MODELING OF MULTI LOCOMOTION OF SOFT ROBOT

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***Abstract* — Inspired by nature, engineers have explored the design of soft bio-inspired robots. Soft-bodied robots have potential to exploit morphological computation to adapt and interact. Modeling of the movement of a worm, a caterpillar and an octopus will be presented and analysed in this work. The models rely on segmented approach and variations of external loadings to achieve the desired kinematics of movement using Matlab/Simulink. The parametric results from the simulation lead to a conclusion of optimal number of segments and performance. The actuation of the robot is foreseen to be achieved by shape memory allows in linear and torsional configuration. Multi locomotion of these bio-inspired soft robots will be analysed.**

***Keywords*— soft robots; bio-inspired engineering; modelling; SMA materials; octopus arm; worm-like robots; caterpillar-like robots; MatLab/Simulink.**

I. INTRODUCTION

Inspired by soft-body living organisms, the locomotion of soft robots is being developed and analyzed. 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) that can deform and absorb much of the energy arising from a impact, having the potential for adaption, sensitivity and agility [1].

They 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, swimming and other movements that help the robot adapt easier in the environment.

By deforming their body, worms can modulate friction forces of ground contact points at the body, creating fundamental processes of locomotion. Inspired by the worms' movement, a peristaltic locomotion by a soft-bodied robot with antagonistic actuation is accomplished in [3]. Worm-like platforms have been developed actuated by magnetic fields [4], piezoelectric actuators [5] and NiTi actuators [6].

Caterpillars are able to bend, twist and crawl, by using passive grip to secure themselves while working in a multidimensional workspace. They use dynamic hydrostatics to vary body tension and can cantilever over gaps that are 90% the length of the body [7]. Studies of caterpillars have led to a soft robotics systems [8], as well as a further understanding of the control of the motion in these animals.

The octopus arm is capable of changing its shape in order to mimic other animals, by elongating, shortening and bending because of the special muscular structure. Octopus arms have constant volume of the muscles having the ability to operate in highly constrained environments by changing their shape [9]. Inspired by the octopus, a dynamic model for a multiple continuum arm robot has been purposed in [10]. Octopus arm has a large degrees of freedom, consisting of flexible components [11] or mechanisms based on kinematic model [12].

This paper is focused on the modeling of multi locomotion of bio-inspired robot, analyzing the movements and their dependence from the number of segments of the robot. The movement of bio-inspired soft-body organisms has been purposed and studied for the use in robotic systems.

Shape memory alloys (SMA) could be used as an actuation force. The SMAs are metal alloys able to memorize their original shape. If the element suffers a damage caused by an external source, it will return to its desired shape after heating the metal. There are two types of

SMAs, the first is one-way memory effect alloy, which is capable of remembering one positon at a certain temperature, and the other type is two-way memory alloys which can remember two positions, one at high and the other at low temperatures. The most common shape memory alloys are nickel-titanium alloys. 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 by those parameters. The coil-type actuator is capable of attaining 200-1600% deformation according to its geometry.

The remainder of the paper is structured as follows: section 2 explains the analytical modeling, explaining the concept and the forces that create the three movements: crawling, rolling and grasping. Section 3 analyzes the created numerical model made in MatLAB for the design of the multi locomotion robot. Section 4 analyzes the measurements from the model. The last section concludes the work and purposes further steps.

II. Analytical Modeling

The kinematics and dynamics of soft-bodied robots are different from the conventional rigid-bodied robots. Theoretically, the final shape of the soft robot can be described by a continuous function, while the modeling of the movement require continuous mathematics, requiring new static, dynamic and kinematic models with the ability of large deformations.

To mimic the kinematic of movement of the worms, caterpillar and octopus, segmented approach has been developed.

A. Crawling and rolling

Inspired by the worms, crawling will be analyzed as a movement. Figure 1 shows the soft bio-inspired worm robot, constructed with n-number of segments. The segments are connected with joint capable of making rotational movement with one DOF.

