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SMART MATERIAL ACTUATION OF MULTI-LOCOMOTION ROBOT

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ABSTRACT

The focus of this research is modeling, simulation and prototyping of multi-locomotion bio-inspired robot. The actuation is based on shape memory alloys (SMAs) smart materials to achieve different styles of movements. Soft-bodied robots have potential to exploit morphological computation to adapt and interact with reduced control complexity. Observing the movement of a caterpillar that could produce different locomotion such as crawling and rolling, our team designed and developed a bio-inspired robot.

Analytical models of the different bio-inspired movements are derived and analyzed in Matlab in this work. The models rely on segmented approach actuated by smart materials in order to achieve the desired position. Smart material actuators are a promising but challenging actuation mechanism because of their design, large deformation possibilities, external stimuli shape change and high power density. The body parts are from a soft silicon elastomer. Between the silicone body parts, SMA spring are embedded, used as actuation force. Between the two segments, SMA spring as actuators are generation strain to bend the body and achieve crawling and lifting.

This work is initial modeling for multi locomotion of soft bio-inspired robot and will be followed by a detailed analytical and numerical modeling and simulation, finalizing with a functional prototype.

Keywords: multi-locomotion, bio-inspired soft robot, smart material actuation

NOMENCLATURE

m_1, m_2	Mass of the segments
k_1, k_2	Stiffness coefficient of the springs
b	Damping coefficient
μ_1, μ_2	Friction coefficient
I	Inertial moment
$M(t)$	External moment
R	Radius of curvature

1. INTRODUCTION

Inspired by soft-body living organisms, multi-locomotion concepts have gained a lot of interests in the last decade. Soft-bodied robots have a continuously deformable structure with muscle-like actuation that results in having a large number of degrees of freedom (DOF). Soft robots have bodies made out of soft and extensive materials (silicone rubbers, polymers and elastomers, and others) that can deform and absorb much of the energy arising from impact, having the potential for adaption, sensitivity and agility [1]. The soft-bodied robots can be used in many applications for search and rescue, for limited unreachable places, enabling robust locomotion. Recently, researchers have found their use in medical wearable applications [2].

Inspired by the nature, bio-inspired soft robots have many movements that they can imitate, such as crawling, rolling, grasping and other movements that help the robot adapt easier in the environment. Caterpillars use passive grip to secure

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themselves to complex substrates [3] and have a multi-dimensional workspace, able to bend, twist and crawl in ways not able for rigid skeletons. They use dynamic hydrostatics to vary body tension and can cantilever over gaps that are 90% the length of the body. Bio-inspired robots platforms could be actuated by magnetic fields [4], piezoelectric actuators [5] and NiTi actuators [6]. This actuation is enabled by the use of smart materials, which differs from the conventional actuation.

Shape memory alloys (SMAs) could be used as an actuation force. One way to use this alloys is like coil spring and torsional spring actuators. The characteristics of these actuators are determined from four parameters: the rod diameter, the wire diameter, the number of active coils and the pitch angle. The force and the stroke of the actuator are also dependent on those parameters. SMA actuators have an extremely large energy density per cycle and power weight ratio, which are widely proposed for bionic soft robots. Nickel Titanium is widely used SMA to achieve locomotion of soft-bodied robots.

Using the flexibility of the SMA actuators in order to enable locomotion of robot allows great robustness [7]. The SMAs spring could be easily designed and controlled according to displacement and force requirements. Design and development of a bio-inspired micro robot actuated from SMA springs is explored by researchers in [8]. Inspired by the worms' movement, a peristaltic locomotion by a soft-bodied robot with antagonistic NiTi coil actuators is accomplished in [9]. The researchers in [10] have developed a soft robot actuated by SMA wire able to achieve crawling and jumping locomotion. Octopus arm robot [11] was fabricated to study the interaction among materials, mechanisms and actuation systems. The main idea is to reproduce several movements for realizing multi-locomotion. The modeling of soft robot arm system actuated by SMA springs was developed in [12] to analyze the locomotion modal.

The synthesis of artificial systems able to replicate the capabilities of caterpillars represent a significant step forward in the development of autonomous robots, medical robots and soft mechatronic systems in general. This technological progress of using smart materials as actuation force has enabled the development of novel biologically-inspired soft robots. These emergent technologies are advanced in the work for the development of the proposed robotic concept inspired by caterpillar.

