Design and development of peristaltic soft robot using Shape Memory Alloy actuators

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degree

of

BACHELOR OF TECHNOLOGY

in

MECHANICAL ENGINEERING

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CANDIDATE'S DECLARATION

I hereby declare that the project entitled **"Design and development of peristaltic soft robot using Shape Memory Alloys as actuators."** submitted in partial fulfillment for the award of the degree of **Bachelor of Technology** in **Mechanical Engineering** is an authentic work.

The project was supervised by **Dr. I. A. Palani, Associate Professor, Mechanical Engineering, IIT Indore**.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

Signature and name of the student(s) with date

CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the students is correct to the best of my/our knowledge.

Signature of BTP Guide(s) with dates and their designation.

PREFACE

This report on **“Design and development of peristaltic soft robot using Shape Memory Alloys as actuators"** is prepared under the guidance of **Dr. I. A. Palani.**

This report gives a detailed design of a Peristaltic Soft Robot which utilizes SMA based actuators for employing its locomotion mechanism and covers every aspect of the new design, if the design is technically and economically sound and feasible.

We have tried to the best of our abilities and knowledge to explain the content in a lucid manner. We have also added 3-D models and figures to make it more illustrative.

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Thank you,
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ABSTRACT

This report presents the study on "Design and development of peristaltic soft robot using Shape Memory Alloys as actuators." The report describes the inspired locomotion mechanism design of the soft robot based on earthworms. A mathematical model of the same is determined which is used to devise an optimum controlling methodology. The design principle is based on the antagonistic arrangement of radial and longitudinal muscle groups of Oligochaetes, a class of animals to which all the earthworms belong. Sequential antagonistic motion is achieved in a flexible braided mesh-tube made of PET (Polyethylene terephthalate) using nickel titanium (NiTi) coil actuators. Additionally, the capabilities of the robot including path tacking, steering in three dimensions and payload capacity are discussed. Utilizing additional NiTi coils placed longitudinally, steering capabilities in three dimensions are incorporated. Flex sensors and a camera were used to sense the kinematical parameters of the robots which enabled the development of closed loop controllers. The complete robot body is made of flexible materials and is resistant to impact failure. The approach used describes complete design, fabrication and control techniques for soft robots.

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Chapter 1

Introduction

1.1 Soft Robotics

Humans have often looked at biological systems for answers to engineering problems throughout our existence. Nature has helped us solve engineering problems such as self-healing abilities, environmental exposure tolerance and resistance, hydrophobicity, self-assembly etc. This art and science of designing and building biomimetic apparatus is known as biomimicry or biomimetics because they mimic biological systems.
Biomimetics is an interdisciplinary field in which principles from engineering, chemistry and biology are applied to the synthesis of materials, synthetic systems or machines that have functions that mimic biological processes. Bio mimetics, in the context of robotic engineering, concerns how to apply biological ideas and phenomena to robotics problems.

Bioinspired robots are a new class of biologically inspired robots that exhibit much greater robustness in performance in unstructured environments than today's robots. This new class of robots will be substantially more compliant and stable than current robots, and will take advantage of new developments in materials, fabrication technologies, sensors and actuators. Applications will include autonomous or semi-autonomous tasks such as reconnaissance and demining for small, insect-like robots and human interaction tasks at a larger scale.

Bioinspired robots are often made using soft and deformable materials like silicone, plastic, fabric, and rubber, shape memory alloy springs or compliant mechanical springs. Such soft robots can actively interact with the environment and can undergo “large” deformations relying on inherent or structural compliance due to their softness and other morphological features.
A disadvantage of soft robots is that their soft structures are difficult to model and, therefore, hard to control.
Current research in bio mimetics and soft robots:

1. **Soft actuator:**

FIGURE 1.1: Soft actuator

Soft fluidic actuators consisting of elastomeric matrices with embedded flexible materials (e.g. cloth, paper, fiber, particles) are of particular interest to the robotics community because they are lightweight, affordable and easily customized to a given application. These actuators can be rapidly fabricated in a multi-step molding process and can achieve combinations of contraction, extension, bending and twisting with simple control inputs such as pressurized fluid. These actuators are used in heart assist devices, soft robotic gloves. Mechanical intelligence can be embedded into these soft actuators to achieve desired performance requirements with simple control inputs.

2. **Squid like soft robot:**

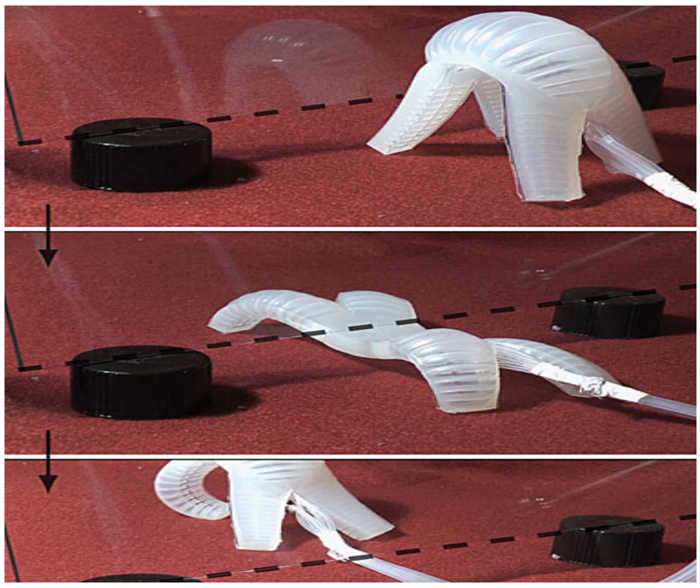

FIGURE 1.2: Pneumatic based soft robot inspired by squids

Scientists at Harvard University have developed an array of "soft" robots based on natural forms, including squid and starfish. When the "body" of the robot is inflated, it arches; when the "legs" are inflated, the robot stands up. Sequential pressurization and depressurization of the legs allows the robot to walk to a barrier (a glass plate). Deflation of the body decreases the height of the robot, and a different sequence of actuation of the legs gives it a kind of undulatory motion, and allows it to wiggle under the barrier. Once on the other side, re-inflation of the body allows it to resume its walk.

Octobot:

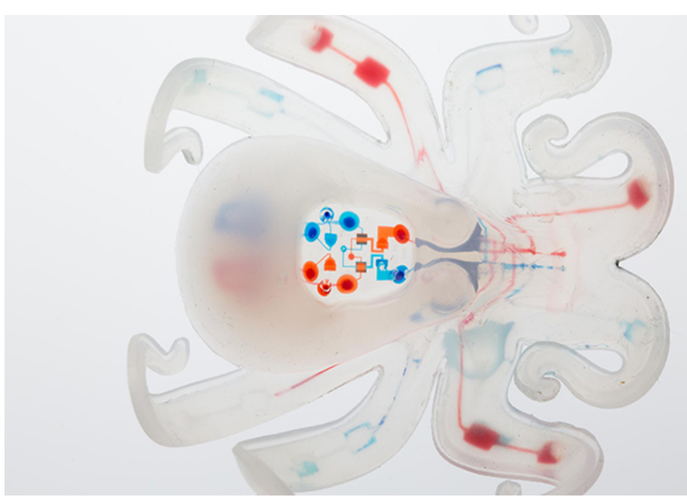

FIGURE 1.3: Octobot: First autonomous, entirely soft robot

The researchers at Harvard University have gone one step further by developing the first autonomous, entirely soft robot named ‘octobot’, powered by a chemical reaction and controlled by microfluidics, The robot is 3D-printed and has no electronics. Harvard’s octobot is pneumatic-based, and so is powered by gas under pressure. A reaction inside the bot transforms a small amount of liquid fuel (hydrogen peroxide) into a large amount of gas, which flows into the octobot’s arms and inflates them like balloons. Octopuses have long been a source of inspiration in soft robotics. These curious creatures can perform incredible feats of strength and dexterity with no internal skeleton.

Jellyfish:

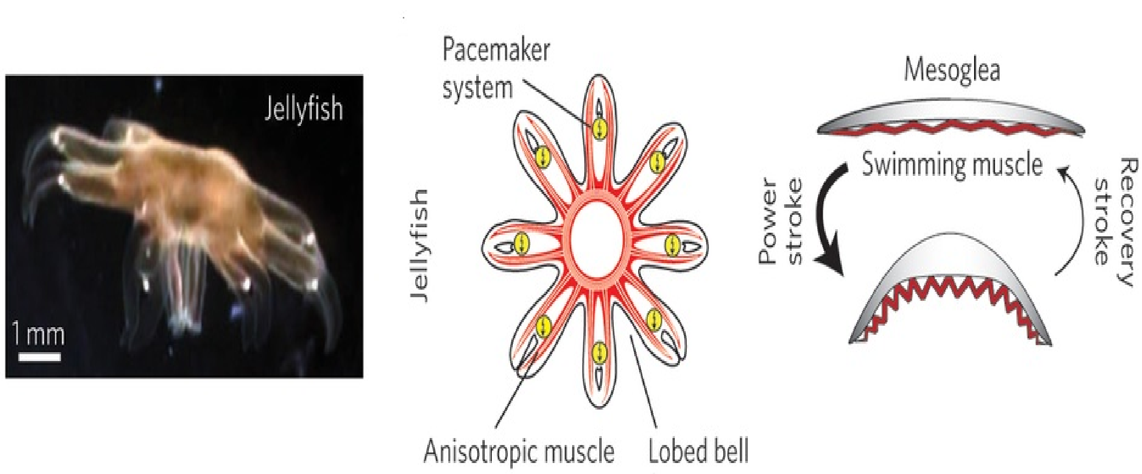

FIGURE 1.4: Soft tissue-engineered structure inspired by Jellyfish

Researchers at MIT have developed a polymeric tissue-engineered structure capable of swimming in a similar manner to a jellyfish is created by mimicking the structural design, stroke kinematics and fluid dynamics of the organism.