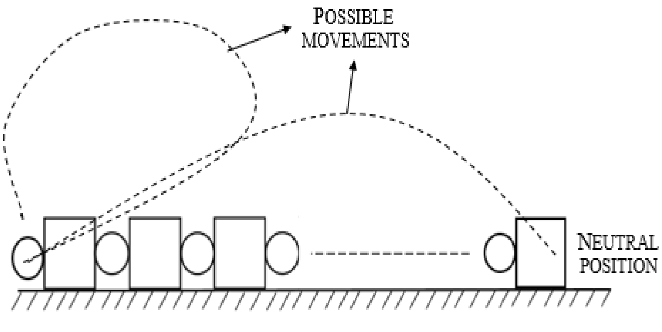

Figure 1. Bio-inspired robot with possible movements of crawling and rolling with n number of segments

Based on this model, Figure 2 shows the six-segmented soft robot. By applying two forces, on the second and the third segment, the robot starts crawling. Depending on the intensity of the external forces, the robot produces two types of movement: crawling and rolling. The dynamic forces allow the robot to crawl and roll. The body reacts with the ground, causing additional forces, as shown on Figure 3. The moments are transferred between the segments in addition to enable continuous movement. The reaction forces caused on one segment from the body are: gravitation force (F_G), load force (F_L), friction force (F_μ) and two moments (M_{N-1} and M_N). The moments between the segments are reaction moments because of the difference and the movement between the segments, caused by the load forces. The load force F_L presents the sum of the applied external forces, as shown on equation 1. To achieve crawling and rolling for the six-segmented robot, only two of them are applied (F_{L2} and F_{L3}). The values of the other forces in order to achieve these types of movements are equal to zero.

$$F_L = F_{L1} + F_{L2} + F_{L3} + F_{L4} + F_{L5} + F_{L6}$$
$$F_L = F_{L2} + F_{L3} \qquad (1)$$

The load force is the only variable parameter that is time dependent. Crawling and rolling is achieved as a movement, since the applied forces and the reaction between the segments.

The reaction forces can be calculated with the following equations 2 and 3:

$$\overrightarrow{F_{LN}} + \overrightarrow{F_{GN}} + \overrightarrow{F_{\mu N}} = m \cdot \vec{a} \qquad (2)$$
$$\overrightarrow{M_{N-1}} - \overrightarrow{M_N} = \vec{\varepsilon} \qquad (3)$$

where:
a is the acceleration
ε is the angular acceleration.

Depending from the intensity of the forces, multi locomotion of the model could be reached. Lower value of the load forces results in crawling, while for higher values, rolling is accomplished.

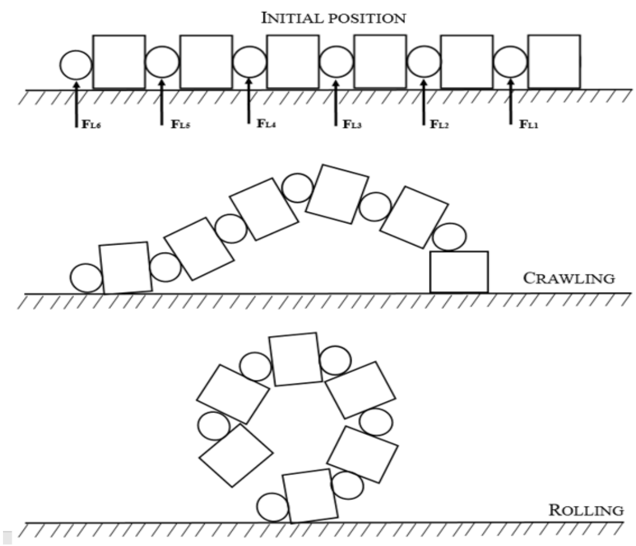

Figure 2. Multi locomotion of six-segmented bio-inspired robot

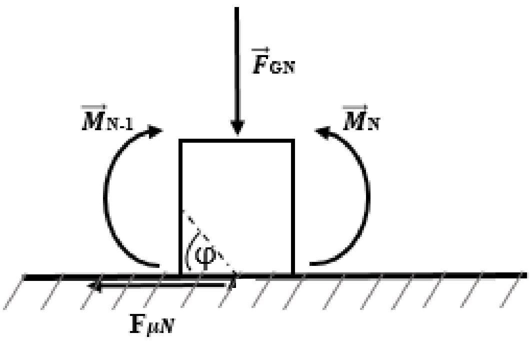

Figure 3. Reaction forces on one segment of the robot

The model of the worm-like robot is similar to the real living organism, because of the segmented body. The only difference is that the real organism has constant volume hydrostat, while the presented model has constant length system. The model of the worm-like robot is identical to the model of the caterpillar-like robot. The different types of movement depend only from the intensity of the force, causing different movements of the robot, crawling and rolling.