The motivation for our research effort aims to explore the multi-locomotion of bio-inspired soft robot, actuated by SMA. The movement of bio-inspired soft-body robot has been analyzed and studied for the use in robotic systems. The focus is on development of a new soft robot with flexible body and multi-motion with smart material actuation. Multiple motions can be achieved by using suitable control of the SMA actuators.

The reminder of the paper is structured as follows: section 2 explains the concept, design and functionality of the multi-locomotion bio-inspired soft robot; Section 3 describes the analytical model, analyzing the possible movements; Section 4 shows the results from the numerical modeling in Matlab software; Section 5 analyzes the created prototype. The last section concludes the work and purposes further steps.

2. MULTI-LOCOMOTION: CONCEPT, DESIGN AND FUNCTIONALITY

The main idea is analyzing soft robot fabricated from elastomer using smart material as actuation force. By combining SMA NiTi springs and magnets in the soft structure, a multi-locomotion of the autonomous robot can be achieved. A multi locomotion robot has a lot of degrees of freedom so that high mobility is expected. The multi locomotion robot is expected to be able to do several movements with a single physical structure. The soft-bodied robot will be continuously deformable and capable of doing numerous applications in emergency situations in places unreachable for the human. Inspired by the caterpillar, multi-segmented body structure will be analyzed, as shown on Figure 1.

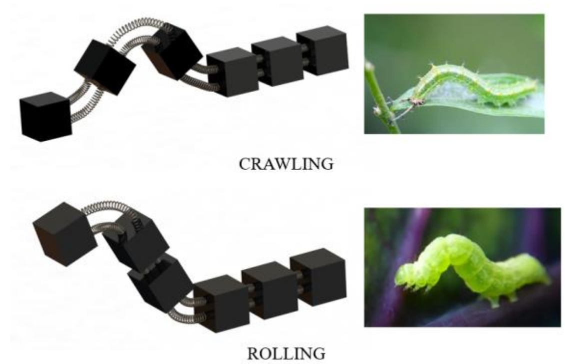

Figure 1. Caterpillar inspired locomotion concept using multi-segmented smart robot (crawling and rolling)

Shape memory alloys are materials capable of providing different strains and forces [5]. Using magnets to locally increase friction, crawling as a movement can be achieved. By applying the NiTi springs in certain place, rolling is achieved.

As mentioned before, our idea was to make multi segmented body using elastomer and this segments would be connected with SMA springs. The springs are implemented between the segments and one spring has the ability to expand and the other to contract. The capabilities of the springs are being used as actuators in order to make the crawling possible. In order to make the model more maneuverable the number of springs between the segments can be increased. The springs mentioned before are connected in longitudinal direction between the segments. If this connections are the only one than we would not achieve another movement besides the crawling, so in order to get the desired rolling movement, our idea was to implement SMA spring that will connect the top sides of two neighboring segments. The difference here is that we use only SMA springs that have the ability to contract. As mentioned before our idea was to implement electromagnets that can be controllable, in the segments. This way we can fix certain segments on the ground and move the others. By using all of these elements we can achieve multi-locomotion on metal surface, or surface that can be magnetized. The smart material properties are shown in Table 1. Due to the lack of resources we implemented metal parts into the segments and magnetized this segments using permanent magnets.

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Table 1. Smart material properties

NiTi springs 	Material: NiTiCu Transition temperature: 65 °C Length when heated: 20 mm Maximum deformation: 150 mm Outer diameter: 6.5 mm Number of windings: 21 Wire diameter: 0.75mm
SMA Springs 	Material: NiTi SMA spring Transition temperature: 90 °C Length when heated: 25 mm Maximum deformation: 10 mm Outer diameter: 11.5 mm Number of windings: 5 Wire diameter: 2 mm
Permanent magnet 	Material: Permanent magnet Length: 75 mm Width: 20 mm

The analyzed structure is capable of producing several movements. The concept of creating smart soft-robot which imitated several movements will be analyzed. The suitability of the proposed approach is demonstrated using analytical and numerical modeling, finalizing with a functional prototype to confirm the functionality. In order to model the robot, only two segments will be analyzed. The bio-inspired structure helps the robot adapt easier in the environment, finding its use in many applications.