1.2 Peristalsis

Limbless crawling is a fundamental form of biological locomotion adopted by a wide variety of species, including the earthworm, snails and snake. To achieve a successful peristaltic locomotion certain elements are required. These are: Radial muscle, Longitudinal muscle and Coelom. As we can see from the figure the earthworm’s

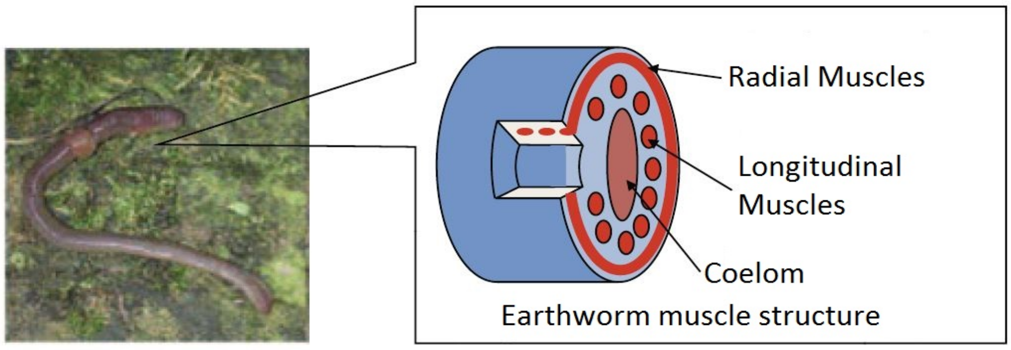

FIGURE 1.5: Muscles structure of earthworm

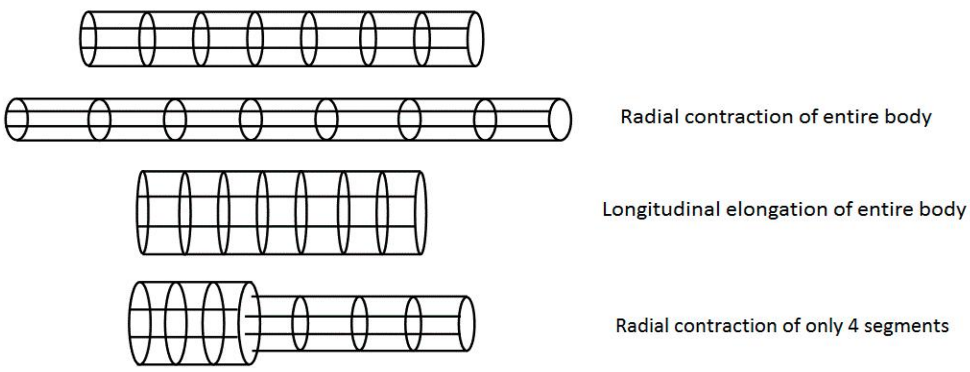

FIGURE 1.6: Earthworm muscle structure schematic

body consists of Radial muscles running in circles concentric to its circumference, Longitudinal muscle stretching along the length of the earthworm parallel to its body's axis, and the Coelom, whose function is to limit the maximum length of the earthworm. These muscles operate upon the liquid-filled body cavity or coelom, which acts as a pressurizable hydrostatic skeleton. With this liquid-filled divided cavity, earthworm segment deformation follows a constant volume constraint. Thus, the hydrostatic skeleton can be considered as an elastic tube that varies it radius and length subject to a fixed internal volume. Contraction of the radial muscles makes the earthworm thinner by reducing its body diameter but also elongates its body. Whereas contraction of the longitudinal muscles results in shortening of the body length and increment its body diameter. The earthworm's body is also divided into multiple segments.

Peristalsis locomotion operates by sending a contraction wave along the series of segment in the earthworm's body, which consecutively contracts the radial muscles in each segment. Now when this wave

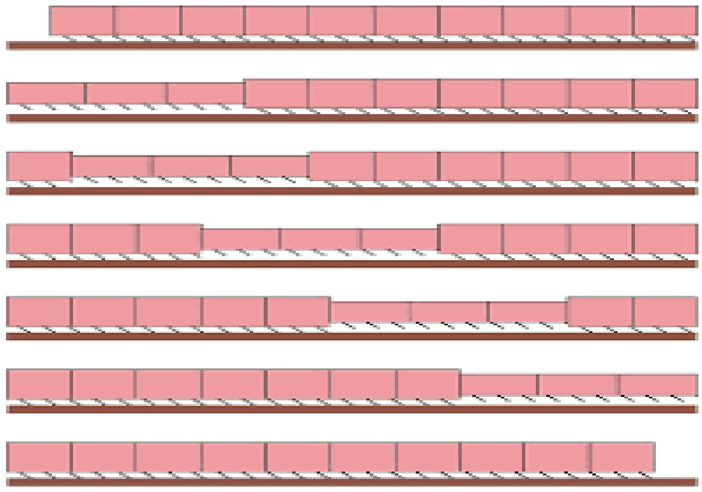

FIGURE 1.7: Contraction wave moving through the body of an earthworm

reaches a segment, its radial muscles contract, thinning that particular segment while also elongating it. However, now as this wave travels to the next segment, the next segment is made to contract. But the earthworm's body being under a total length constraint by the Coelom cannot have two segments elongated at once. The Coelom couples one segment's deformation to another. Here the longitudinal muscles of the previous segment kick in and act to shorten the length of the previous segment, thereby allowing the next segment to elongate without any obstruction.

In this way the Radial muscle and Longitudinal muscle act antagonistically. By contracting the segments sequentially we can successfully achieve peristalsis. As the contraction wave moves along the segments of the earthworm, the earthworm shows a net displacement. Depending upon the characteristics of this contraction wave the earthworm can control its speed.

Chapter 2

Design

2.1 Shape Memory Alloy

A Shape Memory Alloy (SMA) is a material that "remembers" its original shape and that when deformed returns to its pre-deformed shape when heated above its actuation temperature. The two main types of shape-memory alloys are copper-aluminium-nickel, and nickel-titanium (NiTi) alloys but SMAs can also be created by alloying zinc, copper, gold and iron. NiTi alloys are more popular and widely used.

“Shape Memory Effect" refers to the effect of restoring the original shape of a plastically deformed SMA by heating it. This phenomenon results from a crystalline phase change known as “Thermoelastic martensitic transformation. At temperatures below the transformation temperature. SMAs exist as martensitic. This martensite state is soft and can be deformed quite easily by applying a force, a process called de-twinning. Heating above the transformation temperature converts the SMA to its high strength austenitic state and recovers the original (remembered) shape in this process.

Depending upon the composition of the material, SMA can show two types of shape memory effect.

a. **One-way memory effect** : When a SMA is below its transition temperature (martensite state), the metal can be bent or stretched (detwinned) and will hold those shapes until heated above its transition temperature. Upon heating, the shape changes to its

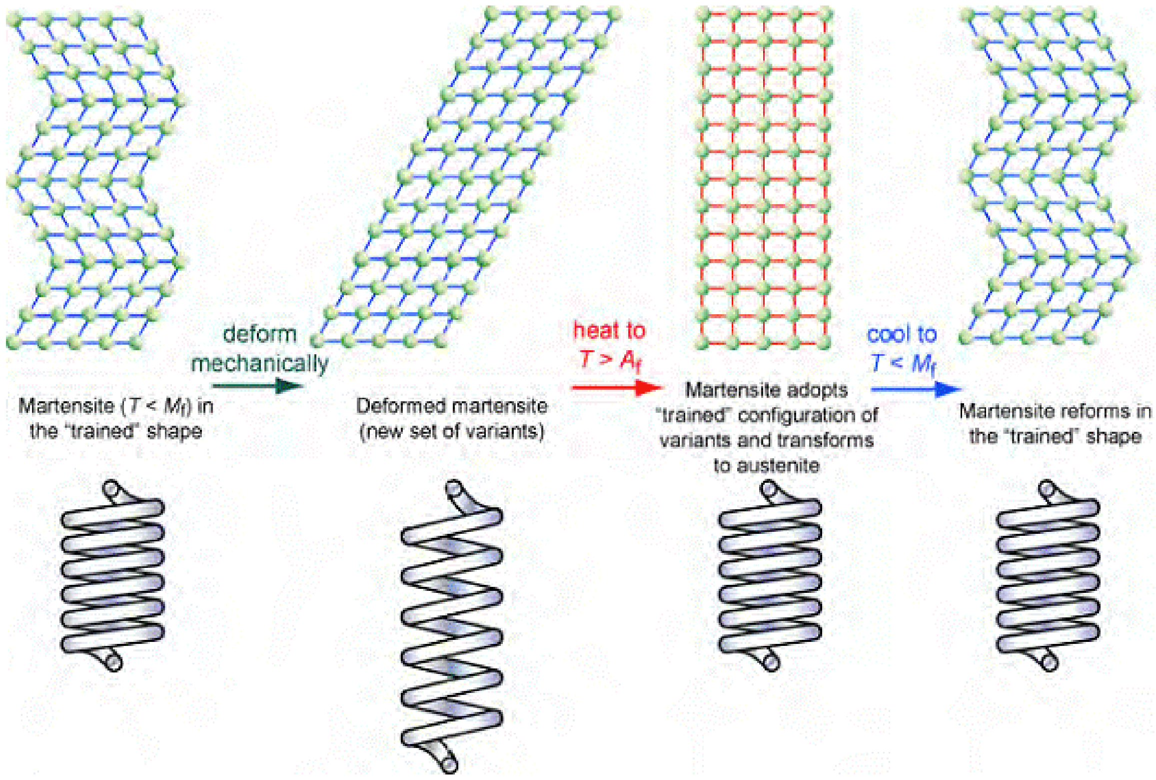

FIGURE 2.1: Four representative states of a NiTi coil spring actuator. From left to right: Twinned Martensite state, detwinned Martensite state, Austenite state, Twinned Martensite state.

original. Now when the metal cools again it will remain in the memorized shape, until deformed again. With the one-way memory effect, cooling from transformation temperatures does not cause a macroscopic shape change.

