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Long-range snake-like robot powered by pneumatic McKibben muscles

Contemporary research on mobile robotics aims at designing robots that will be able to traverse an extremely varied environment. One of the most universal modes of locomotion is the serpentine movement. A majority of modern snake-like robots use electric drives. This study presents a snake-like robot made out of McKibben muscles. Using a pneumatic cable with muscles arranged in series, it is possible to create a robot of any length, limited only by the length of the muscle cables. Because the control system and the body of the robot are separate, the robot can be used for rescue missions involving high risk of explosion of flammable substances and for missions taking place on extremely difficult terrain.

1. Introduction

One of the greatest challenges in contemporary mobile robotics is the need for universality of the robots locomotion. Some robots are designed to be able to move in difficult conditions, while others are designed to traverse a specific terrain. The universality of locomotion is of growing importance. Engineers aim at designing a structure that will enable robots to move in a wide range of conditions. One of such universal modes of locomotion is the snake-like movement. Researchers consider snakes one of the most fascinating animals, as their locomotion allows them to traverse even the most varied terrain. Increasingly complex and universal structures are being designed by imitating these reptiles. The first snake-like robot was created by Hirose in 1972 [1]. It used an electric drive and moved on passive wheels along a plane. A similar solution employing turning modules is described

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in study [2]. Later developments brought snake-like robots that could move in a 3D space [3, 4], swim [5], move vertically along cracks [6], traverse difficult terrain, such as sand or a swamp [7], or even climb [8]. Today, there are many studies addressing snake-like robots. Articles [9, 10] present a review thereof.

Most modern snake-like robots run on an electric drive. However, this type of drive is difficult or even impossible to use in some cases, for instance, in human and animal diagnostics or in environments with a risk of explosion. The latter include collapsed mineshafts and buildings, where the concentration of flammable gas may reach dangerous levels. Sending a rescue team brings an additional risk to their health and life. Alternatively, rescue robots employing serpentine locomotion [11] would be able to traverse the rubble and move through cracks, pipes, or other narrow openings to search for survivors. Such a robot can be constructed based on a pneumatic drive.

As of today, there are several different designs of robots with a pneumatic drive. For instance, the robot presented in [12] uses a hybrid structure that combines pneumatic joints and an electric motors that drives a caterpillar track. In turn, study [13] presents a robot that has a pneumatic drive but is controlled electrically. The use of a pneumatic drive would minimize the risk of causing an explosion. However, the rescue mission may come to a halt if the robot reaches the limit of its range. Therefore, this study attempted to design a pneumatically-driven robot with a long range (up to several meters) and an external control system.

2. Structure of the robot

One of the greatest challenges in designing snake-like robots equipped with a pneumatic drive is creating a structure that can generate a propagating wave along the entire body of the robot. For this purpose, the authors of this study decided to use McKibben muscles connected to one another in series and divided with a piece of pipe and non-elastic braid sleeve. Next, this cable with McKibben muscles is woven along the entire length of the robot, such that the working part of the muscle is parallel to the body, and the non-elastic part is used to weave the muscle between the consecutive sections of the robot. This, coupled with the pneumatic drive, will allow the robot to assume a shape similar to a sine curve within a single plane. Fig. 1 shows a diagram of the weaving of cables and the McKibben muscles as 2D robot structure. In the robot design, the important part is the core. It is the tool cable, and it provides the proper stiffness of the robot. Practically, it is created as the long spring with precisely calculated stiffness and geometry.

This attachment of muscles means that, if the muscles in cable 1 are powered with compressed air, the robot will deflect to a shape similar to the sine curve, since the muscles located in sections I and III will bend the robot in opposite directions. If cable 2 is also powered, sections II and IV will bend in directions corresponding to sections I and III. Next, power is cut off in muscle cable 1, which extends sections I and III, while sections II and IV remain bent. This propagates

