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REGULAR PAPER

A Rhythmic Activation Mechanism for Soft Multi-legged Robots

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Abstract

Compared to standard solutions, soft robotics presents enhanced adaptability to unpredictable and unstructured environments, encompassing advances in fabrication, modeling, and control. The absence of a general theory for the latter is one of the biggest challenges in the field, which constrains these robots' employment in real-world applications. This research proposes the application of Scheduling by Multiple Edge Reversal (SMER) in the activation of soft legs to be applied in multi-legged robots. A soft device was developed to be tested as a robot's leg to evaluate the proposed application. A logic controller for this device was designed using the SMER technique. Image processing techniques were used to assess the functionality of the proposed strategy, which demands limited resources. The vision tracking system is composed of a set of infrared-reflective patches, an infrared illuminator, and a pair of cameras with no infrared filters. Results revealed that it is possible to use SMER techniques to activate soft robotics systems and that the methods employed to develop and test the device were appropriate.

Keywords Locomotion · Stereo vision · Soft robots · Bioinspired robots · SMER

1 Introduction

A relevant research direction in robotics focuses on manipulation systems, whose dexterity in grasping objects is often the primary concern [1]. Another research direction focuses on mobility, which depends on some aspects of the environment to be explored, impacting on the maneuverability, controllability, efficiency, terrain conditions, etc [2].

In this context, soft robots arise as a prominent solution to locomotion and manipulation tasks due to their intrinsically soft and extensible bodies capable of deformation and energy absorption in collisions [3]. The soft robots' capacities lead to their use in many applications such as with wearable devices [4], haptics technologies [5], and surgical tasks [6]. Besides, several types of soft robots were developed inspired by biological systems [7, 8], being capable of animal-like behaviors, such as climbing [9], squeezing [10], swimming [11], among others.

In this context, this paper focuses on mobility features of soft robots, investigating the application of a Soft Pneumatic Actuator (SPA) as a robot leg, in a context where the locomotion of untethered soft multi-legged robots is envisioned as a final goal (e.g., see the application in a soft quadrupedal robot presented in [12]). Note that such a goal is challenging, explaining why only a few works related to quadrupedal soft robots were found in literature [13–16]. These works, inspired by nature solutions, intend to provide robots that better suit their environments by making their bodies more compliant, explaining the rapid expansion of the soft robot field [17]. Soft robots have been employed in many applications, such as mobile or locomotive robots, wearable devices, and soft manipulators [18]. This is due to the fact that this kind of robot is composed of deformable materials, making them formidable to execute dramatic shape changes and support large impacts [19, 20]. An essential advantage of such structures relies on their ability to provide a safe interaction between objects, humans, and the environment [21].

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There is an emerging interest in designing soft legs as parts of "soft machines" that can mimic dynamic biological behaviors by transducing external stimuli into an adjustable function [22]. Furthermore, their flexibility permits to transition between locomotion modes depending on external conditions since they function similarly as dexterous musculoskeletal systems [17, 21]. However, due to the absence of a general theory of how to control soft structures, soft robots' design and control often involve a painstaking trial synthesis procedure [23, 24]. Such control is crucial for soft actuators' ability to move in an unstructured environment and confined (or hazardous) spaces, which a soft mechanism is expected to do [25]. To guarantee that the advanced solution is feasible, it is also necessary to provide a control scheme with limited complexity [26].

One of the main challenges remains in the locomotion of these robots. Locomotion is a complicated process that varies in both time and space, which involves the dynamic analysis of musculoskeletal systems and the understanding and reproducing of complex control systems, their synchronization, and their stabilization [27]. In [15], the movement is achieved by manually opening and closing valves in an attempt to mimic a gait pattern. Unfortunately, the authors themselves acknowledge that such a control technique demands a significant amount of time.

It is important to highlight those soft robots are naturally flexible and adaptable to various tasks and environments due to their smooth and deformable structure. However, their capabilities can be significantly improved if they know the environment they are inserted, which can help them avoid obstacles, move more effectively, grab objects more accurately, and adjust their shape to the environment. However, the insertion of sensors in soft robots' bodies can reduce their mobility [28]. Thus, it is necessary to study techniques that allow soft robots to know the environment in which they are inserted without impairing their mobility. In this sense, computer vision techniques could improve the effectiveness of soft robots without reducing their mobility and flexibility.

1.1 Main Contribution

This research work proposes the application of Scheduling by Multiple Edge Reversal (SMER) multigraph dynamics as an approach for the rhythmic activation of a Soft Pneumatic Actuator (SPA) in the context of a single soft leg. Thus, the simultaneous activation of several legs is outside the scope of this paper and is left for future work.

A SPA consisting of a silicone rod (soft rod) composed with three independent internal cavities was developed to be tested as a robot's leg as a proof of concept. The development of the SPA was carried out using molds manufactured by additive technology from three-dimensional virtual models produced in a specific modeling tool. Another contribution is the adoption of computer vision techniques to reconstruct the trajectory of specific points in the free end of the developed SPA. This study aims to reconstruct the movements performed by the soft leg without losing neither mobility nor flexibility. The main contributions of this research can be summarized as follows:

- A new activation strategy for soft legs to assist the locomotion of multi-legged robots.
- An inexpensive and efficient computer vision system for trajectory reconstruction in soft robotics applications.

Lastly, it is worth mentioning that this article does not deal with vision-based control schemes, although it indeed establishes a fundamental basis for such a crucial extension.

1.2 Organization

This research work is organized as follows. Section 2 details a brief review of the background and related works in soft robotics. Section 3 presents the proposed methodology. Section 4 presents the experiments and results for various situations, which precedes the conclusions furnished by Section 5.

2 Background and Related Works

The robots used in most applications are mainly built with rigid materials, performing tasks efficiently, but with limited adaptability. Usually, those rigid robots are built to be cost-efficient and robust. However, they may lack the characteristics necessary for a sensible environment. In contrast to rigid robots, soft robots have bodies composed of bio-compatible materials and a continuously deformable structure that simulates biological systems to achieve robustness and adaptability. Furthermore, it is known that they are able to ensure reliability and safety [29].

This type of robot's main objective is the development of biologically inspired devices capable of adapting and interacting with the environment more naturally, when they are used in delicate tasks, difficult to access environments, and even for interaction with humans. In order to achieve these objectives, the construction of soft robots is performed with low rigidity materials, such as silicon, polymers, and gels [30].

Soft mechanisms have shown great potential for application in robotics, given the mechanical characteristics that allow them to adapt to the environment they are inserted into, interact more safely with the environment and with humans. However, despite the advantages presented by these robots, they present some challenges that must be overcome. For example, in [31], the authors describe the difficulties involving control architectures since this type of robot continuously adapts to body structure changes and the environment. Another issue mentioned is related to making traditional sensors and actuators smaller, softer, and more flexible. According to [32], in addition to the difficulty in manufacturing and standardizing components (since the manufacturing methods are primitive, limited, and costly), another challenge is the limitation of existing software capable of simulating the dynamics of soft materials due to their many degrees of freedom.

A difficulty is to make the soft mechanisms to know the environment in which they are inserted without hampering their mobility. Besides these challenges, there is still no general theory of how to control flexible structures. Thus, much of the existing solutions in this area come from soft-bodied animals' locomotion strategies. For instance, regarding quadrupedal soft robots, only a few works (e.g., see [14–16]) were found in literature, and only one paper proposes the use of Central Partner Generator to activate soft robots [33]. However, the latter focuses on earthworm-inspired soft robots' behavior, which differs from this paper's approach.

Other challenges in soft robots' performance are position detection, modeling, and control of inherently compliant and flexible materials such as silicone rubber [34]. In this sense, different types of soft pneumatic actuators and control strategies were developed to complement these soft robots' nature, which stretches through inflation or deformation of elastic chambers [35, 36]. Therefore, well-known robot control theories are poorly applicable to this kind of soft robots.

This research devises a pneumatically actuated soft leg to overcome some of those challenges and performs its kinematic study. The activation of the servomechanism relies on SMER multigraph dynamics as an approach for an artificial Central Pattern Generator, which ultimately furnishes the necessary logic control for this device.

