Earthworm-Inspired in-Pipe Soft Robot: Design, Modeling, and Implementation

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***Abstract*— In this paper, the design, modeling, and fabrication of a pneumatically-driven soft robot that can travel through pipes by imitating the motions and capabilities of an earthworm are presented. The development of robots, which are similar to living creatures such as humans, invertebrates, and Mollusca, is rapidly growing. By adopting a specific construction, the in-pipe robot mechanism presented in this study can travel inside pipes to perform inspection duties that are sometimes difficult to access. This robot uses a longitudinal pneumatic actuator, which provides robot elongation; it moves by changing the coefficient of friction and the phase change between the internal gripper systems, which contain McKibben actuators to provide radial diameter changes. The internal gripper systems are attached to the ends of the robot. The suitability of the robot's function is indicated in various experiments. Based on the double-mass spring-damper system, the dynamic equation for the Earthworm-inspired Soft Robot (ESR) motion is obtained. ADAMS is used to model the motion of ESR for validation purposes. Ultimately, when actual conditions are applied to the robot within the simulation, the robot performs the identical movement with a 16% velocity error. Comparing the results illustrates the validity of the theoretical models.**

Keywords*— *Bio-inspired Soft Robot, In-pipe Robots, longitudinal Actuator, McKibben Actuator

I. Introduction

Periodic internal inspection of pipes is an essential operation for industrial facilities, but it has some restrictions. Pips are typically utilized underground or in locations with restricted access and are fixed in situ, so reaching inside long, slender pipes could be challenging. Researchers have been focused on developing new robotics mechanisms for a long time that can travel in the pipes for inspection and maintenance purposes[1-3]. Soft robots are one of the most effective mechanisms inspired by living organisms in nature. In the animal kingdom, there are organisms with components of soft matter. These creatures usually move with their energy stored in their elastic organs[4, 5]. The scientist's inspiration for these natural systems has led to the creation of soft robots. Earthworms are one of the inspirations for a soft robot that has a crawling movement. Earthworms have a segmented body which is called *metameres*[6]. Since they are invertebrates, they lack an exoskeleton and an internal skeleton. They travel underground with peristalsis waves, by the means that waves of muscular contractions alternatively shorten and lengthen the body. [7]. They travel underground with peristalsis waves, by the means that waves of muscular contractions alternatively shorten and lengthen the body. Also, Gullet uses peristalsis waves to transfer food[8]. Similar mechanisms power the propulsion of earthworms, and some modern machinery, such as our robot, mimic this design. The secretion of lubricating mucus aids the whole burrowing process. When forces are assessed according to body weight, hatchlings can push 500 times their body weight, whereas large adults can only push ten times their body weight[9]. They travel through soil by expanding crevices with force. Soft robotics is a branch of robotics using soft and elastic materials that can move independently. A soft robot is a bridge between man and machine, which provides unique opportunities in areas that do not apply to rigid robots. Also, they can prevent problems such as the likelihood of harm to the human body by dealing with the robot[10]. These robots have no problem with unpredictable paths due to their nature and mechanism of movement. In order to deal with the workspace, classical robots, such as rigid robots, need to know or estimate their environment and dynamic parameters, while soft robots do not. Many locomotions of soft robots can be achieved by coordinating the limbs—that is—one of the limbs is stuck, and the other slips. This type of locomotion is an example of stick-slip locomotion (SSL). There is another one in which both limbs slip, but the mass center of the robot moves, which we define as slipping locomotion (SL)[11]. For instance, soft inchworm robots[12] and micro-robots such as the ETH-Zürich Magmite[13] utilize the SSL mechanism[14, 15]. Furthermore, this type of locomotion is used in the pipes. On the other hand, one example of SL is presented in[16, 17]. Typically, SSL uses when the frequency of force is smaller than the natural frequency of the robot[11]. So, we conclude that SSL is better for earthworms and needs more friction coefficient, which is why a fibrillar pad is used. In this study, we designed and fabricated a pneumatic earthworm-inspired soft robot (ESR) for traveling in pipes. Two different types of actuators supply the locomotion mechanism of the ESR. We outline the ESR's mechanical design and fabrication methods and investigate its fundamental properties utilizing modeling, simulation, and experiments.

