American Journal of Mechanical Engineering, 2016, Vol. 4, No. 7, 297-305
Available online at http://pubs.sciepub.com/ajme/4/7/13
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DOI:10.12691/ajme-4-7-13

Experimental Analysis of Fixation Curves of Snake Robot Moving in the Pipe

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Abstract The research field of the snake robots provides a large scale of new information. The snake robots locomotion in pipes represents one of many complicated problems attracting the attention only in recent time period. During this study an experimental environment was designed corresponding to the pipe of U shaped cross section. This article describes a new innovative kinematic structure enabling both rotary and translational movements of links of a snake robot. Combination of these two robot constrains in constructions provides new possibilities of locomotion in a confined space. The main work contribution consists in the analysis of geometric configuration of links in static fixation according to their displacements and required actuators electric power. In the experiment with physical model the method of digital image correlation was used because of the possibilities to take the movement of high dynamic range. Contribution of this experiment furnishes new information and new approach in solving the existing problem.

Keywords: *snake robot, fixation curves, digital image correlation*

Cite This Article: Ivan Virgala, Michal Kelemen, Martin Hagara, Erik Prada, and Tomáš Lipták, "Experimental Analysis of Fixation Curves of Snake Robot Moving in the Pipe." *American Journal of Mechanical Engineering*, vol. 4, no. 7 (2016): 297-305. doi: 10.12691/ajme-4-7-13.

1. Introduction

The first qualitative research of the snake concertina locomotion was made by J. Gray in 1946 [1]. J. Gray investigated the snakes from the view of biology but he and H. W. Lissmann put a good basis for the future snake robot research. During the snake robot motion in confined space the robot uses the walls of confined space for anchoring of robot rear by pushing against these walls. In [2] the authors investigated the snake robot anchoring in confined space and showed how can be energy consumption of anchored link actuators zero by self-locking. The authors declare that minimum number of contact points should exist to rise selflocking and the number depends on the links weight and the coefficient of friction. An algorithm characterizing the force and the motion ambiguities of climbing robot in confined space is investigated in [3]. The mapping of opaque and confined space is dealt by [4] where concertina locomotion is applied. The paper introduced two algorithms of concertina locomotion and the contact detection and the self-occupancy were investigated too. In [5] the authors dealt with the snake robot consisting of thirteen links passed in the pipe. Three control methods were developed, namely the gripping force control, the pipe diameter adaptive control and the curve of pipe adaptive control. Applying these three control methods, the snake robot propels itself successfully in the different diameter pipes, the elbows, the T-shaped and the vertical pipes. A new method of the snake robot kinematic modeling using the concertina locomotion is presented in [6]. A new dynamic curve for modeling different parts of the snake robot is introduced. It is shown that the shape of the dynamic curve may easily be modified using a single parameter. With concertina locomotion deals also prof. David Hu with his team.

In [7] the authors investigated the snake friction on the surface. This paper shows the video sequences of the snake concertina locomotion. From the figures is obvious that with changing channel width the anchoring of snake in channel changes too. According to our knowledge the snake body way of anchoring in the channel or in the pipe and its influence on concertina locomotion was not investigated up to now yet. This fact led us to deal with this problem from the view of suitable utilization of the snake robot static links geometrical configuration.

Our study deals with investigation of snake robot fixation curves which are required to anchoring robot to the walls of pipe. The main contribution of the paper is comparison of particular fixation curves with each other and determination of the optimal fixation curve of static links for concertina locomotion. The curves are investigated from the view of electric energy consumption and stability of static links during concertina locomotion. Uniqueness of this study ensures utilization of digital image correlation for determination of stability of static links.

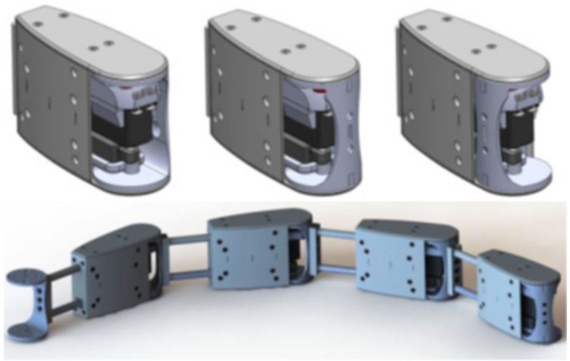

Figure 1. 3D model of LocoSnake link a) +90º b) 0º c) -90º d) 50 (mm) protrusion of every segments

First of all is introduced the snake robot LocoSnake designed for an experimental work. The third chapter deals with the mathematical background of fixation curves presenting the geometrical configuration of snake robot static links moving through the pipe. The fourth chapter deals with two aspects of an experimental analysis of particular fixation curves. The first is a displacement of the static links and the second one is the energetic aspect. The last chapter presents and discusses the results of the experimental analysis and the future work.

2. Experimental 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 rotation joint with the rotation range of ± 90° from the basic position. The next degree of freedom is represented by the translation 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, see Figure 1.

3. Concertina Locomotion in Limited Areas

Biological snake adapts its locomotion to the environment of its motion. For narrow spaces, channels or pipes, the biological snake uses the concertina locomotion based on two main phases [1,8]. During the first phase the snake by its rear pushes against the wall of confined space and the rest of the body moves forward. During the second phase the front of snake pushes against the wall of confined space and the rear pulls forward. By changing these two phases the snake performs the forward motion.