Due to their non-linear properties, soft robot structures do not have an analytical model in general, making it difficult to predict and control their movements and positioning with accuracy. Consequently, one of the research areas that need to be addressed is the performance of spatial control tasks that allow these robotic systems to perform activities with precision [37].

Several researchers have been proposing different methods to estimate the positioning of a soft actuator. For instance, in [38] is proposed a positioning approach in 3D space based on cascade splines, which control the manipulator's tentacle. Such a practice is inaccurate and has been improved through a vision-based feedback loop. In this context, reference [39] utilized Jacobian-based methodology to achieve, at the tip of the manipulator, an average accuracy of 6% of the manipulator's total length. In Marchese et al. [40], a closed-loop control was used to position a flexible arm in 3D space to reach a 0.04 m diameter ball.

This paper also applies computer vision techniques based on brightness-detection to track and reconstruct the movements of a soft leg. The main idea is to improve the robot's effectiveness through an environment without reducing neither mobility nor flexibility. Note that this could not be possible if sensors are attached to the robots' bodies due to their deformable structure. The proposed tracking method employs stereo vision with cameras without infrared filters to track a set of passive infrared-reflective patches installed at the tip of the leg. The tracked points allow accurate positioning in 3D space.

3 Proposed Methodology

This research utilizes part of the methodology proposed in Garcia Sampaio et al. [12], with the inclusion of new tests and changes in the experimental bench. Thus, the same electro-pneumatic driver system, the same SPA, and the same activation strategy were maintained. This work proposes using a stereo vision system, which employs two cameras for the acquisition of images, an algorithm for tracking the luminous points and reconstructing the three-dimensional movement performed by a soft device, also known in this work as soft rod, which main objective is to be used as legs in multi-legged robots. Since two cameras were used, it was necessary to introduce a calibration step for the cameras. The proposed vision system has the sole function of reconstructing the trajectory of specific points on the soft rod, in order to evaluate the application of SMER as activation strategy to the soft rod. The procedures adopted to implement the method devised in this paper are summarized in Fig. 1. The following subsections will present the steps for the development of this work.

3.1 Activation Strategy

Central pattern generators (CPGs) are known to be the basis of rhythmic motor behaviors related to the natural locomotion of vertebrates and invertebrates, amongst other movements [41]. The CPGs produce rhythmic output patterns without the need for sensory feedback. In order to reach rhythmic gait patterns in multi-legged robots, different approaches for artificial pattern generators were proposed [42]. From coupled oscillators systems [43, 44] to artificial neural networks [45], using CPGs in robotics for controlling the locomotion of articulated robots has been widely explored over time. In this work, the Scaling by Multiple Edges Reversion (SMER) was adopted to perform the activation strategy for the proposed soft rod, additionally to the former strategy to generate gait pattern for soft quadrupedal [12] and rigid hexapod robot [46].

Fig. 1 Project organization chart

The choice to use SMER-based CPGs to generate gait rhythms, in substitution to the other already established in the literature as neural networks and coupled oscillators, was taken by the possibility of implementing different gait rhythms and by the necessity to activate several devices (pneumatic control valves). Each leg uses at least 3 air-filling chambers (3 controlled activation). Thus, the implementation of a coupled nonlinear oscillator, different from the SMER approach, becomes costly for the processing unit to be added to the robot in the future.

The Scheduling by Multiple Edge Reversal or SMER is a generalization of the Scheduling by Edge Reversal (SER). According to Barbosa and Gafni [47], the SER method employs graph concepts to organize resources (edges) competition in a fair and egalitarian way when different vertex use the same resources in a shared manner. The SER works so that a sink can only operate if the other sinks are inactive. After operating, this sink will revert the orientation of its edges, allowing the neighboring sink to use the released resources. In the SER, all nodes have the same access rate and only operate once per cycle. The nodes in the SMER present different access rates, operating more than once consecutively in the same cycle, that is, it may exist zero or more edges between the i-th and the j-th nodes. The reverse of the i-th node is r_i, that is, the number of edges that will be reversed from the i-th node to its neighboring nodes at the operation's end. The representation of the oriented-graph in the adopted form is shown in Fig. 2, in which the darkest circle represents the active vertex, and the arrows indicate the edges pointed towards the vertex.

The observation of Fig. 3 permits a comparison between SER and SMER strategies. It is noteworthy that the value of r_i is inversely proportional to the activation rate.

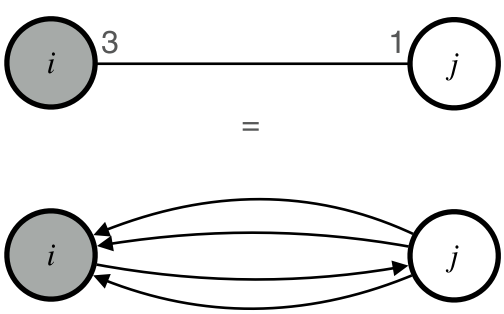

Fig. 2 Representation of the oriented-graph

According to [48–50], for the two vertex i and j to be reversed and become r_i and r_j, it is necessary to define a total number of edges e_{ij} between the i-th and the j-th nodes. The value of e_{ij} that guarantees the minimum number of edges between two vertex depends on the Greatest Common Divisor (GCD) between the reversed pairs of the vertex:

$$e_{ij} \triangleq r_i + r_j - \mathrm{GCD}(r_i, r_j). \quad (1)$$

As stated in [51], Central Pattern Generators (CPGs) are groups of neurons located in the central nervous system and are involved in the production and regulation of various cyclic motor patterns in animals, such as locomotion, respiration, and chewing. According to [48], discrete and analog versions of SMER-based CPGs can be customized for different rhythm patterns in which discrete Oscillatory Building Blocks (OBB) modules are built through the direct adoption of the SMER algorithm while an asynchronous neural network (Hopfield) is used to implement analog OBBs.

Consider the pneumatic soft rod henceforth as a servomechanism and each cavity as a muscle activated via SMER-based CPG. In this context, it is possible to define activation sequences for the servomechanism. Thus, 3 single-leg activation sequences were developed. These sequences were defined according to the percentage of overlap between the activation periods of each cavity. C_1, C_2, and C_3, respectively, correspond to cavities 1, 2, and 3.

In the first activation sequence, each cavity is driven one at a time for a given time Δt, and the overlapping percentage between the cavity activation period of each cavity is 0%. Each cavity's reversibility is equal to 1 and the number of resources for each cavity is also 1. The cycle activation of a leg using this sequence is shown in Fig. 4.

In the second sequence, an initial cavity is activated for a specific time, then two cavities are simultaneously activated for a shorter time, and so on. In this sequence, there is an overlap of 25% between the activation periods of each cavity. The reversibility of each cavity is equal to 1, and the number of resources for each cavity is equal to 3. Figure 5 shows the activation cycle of one leg when the sequence 2 is used.

In the third activation sequence, two cavities remain activated together during a time. In this case, 50% of the total activation period. Again the reversibility of each cavity

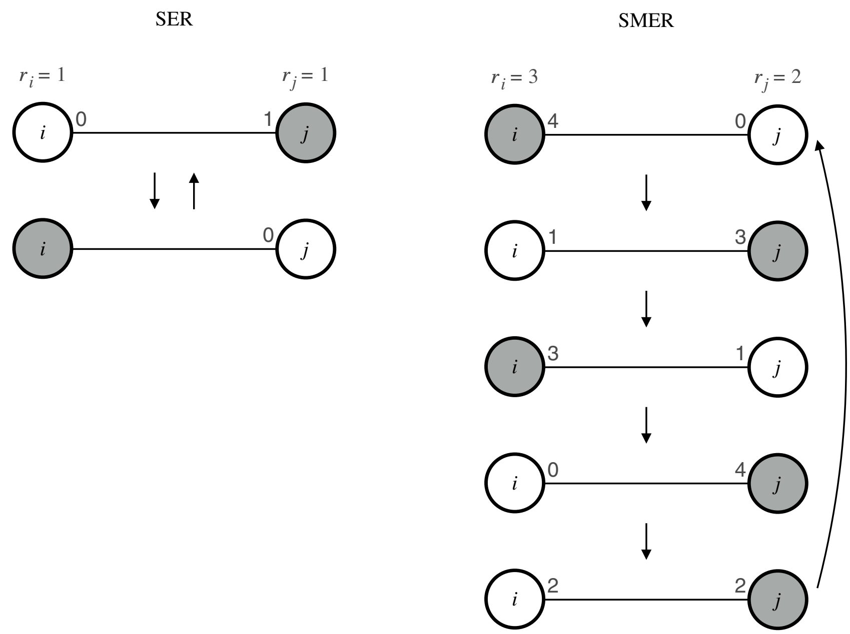

Fig. 3 SER and SMER example [46]

is equal to 1, and the number of resources for each cavity is equal to 2. Figure 6 shows the activation cycle of a leg, using sequence 3.