B. Grasping

Having different boundary conditions on these segments, meaning the fixed part is between the ground and the joint, as shown on Figure 4, different movement can be achieved. This movement is inspired by an octopus arm. The muscles of the octopus are constant volume hydrostats and they change their length and cross section. For the modeling of the octopus-inspired robot, constant length model was constructed.

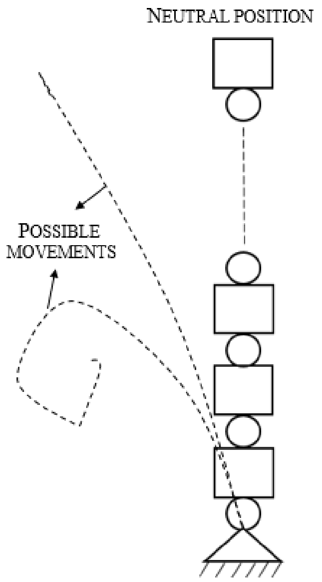

Figure 4. Bio-inspired robot with possible movements of grasping with n number of segment

Between every segment there is a revolute joint capable of making rotational movement with one degree of freedom. To create the movement, moments are applied on every joint between the segments. The reaction forces and the initial and final position for six-segmented body robot are presented on Figure 5.

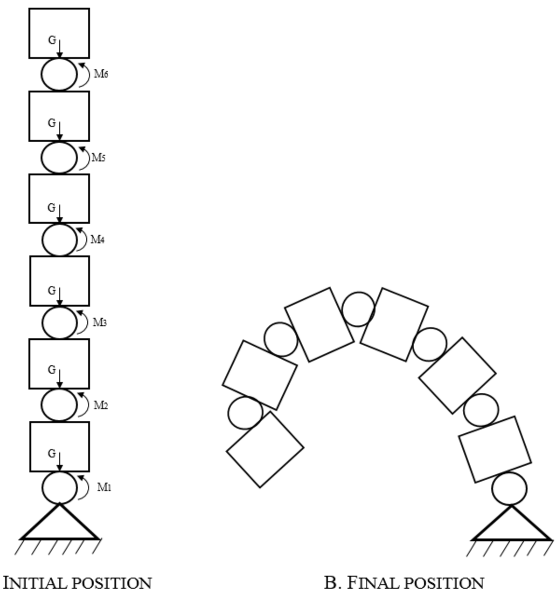

Figure 5. Movement of six-segmented robot

Each applied moment has a different value, which depends from the number and position of segments. When having higher number of segments, the maximum applied moment decreases its value. This is because when having a higher number of segments, the sum of the moments rises because of the higher number of applied moments.

III. NUMERICAL MODELING

The model of the multi locomotion robot is built using Matlab software under SimMechanics module, where every part has its own specific algorithm. The three movements have the same geometric characteristics of the ground and the segments. The ground dimensions are 5x5x0.01 m. The bodies are divided into segments, where every segment is connected with a joint. The segments are cubes with dimensions 0.01x0.01x0.01 m. Polypropylene is applied to the segments as a material with density of 900 kg/m^3.

A. Crawing and rolling

The goal when modeling worm-like robot is to achieve crawling as a movement. Body blocks from the SimMechanics module were used to design the body of the robot. This model is made out of segments that are connected with spherical joints. Two external forces are applied. The intensity of the forces depends of the number of segments. The forces applied for rolling have 3 times higher values than the forces when crawling is achieved.

The modeling for n-number of segments made in Simulink Matlab is shown on Figure 6. The segments are modeled as subsystems, where every subsystem is identical. As it is shown on Figure 6, the subsystem is made of several blocks that represent the shape and the dimensions of the segments. The joint is spherical with three DOF. The actuation force is presented as a sin wave function.

Figure 7 show the Simulink Matlab model, showing the different realized movements. The same model is used for making two movements that result in achieving multi locomotion soft robot.