According to description of concertina locomotion the snake body may be divided into two parts, namely the static part – the part of snake pushing against the walls which is the basis of the dynamic part generation – the part moving forward.

The friction represents a significant role within all snake locomotion patterns [9]. Basically the snake locomotion without friction between the snake body and the environment should not be able. For snake robot concertina locomotion the friction between the static links and the walls of confined space is significant. The higher is the friction between the robot and the walls the more stable is the concertina locomotion performed by the robot. From the research of prof. David Hu [7] it is obvious that biological snake changes static parts of its body according to confined space of its motion. The configuration of the snake body is determined by both the length and the width of the snake and by the pipe too, during the snake locomotion. This fact results in our inspiration to investigate suitability of particular static configurations of the snake robot moving in the pipe.

3.1. Fixation Curves for Convertina Locomotion

The aim of our study is to investigate the static parts of the snake robot moving in the pipe and to focus on efficiency of the static links geometric configuration creating so called “fixation curve”. The static links of robot located in the pipe according to the selected fixation curve create the basis of the snake robot concertina locomotion. Our study investigates four types of fixation curves that may be created by selected number of the robot static links. This chapter introduces the fixation curves with their mathematical background.

The first fixation curve represents Triangle curve, the second one represents Cycloid curve and the third represents Gaussian curve and the fourth represents Arccosine curve. Each of them may be described in mathematical term.

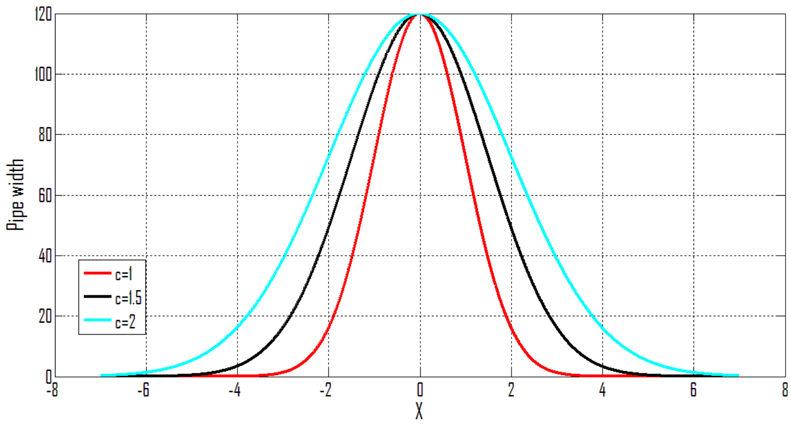

Figure 2. Gaussian curve

Gaussian curve

$$\sigma(x) = ae^{-\frac{(x-b)^2}{2c^2}} \quad (1)$$

where a, b, c are the real constants [10]. The parameter a represents the pipe width, the parameter b only shifts the origin of the coordinate system. The parameter c changes the angle between two robot links contacting the pipe in one point. In other words, the parameter c shows how "sharp" the curve will be in the contact point with pipe. Of course the parameter c depends on the link geometry.

Cycloid curve

$$\sigma(y) = r \arccos\frac{r-y}{r} - \sqrt{y(2r-y)} \quad (2)$$

here r is a cycle radius [11]. The equation represents the one half of the cycloid curve. According to the Equation (2) the curve cannot by influenced by any parameter (cycle radius r is determined by the pipe width that is strictly given).

However, there is a way how to shorten or lengthen the cycloid curve through the parametric expression as follows:

$$x = rt - d\sin(t),\ y = r - d\cos(t) \quad (3)$$

where the parameter d determines both shortening and lengthening of the cycloid curve. With d<r the curve is shorten and with d>r the curve is lengthen.

Triangle curve

$$\sigma(t) = \frac{8}{\pi^2}\left(\sin(\omega t) - \frac{1}{9}(3\omega t) + \frac{1}{25}\sin(5\omega t) - \ldots\right) \quad (4)$$

where ω is an angular frequency. Figure 4 shows various Triangle curves of changing angular frequency. The magnitude of the curve is adapted to the pipe width; in our case it is 120 mm. The increasing angular frequency causes the expansion of the curve. The magnitude of the angular frequency depends on the length of the robot link. The bigger is the length of the link the higher angular frequency of the curve is required [12].

Arccosine curve

$$\sigma(x) = h\arccos(y) \quad (5)$$

where parameter h changes the angle between two robot links contacting the pipe, see Figure 5. The curves rotate by 90 degrees. Final curve is also multiplied by half of the pipe width; in our case it is 60 mm. Peculiarity of this curve is that by using this curve the snake robot has only two contact static points with the pipe.

These four fixation curves will be experimentally analyzed by applying them to snake robot links. All fixation curves shown by above Figure 2 to Figure 5 do not directly copy the snake robot backbone and they reflect the shape of probable combinations of the snake contacts to the pipe.