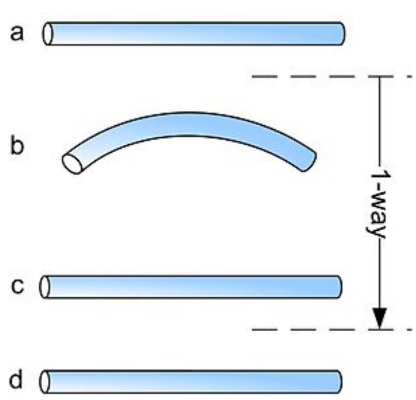

FIGURE 2.2: One-way shape memory effect of SMA

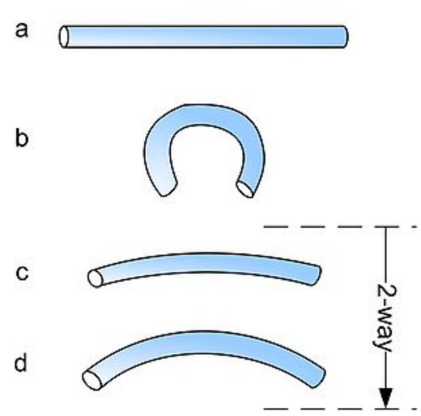

FIGURE 2.3: Two-way shape memory effect of SMA

b. **Two-way memory effect** : In two-way shape memory effect the SMA remembers two different shapes: one below the transformation temperatures, and one above the transformation temperature. Upon heating or cooling the SMA can shifts is shape. Due to this unique property shown by Shape Memory Alloys they find their use in a lot of different applications.

Some applications of SMAs are:

- Medical - Orthodontic wire, Biliary stent, Regional-chemotherapy, Endoscopic guidewire
- Aerospace Engineering - Cryofit, Frangibolt, Pin puller
- Automobiles and Trains - Oil controller, Steam tap
- Construction - Underground ventilation, Static rock breaker

There are also some limitations on the use of the SMA.

- Heat dissipation is slow. External cooling is required for fast applications.
- Range of motion is limited to shape change of the material.
- Stiffness/Flexibility: Stiffness increases at low (room) temperature.
- Relatively expensive to manufacture and machine compared to other materials such as steel and aluminium.
- Most SMAs have poor fatigue properties; this means that while under the same loading conditions (i.e. twisting, bending, compressing) a steel component may survive for more than one hundred times more cycles than an SMA element.

2.2 Components used for the Soft Robot

Earthworm body parts	Robot body parts
Radial muscles	NiTi springs actuators
Longitudinal muscles	Braided mesh tube made of PET
Coelom	Longitudinal, flexible, tendons
Brain	Raspberry Pi

TABLE 2.1: Analogy derived in the soft robot from real earthworm

1. **Polyethylene terephthalate (PET) body :** The main body of the soft robot housing all of its components was made out of PET mesh tube. This same mesh tube also acts as the Longitudinal muscles. This mesh tube is a similar to hollow pipe in its appearance and is made by the braided and interlaced structure of numerous PET fiber strands. PET is a thermoplastic material, meaning that it can be easily reshaped by providing sufficient heating. The required form of mesh tube was obtained by annealing the tube around a solid metal core of desired diameter at a temperature of 220 degree celsius for about 15 minutes. This annealing process provides a new permanent form by resetting the diameter to our requirement. After the annealing process the final unloaded diameter of the PET mesh tube was 45 mm. The unloaded length of this mesh tube was 150 mm.

2. **SMA springs :** NiTi springs discussed in the previous chapter were used for making Radial muscles. A single NiTi spring was

(a) Unannealed PET (b) Metal core used for annealing PET (c) Final annealed state of PET

FIGURE 2.4: Annealing Stages of PET

used for each segment. The solid length of the NiTi spring was L1 = 1.02 cm, wire diameter was d1 = 0.51 mm, the coil diameter was D1 = 3.45 mm and the number of coils was N1 = 20. These NiTi springs had an actuation temperature of about 90 degree celsius. These NiTi springs used were one way actuated, meaning that they could apply force in only one direction. To restore these springs back to their original state external force was necessary.

3. **Bias springs :** The external force needed to restore the NiTi spring is provided by a Bias spring. A single compression spring is used as a Bias spring in each segment. The length of the Bias spring was L2 = 45 mm, wire diameter was d2 = 1.2 mm, the coil diameter was D2 = 20 mm and the number of coils was N2 = 11. These Bias springs were made out of music wires.

4. **Tendon :**

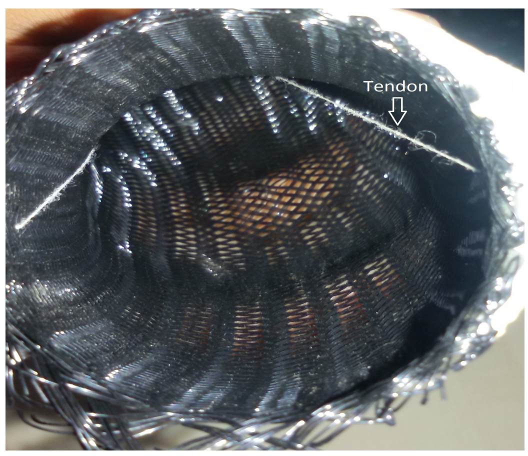

FIGURE 2.5: Thread used as tendon analogous to earthworm coelum

A tendon, made of a flexible, non stretchable thread is used for imposing a length constraint on the robot. As discussed in the previous chapters PET mesh tube was chosen as the body of the soft robot PET-worm. This single mesh tube was divided into three segments each of 5 cm length. Inside of each segment, at approx. in its middle a coaxial configuration of NiTi spring and Bias spring was fitted which were to act as the Radial muscles.

2.3 Design of the Soft Robot

In this configuration the NiTi spring was placed coaxially inside of the compression Bias spring which had a larger diameter than that of the NiTi spring. The length of the Bias spring was chosen such that when the configuration was not actuated, the Bias spring

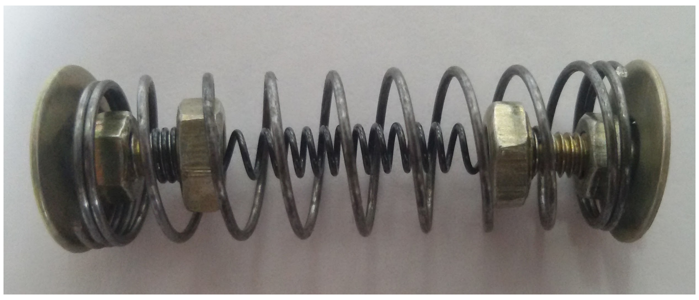

FIGURE 2.6: NiTi spring - Bias spring configuration

exerted a greater force on the NiTi spring and caused it to extend to a length of 45 mm. However, when this configuration was actuated by passing a current through it, the NiTi spring exerted a stronger force on the Bias spring compressing it to a final length of 30 mm. When the current flow was stopped and the NiTi spring was allowed to cool down, the configuration returned to its original length of 45 mm under the force exerted by the bias spring.