II. Design and Locomotion

This section covers the design and fundamentals of the ESR's operation and locomotion.

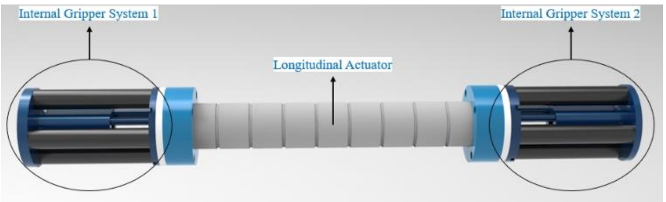

Fig. 1 3D model of soft robot

A. Design

We are going to design a soft robot that has bidirectional locomotion on different types of pipes. It moves like peristalsis-based crawling, similar to that of earthworms' locomotion. The critical point is alternatively changing the friction coefficient of radial actuators and providing a mechanism to produce this application. To do so, we reduce the earthworm body into functional components. The result is a linear soft actuator in order to produce elongation and displacement between the body contact points of the ESR. In addition, to produce the action of slip and stick inside of pipe, we designed two internal gripper systems to activate or deactivate McKibben actuators connected to them. There are four McKibben actuators and two supporter pieces for each section of the internal gripper systems that are employed in the ESR's front and back. Supporter components were designed to keep McKibben actuators in the proper position so that the actuator's expansion for the outside diameter would be maximized. Through independent airflow supply lines, all actuator sets are pneumatically driven. Furthermore, we use fiber for the linear actuator to reduce undesirable radial expansion during inflation.

The designed robot is shown in (Fig. 1). Two flanges are made by a 3D printer which fixes two ends of the longitudinal actuator to the internal gripper systems, thereby preventing air from leaving the actuator.

B. Robot Locomotion

As stated previously, the space between the internal gripper systems and the pipe's interior surface must be filled to create a friction force for the ESR's locomotion. This is done by radial actuators and the inner surface pipe. When air pressure is applied, the McKibben actuators get shorter and make a curve that increases the diameter (Fig. 2). As a result, the internal gripper systems fill the space between the ESR's initial diameter and the inner diameter of the pipe. On the other hand, if no air pressure is applied, there would not be any negligible contact surface of the ESR and the internal pipe surface. Also, we can expect a suitable friction force because of using McKibben actuators. According to (Fig. 2), at first, the ESR is in a rest state (step1). By activating actuators of the internal gripper system 1, the friction coefficient with the pipe's inner surface will increase this section will be fixed in the pipe (step2). Because the other end has no friction forces, it will move forward by activating the longitudinal actuator (step3).

