Snake robot based on McKibben Pneumatic Artificial Muscles

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Abstract: This paper presents a novel design of a snake robot based on McKibben Pneumatic Artificial Muscles. The construction is created of serially connected McKibben PAMs in order to create long muscle line, which can be instantly inflated with compressed air. The innovative construction allows an achievement of efficient snake-type movement irrespective of the robot length. The use of pneumatic drive ensures a long working range and a much smaller diameter than conventional solutions. External control system, which is robot supported with, does not impact on size of the robot. These features support the robot with various of applications, impossible to achieve for conventional snake–like constructions. The paper shows construction and research results of McKibben snake robot.

1. Introduction

Nowadays, the growth of mobile robots is observed. Although, robots which can walk, jump, drive or swim are commonly known, there is still a necessity of develop robots, which provide mobility in unknown or challenging environments. An explanation to this need is an inspiration in biological snake locomotion. Snake-type movement, unconventional to any other animal, provides superior mobility capabilities which allows following the most complex path.

Construction of the robot biomimetic to a snake, requires providing robots own propulsion[1]. Accomplishment of this need requires a design of a mechanism which consists of many serially connected joints modules, allowing locomotion by bending in one or more planes. The first snake robot was developed in 1972 by Professor Shigeo Hirose at Tokyo Institute of Technology [2]. It consists of passive wheels located tangentially along its body. Controlling robots joints enables obtainment of a periodic wave motion similar to biological snakes. Wheels mounted on the robot allows it to move forward on a flat surface.

Further development of snake robots enables two main divisions of the robots, based on a construction and a working environment. Based on the working environment snake-inspired robots can be determined in two general categories: snake robots moving on land and snake robots moving underwater [3]. Construction selection determines robots with passive or active wheels, robots with active threads, robots based on undulation using vertical waves and robots based on undulation using linear expansion [4].

Most of the well-known constructions use an electric drive to achieve serpentine locomotion. Robots consist of several modules, connected in series, controlled by servomotors. [5,6]. It requires placing drives inside the module what affects robots size.

In order to increase robots capabilities, there was research of different types of drives conducted. This effects in use of pneumatic drives as a part of robots power supply. One of the robots, which combines pneumatic and electric drives is the OmniTread [7]. The robot consists of five segments covered by tank treads, which ensure propulsion of the robot. Tank treads are located on the four sides of each element in order to maximize the propulsion ratio. Between segments are located pneumatic bellows, which are acting like actuators. Compliance between the segments allows the robot to passively conform to the terrain and maximize traction.

The Slim Slime robot [8] is a construction which uses pneumatic drive for locomotion. It is composed of six, serially-connected expandable modules. Each module is supported with a compressed air by bellows created from three flexible pneumatic actuators. Bellows are connected with a main tube by inlet and outlet valves, what allows to support each bellow separately without use of many air supply lines. This power system allows to stretch and bend modules in any direction, supporting performance in a 3D workspace. Another example of robot with a pressure drive is Planar Walker: Planar Inchworm Robot [9]. It is constructed as planar inchworm, able to mimic snake or inchworm-like creeping motions. The planar mechanism is based on four linear cylinders and four revolute joints. Supporting the actuators separately enables changing its shape to any quadrilateral type. Also, it allows to change rapidly travel direction of the robot and its rotation.

An innovative approach to snake robots is construction based on fluidic elastomer actuators (FEAs) [10]. It allows of bidirectional bending motion segments by supporting pressure chambers with fluid. The actuators are covered with parallel treads which allows bending without undesired lateral expansion. The twisted bundled tube locomotive device allows locomotion in pipes [11]. It consists of three elastic silicone rubber tubes which are twisted and bonded. The work of the device requires inflating of the tubes with pressure air. When one of the tubes is inflated, it expands and the device deforms into a helix. Sequential pressurizing tubes causes the helical rotation and allows movement along the pipe axis. By changing the order of expansion and retraction, it is possible to achieve the backward motion.

