kinematic model of Concertina

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 $\boldsymbol{r}_i \in \mathbb{R}^2$, to end of the head link $\boldsymbol{r}_H \in \mathbb{R}^2$ and to origin of rear link $\boldsymbol{r}_R \in \mathbb{R}^2$. The protrusion of particular link by prismatic joint is l_i.

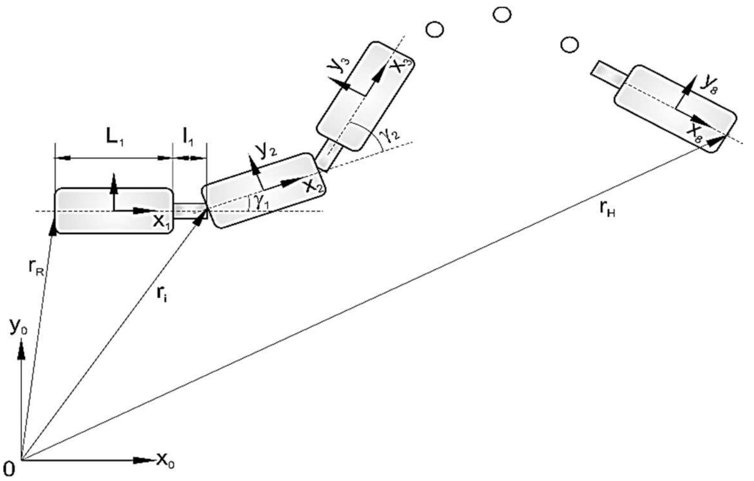

Fig. 3. Kinematic aspect of investigated snake robot

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

$$\mathbf{A}_{i-1}^{i} = \begin{bmatrix} & & & r_{xi} \\ & \mathbf{R}_{i-1}^{i} & & r_{yi} \\ & & & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{1}$$

where $\mathbf{R}_{i-1}^{i}$ 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

$$\mathbf{T}_0^i = \prod_{i=1}^{n} \mathbf{A}_{i-1}^{i}. \tag{2}$$

$\mathbf{T}_0^i$ 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 have. The analysis is based on relation between pipe diameter and length of snake robot link, see Fig. 4.

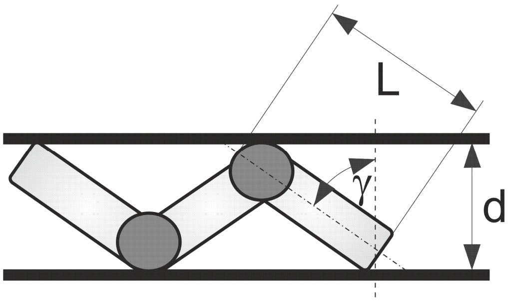

Fig. 4. Relation between pipe diameter and length of snake robot link

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

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

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_i. Graphic expression of this relation in the Fig. 5 is shown.

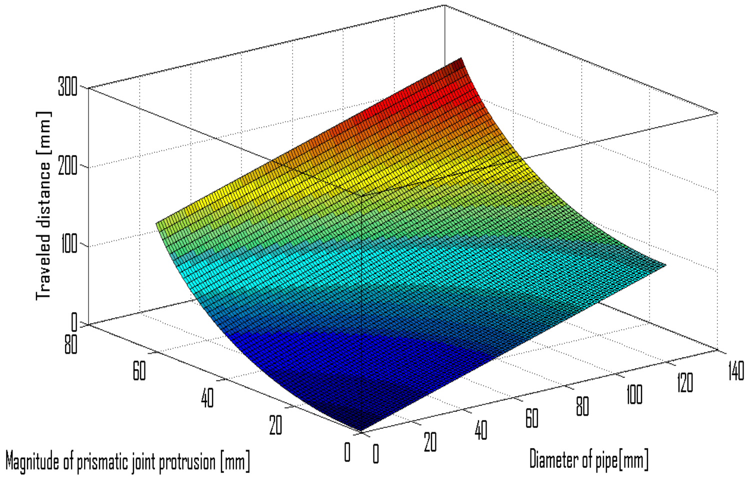

Fig. 5. Dependence of traveled distance on changing pipe diameter and prismatic joint protrusion

From the Fig. 5 is obvious that the higher prismatic joint protrusion is the higher distance the snake robot passes. For graphic expression the following parameters are used: $l_i \in \langle 0,50\rangle\ mm$ and $d \in \langle 0,120\rangle\ mm$, length of link is L = 130 mm. There was considered eight links according the Fig. 2.