3.2 Soft Rod

The proposed Soft Pneumatic Actuator (SPA) is a soft rod with three internal cavities fabricated using Ecoflex 00-30® silicone rubber, which has the advantage of being bio-compatible, having high strength, and low curing time. Table 1 shows the material's properties provided by the manufacturer, Smooth-On [52]. This soft mechanism was fabricated and used during the development of the work presented in [12].

A 3D printed mold was fabricated to manufacture this robot and additive manufacturing techniques were used to construct the rod. Figures 7 and 8 show the manufacturing process of the rod as well as its internal cavities.

3.3 Electro-Pneumatic Driver System

An electro-pneumatic driver system was built based on a design developed by researchers of Harvard University [53] to operate the device proposed in this project. Figure 9 illustrates the diagram of the electro-pneumatic driver system. The electro-pneumatic driver system built for this project is composed of electro-pneumatic valves that are responsible for directing the airflow in the system through open

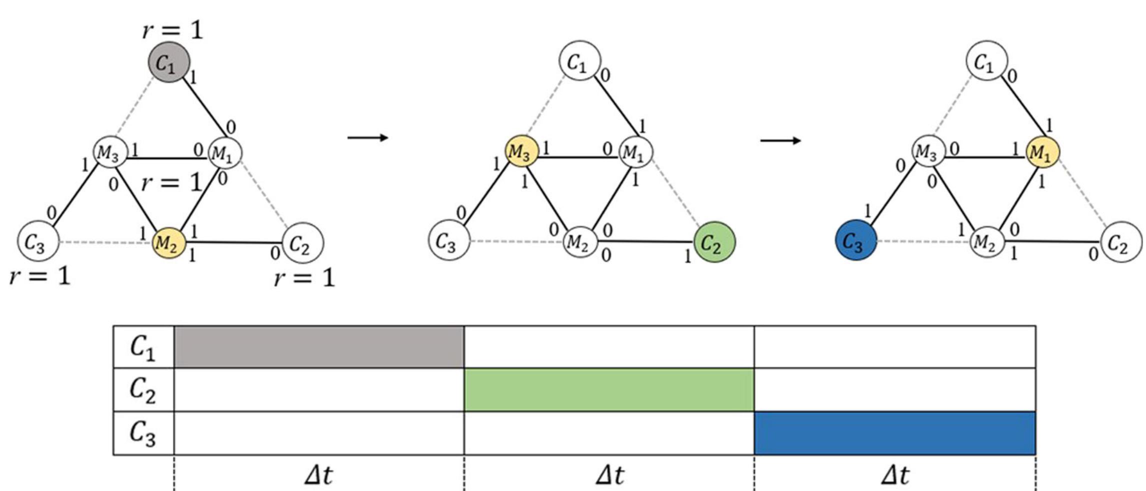

Fig. 4 Activation cycle of one leg using sequence 1 [12]

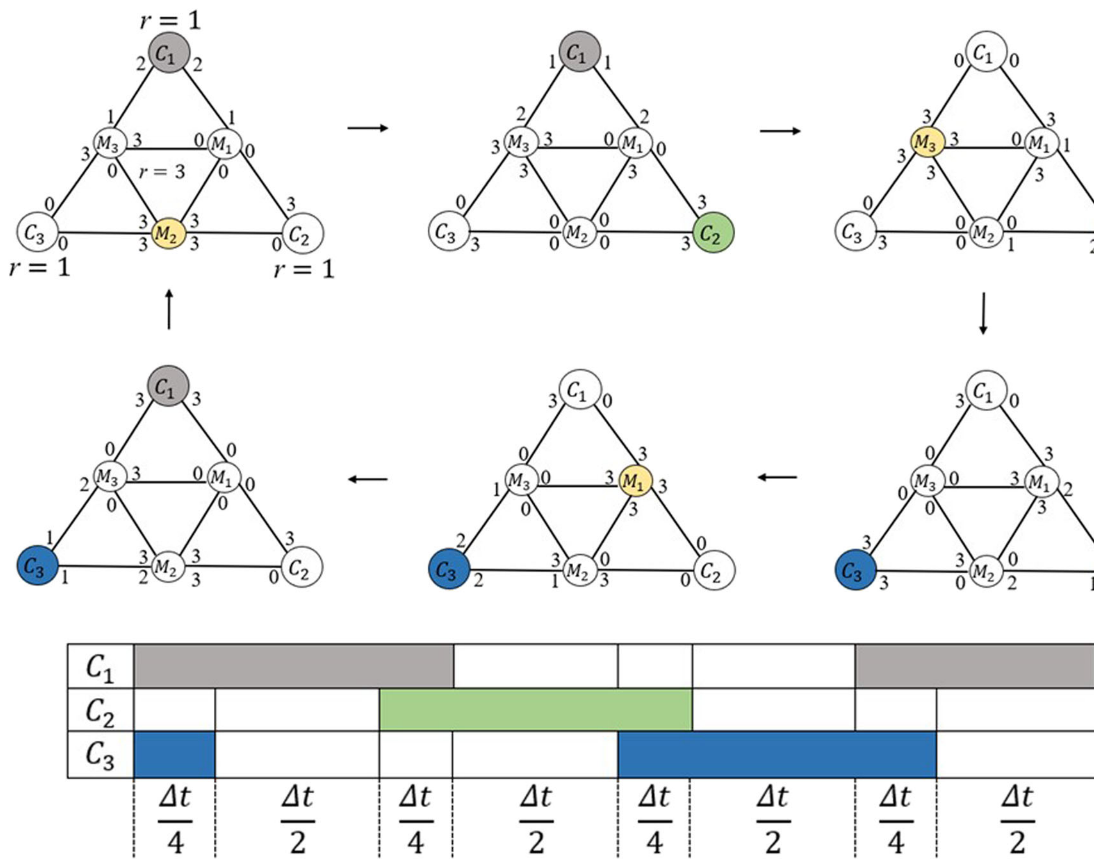

Fig. 5 Activation cycle of one leg using sequence 2 [12]

and close movements; potentiometers, which are responsible for controlling the pressure in the system; switches; IRF520 Metal Oxide Semiconductor Field Effect Transistor (MOSFETs) that are responsible for controlling the opening and closing process of the valves; Atmega2560 Microcontroller, which is responsible for the Pulse Width Modulation (PWM), which controls the opening and closing speed of the valves; and 5 Voltage and 24 Voltage power supplies.