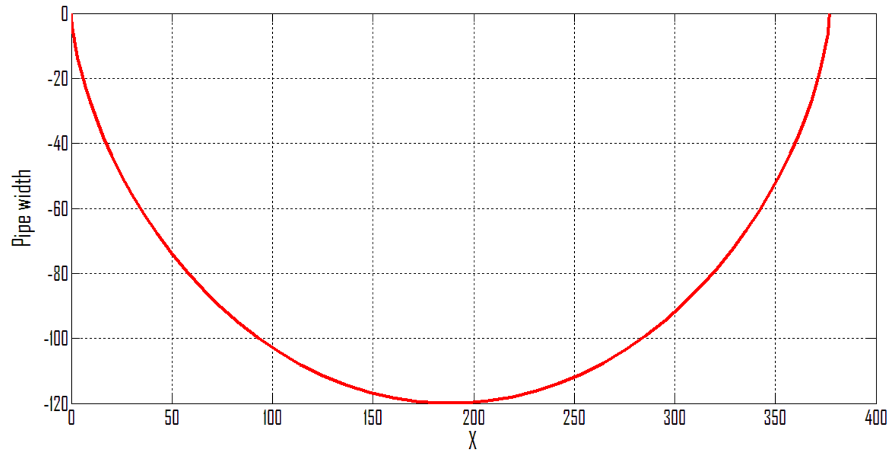

Figure 3. Cycloid curve

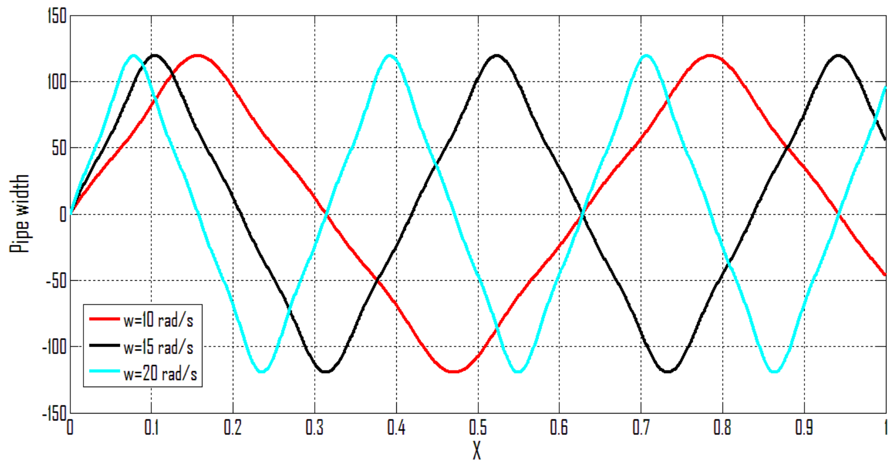

Figure 4. Triangle curve

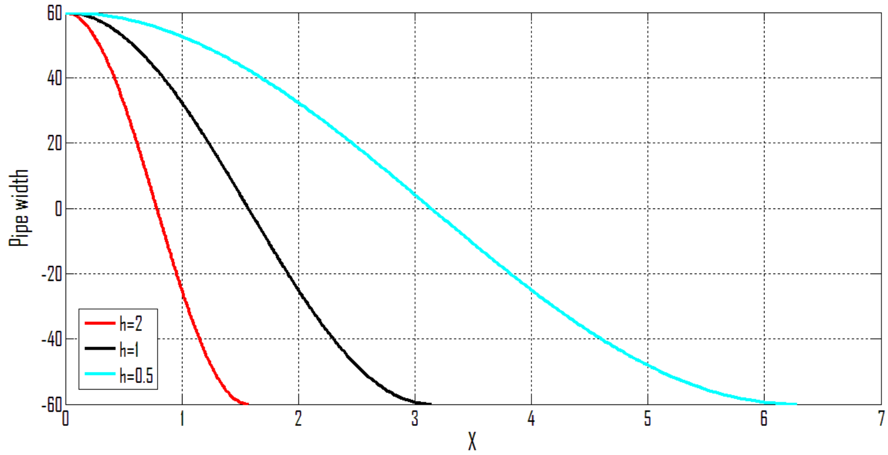

Figure 5. Arccosine curve

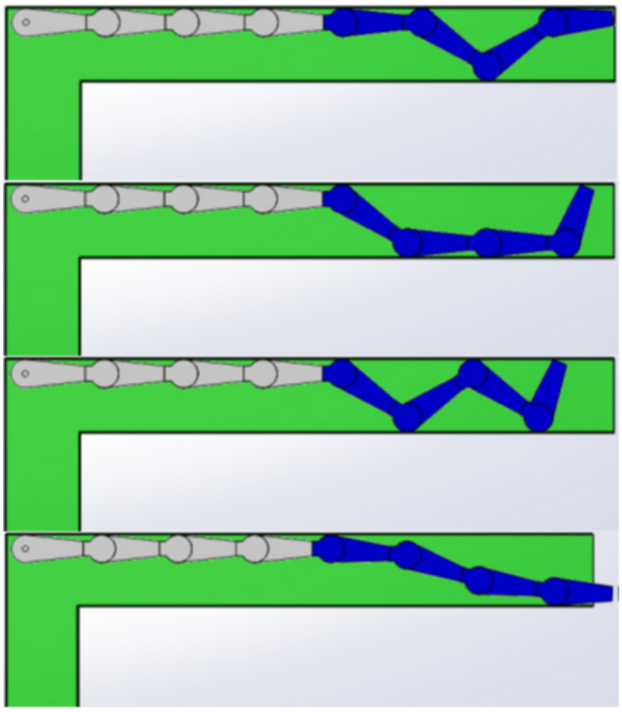

Figure 6. Fixation curves applied on LocoSnake

Consideration of these four mentioned fixation curves on several requirements is based. The first is the requirement of minimum two contact points. The maximum number of the contact point results from the number of the static links; four of them in our case. Therefore the maximum number of the contact points is five; see Figure 6. Next requirement regarding the fixation curves is that it should be mathematically described in order to reach the more convenient programming of controllers for precise positioning of the snake robot joints. The last limitation of choosing the suitable fixation curves is the geometry of the snake robot segments. Not any mathematically describable curve reaching 2 – 5 contact points is suitable to geometry of LocoSnake and regarding the investigated pipe. Due to mentioned reasons only the four fixation curves were considered.

3.2. Fixation Curves Applied on LocoSnake

Now above mentioned fixation curves will be applied to the 3D model of the snake robot LocoSnake. The investigated environment is U-shaped cross section pipe of shape-L and the pipe width of 120 mm. Each of mentioned fixation curves is slightly limited because of the geometric aspects of the robot link resulting what results in that static links will describe these curves only approximately. It is obvious that the smaller are the snake robot links the more precise they copy the fixation curve according its mathematical expression. Each of our four curves is of the different attributes influencing the behavior of the dynamic links. The first fixation curve – Triangle curve, includes five contact points with pipe. The angle of the last link is different in comparison with other static links because of missing the junction part. The second fixation curve – Cycloid curve, includes also five contact points with pipe but with different contact surfaces. The third fixation curve – Gaussian curve, includes four contact points. The fourth fixation curve – Arccosine curve, includes only two contact points. All actuators of snake robot links try to hold their required position during dynamic links motion and it is questionable if they are able to ensure static links not sliding in the pipe.

For our study LocoSnake consists of four static links copying the fixation curves and four dynamic links moving through the pipe. The geometric configuration of LocoSnake moving in the pipe with regard to the fixation curves shows the Fig. 6. Each of them has the same origin located in the axis of rotation of the fifth link. The main aim is to ensure that this origin will not move under the impression of dynamic links motion and increasing surface slope. Surety of static origin ensures good base of performance of the different kinds of tasks like reaching the precise distance between the snake robot head and the scanned object in the pipe (by using camera on the head), overcoming the elbows in pipes and constrictive pipes, etc.