Simulations and Experiments

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 Li = 0.13 m, prismatic protrusion of link is li = 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.

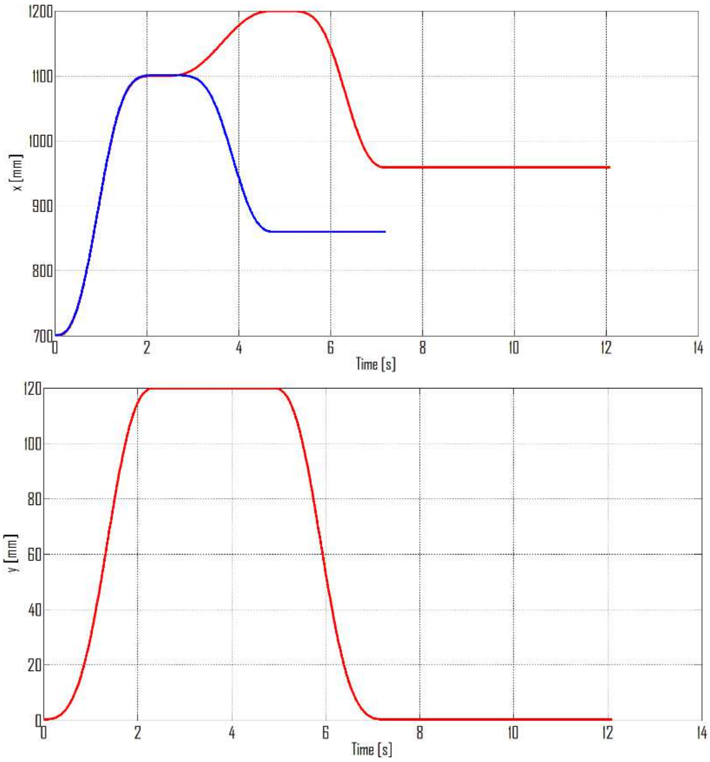

Fig. 6. Position of head link during one locomotion cycle

In the Fig. 6 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 Fig. 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 Fig. 7 shown.