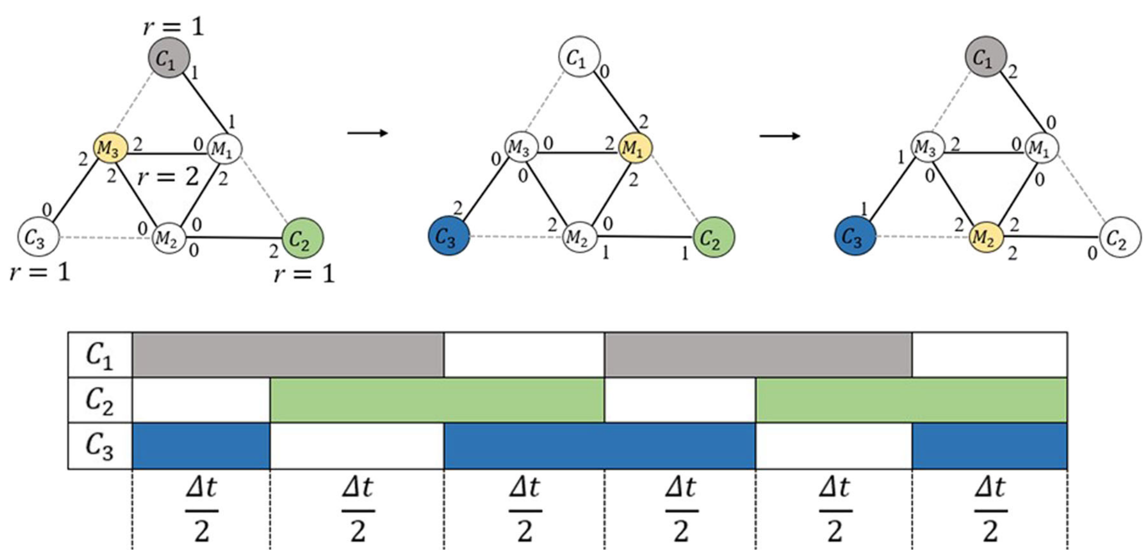

Fig. 6 Activation cycle of one leg using sequence 3 [12]

Table 1 Silicone Rubbers' properties

Property	Value
Specific gravity	1.07 g/cm^3
Specific volume	0.719 kg/cm^3
Cure time	4 hours
Tensile strength	1.38 MPa
Shore hardness	00–30
Elongation at break	900%
Shrinkage	0.0254 mm/mm
Minimum useful temperature	− 53.08 °C
Maximum useful temperature	232.22 °C

With the proposed electro-pneumatic driver system it is possible to control the opening and closing speed of the solenoid valves, by using Pulse Width Modulation (PWM) throughout a previous defined logic in the Atmega2560 Microcontroller. When the valves are opening and closing they allow the air to flow through and activate the soft rod. Figure 10 shows the electro-pneumatic driver system built for this project.

3.4 Vision-Based Tracking System

The vision setup comprises two infrared Camera Module v2 (Pi NoIR), one infrared illuminator, a set of infrared-reflective patches, and two Raspberry Pi (RPi). Each camera must be attached to an RPi due to a hardware characteristic. The vision setup can be seen in Fig. 11.

All videos were recorded with resolution VGA (640 × 480 pixels) at 90 FPS. The cameras' automatic controls were disabled and the parameters were manually set as follows: ISO 100; aspect ratio 4:3; full FOV; white balance "grayworld" (to fix incorrect automatic white balance due to the lack of the IR filter in NoIR camera). Figure 12 shows a frame recorded by the left camera after the proposed marker tracking system. The glowing spots near the center of the image are the infrared patches installed on the free end of the soft rod (markers 1, 2, 4 and 6). The right and left glowing spots (markers 3 and 5) are installed at the same base where the rod is fixed and are used as reference points. The distance between these markers (152.4 mm) is used to convert the $X - Y$ (planar) positioning of the moving markers from pixels to the metric system. The detection of the spots is based on brightness. An empirical threshold ($T = 0.98$) is used to binarize all frames from the recorded videos. The tracking of each marker is performed by considering the distance between them along with the frames. Markers closer than 10 pixels in consecutive frames are considered different instances of the same marker.

Suppose the camera is far enough from the rod, and the movement is small. In that case, some approximations can be employed (to avoid ambiguities), and the planar $X - Y$ movement can be tracked using single-view geometry with small errors. Track 3D movement through a single-view is difficult due to geometry ambiguities. This work proposes to use stereo vision to track the movement made by the free end of the servo mechanism. Such a technique allows tracking the soft mechanism's 3D movement without adding rigid sensors in it. The demonstration of the geometry involved can be found in [54].

Figure 13 illustrates the adopted technique to obtain the z coordinate (depth) of a marker. This figure can be

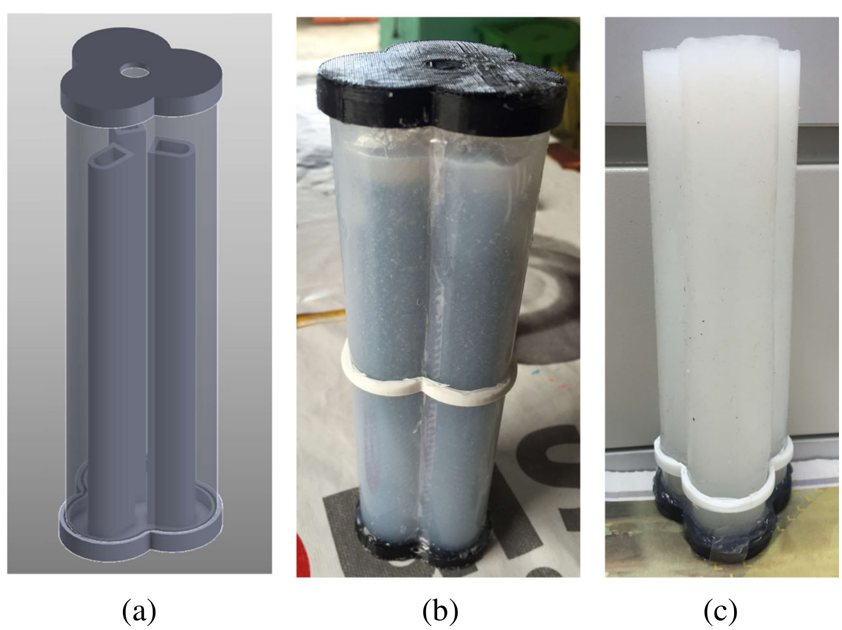

Fig. 7 Manufacturing process for the soft rod: **a** digital 3D model of mold's parts, **b** 3D printed parts and assembly for silicone filling and cure, **c** unmolding the soft rod

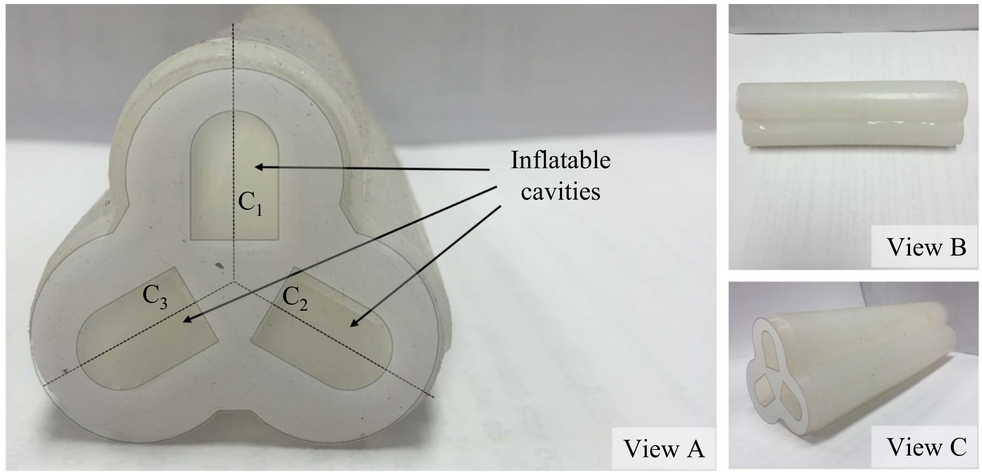

Fig. 8 Soft rod and its inflatable cavities

interpreted as the top view of the camera setup, with the blue area representing the field of view (FOV) of the left camera and the green representing the FOV of the right one. The dashed red lines indicate the projection of a marker X onto both image planes. So, x_1 is the projection of X onto the left image, and x_2 is the projection onto the right one. The f is the focal length, and b is the distance between the cameras' centers (for more details about the pinhole camera model, refer to [54]). In this methodology, one can only determine the z distance of an object covered by the FOV of the two cameras. Such a region is illustrated by the grayish region in Fig. 13.