Blue links present the static parts of the snake robot pushing against the wall of pipe and forming the base of the concertina locomotion. While the blue links are static by pushing against the walls, the white links are moving through the elbow of the pipe. The motion algorithm of the snake robot dynamic part is based on the geometry of both the pipe and the snake robot. The algorithm focusing on the performance of the motion through the pipe elbow and to the specified point was prepared. The following chapter experimentally analyzes an efficiency of the particular fixation curves.

4. Experimental Snake Robot Static Links Analysis

At the beginning we may say the hypothesis that the snake robot LocoSnake is able to fix itself in the U-shaped cross section pipe so that during its locomotion through the pipe it does not leave the pipe arbitrarily under the impression of circumstances affecting the experiment. For verification of this hypothesis we have used experimental approach by analyzing of fixation changes for combination of different input parameters. The aim of the experiment was to verify the fixation curves ability to maintain static and to find out a suitable combination of the input parameters. The combination of the input parameters was proper when the total electric power required to the actuators was the least with the different fixation curves and the different pipe surface slope, obviously with well-preserved positions of snake robot static links. During the experiment the displacement of the fifth link (the origin of coordinate system for dynamic links) was measured through the digital image correlation [15].

4.1. Digital Image Correlation

Digital image correlation (DIC) is an optical method based on the correlation principle of the investigated object shot by CCD cameras during its loading. The correlation process of the acquired digital images, also called correlation, is performed gradually on small image elements called facets. Shape of this elements use to be squared with usual size from (15x15 pixels to 30x30 pixels) [13,14,15,18]. Stochastic black and white pattern is created on the object surface in order to correlation of identical parts of the images.

4.2. Experimental Analysis

Dynamic links behaviour expressed by the direct kinematics considerably influences the static links. During the motion the head link moves through elbow of the pipe. To reach the head link required position the robot uses a combination of both rotation and translation motion of the actuators. Rotation and translation constraints within each link are the substantial advantage of the kinematic configuration of LocoSnake. This kinematic configuration provides a more realistic and sophisticated locomotion through the elbow of the pipe or T-shaped pipes.