3. ANALYTICAL MODELING

As mentioned before in the concepts, a multi segmented body was used for the analytical modeling. Figure 2 shows n-segmented body and the connections between the segments. The connections between the segments are NiTi springs which show different characteristics when exposed to heat. This spring also represent actuators when we want to achieve movement. The springs are represented with their stiffness coefficient and their dumping characteristics are represented with one dumping coefficient. An approximation was made that the springs show linear characteristics due to the fact that the springs that are studied show linear characteristic when heated.

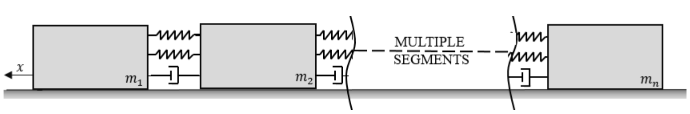

Figure 2. Segmented approach

In order to model the movement of the soft robot, only two segments will be analyzed creating functional unit as shown on Figure 3. We state that the spring with stiffness coefficient k_2 expands after transition temperature is reached and the spring with the stiffness coefficient k_1 contracts. In that moment the springs act as actuation force.

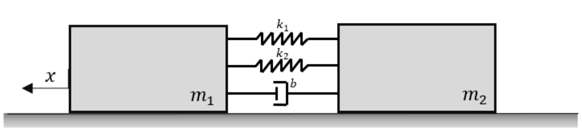

Figure 3. Functional unit

If we assume that the model wants to move to the left, the modeling is analyzed in that way that the first segment with mass m_1 has to make a movement, as shown on Figure 4. In order accomplish the movement, the second segment m_2 needs to be fixed, so its movement, velocity and acceleration become zero. This was later implemented in the friction coefficient, but now we did the modeling as both of the segments move. The differential equations are set for this setup. In this situation, the spring with stiffness coefficient of k_2 acts like an actuator because it is expanding. That's why the expression in the differential equation $k_2(x_1 - x_2)$ is changed with an external force F_2, that makes the movement possible while other elements continue to react as reaction forces, and their characteristics are not changed. The equations 1,2 and 3 show the differential equations of movement.

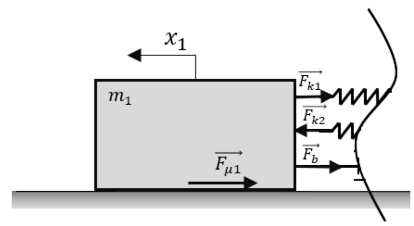

Figure 4. The external forces when mass m_2 is fixed

$$m_1\ddot{x}_1 + b(\dot{x}_1 - \dot{x}_2) + k_1(x_1 - x_2) + \mu_1 m_1 g = k_2(x_1 - x_2) \quad (1)$$
$$m_2\ddot{x}_2 + b(\dot{x}_1 - \dot{x}_2) + k_1(x_1 - x_2) + \mu_2 m_2 g = k_2(x_1 - x_2) \quad (2)$$

$$\begin{cases} \ddot{x}_1 = \frac{k_2}{m_1}(x_1 - x_2) - \frac{k_1}{m_1}(x_1 - x_2) - \frac{b}{m_1}(\dot{x}_1 - \dot{x}_2) - \mu_1 g \\ \ddot{x}_2 = \frac{k_2}{m_2}(x_1 - x_2) - \frac{k_1}{m_2}(x_1 - x_2) - \frac{b}{m_2}(\dot{x}_1 - \dot{x}_2) - \mu_2 g \end{cases} \quad (3)$$

Where the actuation force is $F_2 = k_2(x_1 - x_2)$.

After the first segments passes certain distance, the spring with stiffness coefficient k_2 stops to act as an actuator. Now in order to make the second mass follow the first segment, the first segment is fixed, and the spring with stiffness coefficient k_1 is actuated (Figure 5). Now the forces that affect the segments are changed so we set another pair of differential equations, shown on equation 4,5 and 6. In order to make the spring with stiffness coefficient k_2 to act like an actuator the expression $k_1(x_1 - x_2)$ is changed with an external force F_2.