Considering that the references (0, 0) are at the centers of each image, there are 3 cases to take into account. Case 1 is when the object is in the left light gray region, so $x_1 \geq 0$ and $x_2 > 0$ and z is given by

$$z = \frac{bf}{|x_2| - |x_1|}. \tag{2}$$

Case 2 occurs when the object is in the dark gray region, so that $x_1 < 0$ and $x_2 > 0$, and z can be obtained by rewriting the Eq. 2 according to

$$z = \frac{bf}{|x_1| + |x_2|}. \tag{3}$$

Finally in Case 3, when the object is in the left light gray region, $x_1 < 0$ and $x_2 \leq 0$, and z is

$$z = \frac{bf}{|x_1| - |x_2|}. \tag{4}$$

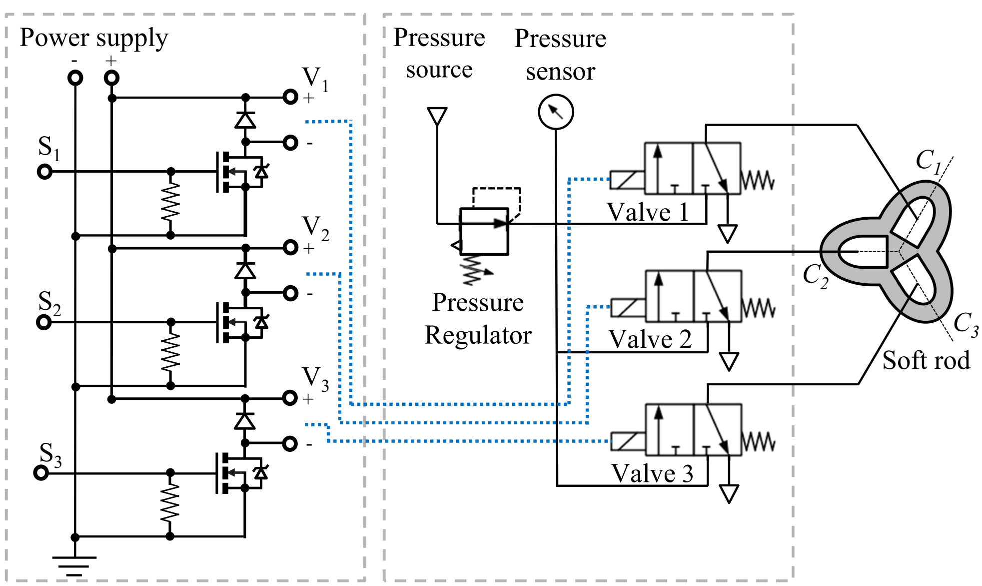

Fig. 9 Diagram of the electro-pneumatic driver system without microcontroler

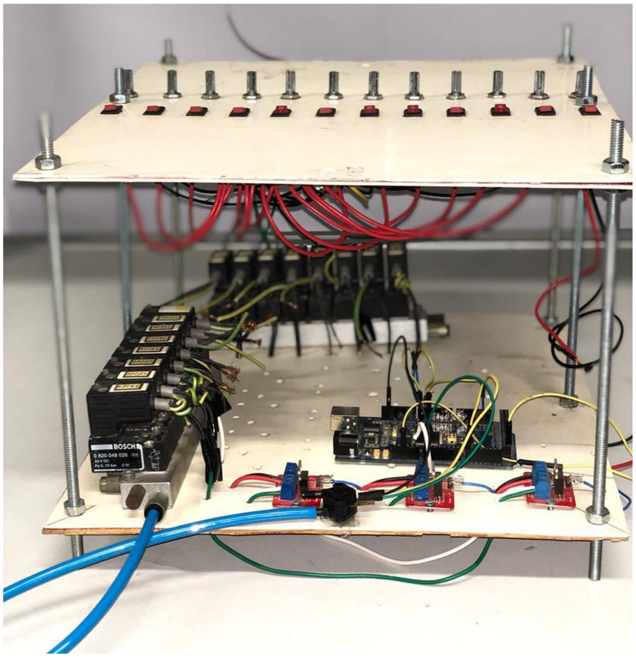

Fig. 10 Electro-pneumatic driver system

The values of x_1 and x_2 can be obtained by the tracked objects' coordinates in the left and right images, respectively. The intrinsic parameters (such as f) of the cameras, and as their extrinsic parameters (such as b), can be obtained through a camera calibration process. Using these parameters, it is possible to extract metric information (3D) from two-dimensional (2D) images [55]. Among the plethora of calibration techniques that have been developed over the years, this paper utilizes the technique proposed in [55],

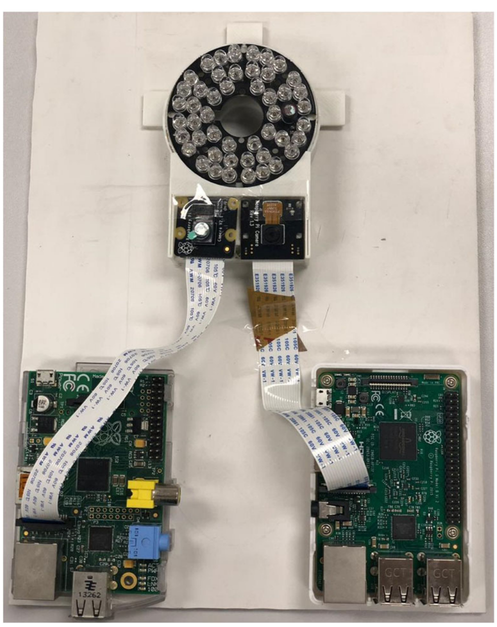

Fig. 11 Vision setup used to record the movement

which guarantees flexibility, low cost, robustness, and high efficiency. This technique consists of extracting strategic points from an image that contains a calibration pattern (chessboard, for example) to estimate the parameters of the camera, estimate the distortion coefficients, and finally apply a correction, if necessary. Figure 14 shows the left and right views, a pair of frames from aligned videos, used to calibrate our stereo vision setup. The temporal alignment was obtained by blinking a lantern in front of the cameras before recording the board movements.

3.5 Experimental Bench

An experimental bench was built for this project (Fig. 15). The servo mechanism was fixed by the upper part, leaving the lower part free to perform the movements, and infrared-reflective patches were fixed on the free end of the rod. Two cameras were positioned to record the movement of the free end of the servo mechanism, as can be seen in Fig. 11. An algorithm based on brightness was used to track the infrared-reflective patches' movements and analyze the movement performed by them over all the videos' frames. Such a technique does not limit the soft mechanism's movement, thus allowing the analysis of its kinematics.

4 Results and Discussions

In order to evaluate the efficiency of applying computer vision techniques to track the movement of a soft mechatronic system, a few experiments were carried out. As mentioned before, this study aims to recover the movements performed in the three-dimensional space (3D) by the soft leg while keeping its main characteristic of being soft and flexible. That was possible by using computer vision techniques, which allowed us to track the movements performed by the soft leg without using any hard sensors attached to it.

For the performed tests, parameters such as total activation time, Δt, of each cavity (C_1, C_2, C_3) were considered constant and equal to 2.5 s for all 3 sequences presented in Section 3.1; PWM frequency for activating the valves was kept constant and equal to 30 Hertz for all tests; the number of links was fixed in 2; the valves remained opened for 68% of Δt. In other words, the valves remained opened for 1.7 s and remained closed for 0.8 s for each activation cycle. For more details of how the number of links and the time the valves remain opened affects the soft leg movements, please refer to [12].