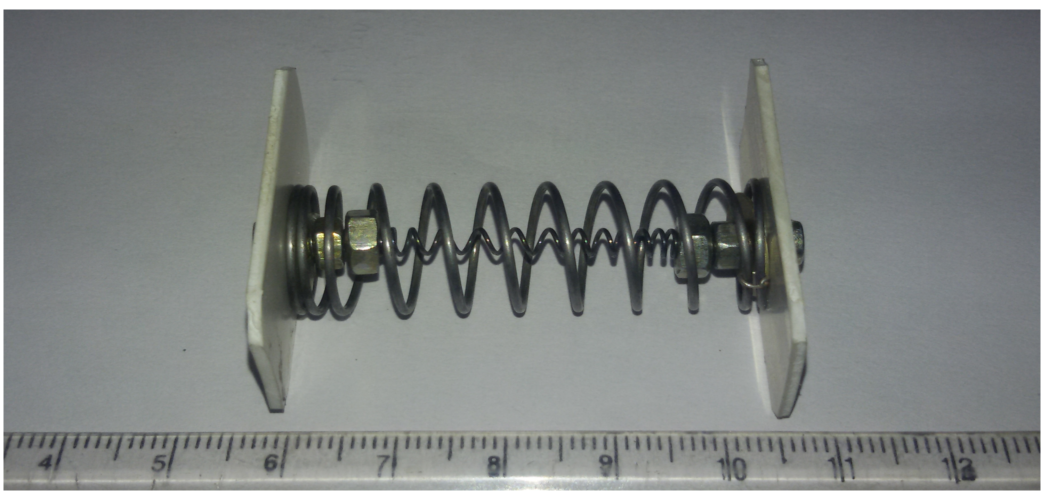

FIGURE 2.7: NiTi spring in unactuated state

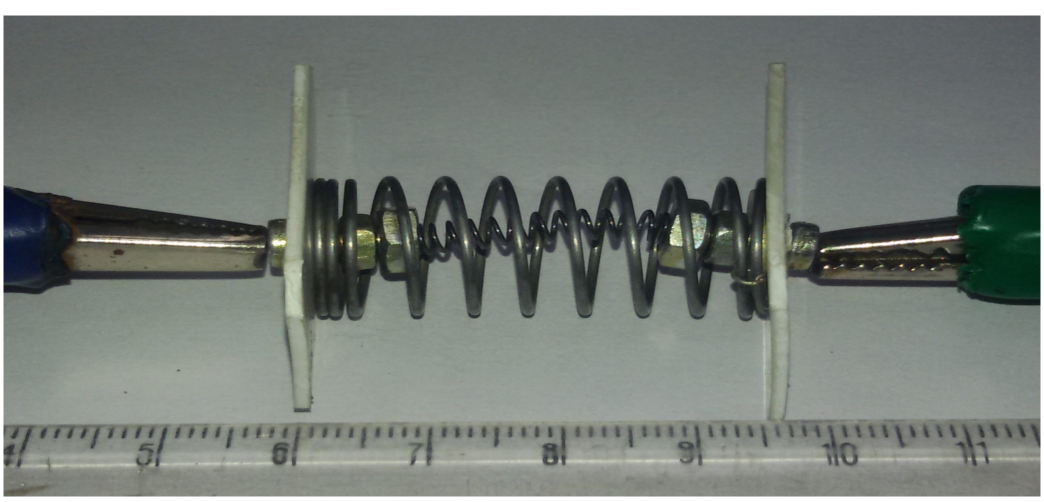

FIGURE 2.8: NiTi spring in actuated state

With the help of small nut and bolts this setup was fitted inside of the PET mesh tube such that the ends of the NiTi spring - Bias spring configuration were at two diametrically opposite points.

On the outside ends of this configuration, a rectangular fiber plate of dimension 30mm * 20mm was attached which facilitated an even distribution of the radial force exerted by the NiTi spring - Bias spring configuration on the PET mesh tube while under actuation. Duplicating this same setup for each segment we got the Radial muscles in place.
Two tendons running parallel to the length of the PET-worm were attached from the inside such that each of them was always diametrically opposite to the other. These tendons were fastened with the help of nuts and bolts to the PET mesh tube. The length of the tendon was equal to the the length of the mesh tube with only one segment actuated at a time.

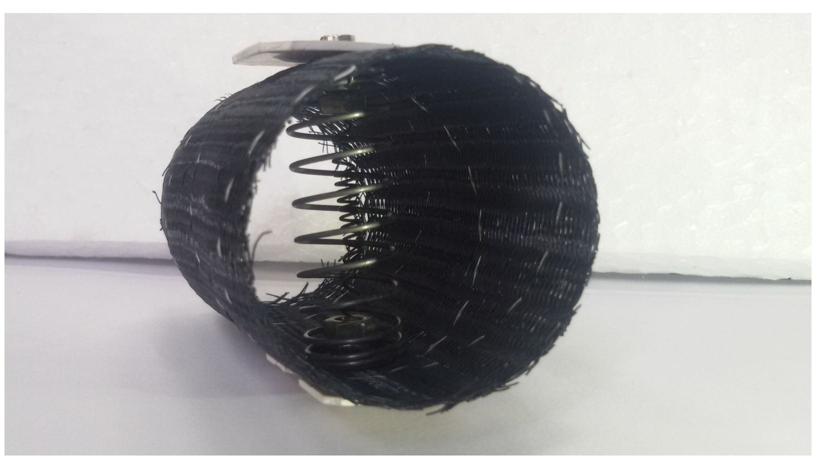

FIGURE 2.9: NiTi spring in PET

Since shape memory actuation is a thermal process, the actuators were electrically driven by Joule heating. A rapid large pulses of current, in comparison to longer small current signals. This was done to avoid prolonged heating of the NiTi spring which could damage the NiTi spring itself and the PET mesh tube by inducing permanent deformations.
As the NiTi springs of a given segment contracts, the segment elongates and this leads to the longitudinal contraction of the

remaining segments because of the length constraint imposed by the tendons. When the current flow is stopped in the NiTi spring, the Bias spring restores the segment to its original state. The NiTi spring in the first segment (1) actuate, contracting the mesh tube radially and expanding it in the longitudinal direction and effectively moving the robot a step forward. The total length constraint by the tendons causes the last segment (3) to contract longitudinally. This arrangement induces the necessary antagonism between the deformation in longitudinal and radial directions. Repeating this process of sequential actuation of all the segments, the robot moves forward by Peristalsis.

Chapter 3

Experimentation and Results

3.1 Experiment Setup :

3.1.1 SMA modelling setup:

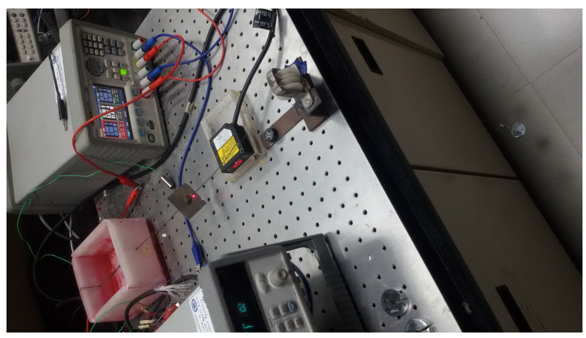

FIGURE 3.1: SMA spring model evaluated on thermo-mechanical test bench

Before experimenting on the robot, some preliminary analysis of the SMA actuatur was carried out. Following was the result recorded for the spring for displacement time relationship. By system

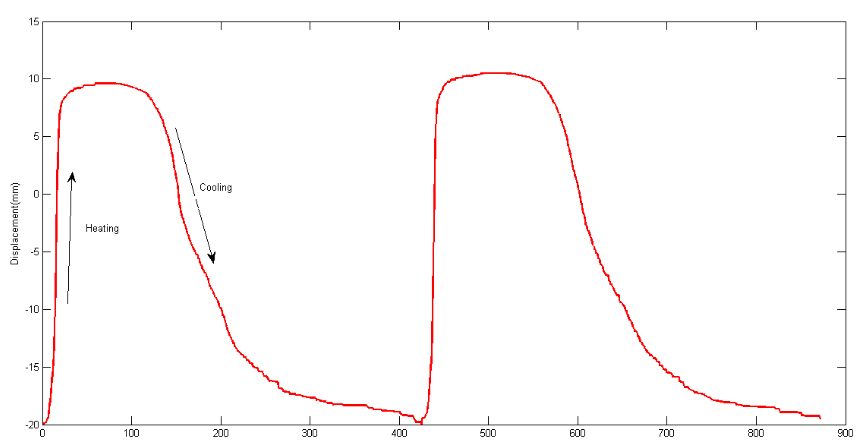

FIGURE 3.2: Displacement-time relationship for SMA spring.

identification techniques SMA's transfer function was found as

$$H(s) = \frac{0.6146}{1481s + 1} \tag{3.1}$$

3.1.2 Soft Robot:

The experiments on the robot were carried out using Matlab and Raspbian environments. Programmable power supply was used as a power source during experimentation while data was logged onto a Data Acquisition System(DAQ).

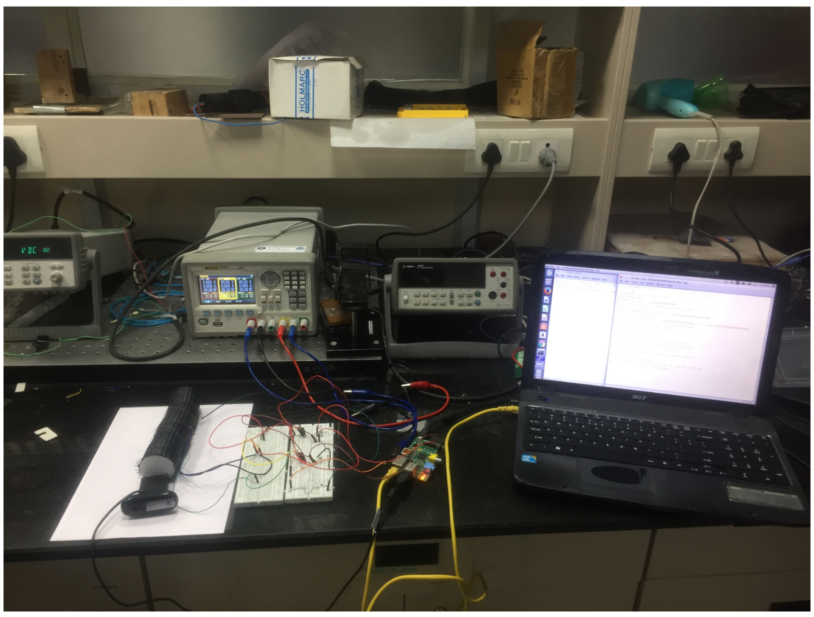

FIGURE 3.3: Experiment setup for observing the response of the robot.