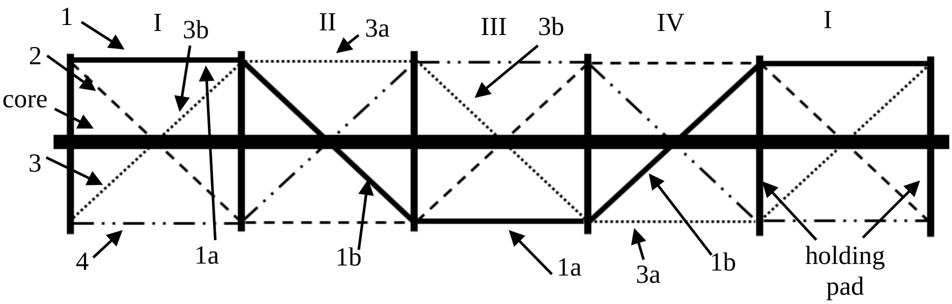
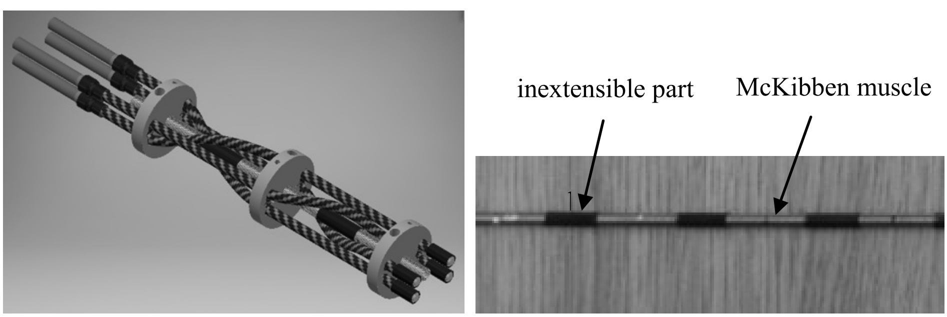


Fig. 1. Diagram of muscle attachment in the snake-like robot 1, 2, 3, 4 – subsequent cables with McKibben muscles; 1a – working part of cable 1 (McKibben muscle), 1b – non-working part of the cable 1, 3a – working part of cable 3 (McKibben muscle), 3b – non-working part of the cable 3

the wave of displacements from sections I and III to sections II and IV, and the wave shifts right, according to Fig. 1. Next, muscle cables 3 and 4 are powered, and the other cables have power cut off at the right moment, thus propagating the wave of displacements along the entire length of the robot. This design means that the length of the part of the robot that performs the sine movement depends only on the length of the muscle cables. Fig. 2 shows a sample structure employing this design.



(a) (b)

Fig. 2. a) sample structure of a snake-like robot based on McKibben muscles; b) cable with McKibben muscles used to construct the robot

The velocity and character of the propagating wave is strictly associated with the length of the individual sections, shortening of the McKibben muscles, and the work time of each cable (i.e., to the control system).

For the purposes of designing a prototype, a single section is limited to the model shown in Fig. 3, in which l_1 and l_2 are a working and non-working McKibben muscle, respectively, x is the diameter of the holding pad for the muscles, and α is the bend angle of a single section of the robot. The core should be in the middle between l_1 and l_2 muscles but it is omitted for the sake of clarity of the figure.

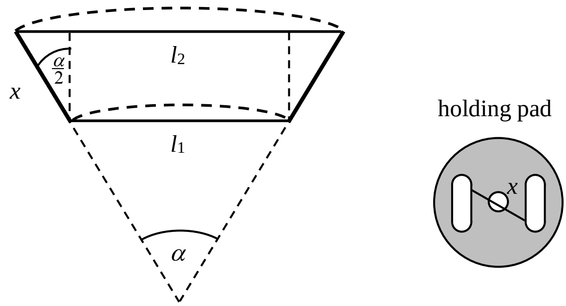


Fig. 3. Simplified model of a single section of the robot

The aforementioned assumptions lead to the following equation:

$$\sin\frac{\alpha}{2} = \frac{l_1 - l_2}{2x}\,. \tag{1}$$

The decision was made to use McKibben muscles made of a silicon pipe (the core of the muscle) and a nylon braid sleeve (commonly used to protect electrical cables). This muscle design was assessed for muscle shortening (δ) in the function of pneumatic pressure (Fig. 4).

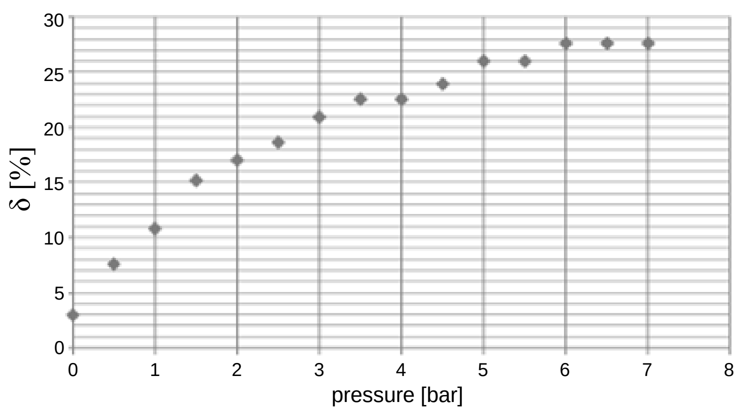


Fig. 4. Muscle shortening in the function of pneumatic pressure

The assessment indicated that beyond the value of 3 bar, any further increase in pressure reduced the rate of muscle shortening, which meant that the muscles worked less effectively. Thus, it was decided that the robot would be powered with a pressure of 3 bar.