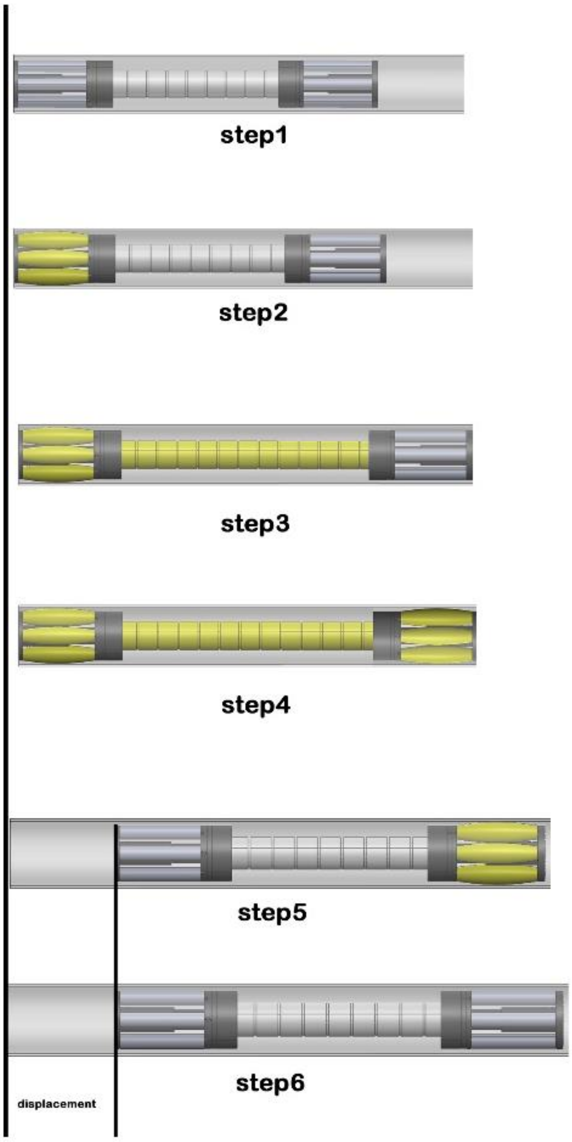

Fig. 2 Sequences of locomotion of robot. Yellow indicates inflation and grey implies deflation. Step1: Normal mode and none of the actuators are inflated, both front and rear internal gripper system are in contact with the surface. Step2: One of the vertical actuators is inflated. Step3: Inflation of longitudinal actuator. Step4: Inflation of the other vertical actuators Step5: Center of mass moves. Step6: Normal mode

By activating actuators of the internal gripper system2 and deactivating actuators of the internal gripper system1 and longitudinal actuator, another end of the ESR will move forward (step4, 5).

Now, by deactivating actuators of the internal gripper system1, the ESR is in a rest state too. Therefore, by repeating these steps, we can produce the ESR's desired locomotion.

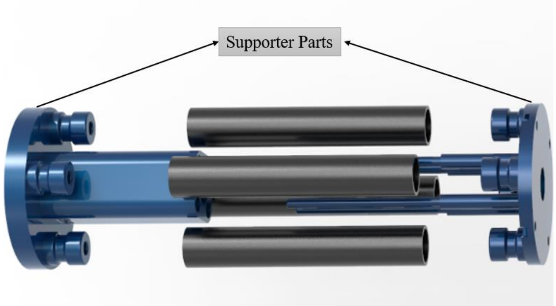

Fig. 3 Internal Gripper System

III. Fabrication

A. Fabrication of Longitudinal Actuator

The principal body material for the ESR longitudinal actuator is a type of silicone rubber that can be cast (Silicone Rubber RTV2 -325). For our aim, we combine a hardener (4 wt%) with silicone rubber. The properties of silicon and hardener mixtures are described in (Table 1).

Table 1 Properties of silicon and hardener

Property	Amount
Viscosity	130000 cps
Specific Weight	1.35
Hardness	25 SHORE A
Tensile Strength	550 psi
Elongation	170%
Contraction	0.1%

First, the liquid silicone is ventilated by a vacuum pump for 10 minutes, then silicone hardener is added and mixed homogeneously (steps 1, 2). Now, we can pour silicone into the mold (step3). After 12 hours, the fiber around the grooves that are on the actuator is winded. By so doing, it increases only in the axial direction (step4). Now, the actuator is put in another mold, and silicone is poured to prevent the movement of fiber and improve strength (steps 5, 6). The result is shown in step 7(Fig. 4). All other components are produced using a 3D printer, and their material is PLA.

Fig. 4 fabrication of Longitudinal Actuator

B. Fabrication of Internal Gripper Systems

As mentioned, we created a gripping force inside the pipe using McKibben muscles as radial actuators. An appropriate friction force can be provided inside pipes by McKibben actuators.

For the fabrication of McKibben actuators, we used some special braided covers on the rubbers to restrict the longitudinal increases of rubbers inflated, forcing them to decrease the length and increase the diameter.

We placed guide surfaces on the supporter parts under the actuators to prevent internal expansion, ensuring that all radial expansion is external (Fig. 3). Supporter components are produced using a 3D printer, and their material is PLA.

IV. Robot Control and Operation

Operation and controlling of robot actuators are shown In (Fig. 5). We use a Bluetooth module (hc05) with Arduino (Mega 2560) for connection and operating by the mobile controller. When the Arduino board receives input signals from the mobile controller, it activates or deactivates relays using the control program compiled on it. Relays output can activate and deactivate on/off valves that are used to control air pressure on actuators. For each actuator, we have two buttons in our mobile controller software that can activate or deactivate them by hand. If we want to have continuous locomotion, we can write a program in Arduino and activate and deactivate actuators according to sequences explained in the previous section (the locomotion of the ESR).