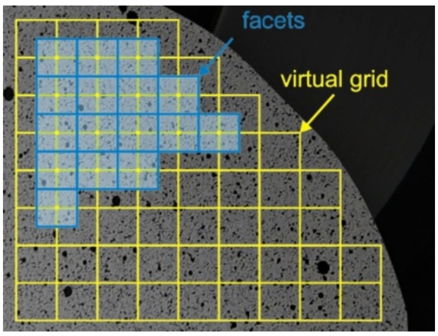

Figure 7. Facets and virtual grid on the object surface with created black and white ran-dom pattern

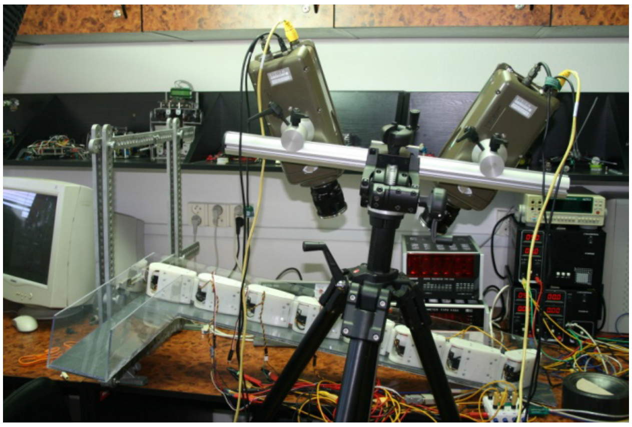

Figure 8. Stereo DIC cameras focusing on the static segment of LocoSnake

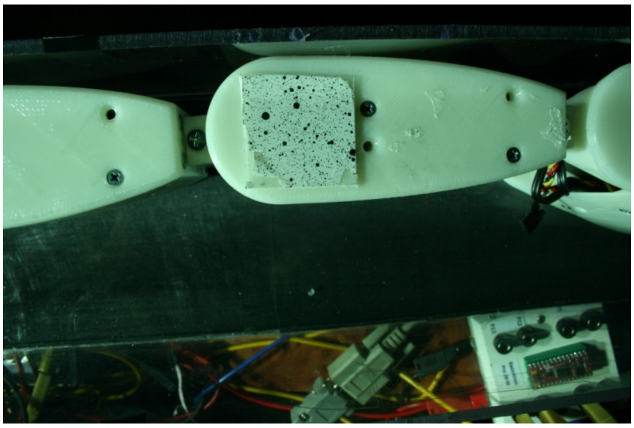

Figure 9. Stochastic black and white pattern on LocoSnake segment

During the experiment the snake robot was controlled by two C Basic Atom-Pro-28M microcontrollers. The first microcontroller controlled the static links and the second microcontroller controlled the motion of the dynamic links. These two microcontrollers were satisfactory in our experiment. The pipe of polycarbonate desk was prepared and U-shaped by special glue for the experiment [15,16,17].

5. Experimental Results

The first matter concerning the experiment was to design the static links fixation curves in P-Basic by consideration of their mathematical background. Basic AtomPro 28-M microcontroller in conjunction with special electric circuit is able to control even 32 servomotors separately. LocoSnake consists of 8 rotation servomotors HS-645MG and 8 linear servomotors Firgelli L12. After programming the microcontrollers each four fixation curves were examined in order to determine their function and suitability to different pipe surfaces slopes. During the initial measurements we found the Arccosine fixation curve results as not satisfactory. For pipe surface slope 0º the static links was not static but it moved for a small displacement. For higher pipe surface slopes the robot fell down from the pipe because this fixation curve could not reach the fixation in the pipe. Due to this fact the Arccosine fixation curve was excluded from the measurements and the experiment continued without it. The figures below show the results of experimental analysis.