A camera feed was utilised as feedback for the system so as to enable the robot to alter its course. The feedback was given to Raspberry Pi which helped in performing the controlling methodologies.

3.1.3 Circuit

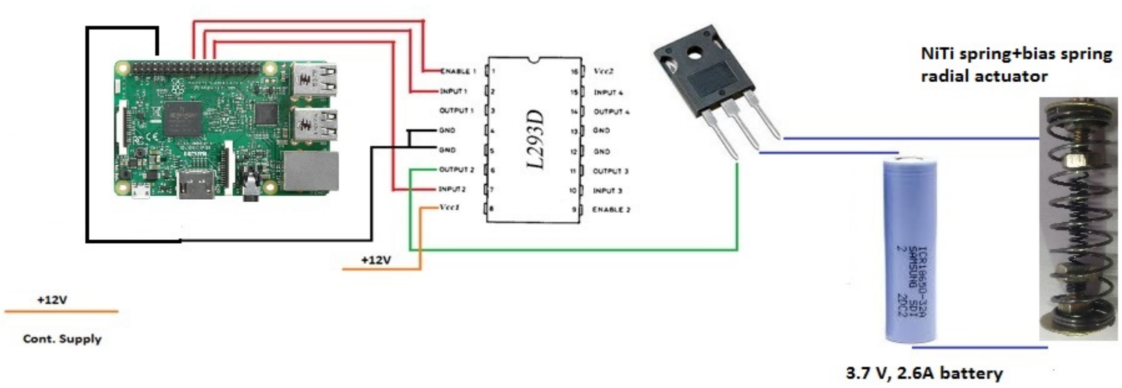

FIGURE 3.4: Circuit Diagram

The electronic circuit consists of Raspberry Pi, the main controller for the robot, which sends control signals to a motor driver which drives the MOSFET. MOSFET uses a separate actuation power line from small Li ion batteries to power individual NiTi springs.

3.2 Mathematical modelling :

Step	Percent fit %
6V	83.52
5V	91.68
4V	85.62

TABLE 3.1: Fit percent with the step response

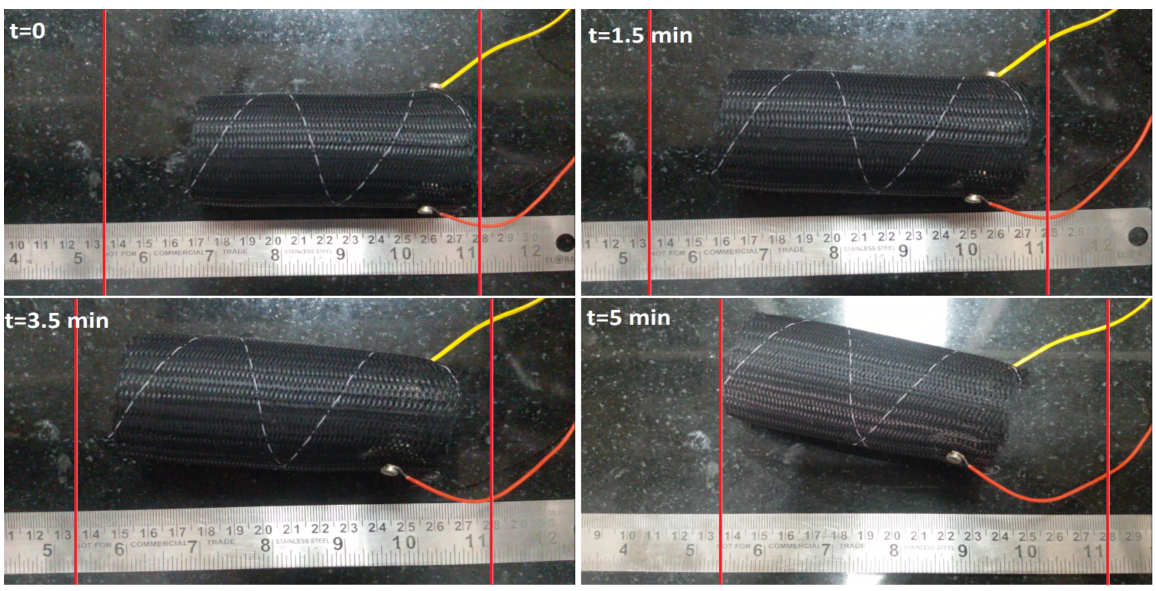

FIGURE 3.5: Snapshots depicting the longitudinal movement of the robot. Side-slippage can be seen as the robot drifts rightwards in each frame.

Step input response of the PETworm was studied for two segments. It can be seen that the maximum elongation of the second segment is less than that of the first segment. This is because of the extra weight that the second segment has to push.

To design a high-performance feedback control system, it is very helpful to have a dynamic model of the robot (the system being controlled); in this case, a model relating the elongation of a segment of the PETworm to the applied voltage. As the robot was made using soft materials it was difficult to model it using first principles. So we used the concept of system identification.