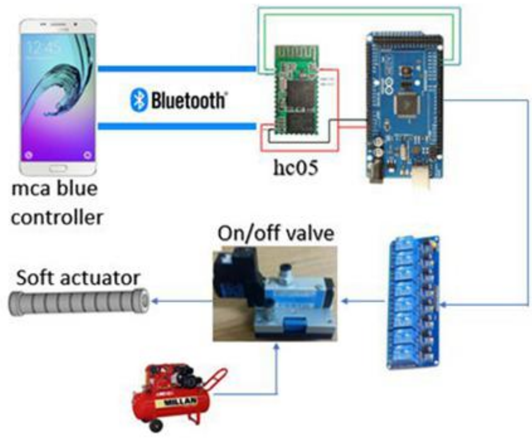

Fig. 5 schematic of operation

V. Modeling and Simulation

A. Modeling

The proposed robot can be modeled using a double mass-spring-damper system. System modeling has shown in [18] (Fig. 6). For this robot, the central longitudinal actuator is modeled as a massless elastic spring with stiffness constant (k) and a damper constant (c), given its function and elastic nature,. The internal gripper systems are modeled as two blocks with masses m1 and m2. Also, frictional forces, f1 and f2, are produced by McKibben actuators. In this work, we molded the stick-slip friction f(t) based on the method introduced in [19].

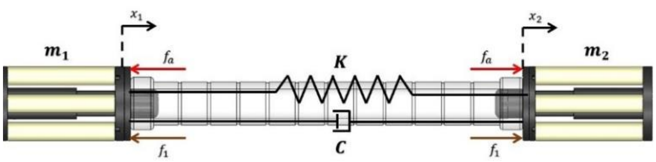

Fig. 6 double-mass-spring-damper system

$$f(t)=\begin{cases} f_k(t), & \text{if } |\dot{x}|\geq|v_s|; \\ f_{sys}(t), & \text{if } |\dot{x}|<|v_s| \text{ and } |f_{sys}(t)|<|f_s| \\ f_k(t), & \text{if } |\dot{x}|<|v_s| \text{ and } |f_{sys}(t)|>|f_s| \end{cases} \quad (1)$$

$$f_{k_i}(t)=\text{sign}[\dot{x}_i(t)]\mu_{k_i}(t)m_i g, \quad for\ i=1,2 \quad (2)$$

$$f_{s_i}=\mu_{s_i}(t)m_i g \quad for\ i=1,2 \quad (3)$$

$$f_{sysi}(t)=-k\Delta x(t)-c\Delta\dot{x}(t)+f_a(t) \quad for\ i=1,2 \quad (4)$$

$$f_a=A\times p_a(t) \quad (5)$$

Here $f_k(t)$ is dynamic friction force, f_s is peak static friction force, and f_{sys} (t) is the consequence of the spring, damping, and actuation forces exerted on the blocks, where Δx and $\Delta\dot{x}$ are the differences in displacement and velocity between m1 and m2, and f_a is actuator force due to its pressure (p_a), and A is inner section area of the actuator.

Finally, the system can be described using a single-input–multiple-output (SIMO) state-space realization.

$$\begin{aligned} \dot{x}(t)&=Ax(t)+Bu(t), \\ y(t)&=Cx(t)+Du(t), \end{aligned} \quad (6)$$

Where:

$$A=\begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{k}{m_1} & -\frac{c}{m_1} & \frac{k}{m_1} & \frac{c}{m_1} \\ 0 & 0 & 0 & 1 \\ \frac{k}{m_2} & \frac{c}{m_2} & -\frac{k}{m_2} & -\frac{c}{m_2} \end{bmatrix} \quad B_1=\begin{bmatrix} 0 & 0 & 0 \\ \frac{-1}{m_1} & \frac{-1}{m_1} & 0 \\ \frac{1}{m_2} & 0 & \frac{1}{m_2} \end{bmatrix} \quad (7)$$

$$C=I_{4\times4} \quad D=0_{4\times1} \quad u=\begin{bmatrix} f_a \\ f_1 \\ f_2 \end{bmatrix} \quad y=\begin{bmatrix} x_1 \\ \dot{x}_1 \\ x_2 \\ \dot{x}_2 \end{bmatrix} \quad (8)$$

B. Simulation

After obtaining the theory equations of the ESR in the modeling section, all terms of these equations use for validations in ADAMS software.