It was noted that an initial stretching of the silicon pipe (the core of the McKibben muscle) relative to the braid sleeve caused a different value of muscle shortening at the same pressure. Consequently, the value of the initial stretching of the muscle core that provided optimal shortening was determined. Fig. 5 shows the experimental results. During the experiment, it was very difficult to get a precise tension of the McKibben muscle core, therefore there are presented only the few points without the statistic calculations. It is also worth mentioning that, with an initial stretching of about 14%, the muscle started to elongate.

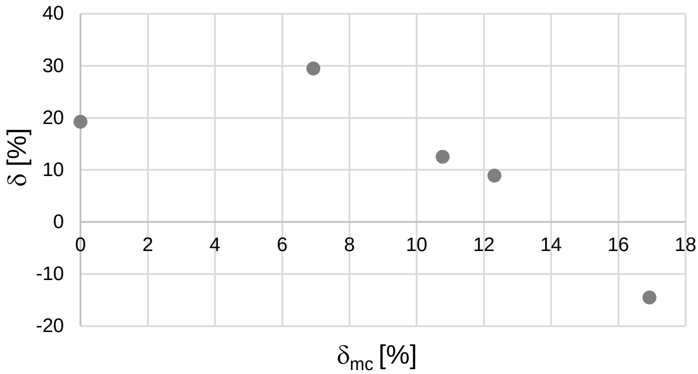


Fig. 5. Plot of the function of muscle shortening depending on the tension of the McKibben muscle core (δ_{mc})

The research indicated that the highest shortening of the McKibben muscle (about 30%) was obtained for an initial core stretching of about 7%. Subsequently, the bend angle of the robot was calculated for each McKibben muscle length, for a diameter of the holding pad (x) of 17 mm (Fig. 3).

The results of the calculations, shown in Table 1, indicate that the longer the muscles, the greater the bend angle that can be achieved. Furthermore, bend angle per unit of robot length was calculated. The bend angle of the body corresponding to each millimeter of body length was similar for all muscle lengths (Table 1). Therefore, muscle length will not directly affect the minimal bend angle of the robot. On the other hand, the use of shorter muscles would necessitate a higher number of pads with handles to separate the sections from one another. Because the part of the robot with the pad is not involved in the bending of the body, the more partitions there are, the lower the bend angle will be. Thus, the use of too many partitions that connect the muscles is inadvisable. On the other hand, if

Table 1.

Relationship between the bend angle of the robot and length of McKibben muscles

Length l_2 [mm]	Length l_1 [mm]	Angle α [°]	Unit angle [°/mm]
40	28	41.3	1.0
45	31.5	46.8	1.0
50	35	52.4	1.0
60	42	63.9	1.1
70	49	76.3	1.1

excessive length and bend angles are used, the muscle will touch the core of the robot, reducing the efficiency of bending. A series of simple experiments indicated that, for McKibben muscles with a length of 45 mm and under a pressure of 3 bar, the muscles located on opposite sides of the core of the robot did not touch the core; consequently, the robot was constructed using these parameters.

3. Robot testing

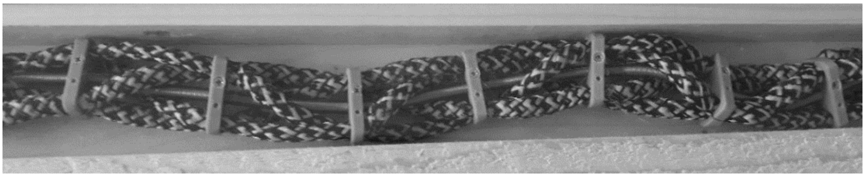
The snake-like robot was built from four cables equipped with McKibben muscles with a length of 45 mm arranged in series. Located between the muscles is the non-elastic part of a cable that does not change its diameter but has a high transverse elasticity (Fig. 2b). The non-elastic part allows the cable to be woven between the individual sections, such that the muscles are always parallel to the core of the robot (when the robot is powered off), whereas the non-elastic part is used to move the cable to the other side of the core (Figs. 1 and 2a). Each section is about 50 mm long and divided by partitions, which also secure the muscle cables. The cables are woven such that the robot can only bend within a single plane. Thus, the wave of displacements that propagates along the length of the robot is also contained within a single plane. Note that thanks to this structure, the robot has a low torsional rigidity relative to the longitudinal axis, which allows it to adjust to the terrain.