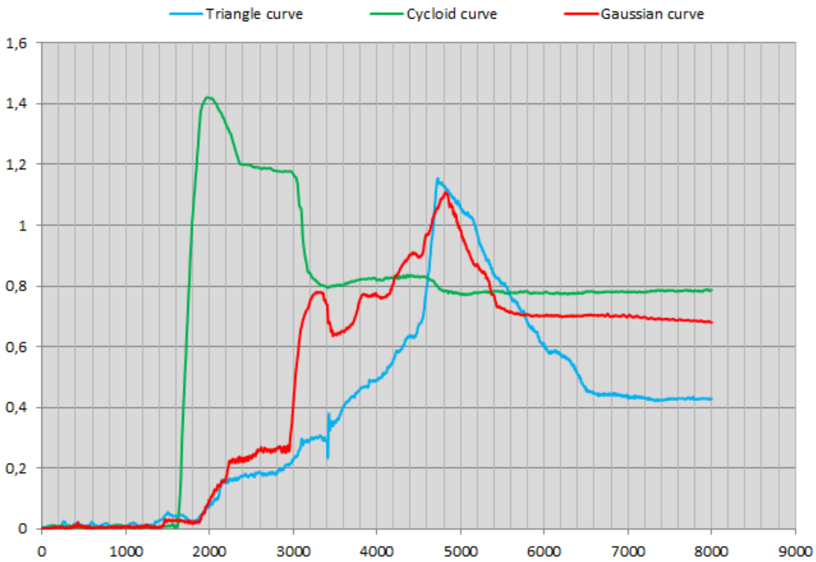

Figure 10. 0º pipe surface slope with 3V supply voltage of actuators

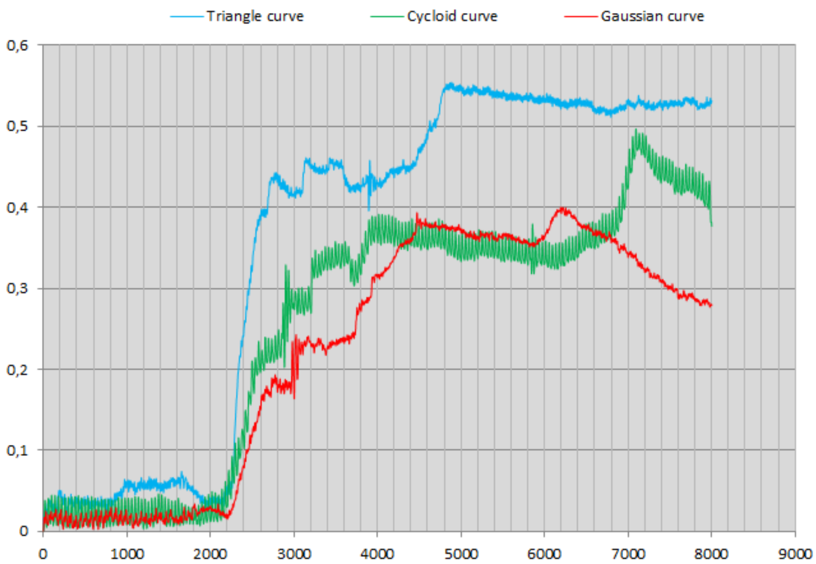

Figure 11. 0º pipe surface slope with 8V supply voltage of actuators

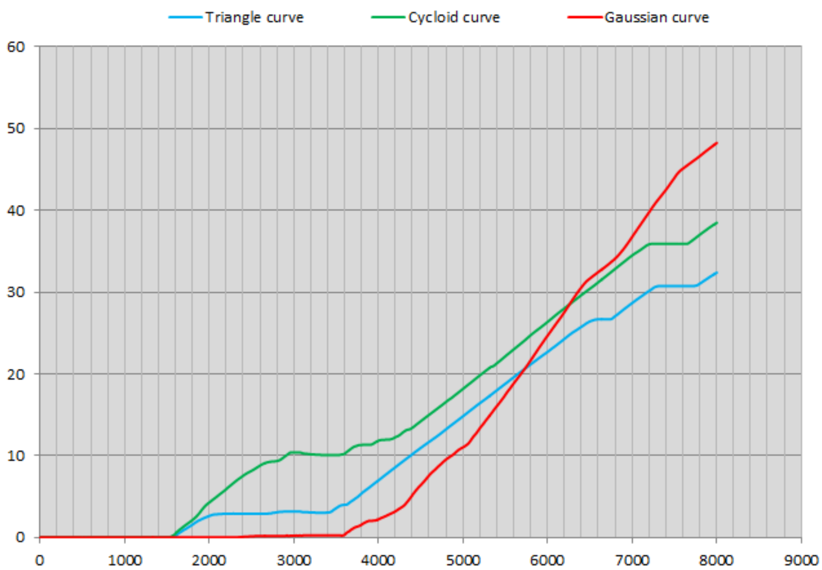

Figure 12. 10º pipe surface slope with 3V supply voltage of actuators

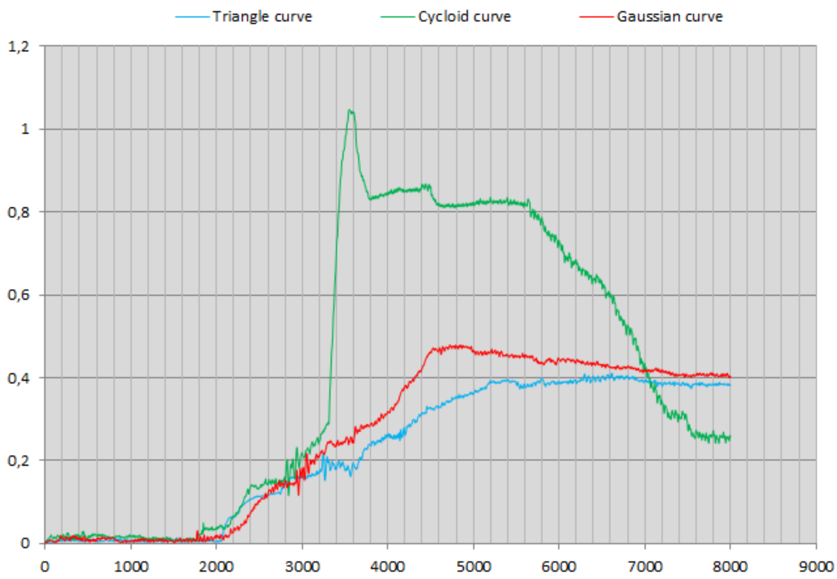

Figure 13. 10º pipe surface slope with 8V supply voltage of actuators

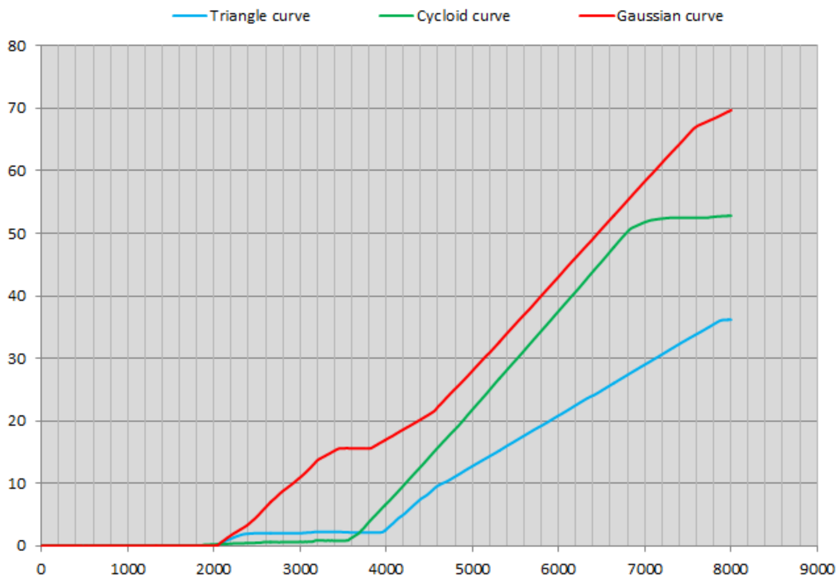

Figure 14. 20º pipe surface slope with 3V supply voltage of actuators

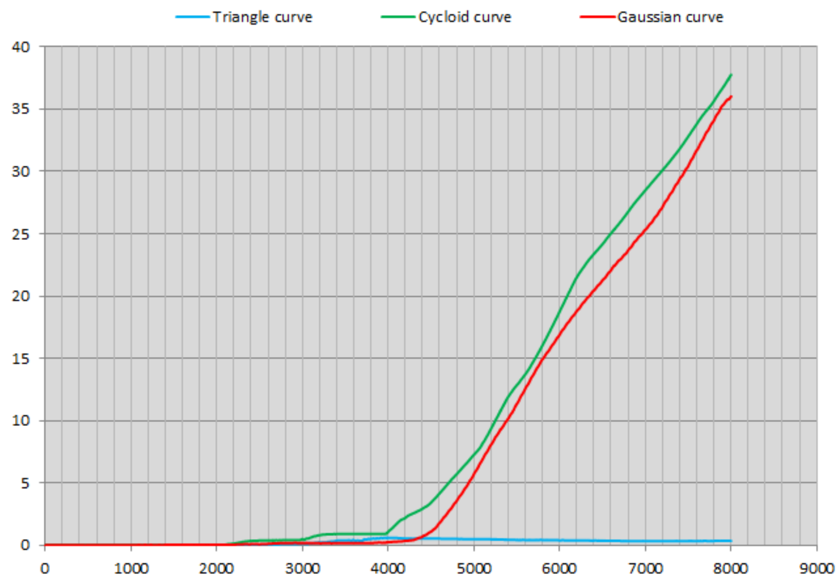

Figure 15. 20º pipe surface slope with 8V supply voltage of actuators

Figure 9 – Figure 15 evaluate the total displacement in two axes. The figures show only the conditions with boundary voltage supply that means 3V – 8V. Total displacements represent a vector expression of the displacements in the direction of the axes X, Y, Z. From the graphs it is obvious that static links are not able to hold their position with 3V voltage supply of actuators with exception of 0º pipe surface slope condition. Figure 10 shows the most precise fixation curve as the triangle curve because of the final position of the fifth link. For 8V supply voltage the displacements are almost the same and remain at initial position during the LocoSnake dynamic links motion. Significant changes appear for 10º pipe surface slope. Cycloid and Gaussian fixation curves were not able to hold robot in initial position and robot fell out from the pipe while Triangle fixation curve was able to hold robot in the pipe even though with significantly displacement. By increasing supply voltage to 8V all three fixation curves were able to fix robot in the pipe with minimum displacement even the Cycloid fixation curve results were worse in comparison with Triangle and Gaussian curves. For 20º pipe surface slope neither Cycloid nor Gaussian curve was able to hold the robot in the pipe not even with 8V supply voltage.