For this work, new experiments were carried out considering the same activation sequences presented in [12]. Thus, it is necessary to compare the former results with the results obtained in the new experiments. In Fig. 16 it is

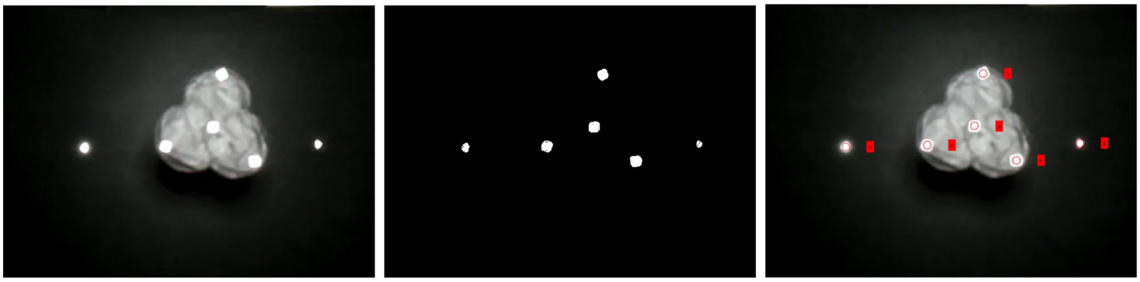

Fig. 12 Result of the detection and tracking method employed to a frame from the left camera. The detection leads to the markers (white circles with inner red circles). The tracking leads to its labels (red numbered rectangles). Left: original frame; Center: detection of the markers after binarizing image with a threshold T = 0.98; Right: The tracking is performed through distance. Markers closer than 10 pixels in consecutive frames are the same

possible to observe the movements performed by the soft leg in the sequences 1, 2, and 3 respectively. In red are the experiments carried out for this work, and in blue are the experiments carried out in [12].

It is possible to see in Fig. 16 that the movement performed by the soft leg continues following the same characteristics of the previous work. However, there is a slight inclination to the left in the red graphs that could have been caused by the cameras' positioning and the fixation of the top of the servo mechanism. In [12] only one camera was used, thus ensuring that it was parallel and centralized with respect to the free end of the leg. In this work, two cameras were used and were separated by a distance of 26.5 mm. The midpoint between the cameras was not exactly aligned with the center mark and the free end of the soft mechanism. This causes the incidence of parallax error in the images of the two cameras, that is, each camera sees the free end of the

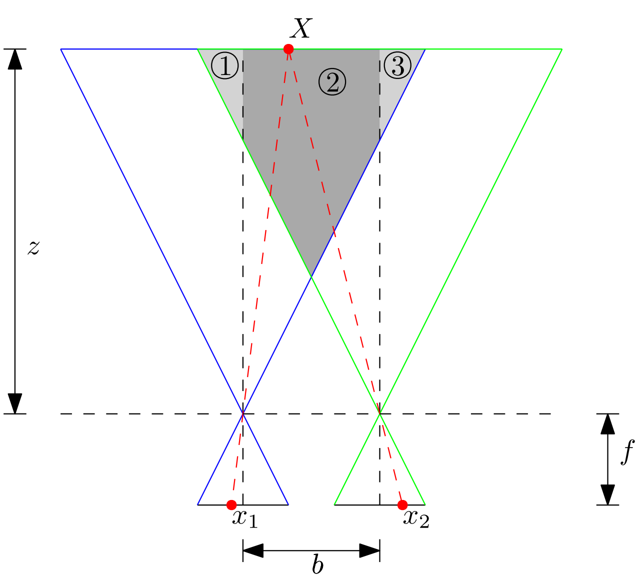

Fig. 13 Two view geometry employed to obtain the z coordinate (depth) of point in 3D space

leg slightly tilted to the left. Thus, the resulting image from the two cameras tends to be tilted to the left. In the previous work, the fixation at the top of the servo mechanism allowed it to move from the original position as the movement occurred, causing a small displacement in the results. For this work, this problem was fixed. In other words, the soft leg was fixed in a way that does not allow this displacement to occur, thus ensuring a more accurate result. Also, a new experimental bench was built for this work, so the distance between the cameras and the soft leg is different from the previous work, as well as the pressure from the pneumatic air source is different, causing the results to have different amplitude and small changes in its shape for each activation sequence. Since this work's main contribution is to reconstruct the movement in three-dimensional space (3D) performed by the soft mechanism, it can be considered that those differences between the previous work and this work do not affect the final results.

This research's main idea is to improve the robot's effectiveness through an environment without reducing neither mobility nor flexibility through the use of stereo vision with cameras without infrared filters to track a set of passive infrared-reflective patches installed at the tip of the leg. The tracked points allow accurate positioning in 3D space. Thus 3 experiments were carried out and will be presented in the following sections.

4.1 Experiment 1: 3D Movement for Sequence 1

The first experiment intends to reconstruct the soft leg movement while it is activated by sequence 1, in the three-dimensional space. For that, it was used the techniques presented in Section 3.4. In Fig. 17a it is possible to observe the 3D movement of the soft leg, and in Fig. 17b it is possible to observe the x, y and depth (z) variation through the frames of the video. Note that in Fig. 17b, it is possible to observe in more detail the cyclic movement performed in Fig. 17a. The soft leg starts its movement in a resting position, hits a maximum amplitude, returns to the resting

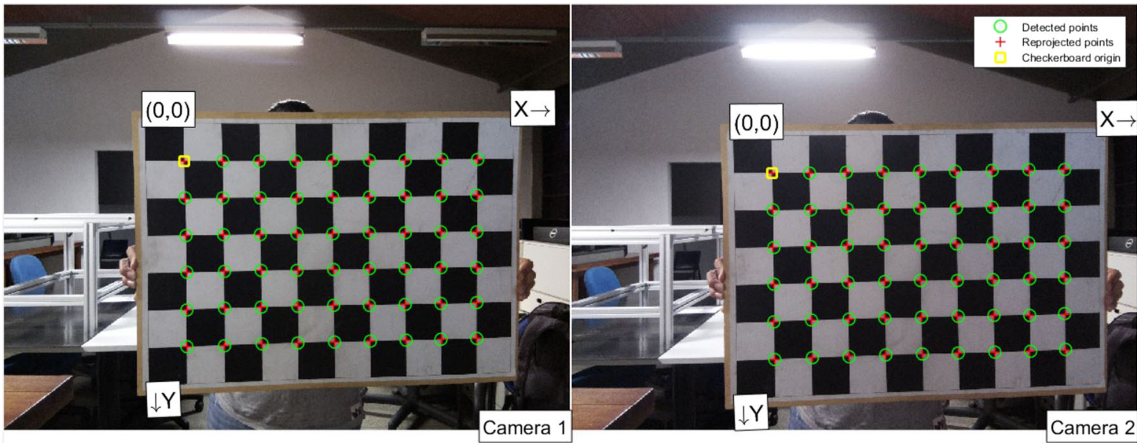

Fig. 14 A pair of frames from the temporally aligned videos used in the calibration process

position, and then reaches a minimum amplitude. This cycle repeats according to the activation period. In sequence 1, the cycle repeats for 7 to 8 times during the period that the soft leg is moving, as it can be seen in Fig. 17b the leg returns to the initial point approximately every 1000 frames.

4.2 Experiment 2: 3D Movement for Sequence 2

The experiment 2 aims to reconstruct the soft mechanism's 3D movement when activated by the sequence 2. Figure 18a shows the leg's 3D movement, while Fig. 18b presents the cyclic movement of z over time. In sequence 2 the cycle repeats for 10 times during the period that the soft leg is moving, as it can be seen in Fig. 18b the leg returns to the initial point approximately every 500 frames.

4.3 Experiment 3: 3D Movement for Sequence 3

Finally, the third experiment intends to reconstruct the soft leg movement in three-dimensional space while activated by sequence 3. As in the experiment 1 and 2, in Fig. 19a, it is possible to observe the 3D movement of the soft leg, and in Fig. 19b, it is possible to observe the variation of z over time, and the cyclic movement performed in Fig. 19a. In sequence 3, the cycle repeats for 15 times during the period that the soft leg is moving, as it can be seen in Fig. 19b the leg returns to the initial point approximately every 300 frames.