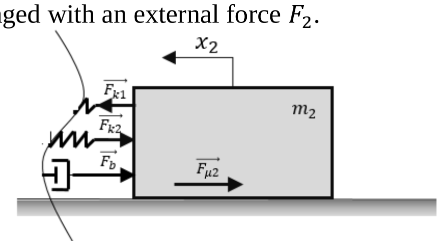

Figure 5. The external forces when mass m_1 is fixed

$$m_1\ddot{x}_1 + b(\dot{x}_1 - \dot{x}_2) + k_2(x_1 - x_2) + \mu_1 m_1 g = k_1(x_1 - x_2) \quad (4)$$
$$m_2\ddot{x}_2 + b(\dot{x}_1 - \dot{x}_2) + k_2(x_1 - x_2) + \mu_2 m_2 g = k_1(x_1 - x_2) \quad (5)$$

$$\begin{cases} \ddot{x}_1 = \frac{k_1}{m_1}(x_1 - x_2) - \frac{k_2}{m_1}(x_1 - x_2) - \frac{b}{m_1}(\dot{x}_1 - \dot{x}_2) - \mu_1 g \\ \ddot{x}_2 = \frac{k_1}{m_2}(x_1 - x_2) - \frac{k_2}{m_2}(x_1 - x_2) - \frac{b}{m_2}(\dot{x}_1 - \dot{x}_2) - \mu_2 g \end{cases} \quad (6)$$

Where the actuation force is $F_1 = k_1(x_1 - x_2)$.

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When analyzing the rolling as a movement, another spring was added in the model above the two segments that makes the rolling possible (Figure 6). This spring acts as an actuator when we want to make the model roll and in order to return it in its previous position we activate the magnet bellow the lifted segment.

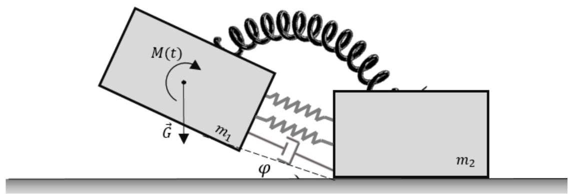

Figure 6. Model for accomplishing rolling

In the model, the influence of the springs that are responsible for the crawling, is replaced with a dumping segment. This approximation is made due to the fact that this springs try to prevent the rolling of one of the segments. After placing a moment equation, and adding all of the moment that affect the model, we get the differential equation 7 and 8.

$$I\ddot{\varphi} + b\dot{\varphi} = M(t) - mgRcos\varphi \tag{7}$$

$$\ddot{\varphi} = \frac{M(t)}{I} - \frac{b\dot{\varphi}}{I} - \frac{mgR}{I}cos\varphi \tag{8}$$

The effect of the spring that acts like an actuator is replaced with a moment, with center of rotation with radius R. Figure 7 shows the possible movement of the two-segmented structure, showing the translational movement in the first 3 positions accomplishing the crawling movement, while in the last position the rotational movement when achieving rolling is shown.

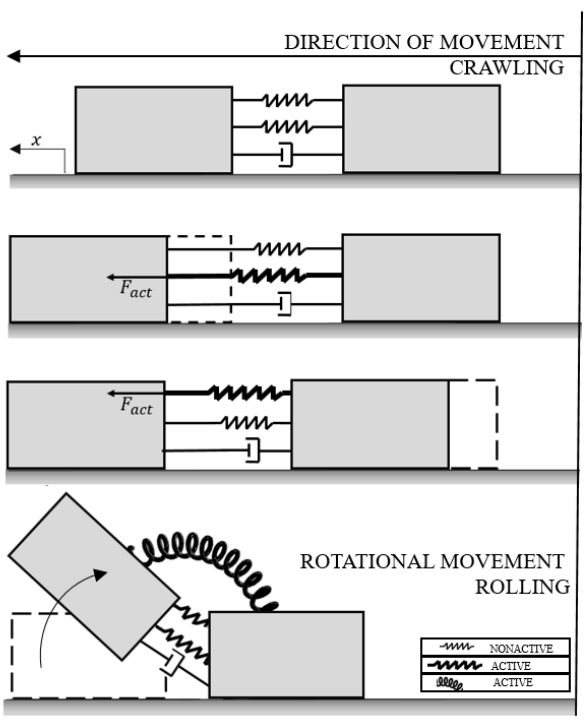

Figure 7. Possible movements of the segmented structure

4. NUMERICAL MODELING AND SIMULATION

The numerical modeling and simulation was conducted by using the software package Matlab/Simulink. All of the variables were defined in m.file, while the modeling of the system was done in Simulink. As mentioned before, only two segments of the body were analyzed in order to model the multi-locomotion. The movement of the system is achieved by actuating one of the NiTi springs. The spring with stiffness coefficient k_1 has the ability to contract, when it reaches the transition temperature, while the spring with the stiffness coefficient k_2 has the ability to expand. Due to the fact that, the springs have different characteristics, when they are heated and when they are not, they also apply different actuation force. This characteristics were implemented in the model, so when the spring is used as actuator, the intensity of the force is higher and has a tendency to move the segments. Figure 8 shows the Matlab model used for achieve crawling as a movement, while table 2 shows the properties used in order to model the system.