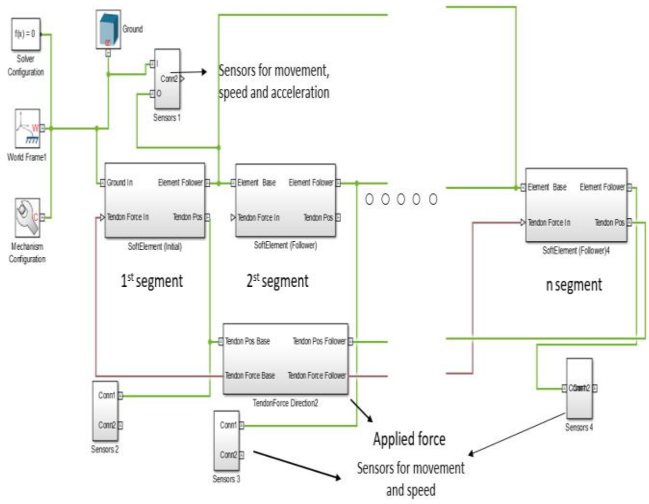

Figure 6. Matlab/Simulink model for crawling/rolling

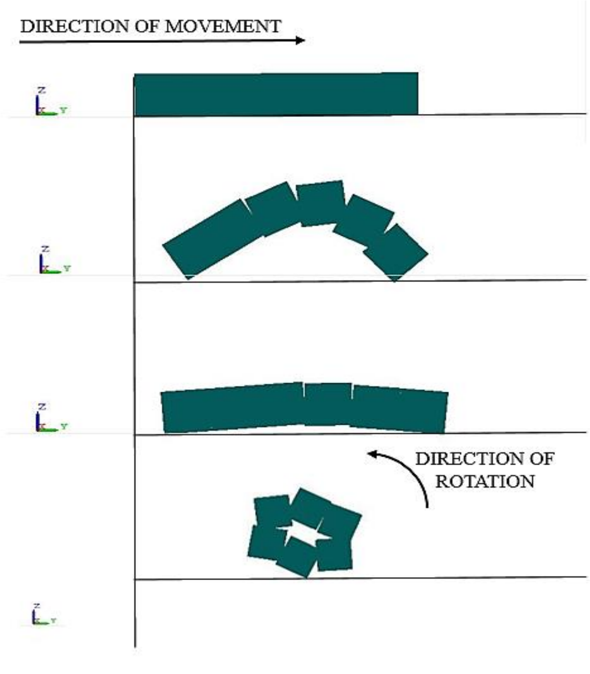

Figure 7. Movements of the bio-inspired soft robot (crawling and rolling)

The intensity of the forces depends from the type of movement. When having rolling, the applied forces have 3 times higher values than the forces when crawling is achieved. For example, for six-segmented model, the applied forces are 300N and 400N when having crawling, while for rolling the applied forces are 900N and 1200N.

B. Grasping

By changing the boundary condition, grasping as a movement inspired from an octopus arm could be accomplished. The Simulink model for the octopus-like robot is shown on Figure 8 and is consisted of eight subsystems that represent the each hand of the octopus. These subsystems are positioned at equal distance. Each hand of the octopus has the same number of segments. The position of the hand is determined with rigid transform blocks by setting the coordinate system for each hand. Revolute joint is established between every segment, capable of making rotational movement with one DOF. In order to make the movement, sin wave input is added on each joint. In order to make the movement more natural, the same frequency and phase are used for each joint, only the amplitude remains a variable parameter. By adding different amplitude to a different joint, the desirable movement could be achieved. Every arm of the octopus-like robot is able to be simulated individually.

Figure 9 shows the Matlab model of the movement of the robot, where each hand of the model consists of six segments. The Figure shows two final positions of the robot.

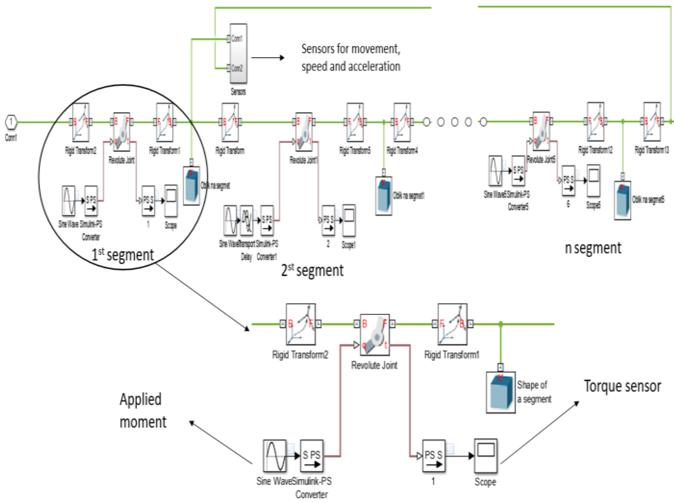

Figure 8. MatLAB/Simulink model for grasping

Figure 9. Movements of the bio-inspired soft robot (grasping)

The number of segments directly affect on the value of the applied moments. When having a higher number of segments, more natural movement can be realized. The number of segments is inversely proportional with the value of the maximum applied moment.