Active Scope Camera (ASC) is a device which uses friction anisotropy in order to change friction depending on the direction of movement [12]. It is implemented by covering the surface of the drive with cilia. Moving forward is achieved by alternately sliding two parts covered with cilia using linear actuator. In order to increase robots capabilities, there were used McKibben Muscles, which flexibility allows bending. Another type of snake robots with pressure drive is construction based on Stewart platform [13]. It consists of connected in series, parallel platforms with pneumatic actuators placed between. An example is the Modular Pneumatic Snake Robot [14]. The construction is based on segments which consists of hollow cylinder and a plate, connected by a joint. Around the joint are mounted three flexible chambers working as pneumatic actuators. While one of the chambers is supported with pressure it expands and move the joint. Alternate filling chambers with air pressure allows the robot movement.

2. Novelty of the solution

The most important part of constructing snake robots is designing power and control system which allows serpentine movement. Most of the known solutions use electrical drives. That requires separate power device for each robotic module and is complicated in control. The structure using pneumatic support or pneumatic drives has limited functions. Also, dimensions of the robots are limited due to size of motors or amount of pneumatic wires, in case of mechanisms supported by pneumatic systems. The solution [15], presented in this paper eliminates these obstacles by using innovative power supply method based on McKibben Pneumatic Artificial Muscles (PAM). Instead of equipping each element of the robot with electric drive and control device, there is one system, allowing locomotion of the whole robot used.

The construction is created of serially connected McKibben PAMs, in order to create long muscle line, which can be instantly inflated with pressured air. To achieve a serpentine movement, there was a wave propagation method used. By using few of the McKibben lines assembled and supplied in specific order, it is possible to achieve the sinusoidal shape of the robot, The shape changes according to which McKibben line is powered. As a result, the wave propagation and a movement of the robot can be observed. The main advantage of this solution is control of the whole length of the robot by one control system. Sequential control of each McKibben line is possible with use of one power supply, equipped with pneumatic valves located at the end of the robot. As opposed to method, where drives are placed inside robot modules, the McKibben solution does not require specious elements, able to fit the control and power system. Due to that, dimensions of the snake robot based on McKibben PAMs depends of the size of power supply elements – in this case pneumatic artificial muscles. It allows to create a robot with much smaller diameter than conventional solutions, while preserving the length of the robot required by the constructor. In result, it is possible to design a pneumatically-driven robot with a long range (up to several meters) and an external control system.

Pneumatic drives allows application of the robot in the environments where using of electrical drives is impossible or can be dangerous, as human or animal diagnostics or environments with a risk of explosion. Moreover, small diameter of the device allows mobility in narrow pipes, while high range supports access to places impossible to achieve for conventional snake–like constructions.

Beside of solution with McKibben muscles, there is also planned to develop the snake robot based on Transversal PAMs [16], which construction can be beneficial in achievement of requirements.
In this paper, there is presented third generation of the snake robot based on McKibben PAMs.

3. Construction of the robot

The innovative power system, consisting of McKibben PAMs, requires unconventional construction of the snake robot. It consists of four individually supplied lines of McKibben muscles connected in series (Fig. 1). Between McKibben muscles there are placed strengthened tubes in order to create a line of McKibben PAMs, separated by non-working channel, which allows distribution of pressure through the whole tube. McKibben's PAM lines are placed in a dedicated holders with the distance between each holder equals 50 mm. The core, created from McKibben PAMs, is covered by two steel ribbons and a silicone cover (Fig.2). Steel ribbons protects robot from influence of external factors, while the silicone cover separates the robot drive from working environment and helps avoiding sudden air leaking. This solution enables creating 2000 mm long snake robot with the diameter of 17 mm, what can be beneficial for unconventional usage.