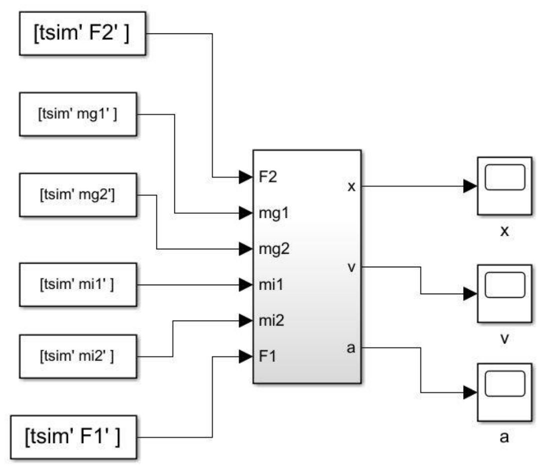

Figure 8. Matlab model for crawling

Table 2. Properties

PROPERTY	DIMENSIONS
m_1	$0.2\ kg$
m_2	$0.2\ kg$
μ_1	0.1
μ_2	1
g	$9.81\ m/s^2$
k_1	$0.1\ N/m$
k_2	$0.1\ N/m$
$b_{crawling}$	$0.001\ Ns/m$
$b_{rolling}$	$0.033\ Ns/m$
R	$0.77\ m$

On the other hand when the spring is in cold state, it has the characteristics of a spring force that tries to prevent the movement. To make the system to change its original position, one of the segments is fixed using on and off signal (1 and 0), which represents the magnet and prevents that particular mass of moving, as shown on Figure 9.A. The stiffness coefficient μ_2 is selected to have value of 1 because in this way we will simulate

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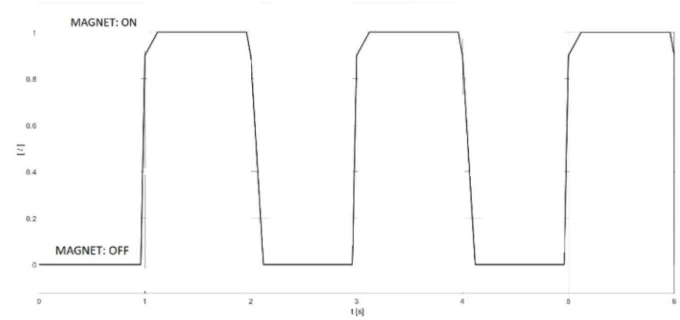
a complete stop of the segment. The value of the stiffness coefficient μ_1 is determined during the research process as most desirable. If in reality this coefficient is higher than the model will preform certain movement but with smaller intensity.

If we assume that the system is in a stand still position, and we want the first segment from the left, to move left. The first segment should move away from the second segment, so the second segment is fixed. The spring with stiffness coefficient k_2 is actuated. The spring expands, and so does the first segment. Next, the second segment has to follow the first segment. In order to do that, the first segment is fixed and the spring with stiffness coefficient k_1 is actuated. The spring contracts and sets the two segments on a same distance as they were before we start the movement, but now both of the segments have crossed some distance. The cycle repeats, as long as we want the system to move.

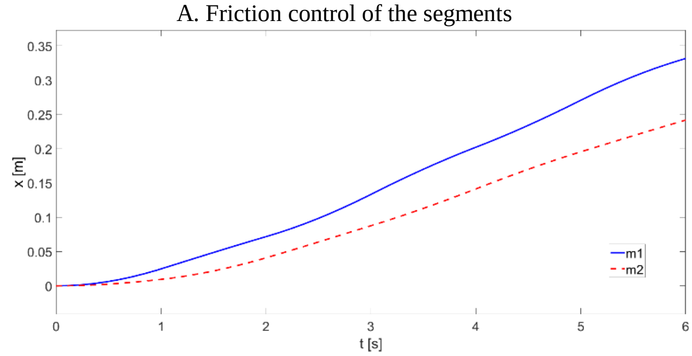
To accomplish locomotion of the segments in the numerical modeling, the friction coefficient was changed from low to high. Low friction coefficient is activated when the mass is moving, and high when the segment is fixed. To make the segment fixed, the friction force must have the intensity equal to the forces that want to move the segment, but in opposite direction. The approximation that the friction force is equal to the actuation force and continuous movement is established in the model, as it is shown on Figure 9.B. For 6 seconds, the segment with mass m_1 has achieved translational movement of 0.33 m, while the segment with m_2 has achieved movement of 0.19 m.