IV. MEASUREMENT ANALYSIS

Analyzing the crawling as a movement inspired by the worms, the velocity is being measured. Figure 10 shows the dependency between the velocity and the segments of the body. From the Figure 10, it can be concluded that for lower amount of segments, the velocity is higher. For example, for six-segmented body, the velocity is 60.4 mm/s, while for ten-segmented body the velocity is 14 mm/s. For lower number of segments, the velocity is higher because of the higher intensity of the forces and the lower weight of the body. Two external forces could be applied when having a soft robot consisted of maximum 12 segment. When having more than 12 segments, third external force has to be applied, because of the bigger length and weight of the body.

As a result of the worm-like model, it can be concluded that the movement can be achieved for the smaller value of the external forces as the number of segments increases. On the other hand, higher velocity can be achieved when having a smaller number of segments.

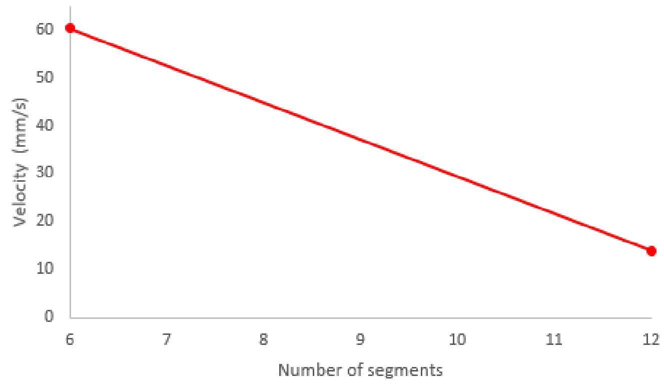

Figure 10. Relationship between the velocity of the robot and the number of segments in crawling

Figure 11 shows the angle of rotation of the octopus-like model. The angle of rotation is higher when having a higher number of segments. For example, for six-segmented model, the angle of rotation is 246°, while for the fourteen-segmented body the angle of rotation is 323°. The angle of rotation increases because of the instability when having a higher number of segments (the length and the weight are higher). Better movement is achieved when having a higher number of segments. Also, the results show that for higher number of segments, the maximum torque and amplitude are decreasing. The relative velocity between the last and the first segment is increasing as the number of segments grow.

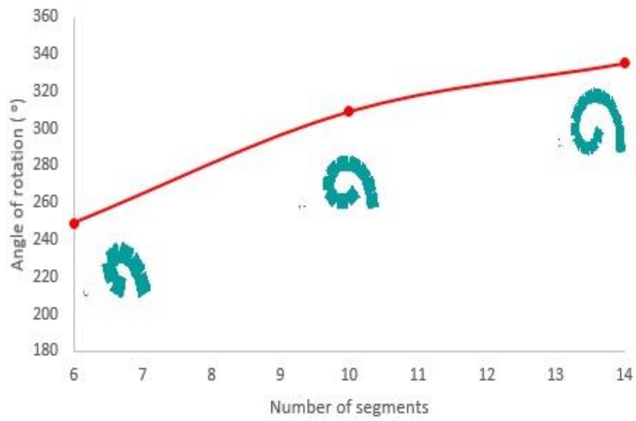

Figure 11. Relationship between the angle of rotation of the robot and the number of segments in grasping

The measurements from the analysis start from six segments as a minimum number of segments, because the movements could not be established when having a lower number of segments. The Simulink models of the multi locomotion bio-inspired robot provides possibilities for upgrading the design of the model through applying different input signals in order to achieve more complex motion.

V. CONCLUSIONS

This paper introduces modeling and a simulation of a segmented bio-inspired robot in multi locomotion mode. Parametric variation of outside load and different boundary conditions result in different locomotion loads: crawling, rolling and grasping.

The number of segments directly influence the kinematics of the motion and the robot performance such as velocity. Combining multiple segmented linear robots, a complex 3D functionalities could be achieved. In this case, an octopus inspired grasping has been presented. Using smart materials, such as SMAs prints that localize the actuation, linear and rotational movement could be accomplished. This work is initial modeling for multi locomotion of segmented continuous robots and will be followed by a detailed multi-body dynamic simulation, FEA, finalizing with a functional prototype.

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