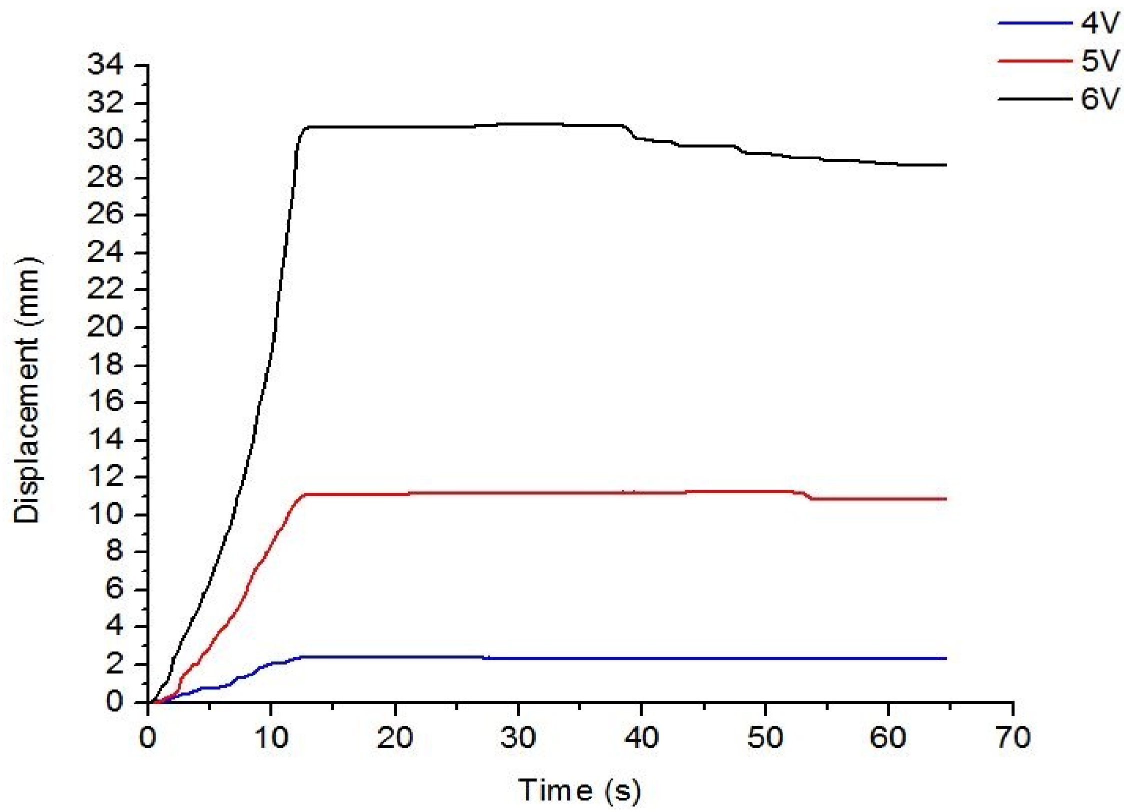

FIGURE 3.6: Longitudinal Elongation of first segment

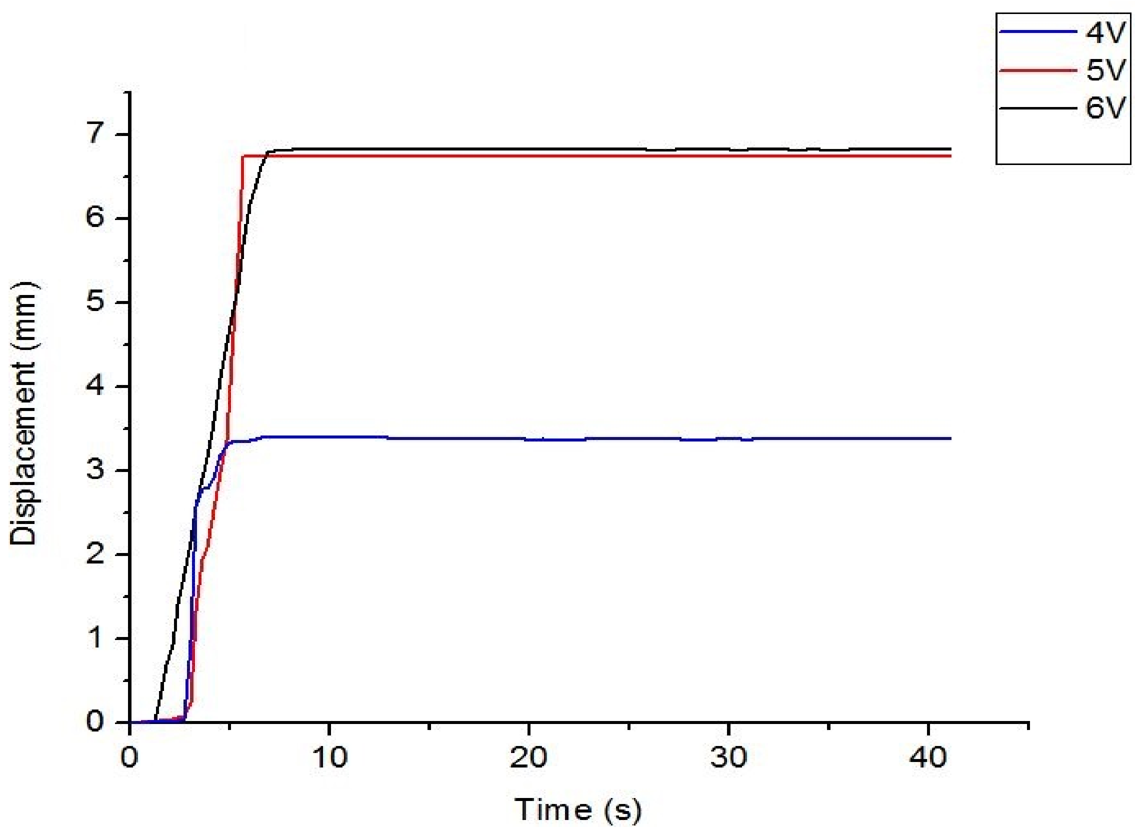

FIGURE 3.7: Longitudinal Elongation of second segment

A time domain approach was used to identify the robot model. Multiple experiments were carried out and the data was fit into transfer functions of increasing orders. The linear-behaviour-assumption is justifiable since small-signal behaviour of SMA is relatively linear and exhibits relatively little

hysteresis.
System Identification Toolbox in MATLAB was used to calculate the coefficients of the transfer functions. It was found that the percent fit in the second order transfer function (with no zeros) was significantly higher than the other transfer functions. We also observed that the percent fit decreased drastically for system orders greater than four.
The discrete transfer function for the robot was found to be:

$$H(z) = \frac{0.009}{1 - 1.922z^{-1} + 0.9263z^{-2}} \tag{3.2}$$

Chapter 4

Robot Capabilities

Advances in soft and smart materials, compliant mechanisms, and non-linear modelling have led to a more and more popular use of soft materials in robotics worldwide. A series of soft robots based on pneumatic actuation have been developed.
The soft robot was equipped with certain faculties so as to enable it to interact effectively with the environment. The SMA actuators were incorporated facilitating the robot to move smoothly.

4.1 Steering

Robot was provided with muscles to allow it to alter its coarse in a plane. Made of the same NiTi coil spring actuators, these muscles can actively change the length of one side of the robot to induce a rotational bias to the locomotion direction.The contraction of one of the steering muscles transforms the motion axis by creating a uniform bending curvature of the body. Therefore, assuming no side-slippage, the robot is constrained to follow the arc created by its own body. Given the radius of curvature ρ, the angular speed of the robot is written using the linear speed of the arc-

$$\omega = v/\rho \tag{4.1}$$

To force these actuators to work consistently, we utilize feedback control. Two closed cloop systems were devised empowering the bot to steer and follow a path on a plane.The following approach was followed for detecting the path to be tracked by the robot-

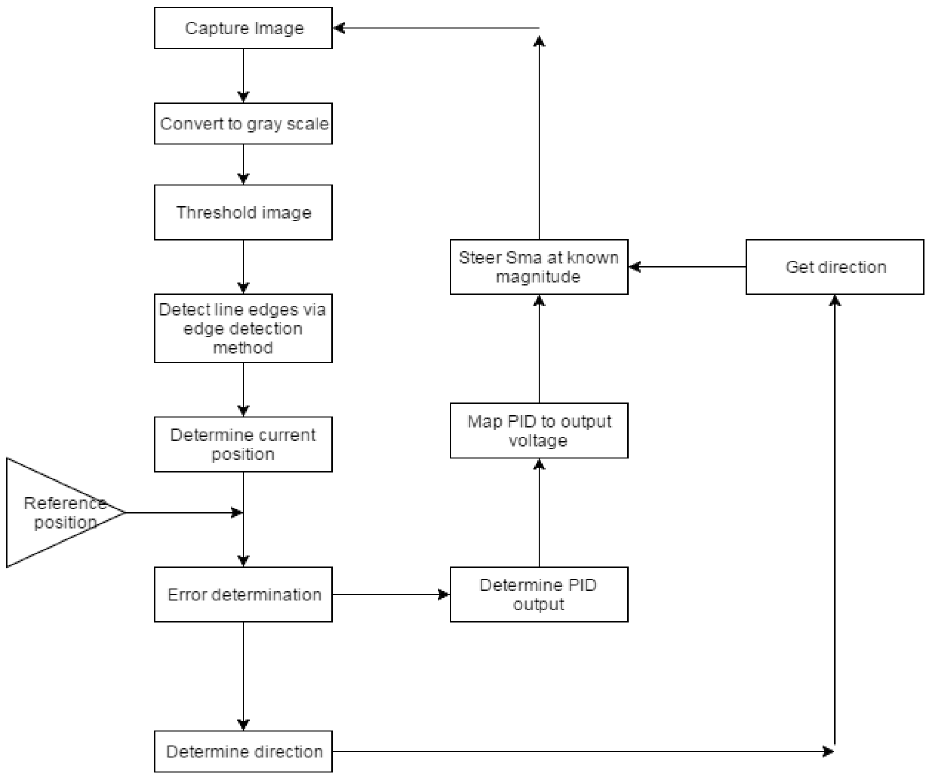

FIGURE 4.1: Control logic for robot

4.1.1 Steering

Flex sensor- The flex sensors were used as a steering feedback. On actuating one of the muscles, the flex sensor, bent along the arc created by the PETworm body. Bending of the sensor was used to determine how much has the front segment displaced angularly with respect to the rest of the body.

FIGURE 4.2: Flexsensor attached to the mesh

4.1.2 Path tracking

A camera mounted in front of the robot provided with real time feed which worked as a feedback to the path tracking mechanism. The simplest closed loop controller uses a bang-bang control algorithm. The controller based on the vision feedback decides the direction of the path with respect to the orientation of the bot and determines which of the actuators to actuate.

Along with a bang-bang controller, another closed loop controller used was that of Proportional IntegraL Derivative (PID) controller for controlling the robot. The output was supplied proportional to the pixelated error found from computer vision. The output was then mapped to give particular voltage values.

The vision feedback was evaluated using image processing techniques. First, a region of interest was marked. Then, the tracked path was determined using thresholding. This allowed to get the centre of the path which was taken as the reference to compare with the current orientation of the robot.

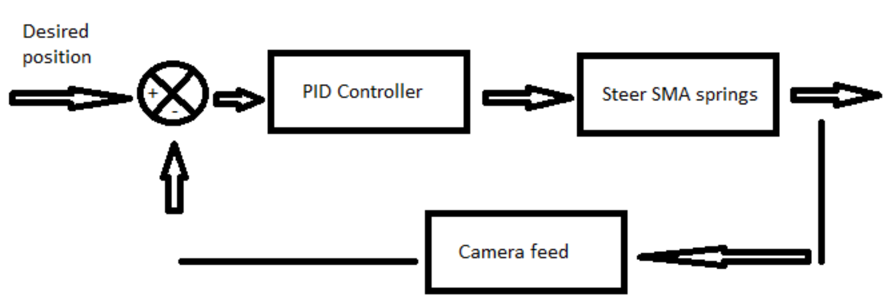

FIGURE 4.3: Steering logic

FIGURE 4.4: PID control via Computer Vision

After determining the direction, the controller, thereby turns on the NiTi spring for a fixed period allowing the robot to steer in the desired direction.