Figure 1 McKibben line

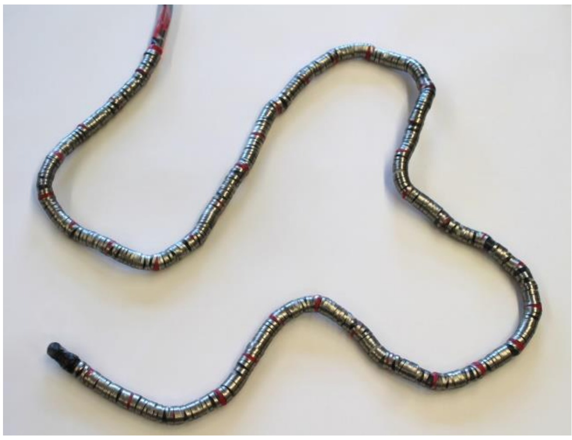

Figure 2 Snake robot based on McKibben PAMs

Snake-like locomotion requires creating a movement based on the wave propagation. Supporting McKibben lines sequentially creates a particular weave of the robot. The robot is divided in sections, each 50 mm long, which take quarter of the sinusoidal shape, while specific McKibben line is supplied with the pressure. The snake's movement is based on repeatable sequence of suppling McKibben lines (1,2,3,4) in particular order as shown in Figure 3. When the 1^{st} and 2^{nd} line are powered and 3^{rd} and 4^{th} are released the robot bends, creating a sinusoidal shape, as shown in Figure 4. Then, the 1^{st} and 4^{th} line is released and following, 2^{nd} and 3^{rd} line are powered creating sinusoidal shape of varied phase.

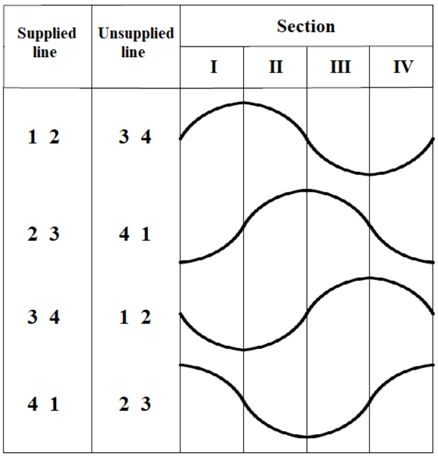

Figure 3 Shape of robot with selected muscles lines supplied

Subsequently, 3^{rd} and 4^{th} lines are powered, while 2^{nd} and 3^{rd} line is released. The last part of the cycle requires 4^{th} and 1^{st} line powered while 3^{rd} and 2^{nd} are released. Repetition of these cycles allows dynamic change of sinusoidal shape phase and effects in robot motion.

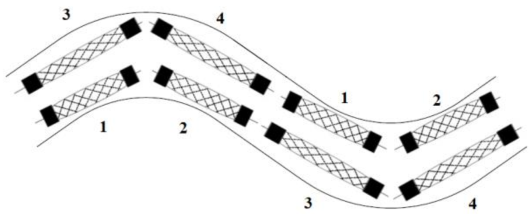

Figure 4 The location of McKibben muscles while 1^{st} and 2^{nd} lines are supplied

4. Working principle

The construction of the robot allows its movement both on the land and underwater. Due to method of locomotion, using wave propagation, behavior of the robot is different for various types of working conditions. Two characters of work can be distinguished for high friction and viscoelastic environment. Research of robots movability in high friction environment has been already presented [17]. Based on the results, it is observed, that while moving, the robot is pushed away from the high friction track. The touching point, marked on the robots surface, travel along the curve resembling a cycloid (Fig. 5). Further observation of the robot operation shows, that moving forward is allowed by friction forces appearing between the robot surface and the track. In the high friction environment, robot moves in the same direction as the direction in which the wave is propagated.

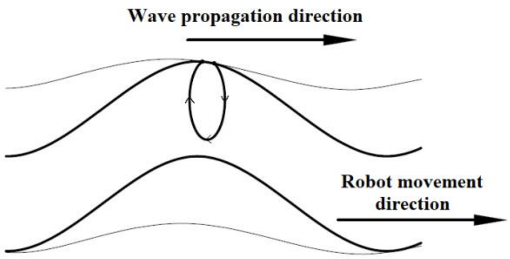

Figure 5 Robot movement in high friction environment

Different type of robot behavior can be observed in viscoelastic environment. Significantly smaller values of friction not allow the robot to push away from the track. The dependence of forces appearing in this conditions is presented in Figure 6. The force N of robot reaction to the track is perpendicular to friction F_f. Due to the small value of friction F_f, the direction of net force F changed and is opposite to the direction of wave propagation. It caused the change of direction of robots locomotion. In viscoelastic environment snake robot is moving in the opposite direction to wave propagation.