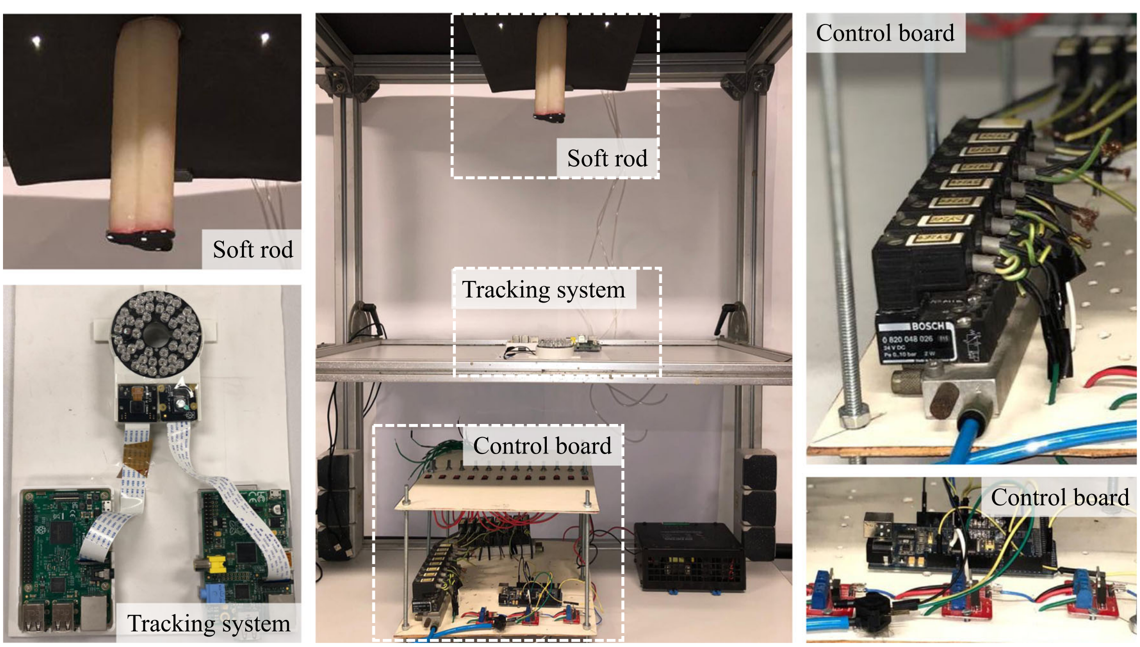

Fig. 15 Experimental bench

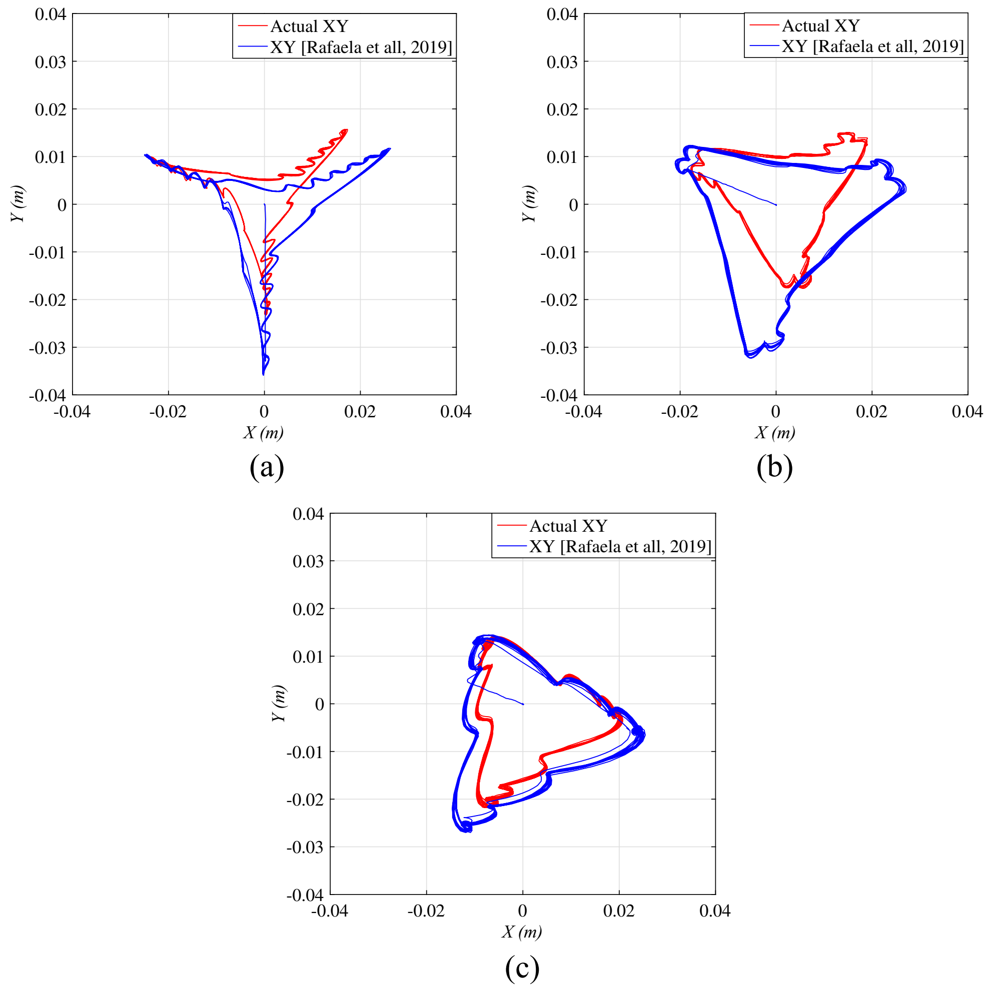

Fig. 16 Movement performed in a two-dimensional space by the soft leg in sequences 1, 2, and 3, respectively

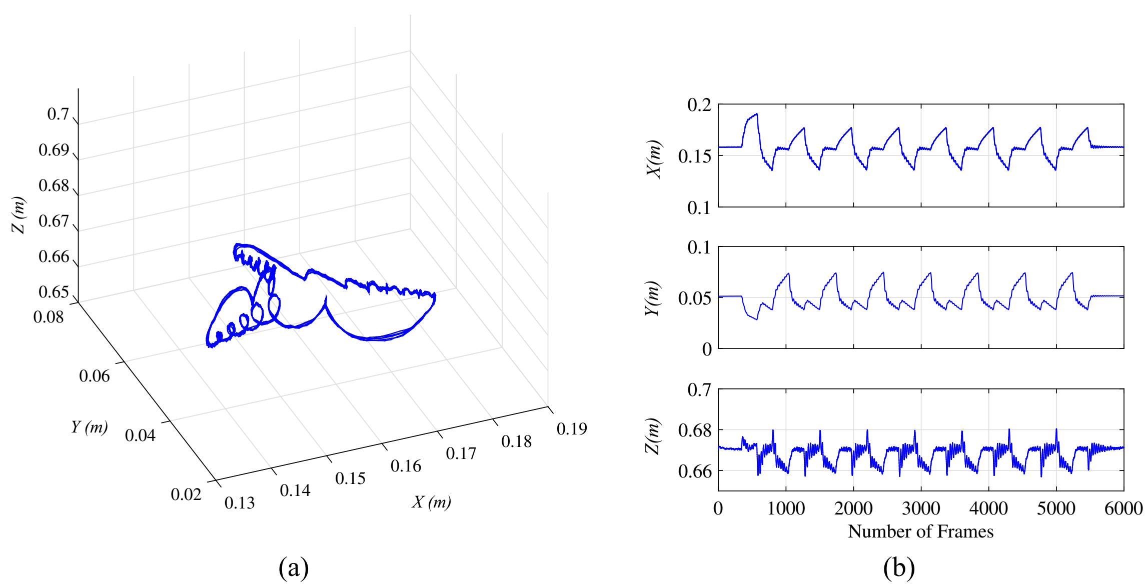

Fig. 17 **a** 3D Movement performed by the soft leg in sequence 1 **b** x, y and z over the frames