4.2 3D Motion

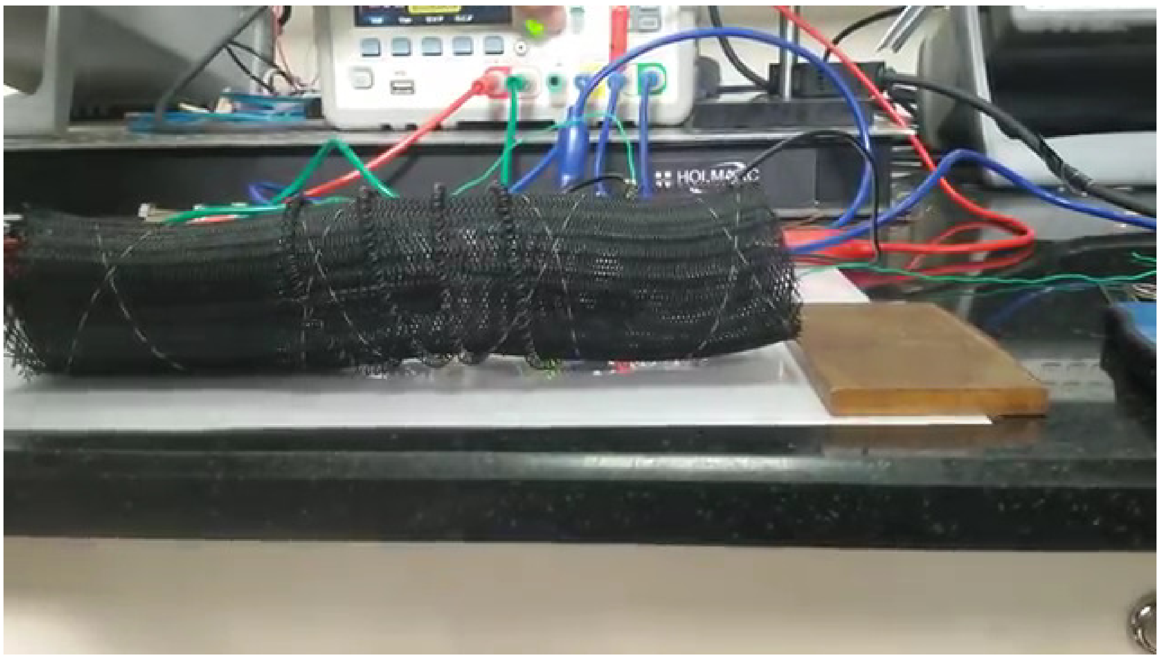

FIGURE 4.5: At t=0 min, 3D steering springs are actuated

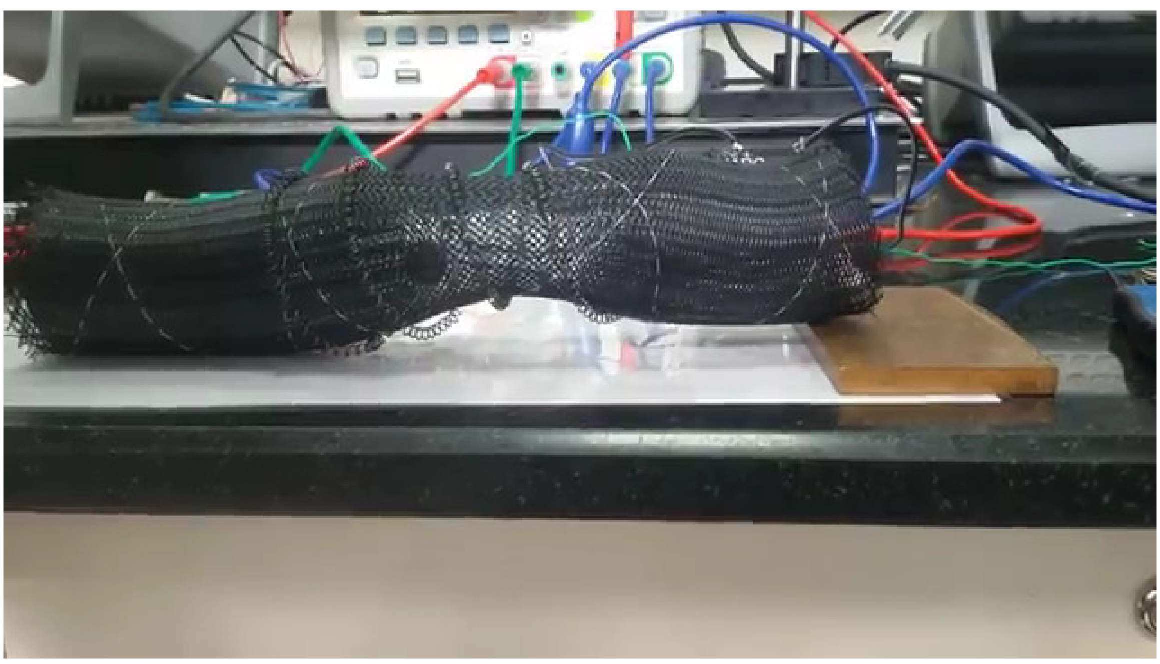

FIGURE 4.6: At t=0.5 min, robot is found to traverse a upwards displacement of 15mm

For 3D motion, the robot utilised NiTi SMA springs tied longitudinally to its surface over top and bottom. This allowed the robot to traverse in three dimensions. The NiTi coils were heated again and followed the same principle as before.

4.3 Payload determination-

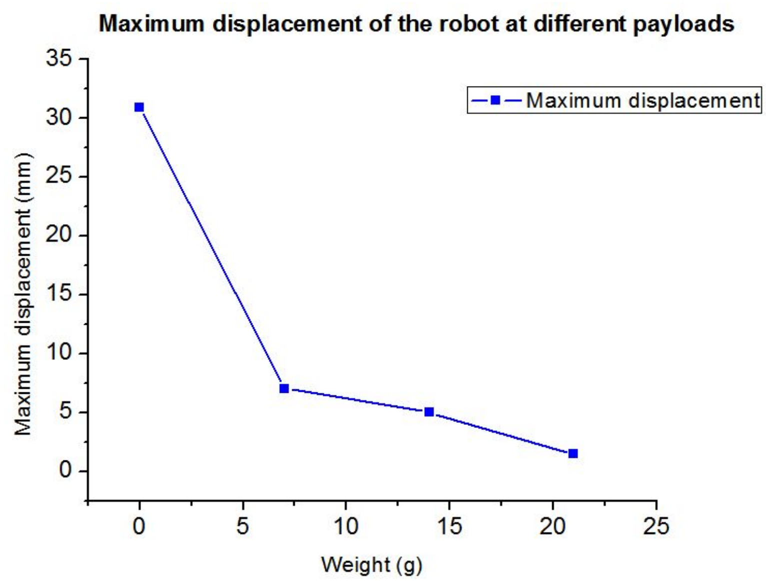

FIGURE 4.7: Displacement of the first segment at different payloads

The robot was found to be capable of carrying a load of 30 grams. The robot was loaded with different loads at the second segment and the displacement of the first segment was observed. The figure shows the observed displacement of the first segment at different loads.

Chapter 5

Conclusion and Future Scope

5.1 Conclusion

Our project successfully demonstrated a completely soft robot capable of peristaltic locomotion thereby mimicking a biological earthworm. Using NiTi springs and bias metallic springs as actuators and the inherent antagonism of the soft braided mesh body made of PET, robot propels itself by sending a traveling contraction wave over its segments. The robot moved at a speed of 1cm/minute. It was capable of handling 30 grams of payload per segment. Steering capability was incorporated to the robot by using four longitudinal springs on four sides of the robot body which gave the robot a maximum of 30 degrees of steering angle in xy plane and 15 degrees in the vertical plane. A miniature camera was also attached which gave live feed of the robot's environment. Using computer vision techniques, the robot could track paths which gave it a certain degree of autonomy.

Mathematical model of the robot was developed to aid in development of robust controllers. System Identification techniques were used to identify the dynamics of the robot. The robot was found to be approximately linear in second order. The obtained model allowed us to successfully apply well developed control techniques that are primarily used for rigid robots thus expanding the potential of the field of control theory for robotics.

As mentioned, some side-slippage occurs due to the lack of friction normal to the body axis. A gripping mechanism can be designed using suction cups to keep the robot on its desired trajectory. The locomotion speed can be increased by increasing the number of segments and using the gripping mechanism to prevent backward slippage which occurs due to insufficient number of segments making contact with the ground. These issues can also be addressed by considering the target locomotion gait algorithm into robot design and adjusting the radius and length of the robot for improved performance. Frequency domain model identification techniques can be used to obtain accurate robot model as AC behaviour of SMA is more repeatable and therefore more reliable, than DC behaviour.

5.2 Future Scope

As mentioned, some side-slippage occurs due to the lack of friction normal to the body axis. A gripping mechanism can be designed using suction cups to keep the robot on its desired trajectory. The locomotion speed can be increased by increasing the number of segments and using the gripping mechanism to prevent backward slippage which occurs due to insufficient number of segments making contact with the ground. These issues can also be addressed by considering the target locomotion gait algorithm into robot design and adjusting the radius and length of the robot for improved performance. Frequency domain model identification techniques can be used to obtain accurate robot model as AC behaviour of SMA is more repeatable and therefore more reliable, than DC behaviour.

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Appendices

Appendix A

Robot Steering

A.1 Computer Vision

The path tracking was employed by capturing the image feed. From the captured image, a region of interest was carved. The processing techniques were applied on this region only. The RGB image was then converted to grayscale. A greyscale image only has the intensity information and thus, contains only a single value at a pixel. Unlike one-bit bi-tonal black-and-white images, grayscale images have many shades of gray in between.

Thresholding-

For segmentation thresholding was used. From a grayscale image, thresholding can be used to create binary images. It replaces each pixel in an image with a black pixel if the image intensity is less than some fixed constant T, or a white pixel if the image intensity is greater than that constant. For example, the image below first is converted to a greyscale image which is thereby, is converted to a binary image.