Table 2. Simulation Condition

Simulation parameters	
Total Mass of each McKibben actuators, m[g]	53
Mass of longitudinal actuator, m[g]	95
Spring stiffness constant, k[N/m]	7.45
Spring damping constant, c [N.s/m]	9.5
Static Coefficient	0.5
Dynamic Coefficient	0.3

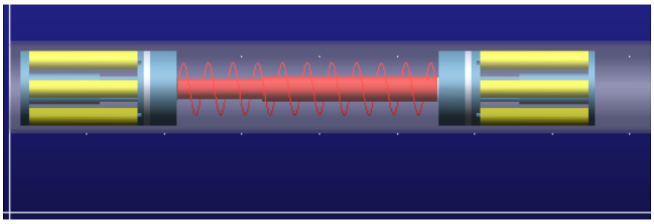

Fig. 7 ESR simulated in ADAMS

After designing the robot, to validate the dynamic equations, ESR must be simulated in ADAMS. This software provide similar condition, like real environment, by applies all the conditions including: the friction forces at 0.4 bar between McKibben actuator (m1 & m2 in modeling) and surface, the longitudinal actuator forces on m1 and m2 at 0.75 bar air pressure, , the mass of each section, applying the ESR movement step, and all the movement restrictions of the robot.

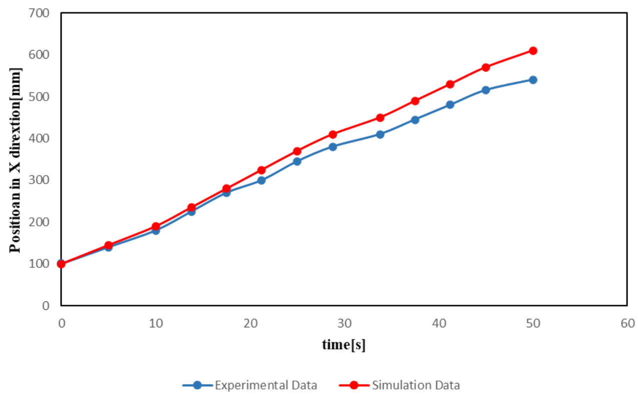

Fig. 8 Robot's displacement changes with time in experimental tests and ADAMS simulation

The robot was simulated on flat surface, because of its motion. The theoretical relations of this part are explained in detail in the section modeling.

After measuring the position of the robot inside the tube experimentally, in the simulation section to validate the motion equations of the robot, instead of the longitudinal muscle, a spring with coefficients K and C is placed. Longitudinal muscle coefficient obtained by performing the test, whose values are given in Table 2. In this section, by applying the robot's forces according to the time step of their application, the position of the robot in the X direction is obtained in this state. As it is clear from the diagram, the position of the robot in the experimental and theoretical state is completely consistent at the beginning. But after 30 seconds, a difference is created. This amount of error, which finally reaches about 50 mm in second 50.

Finally, the average speed of the robot in the simulation is 10.2 mm/s and the speed of the robot in the experimental test is 8.8 mm/s. which reports an error of about 16% at maximum point.