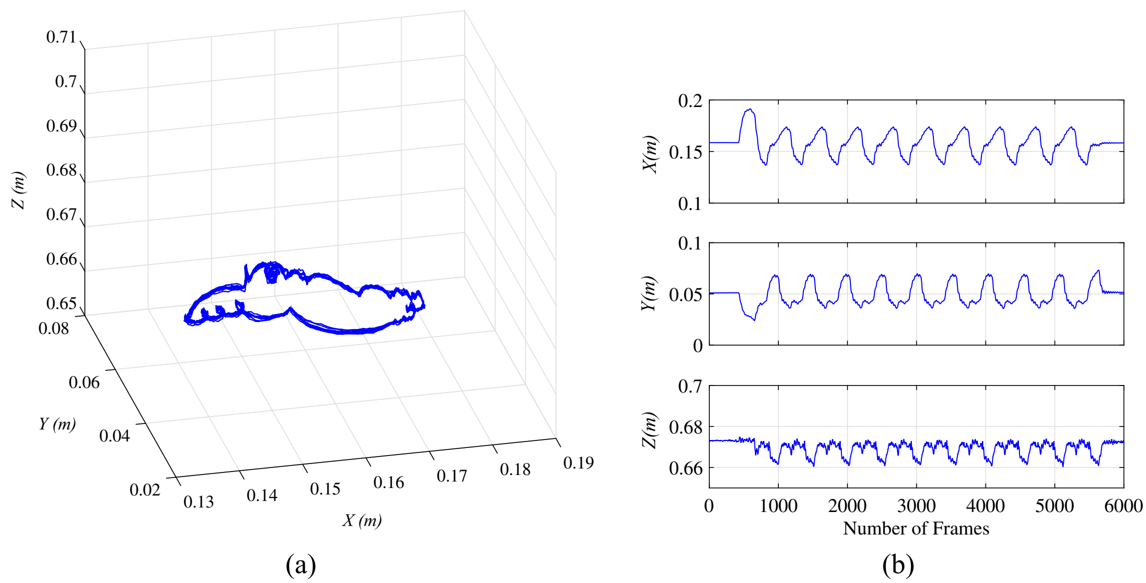

Fig. 18 **a** 3D Movement performed by the soft leg in sequence 2 **b** x, y and z over the frames

4.4 Analysis of Experimental Results

Comparing the three results, it is possible to observe that the 3D movement follows the same cyclic behavior that can be seen during the 2D movement (Fig. 16). Also, it is possible to see that during sequence 3, the depth variation tends to be smaller than in sequence 1 and 2, which occurs because the amplitude of the movement in the two-dimensional space tends to be bigger than in the other two sequences. That happens because the soft rod tends to expand more in the transverse direction thus not expanding much in the longitudinal direction. That same behavior can be seen in the sequence 1 since it has the smallest transverse movement, so its depth variation tends to be greater than in the other sequences. The rod's elastic property causes that when it expands in the transverse direction, then the expansion in the longitudinal direction tends to be smaller. The same is true when it expands more in the longitudinal direction.

A Moving Average Filter was applied in depth (z) results to smooth them and improve the visualization of the data.

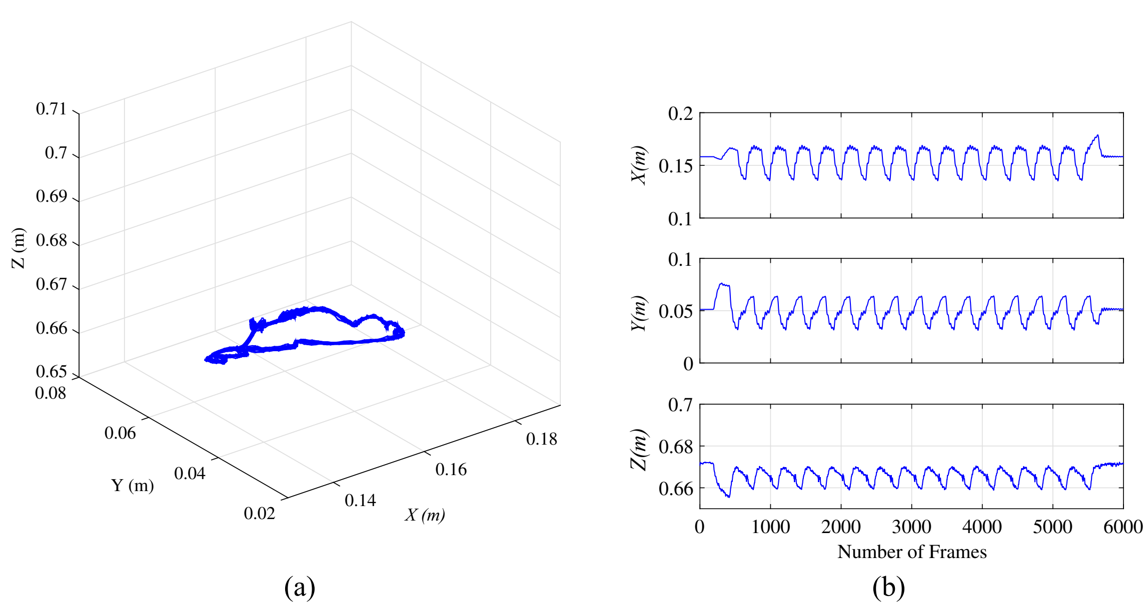

Fig. 19 **a** 3D Movement performed by the soft leg in sequence 3 **b** x, y and z over the frames

Comparing the filtered results and the non-filtered results were possible to see that the filter didn't change the results at all. It only reduced the noise caused by the system's natural vibration. Such noise is caused by a composition of several factors, including the natural vibration of the system caused by the opening and closing movement of the valves; the hyper-elastic constitution of the rod that vibrates at its own natural frequency; the z calculation method itself; and finally the vision system itself. For future work, it is suggested to separate these compositions and analyze each one individually to verify the one that generates more noise.

Also, considering that all the videos had the same duration (70 s), it is possible to see that sequence 1 is slower when compared to the other sequences. Sequence 1 returns to the initial point around every 1000 frames, and 7 cycles are completed during the total time. On the opposite side, the sequence 3 is the faster one since it completes 14 cycles during the total time, and the soft leg returns to the initial point around every 300 frames.

The results showed that it is possible to accurately recover the soft leg's 3D movement, using computer vision techniques without hard sensors attached to the soft mechanism.

5 Conclusions and Future Work

Soft robots are an emerging field of research in the robotics area due to their potential application in complex and delicate tasks. The reason relies on the fact that the mechanical characteristics that allow them to adapt to the environment. However, this area presents some challenges, such as the possibility of soft mechanisms needing to know the environment in which they are inserted into without hampering mobility. Therefore, this research presented the SMER as the activation method of soft rods used as legs in multi-legged robots.

In order to understand the behavior of the soft servomechanism under different configurations, a few experiments were proposed to verify the effectiveness of the SMER technique as an activation method. Another contribution presented in this research was the application of a computer vision technique to track and recover the developed robot's movement without reducing neither mobility nor flexibility.

This research opens a wide field of future studies. For instance, more studies regarding the system's mathematical modeling could be carried out to improve performance. Besides that, tests on varying device standards, as well as more studies related to the SMER approach can be performed.

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Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Rafaela Aparecida Garcia Sampaio, Fabrício Lopes e Silva and Cristiano de Souza de Carvalho. The first draft of the manuscript was written by Rafaela Aparecida Garcia Sampaio and all authors commented on previous versions of the manuscript. Introduction section, and Background and Related Works section were performed by Milena Faria Pinto and Diego Barreto Haddad. Vision-based tracking system section was performed by Gabriel Matos Araujo. The Activation Strategy section was performed by Cristiano de Souza de Carvalho and Felipe Maia Galvão França. All authors read and approved the final manuscript.

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Declarations

To ensure objectivity and transparency in research and to ensure that accepted principles of ethical and professional conduct have been followed, all authors provide these declarations statement bellow.

Ethics approval and consent to participate The authors have no conflicts of interest to declare that are relevant to the content of this article.

Consent for Publication All authors are consent to publish.

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