The effects of the fixed segments can be observed on the diagrams of velocity and acceleration (Figure 9.C and 9.D). The effect of the magnets lasts one second, and it is visible that we have sudden change in the parameters, on every second. Because of the approximation that is made, the velocity and the acceleration are not equal to zero, but show sudden decrease. For 1 second, the velocity of the first segment is 0.05 m/s, the velocity of the second segment 0.018 m/s. The velocity of the second segment is lower for 0.032 m/s when the first segment reaches its higher values.

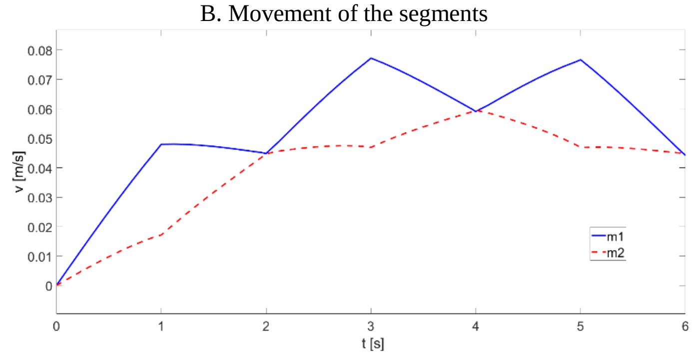
The rolling was modeled, on the same principles as the crawling. The difference in this case is that the springs that were used in the modeling of the crawling were excluded and their influence was approximated with damping coefficient b. As actuation force was used a NiTi spring with the ability to contract when actuated, and in order to return in its previous position a magnetic force was used. Figure 10 shows the time required to achieve angle of 90^{o}, which is 0.93 seconds. The greater the moment, the less time is required to reach the desired angle and lift up the segment.



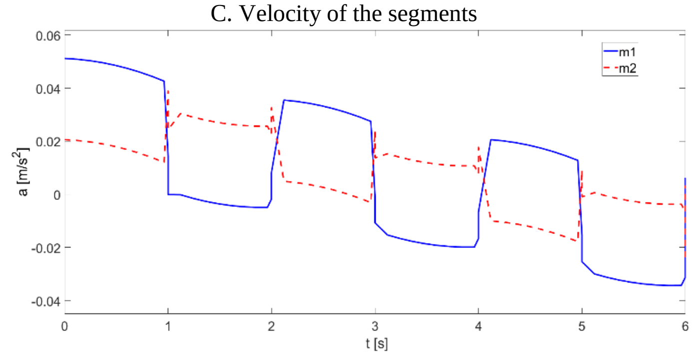
A. Friction control of the segments



B. Movement of the segments



C. Velocity of the segments



D. Acceleration of the segments

Figure 9. Results for the control, movement, velocity and acceleration for the two segments

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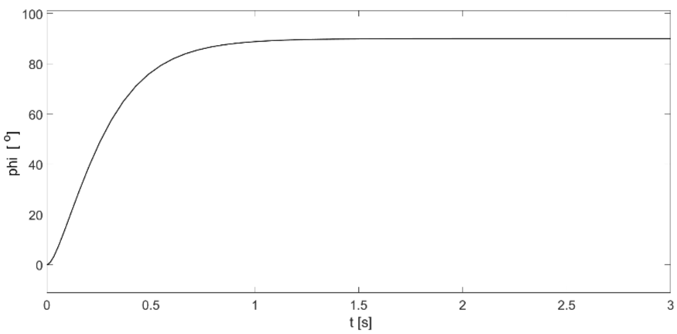

Figure 10. Time to establish rolling of 90°

The influence of the springs used in crawling is very important segment while modeling. Their dumping coefficient has a great influence on the system. For example, if the dumping is low, the system will reach the angle faster with few oscillation, and it will take longer time to settle. On the other hand, if the dumping is high, than the system will reach the desired angle slower without oscillation. For the modeling of this system, high damping ratio was used.