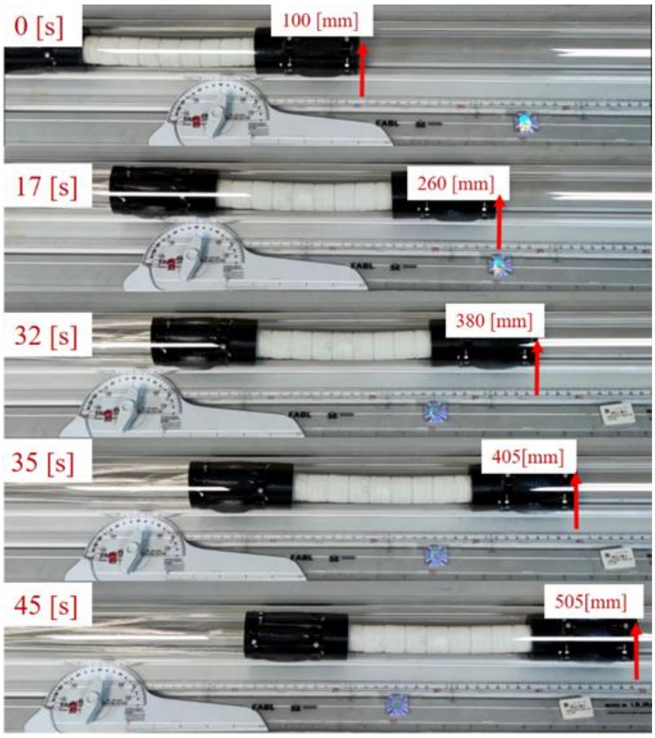

Fig. 9 Test of robot locomotion through a pipe

VI. EXPERIMENTS

Simulation with ADAMS and Several tests were performed to examine the behavior and functional principles of the proposed mechanism.

A. *Impact of Pressure Level on Longitudinal Actuator Length*

In this experiment, the length variations of the longitudinal actuator were measured under varying pressure circumstances. This experiment will allow us to identify the optimal pressure at which the linear actuator can operate properly without risking damage (Fig. 10).

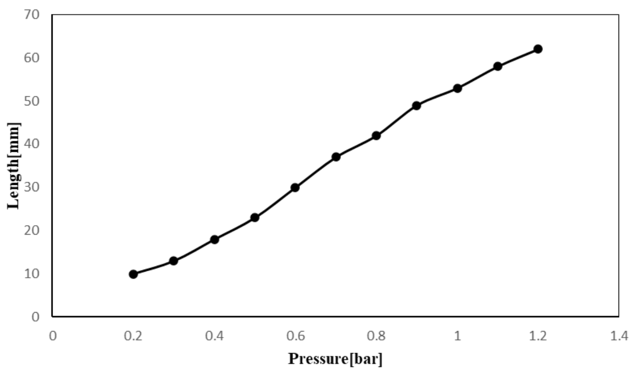

Fig. 10 Longitudinal actuator length changes according to its pressure

In order to achieve this, we first positioned the robot inside a 54mm inner diameter pipe and pressurized the internal gripper system 1. This prevents moving this segment of the ESR. After that, the elongation length was measured while the linear actuator was inflated with a different pressure range. We conducted this measurement three times for each pressure range increment.

B. *Longitudinal Actuator Force*

In this experiment, we determined the amount of force the linear actuator is capable of producing under various pressures. Using a load cell to measure the force is necessary for this experiment, but first, the load cell needs to be calibrated using standard weights.

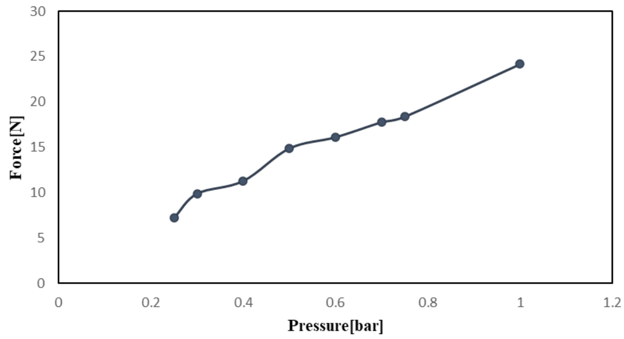

Fig. 11 diagram of Longitudinal Actuator Force

Then, we positioned the ESR within a 54mm diameter pipe, compressed the internal gripper system 1, and connected the internal gripper system 2 to the load cell. We acquired data by measuring force from the load cell by applying varying pressures to the longitudinal actuator (Fig. 12). As seen in (Fig. 11), the force generated by various air pressure increases, and this information will be used as input for the ADAMS simulation that we covered in further detail.

C. *Friction Forces*

We carried out friction tests using a load cell to examine the friction characteristics of the McKibben actuators that generate the grip forces inside the pipe. Prior to pressurizing the internal gripper system 1 and attaching the internal gripper system 2 to the load cell, the ESR was first placed within a 54mm diameter pipe. The static and dynamic friction forces will then be measured by the constant velocity movement of the pipe. The pressure effect of the actuators on the frictional force is shown in (Fig. 13).