Five different tracks were designed for the robot to traverse in order to assess its locomotion (Fig. 6):

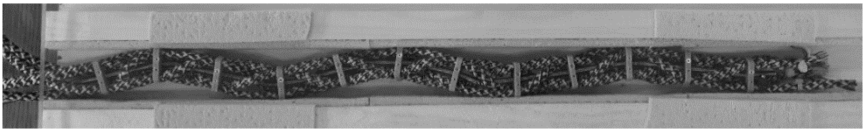
- Track I: made of wooden planks;
- Track II: made of wooden planks, with walls lined with flat sponges;
- Track III: made of wooden planks, with walls lined with sponges and Teflon tape;
- Track IV: made of wooden planks, with walls lined with sponges and Teflon tape, and ground lined with Teflon tape;
- Track V: made of wooden planks, with walls lined with sponges of different thickness and Teflon tape, and ground lined with Teflon tape.

The control strategy was very simple and based on switching on/off the compressed air supply of the cables with McKibben muscles. The cables' supply was controlled by the IDEC SmartAxis FT1A-H40 PLC controller and four 2/5 valves (Fig. 7). The robot cables were connected with valves with 4 mm diameter pneumatic pipes. The compressed air supply was switched with 1 Hz frequency between the cables with McKibben muscles, consequently it was 0.25 Hz frequency for the full cycle of the robot. The series of experiments was conducted to determine the mean velocities of the robot on each track. Table 2 presents the results.

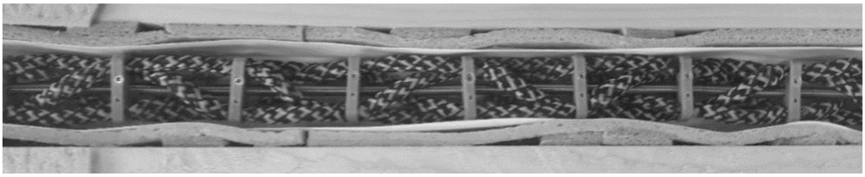
The series of experiments led to the conclusion that the robot moved the fastest on Track II (Fig. 6b) and the slowest on the track lined with Teflon tape (Fig. 6c). A camera positioned over the robot recorded its mode of locomotion in order to determine what forces caused the robot to move. Next, a point tied to the holding



(a)



(b)



(c)

Fig. 6. Sample tracks for the robot to traverse: a) track made of wooden planks; b) track made of wooden planks, walls lined with sponges; c) track made of wooden planks, walls lined with sponges and Teflon tape

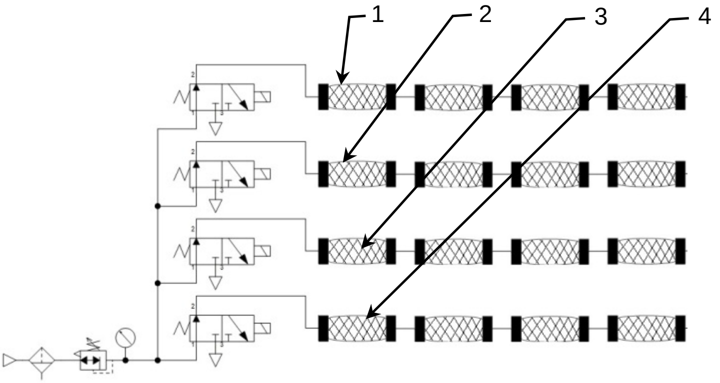


Fig. 7. The pneumatic schema of the snake-like robot

Table 2.

Mean velocities of snake-like robot over different tracks

	Track I	Track II	Track III	Track IV	Track V
Velocity [mm/s]	1.18	1.33	0.73	0.99	0.90

pad was selected in the footage, and the position of the robot was marked in each frame. Fig. 8 shows the results of this procedure.