FIGURE A.1: Original image

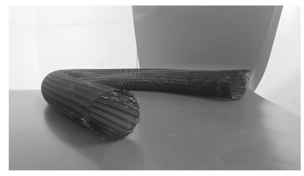

FIGURE A.2: Grayscale image

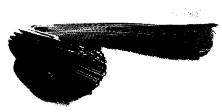

FIGURE A.3: Binary image

A.2 Python Code for Raspberry Pi for camera feeedback

```
def get_cverror(desired_pos=0,setpos=False):

########get image error by seeing how far the black line is fro
        cam1 = cv2.VideoCapture(0)
        ret,img1=cam1.read()
        cam1.release()
        reached=False
        curr_pos=0
        pos1=numpy.zeros((121))
        pos2=numpy.zeros((121))
        hits=numpy.zeros((121))
        size=img1.shape
        roi=range(180,301),range(size[1])
        img2=img1[180:301,range(640)]
        img2=cv2.cvtColor(img2,cv2.COLOR_BGR2GRAY)
.       ret,img2=cv2.threshold(img2,100,255,cv2.THRESH_BINARY_I
        for row in range(len(roi[0])):
            mat=numpy.diff(img2[31,:])
            for col in range(639):
```

```
                if(mat.item(col)!=0):
                    if (not reached):
                        pos1[row]=col
                        reached =True
                    else:
                        pos2[row]=col
                    hits[row]+=1
        curr_pos+=(pos1[row]+pos2[row])/2
    curr_pos/=len(roi[0])
    img3=img
    cv2.line(img3,(int(current),180),(int(current),301)
    cv2.imwrite('a.jpg',img)
    cv2.imwrite('b.jpg',img2)
    cv2.imwrite('c.jpg',img3)
    print("The centre position is {0}".format(curr_pos)
    if (setpos==True):
                desired_pos=curr_pos
                return curr_pos
    else:
                error=desired_pos-curr_pos
                if error<0:
                        GPIO.output(3,1)     ###Go right
                elif error>0:
                        GPIO.output(4,1)     ###Go left
                return error
```

A.3 Flex sensor analog feedback

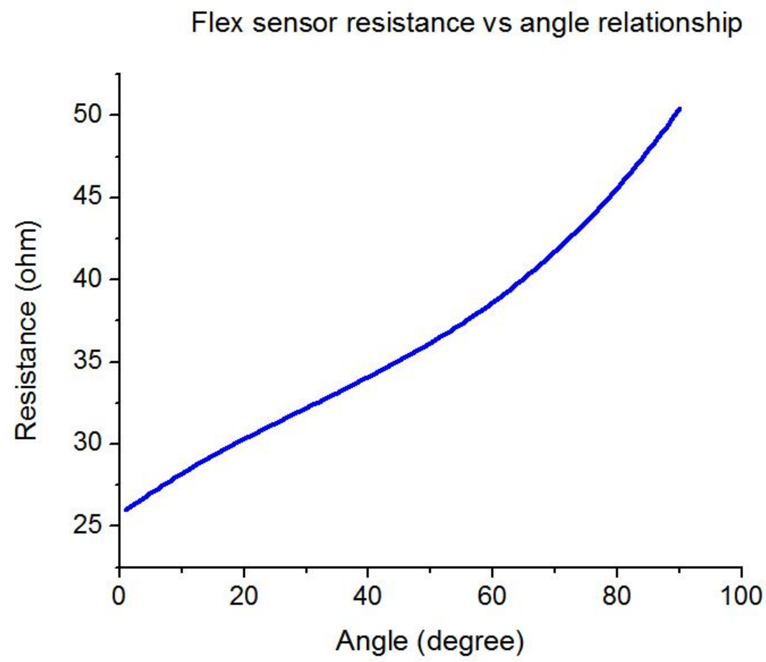

FIGURE A.4: Angle-resistance relationship for the flex sensor.

Flex sensor was used for getting feedback for 2-D steering mechanism. A flex sensor transforms angular displacement into resistance value. For determining the non-linear relationship, an experiment was carried out to fit a polynomial.

Appendix B

Finite Element Analysis

The finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. It subdivides a large problem into smaller, simpler parts that are called finite elements. The simple equations that model these finite elements are then assembled into a larger system of equations that models the entire problem.
Ansys structural analysis was used to evaluate the deformation and the resulting forces in the SMA spring via FEM. In this case, 3D structural equation was applied and the model was assumed to be non-linear. All nonlinearities including large deformations, plasticity, creep, stress stiffening, contact (gap) elements, hyperelastic elements etc were considered while solving.

Preprocessing-

- SMA material properties were added.
- Meshing- Triangulated meshing was followed
- Constraints/loads are added

Postprocessing-

- Deformation plots
- Stress plots
- Observing Newton Raphson Residuals

Newton Raphson Residuals

NR plots tell us the square root of the sum of the squares of the residuals in the global X, Y, and Z directions. The plots don't show us direction information, but they do show where the residuals and hence the force imbalances are the largest. In the example in the figure, Newton Raphson residual plots indicates that the model did not converge as accurately at the body contacts. In the rest of the region, the model was adequately solved and hence, can be used for the application.

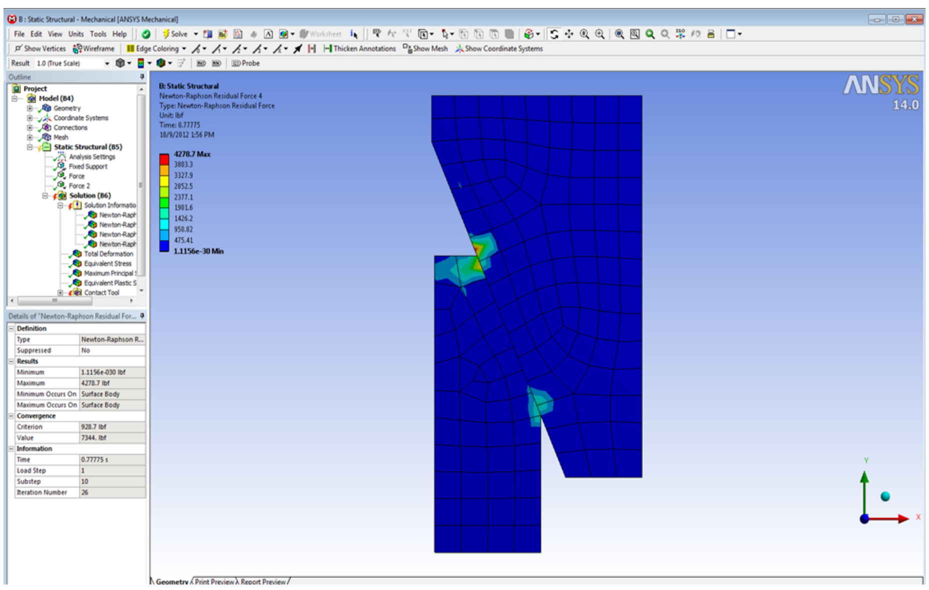

FIGURE B.1: The Newton Raphson residuals in Ansys

Appendix C

Control Theory : Overview

Control theory allows obtaining information of dynamical systems with inputs, and how their behavior is modified by feedback. The usual objective of control theory is to control a system, so its output follows a desired reference which may be a fixed or changing value.

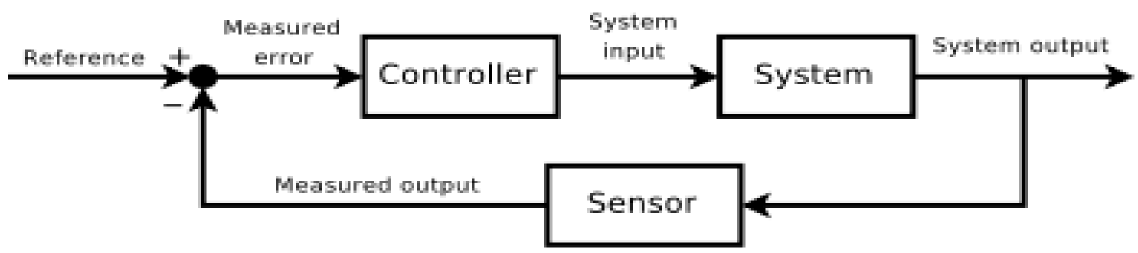

FIGURE C.1: A block diagram of a negative feedback control system

C.1 System Identification

It becomes necessary to identify a system as was done in this case for soft robot. The process of determining the equations that govern the model's dynamics is called system identification.
In our case, it was done off-line i.e., executing a series of measures from which to calculate an approximated mathematical model, typically its **transfer function**.
The SMA Spring's transfer function was found to be linear in a first order with appropriate fit.
Such identification from the output, however, cannot take account of unobservable dynamics.

C.2 Bang-Bang Controller

A bang–bang controller or an on–off controller, also known as a hysteresis controller, is a feedback controller that switches abruptly between two states. They are often used to control a plant that accepts a binary input, for example a furnace that is either completely on or completely off.

C.3 PID controller

A proportional–integral–derivative controller (PID controller) is a control loop feedback mechanism used to apply a correction based on proportional, integral, and derivative terms, (sometimes denoted P, I, and D respectively) which give their name to the controller type. Proportional control makes systems run smoother than bang-bang. While most biological systems are proportional, many engineered and all too many political and social systems are bang-bang.