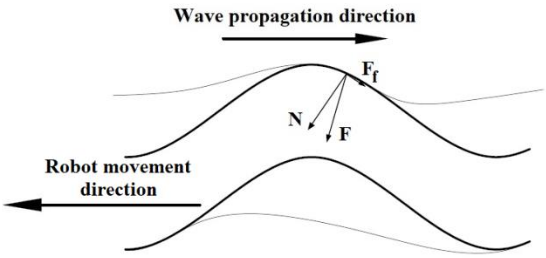

Figure 6 Robot movement in viscoelastic environment, (F_f – friction, N - reaction force, F – net force)

5. Research methods

In order to achieve robots locomotion, there was a dedicated controlling system required. The repeatable supply system of the McKibben lines is supported by four pneumatic valves 3/2 controlled by the PLC. Adequate locomotion of the robot requires smooth movement of each wave. It was accomplished by setting a proper value of damping at throttling valves located before valves. The scheme of controlling system is presented in Figure 7.

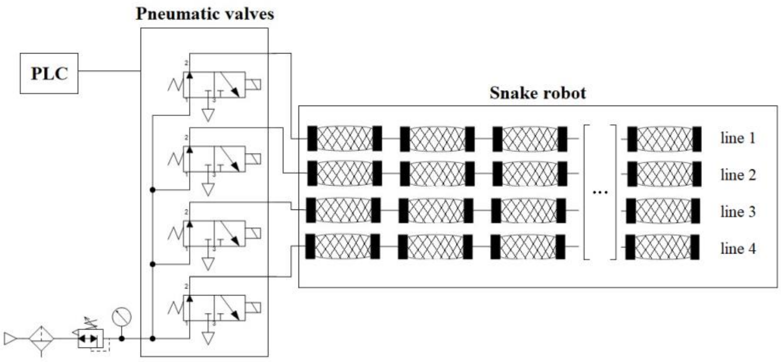

Figure 7 The scheme of controlling system

One of the possible uses of the robot is diagnostics of humans or animals. The shape of the robot is dedicated to use as a device for colonoscopy or endoscopy. Therefore, it was necessary to prepare the robot for usage by studying its behaviour in viscoelastic environment.

First part of the research refers to robots locomotion in different friction value environments. In order to create a proper dimensions of the human intestine, there was used a 1 m long PMMA tube of inside diameter 56 mm. Inside the PMMA tube there was placed a silicone tube of diameter 42 mm.

Movement inside the intestine is characterized by small value of friction – based on the previous experiments the friction between intestines and silicone is equal 0,04. Unfortunately, the friction value adequate to human intestines was impossible to achieve by experimental methods. In order to approach model conditions, there were different types of lubrication poured into the PMMA tube. Based on the previous research there were chosen lubricants which showed the smallest friction in contact with silicone rubber, which both the tube and the robot were covered. There was used baby oil, dish soap and a combination of paraffin oil and a baby oil. The values of friction for different types of lubricant are showed in Table 1. Also, there was examined robots motion with no lubrication – the surfaces were dry and friction occurred between silicone layers.

Table 1 Friction values depending on lubrication method

Lubrication	**Friction**
Dry (silicone-silicon friction)	0,75
Baby oil	0,34
Dish soap	0,21
Paraffin oil + Baby oil	0,18

To obtain a locomotion of the robot, the McKibben lines were supplied with the air pressure of value 0,2 MPa and frequency of 0,25 Hz. The robot was inserted into the silicone tube via inlet of diameter 30 mm. The results of movement speed depending on friction are showed by Figure 8. The most important observation is, that direction of robots motion depends on a value of friction obtained by different type of lubrication.

The dry contact, with no lubrication between surfaces, which has the highest value of friction from examined cases, allows obtaining the movement in direction of wave propagation, with speed equals 3,48 cm/min. Decreasing the value of friction leads to stop the robot and then, obtaining the movement against the direction to wave propagation.