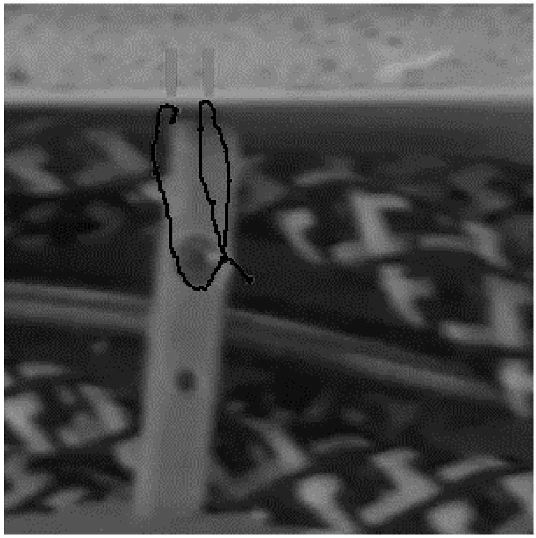


Fig. 8. Subsequent positions of the point tied to the pad of the robot

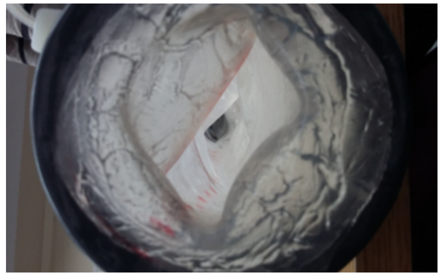
The results indicate that the marked point traveled along a curve resembling a cycloid. Note that the shape of the curve is distorted whenever the curve touches the track, which indicates that the pad is pushed away from the track. Observation of the robot's operation and an analysis of the point tied to the corner of the holding pad suggest that the primary forces that drive the robot forward are the torques exerted by the pad onto the track over which the robot is moving. The robot moved in the same direction as the direction in which the wave propagated.

It is worth mentioning that the robot is able traverse a track lined with Teflon, i.e., a low-friction terrain.

A Generation II robot was designed in order to test its locomotive ability in very difficult conditions. Generation II was also based on the calculations and structure described in Section 2. The robot was constructed using a nylon braid sleeve and a silicon core. The pads were replaced with handles printed in a 3D printer. The handles were used to minimize contact between the muscle cables while maintaining an appropriate alignment relative to the core of the robot. Because the Generation II robot was assumed to be tested in an environment containing liquids, its body was wrapped in two springs, one left-hand and one right-hand. Next, the springs were covered with a silicon pipe with a width of 0.2 mm, which protected the body of the robot from external factors. Fig. 9a shows the full design.

A measurement tunnel was designed for the Generation II robot that simulated an environment with high damping and elasticity coefficients. The tunnel was made of a polyurethane pipe with a diameter of 80 mm and wall thickness of 3 mm.

(a)



(b)

(c)

Fig. 9. a) Generation II snake-like robot with a pneumatic drive; b) front view of the tunnel simulating an environment with high damping and elasticity coefficients; c) robot introduced into the tunnel

The polyurethane pipe was lined from the inside with a silicon pipe with a diameter of 40 mm and wall thickness of 1 mm. A transparent grease was applied between the two pipes to introduce damping. As a result, the walls of the experimental tunnel bent when the robot exerted pressure on them and slowly returned to the original shape when the pressure disappeared. Note that the coefficient of friction between the robot and the pipe was high.

The robot was introduced into the tunnel and its velocity over three different distances was measured several times. Table 3 shows the results of this experiment.

Table 3.

Measurement of time and velocity of Generation II robot

Distance covered by the robot [cm]	Time (measured from the starting point)	Velocity [mm/s]
10 cm	2 min 40 s	0.63
20 cm	5 min 20 s	0.63
30 cm	8 min 40 s	0.58

The results of the experiment showed that the robot was able to traverse this environment. Its velocity was similar for all three distances. Even though robots of this type move at a slow velocity, which to a large extent depends on the frequency with which the cables are switched on and off (the study showed that the full sequence of power switching amounted to 1 Hz), the research has shown that they are able to move in environments with high elasticity and damping coefficients.

4. Conclusions

A prototype of a snake-like robot equipped with a pneumatic drive was constructed. McKibben muscles were used as the power units. The muscles were distributed in series along the power cable and were divided with a non-elastic part with a high transverse elasticity. This structure allowed the robot to perform a serpentine movement within a single plane and provided a low torsional rigidity in the plane perpendicular to the axis of the robot. Consequently, the robot was able to adjust to the environment and could traverse even very difficult, uneven terrain or environments with high damping and elasticity coefficients. It is also worth underlining that the length of the robots depends solely on the length of the power cables, which means that it is possible to construct a several-meter-long robot in order to reach places inaccessible to traditional snake-like robots. Importantly, the control system is external to the body of the robot, which allows it to be used in areas with a risk of explosion. An undeniable advantage of this solution is that during operation, the entire robot performs a sine-wave movement, which means that every section of the robot takes an active part in locomotion. A series of experiments indicated that the robot is able to traverse environments with both a low and a high coefficient of friction between the robot and the terrain, which is yet another advantage of this design. Future development of the robot should include designing a lead section that would allow the robot to cross tall obstacles. Furthermore, it is worth testing the effect of different drive units, such as transverse muscles, on the velocity of the robot [14].

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