5. PROTOTYPING

The main body (segments) are from a soft silicon elastomer. Between the silicone body parts, SMA spring are embedded, used as actuation force. Between the two segments, SMA spring as actuators are generation strain to bend the body and achieve crawling and lifting. These SMA springs are bonded to the body walls. Additional, magnets are used for providing the movement.

The experimental setup and possible movements of the prototype are shown on Figure 11. The created prototype is based on the theoretical work that was described before. The segments were created using silicone and magnets incorporated inside. The spring with stiffness coefficient k_1 was replaced with two NiTi springs in order, to prevent the model from going sideways. The central NiTi spring in the prototype represents the spring with stiffness coefficient k_2. To establish lifting, one NiTi spring was used with ability to contract when heated. As an external energy we use 9V current to stimulate the spring, depending on which spring we want to actuate.

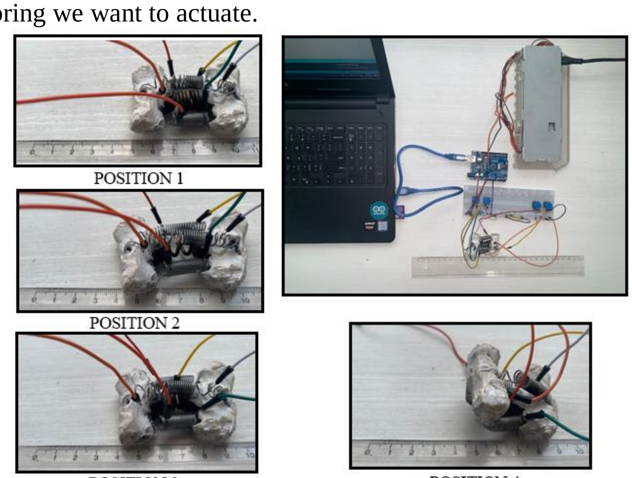

Figure 11. Prototype: multi-locomotion and experimental setup

Figure 12 shows the relation between the time and the angle of rotation when voltage is applied. The time needed for the segment to achieve 90° is 4.64 seconds.

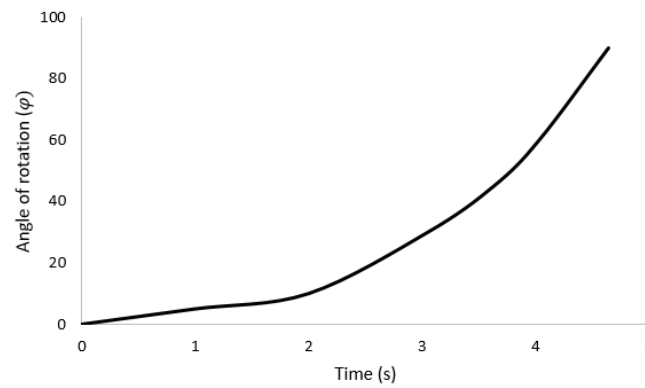

Figure 12. Relation between the angle of rotation and time when rolling

The work of this paper shows developing affordable multi-locomotion robot based on low-budget SMA wires. The combination of different smart materials in this stage (magnets, one-way and two-way SMA springs) can be further developed to incorporate magneto active materials. With this integration, modularity of the structure can be achieved, using n-number of segments. We will further explore the potential to develop vertical movement.

6. CONCLUSIONS AND FUTURE WORKS

Multi locomotion of a soft bodied robot using affordable SMAs for smart actuation has successfully completed in this student project work. Understanding bio-inspired engineering concepts, mimicking the movements from nature to design autonomous robot and introducing SMAs for actuation has been a challenge our team toon on.

The movements of the segments needed to achieve multi-locomotion were analyzed through analytical modeling in Matlab/Simulink. The prototype shows the trends to follow the mathematical model. Multi-segment soft robot will be designed and developed in the future to be tested in different outside environments unreachable for people.

This work has shown to be good base for further development of connecting the multiple segment and achieving the multi-locomotion of the soft robot inspired by a caterpillar. We also plan to use augmented reality to place the robot in real life situations and get a better understanding of the functionalities we need to further develop. Model based control is another challenge we will work on in the future.

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