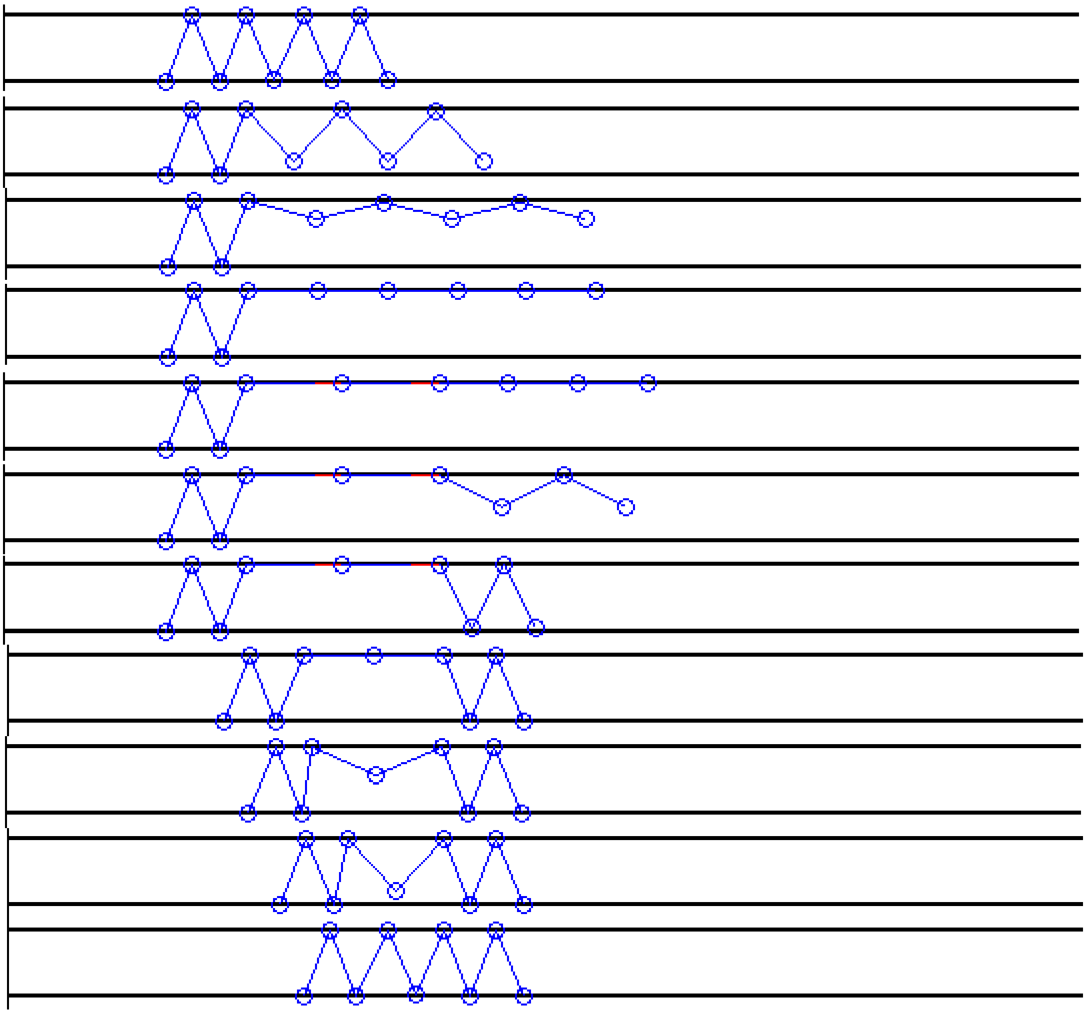

Fig. 7. Simulation of concertina locomotion in Matlab

In the Fig. 7 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 Applied Mechanics and 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.

Fig. 8. Experiment with snake robot LocoSnake

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 increase the 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.

In the Fig. 8 one locomotion cycle is shown. Our interest was focused on traveled distance during one cycle. Traveled distance during experiment is only 162 mm what differs from simulation about 96 mm. There are several logical reasons. First of all, in simulation model there was considered with segment as link with neglected width. This changes kinematic configuration in the pipe. Next reason is, in simulation model next adjoining link has origin at the end of previous link. In real model of snake robot, next adjoining segment has origin at the end of previous link only in the case when there is 0° angle between two adjoining segments. In the case when there is a non-zero angle between two segments, the situation is different, see Fig. 9.

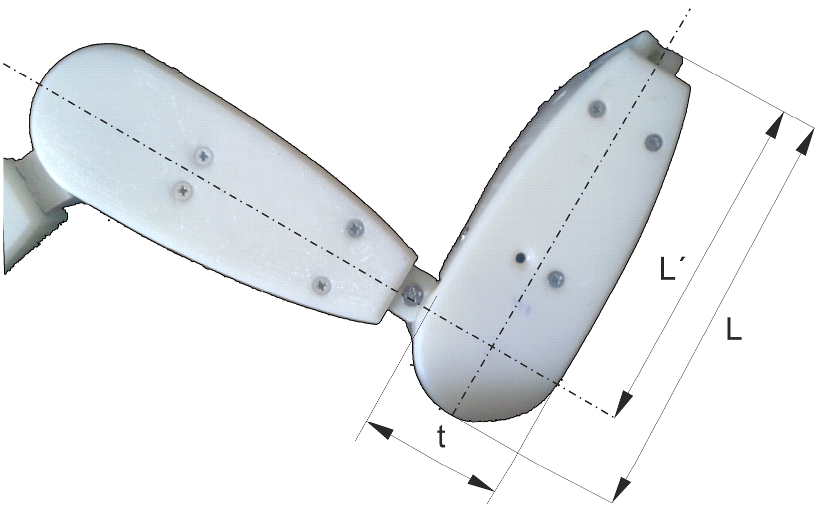

Fig. 9. Geometry of LocoSnake segment

Considering Fig. 9, in simulation model the left link would be offset with value L - L´ in the direction of axis of right segment. In simulation model the rotation axis of revolute joint is also the contact point with the wall of pipe. In real model, the rotation axis of revolute joint and contact point of segment with wall of pipe are two different places.

Of course, these differences between simulation and real model result in different traveled distance during one locomotion cycle.

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

This paper was supported by project VEGA1/0872/16 “Research of synthetic and biological inspired locomotion of mechatronic systems in rugged terrain” and project VEGA 1/0389/18 “Research on kinematically redundant mechanisms”.

References

1. *J. Gray*, The mechanism of locomotion in snakes, in: Journal of Experimental Biology, 1946, Vol. 23, No. 2, pp. 101 - 120.

2. *H. W. Lissmann*, Rectilinear locomotion in a snake, in: The Journal of Experimental Biology, 1949, pp. 368 – 379..