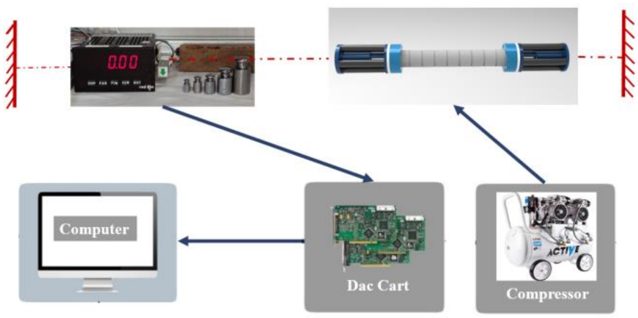

Fig. 12 Block diagram of experimental test

We have used a pressure sensor to read the pressure amount, which minimum pressure it can measure is 0.25 bar. It shows that friction force increases when pressure increases. However, higher pressure creates higher friction forces, but it can damage the robot's structure, so we did not increase the pressure more than 0.75 bar during the locomotion test for safety purposes.

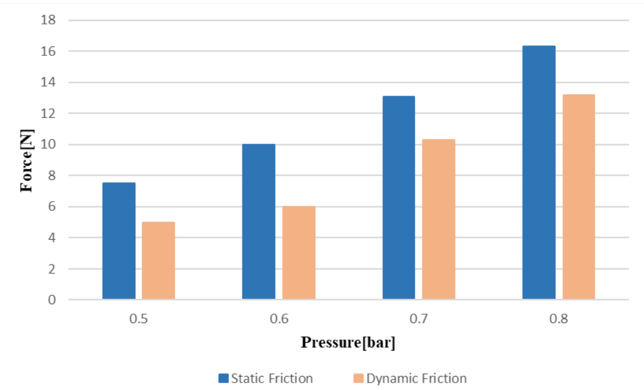

Fig. 13 Static and dynamic friction force of McKibben actuator

D. *Locomotion Test in Straight Pipe*

The purpose of this experiment was to evaluate the ESR's locomotion performance. In order to study the ESR's motion and velocity, we positioned it inside a horizontal 54mm pipe.

In (Fig. 14), the ESR's velocity inside the horizontal tubes is written. In this operation, the pressure of the McKibben actuators is constant, and only the pressure of the longitudinal actuator changes.

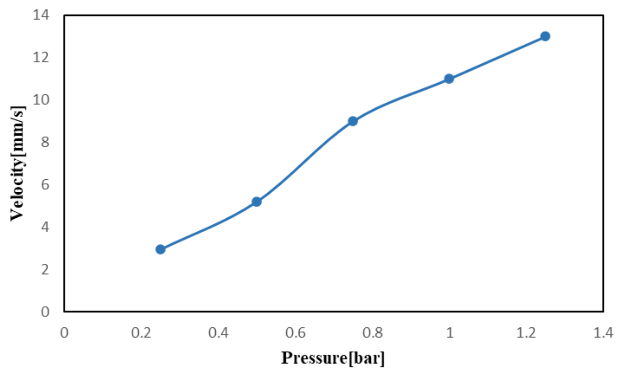

Fig. 14 ESR's velocity changes according to pressure

The velocity of the ESR does not change linearly with increasing pressure. On average, the ESR's speed for the longitudinal actuator's pressure at 0.75 bar, and the constant pressure for McKibben actuators, is 9 mm/s.

VII. Conclusion and Future Works

This work presents a soft robot with pneumatic actuators that can travel in pipelines and is inspired by earthworms. First, we introduced design and modeling based on a worm's locomotion. We modeled it as a double mass-spring-damper system and obtained its equations of motion in state space. For the fabrication of each part, we used a 3D printer to produce molds and some parts and silicon rubber for producing a soft actuator. Then, the mechanism of movement is presented step by step. Several experiments were conducted to clarify the ESR's characteristics, such as the effect of the pressure condition on elongation length, the linear actuator's generated force, and the McKibben actuator's friction forces. The requirements to produce the locomotion pattern were also explored.

There are numerous things we can do to improve our worm robot, but we will just focus on two because they are the most significant and will be discussed in greater depth.

First, we want to use sensors to evaluate and read the ESR's location and the distance it has gone in every time. It is important and needed, for we want to control it and do some tasks in some locations and conditions.

Second, our robot should be able to move on a curve path in general. Therefore, we must use other actuators besides the primary actuator to produce this curvature movement. We are supposed to do it in our future research.

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