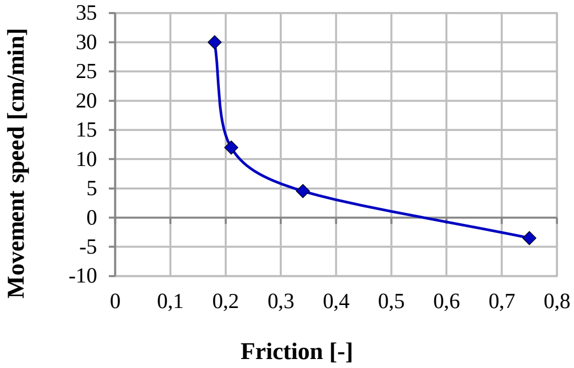

Figure 8 Movement speed of the robot in relations to friction from different types of lubrication

Also, the use of combination of paraffin oil and baby oil, which has the smallest value of friction from examined lubricants, shows significant increase of the locomotion speed. In this case, there is possible a movement with speed equals to 30 cm/min. That shows great capabilities of robot usage in conditions of viscoelastic environment.

The efficiency of serpentine movement depends on a bending amplitude and a bending angle of each wave of the robot. The presented robot requires additional cores created from ribbon bands and silicone cover. Adding core layers to the bending mechanism affects the robot locomotion, therefore it is necessary to investigate its influence on working system.

6. Research

Presented snake robot, in order to fulfil its purpose, has to move according to constructor requirements, generating the same force at each of the sections. Due to that, it is necessary to obtain the same bending amplitude at each wave of the robot. Otherwise, the robots locomotion will be unpredictable and can cause damages of the environments where it is working in. In the second part of the research, there was examined influence of previously mention factors to robots movement.

There were measured values of the bending amplitude and angle of the four subsequent waves of the snake-like robot. There was tested the dependence of measured parameters based on the pressure and number of robot layers. In the research, the McKibben lines were supplied sequentially, in order to achieve full bending of each wave. The measurement was conducted for the value of pressure from 0,1 MPa to 0,3 MPa, changing every 0,05MPa. The robot's bending angles and amplitudes were measured (Fig.10) and examined for three cases: without layers (only muscles in handles), with ribbon bands on, and with ribbon bands and silicone cover on, what is shown in Figure 9.

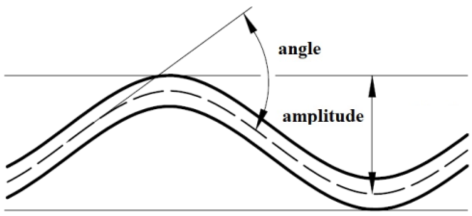

Figure 9 Angles and amplitudes measurement

The results of influence of number of layers to bending angles are presented in Figure 10. It is indicated, that bending angles decrease along with the application of the next layer. For value of pressure 0,15 MPa the angles obtained for 2nd and 3rd muscle lines equals -34° for construction with no layers, -31° for ribbon band add on and -25° for ribbon band and silicone cover. This leads to the conclusion, that an application of ribbon bands caused the greatest change in results, while application of next layer which is silicone cover did not affect the results significantly. The values of bending angles for 1st and 4th muscle line were measured from the same reference point and their values are opposite in relation to 2nd and 3rd muscle lines. For value of pressure 0,2 MPa the angles obtained for 1st and 4th muscle line equals to 42° for construction with no layers, 34° for ribbon band add on and 26° for ribbon band and silicone cover. The limitation of the range of robots movements according to number of layer increases with the higher value of the pressure. Although, the highest of tested values of pressure, which is 0,3 MPa, allows achievement of the largest bending angles, the influence of layer number is higher. Therefore, the most advisable value of pressure is 0,2 MPa, due to the fact it allows to achieve large bending angles with smallest impact of number of layers.

Figure 11 presents the result of the impact of number of layers to bending amplitude. The values for 2nd and 3rd muscle line are negative due to the reference point specified for sinusoidal shape of robot. Accordingly, the bending amplitude for 1st and 4th muscle line is described by positive values as it placed on the opposite side of the reference point. The value of a bending amplitude of 2nd and 3rd muscle lines with no layers add on is equal -13 mm for pressure 0,1 MPa and -37 mm for pressure 0,3 MPa. Based on the results can be concluded, that increasing value of pressure allows to achieve higher values of a bending amplitude. As in studies of the bending angle, the achieved value of bending amplitude changes while additional layers are added. The 2nd and 3rd muscle line bending