The only Triangle fixation curve was enabled it. Using the Triangle curve the robot slid down but it was always able to stop and did not fall out from the pipe. The last measured angle was 30º. For 8V supply voltage the robot was able to stay in the pipe only with Triangle fixation curve, see Figure 16. During the measure of snake robot displacement the electric power required for its actuators was measured by means of input/output measuring card MF624 cooperating with Matlab/Simulink through Real Time Toolbox. The measuring card consists of 14-bit analog inputs processing the voltage signal. It is necessary to be aware of the fact that in spite of fixed LocoSnake robot static part the total captive holding of the static part during the dynamic part motion is not possible in time of the experiment.

This fact directly relates to the total toughness of the mechanism. Based on the robotic snake LocoSnake experiment it was found that the particular rigid bodies of the snake robot and their mutual joints transfer even the marginal motion during the locomotion performed by the unfixed part of the robot. This motion is transferred to the entire fixed part also in the places of the contacts. Thus, if the motion results in the displacement of the first static fixed segment then the following segments of the robot, the final tail segments, will be displaced too. Important are the dimensions of the displacements and the trend of developing dependency of the displacements and the time for any of the curves combination, the pipe sloping and the action segments supply. Figure 10 to Figure 16 show the initial part of the snake dynamic segment motion. The more important part for the purpose of the fixation is the final time of the measurement of 8000 ms when the algorithm controlling the particular action part of the segments within the dynamic part of the robotic snake and completed its activity of putting the head segment to required position resulting from Section III. The diagrams of the particular curves show the subsequent development of the displacement of the fixed part and the total change of the displacements compared with the initial part. The most ideal are the dependencies on the sequential constant displacement indicating the fixation of the static part within the final algorithm phase.