3. *S. Hirose*, Biologically Inspired Robots: Snake-like Locomotors and Manipulators, Oxford University Press, 1993, Oxford.

4. *A. Akbarzadeh*, Jal. Safehian, Jav. Safehian, H. Kalani, Generating Snake Robot Concertina Locomotion Using a New Dynamic Curve, in: International Journal of Modeling and Optimization, 2011, Vol. 1, No. 2, pp. 134 – 140.

5. *F. Barazandeh*, B. Bahr, A. Moradi, How Self-Locking Reduces Actuators Torque in Climbing Snake Robots, IEEE International Conference on Advanced Intelligent Mechatronics, 2007, pp. 1 – 6.

6. *H. Marvi*, D. L. Hu, Friction enhancement in concertina locomotion of snakes, in: Journal of the Royal Society, 2012, pp. 1 – 14.

7. *H. Kalani*, A. Akbarzahed, J. Safehian, Traveling Wave Locomotion of Snake Robot along Symmetrical and Unsymmetrical Body Shapes. In: Robotics (ISR) - 6th German Conference on Robotics, pp. 62 – 68, 2010.

8. *Suzumori, K.*, Wakimoto, S., Takata, M., A miniature Inspection Robot Negotiating Pipes of Widely Varying Diameter. Proceedings of the 2003 IEEE International Conference on Robotics & Automation, Taiwan, pp. 2735 – 2740, 2003

9. *K. Trnka*, P. Božek, Optimal Motion Planning of Spot Welding Robot Applications. In: Applied Mechanics and Materials, ICMMME 2012, ISSN 1660-9336, pp. 589-593.

УДК 004.896

Іван Віргала, Філіп Філаковскі

СПІРАЛЬНЕ ПЕРЕМІЩЕННЯ РОБОТА-ЗМІЇ В ТРУБОПРОВОДІ

Актуальність теми дослідження. *Нині робототехніка й мехатроніка стають мейнстрімом. З розвитком цих сфер також збільшуються обчислювальні можливості. Значна увага приділяється чисельному моделюванню й алгоритмізації в кінематичному й динамічному моделюванні. Обстеження труб є загальновідомим інженерним завданням. Для цього завдання зазвичай використовуються колісні роботи. Інші підходи засновані на біологічно подібних механізмах, таких як робот-черв'як. Наше дослідження стосується іншого виду робота для перевірки труб, а саме робота-змії.*

Постановка проблеми. *Моделювання і тестування робота-змії, що рухається в трубі з метою контролю.*

Аналіз останніх досліджень і публікацій. *Перевірка труб переважно виконується роботами на колесах. Однак роботи-змії мають великий потенціал для такого застосування.*

Виділення недосліджених частин загальної проблеми. *Дослідження в перетині вигнутих труб досі залишається актуальним предметом досліджень.*

Постановка завдання. *У статті розроблена й експериментально перевірена модель руху робота-змії.*

Виклад основного матеріалу. *У цій статті досліджено область чисельного моделювання в програмному забезпеченні MATLAB. У статті представлена модель пересування зміїного робота, що рухається у вузькій трубі. Потім представлена, кінематична модель для робота і моделювання руху робота в програмному забезпеченні MATLAB. Згодом експерименти проводяться з експериментальним зміїним роботом LocoSnake. У висновку порівнюються й обговорюються результати моделювання й експерименту.*

Висновки відповідно до статті. *У статті представлена модель спірально подібного переміщення робота-змії з чисельним моделюванням та експериментальною перевіркою. Результати експерименту відрізняються від моделювання, головним чином, через відмінності кінематичної конфігурації між моделюванням і реальною моделлю. Експеримент також демонструє унікальність кінематичної конфігурації, що використовує як обертові, так і призматичні з'єднання, що є важливим для спірального переміщення.*

Ключові слова: *спіраль; кінематика; переміщення; робот-змія.*

Рис.: 8. Бібл.: 9.

Ivan Virgala – assoc. professor, Technical University of Košice, Faculty of Mechanical Engineering, Institute of Automation, Mechatronics and Robotics, Department of Mechatronics (Park Komenského 8, 042 00 Košice)

Filip Filakovský – PhD student, Technical University of Košice, Faculty of Mechanical Engineering, Institute of Automation, Mechatronics and Robotics, Department of Mechatronics (Park Komenského 8, 042 00 Košice)

Virgala, I., Filakovský, F. (2018). Concertina locomotion of a snake robot in the pipe. *Technical sciences and technologies, 4* (14), 109-117.