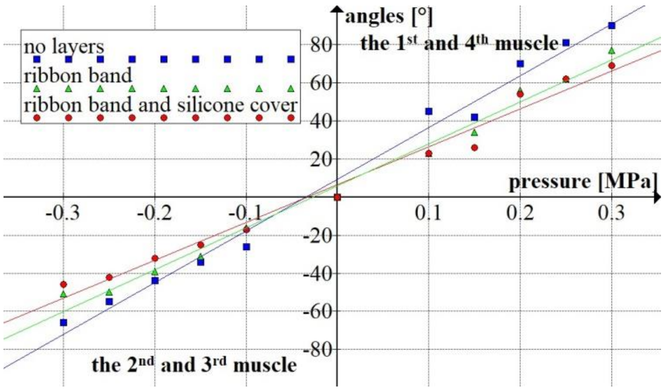

Figure 10 The impact of number of layers to bending angles

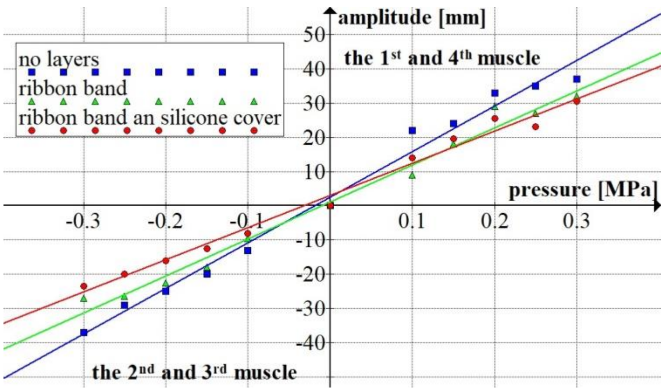

Figure 11 The impact of number of layers to bending amplitude

amplitude, tested with pressure 0,2 MPa, achieves -25 mm for construction with no layers, -22,5 mm with ribbon band and -16 mm with ribbon band and silicone cover. It shows, the adding layers to the construction decreases values of measured bending amplitude and has significant influence on robots shape while moving. Also, the most beneficial range of air pressure values is from 0,15 MPa to 0,25 MPa, when bending amplitude values are high with small increase of additional layers.

The last part of the research was about the differences of measured bending amplitude for two pairs of muscle lines. As it was mentioned previously, achievement of similar values of bending amplitudes for subsequent waves of the robot is beneficial to its locomotion. Figure 12 presents the results of comparison of bending amplitudes, for four subsequent waves, while 2nd and 3rd muscle line or 1st and 4th muscle line are supplied. Due to the internal stress of the robot lines and the shifting of reference point while measuring, the values of amplitudes for each wave are slightly different. However, that values achieved for subsequent waves of the robot are compatible and allow efficient motion of the robot.

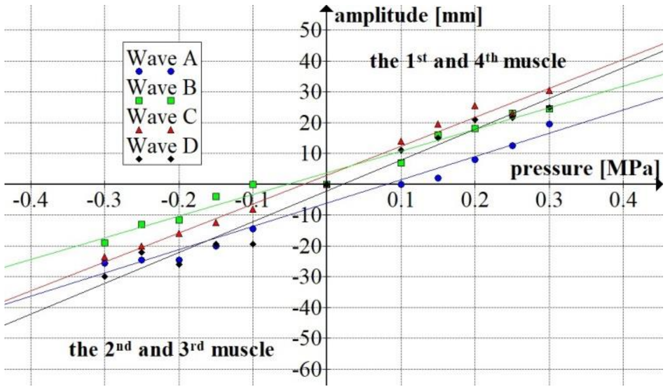

Figure 8 The comparison of bending amplitudes for 2nd and 3rd muscle line and for 1st and 4th muscle line

7. Conclusions

The use of McKibben PAMs allows to create a long range robot with much smaller diameter than conventional solutions. The external control system enables supporting full length of the robot without affecting on its dimensions. The research results show, that it is possible to achieve similar bending angles and amplitudes for subsequent waves of the robot. However, there was observed an impact of the number of robot layers to the values of these factors, what imposes selection of most beneficial range of power pressure. Based on the friction influence research, can be stated, that robot locomotion changes due to the type of lubrication. Therefore, it is necessary to consider friction and adjust a direction of wave propagation to achieve required locomotion

Acknowledgments

The foregoing research was co-financed by The National Centre for Research and Development, under LIDER Programme, for 2017-2019, LIDER/20/0106/L-7/15/NCBR/2016.

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