Figure 10 and Figure 16 and the Gaussian and Cyclic curves show the higher order changes of the position then the proper cases in Figure 10, Figure 11, Figure 13 and Figure 15 for triangle curve. This way these big changes of the fixed position negative influence the positioning of the head segment. After analysing of the results of the experiment, we can observe an important influence of the friction effects that influence the possible movement of the static part of the robotic snake. In a figurative sense, by increasing the applied force of the actuators in joints, we are trying to create bigger effect on the pipe walls and therefore increase the friction. In our case, the friction between pipe and the lower part of the individual segments is largely used. It is caused by large friction surface of individual segments of the robot, while these covers are made from ABS material similarly like other structural parts of the robot. When we focus on the results obtained from the experiment, we will discover that in the early time points a sporadic shift of the static parts occurs. Subsequently, after overcoming of a certain friction, a stir occurs, and the static part starts to move little linearly.

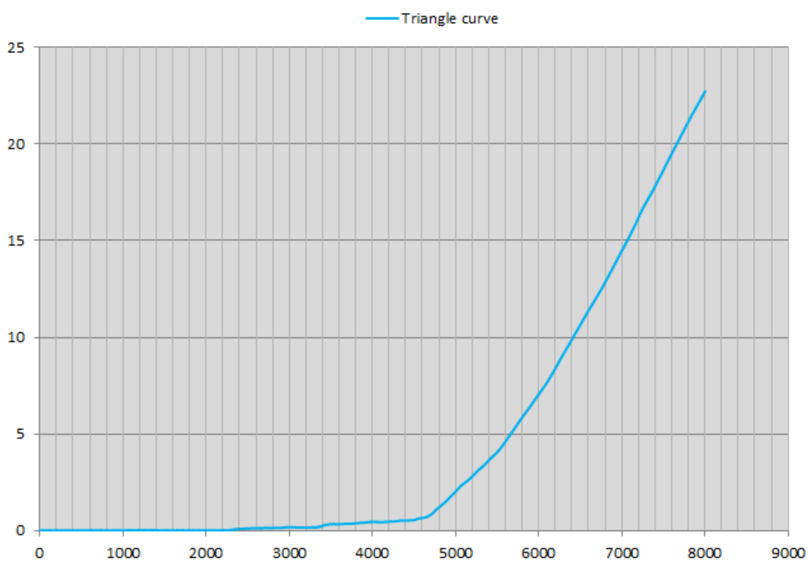

Figure 16. 30º pipe surface slope with 8V supply voltage of actuators

6. Conclusion

Snake robots present broad range of application where conventional mechanisms are not applicable or not effective. These robots, inspired by the nature, offer solutions for designers and researches and they also bring a lot of undetermined questions and problems. The snake robots found its application within the pipe inspection tasks that is the area not investigated in detail up to now yet. The paper deals with the snake robot static links fixation in the pipe resulting in basis of the concertina locomotion. The geometric configuration of the static links position can be described by some kind of curves called the "fixation curves". In the paper various fixation curves are investigated in order to obtain the most advantageous geometric configuration of static links. It was found that from the view of initial position holding the best fixation curve is Triangle curve able to hold the initial position almost without displacement until 20º slope of pipe surface and partly until 30º slope of pipe surface. The reason why we have focused on the usage of the selected type of the fixation curves used for the static part of the snake robot at various changes of tilt in our work was focusing on the extreme values of the change of fixation status. However, this problem gives us higher variability of the possible existing combination statuses that can occur at change of the tilt angle, supply voltage of servomechanisms and change of fixation curve. Static and dynamic part of the robotic snake designed by us have been determined according to the need of the minimum number of snake's articles which were necessary to use for creation of the specific fixation curve. It is obvious that if the robotic snake had a higher number of articles, the static part of the robot would consist of the higher number of links. Dimension of the fixing pipe plays an important role at determining the appropriate number of articles. The smaller the pipes diameter is with the respect to the robotic mechanism, the more difficult it is for the robot to create the appropriate fixation curve. The influence of the dynamic part of the robotic snake is also difficult to be quantified. For the exact determination of the appropriate influence of the dynamic part, it is necessary to conduct a large number of measurements, while specific movement of the dynamic part of robot is still taken into consideration. For this reason, we have used the preprogrammed movement of the dynamic part of robot during this experiment. Our study opens wide range of probabilities of future work within this field. In the future our team wants to deal with the snake robot autonomous selection of suitable fixation curve on the basis of the pipe surface slope measured by inner sensors. The future work also concerns in autonomous control of the actuators voltage supply in order to hold the robot initial position in the pipe. For this purpose each link of the snake robot LocoSnake will incorporate the pressure sensors.

Acknowledgements

The author would like to thank to Slovak Grant Agency – project VEGA 1/0872/16 and KEGA 048TUKE-4/2014.

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