

DESIGN, CHARACTERIZATION, AND APPLICATIONS OF SOFT 3D PRINTED STRAIN GAUGES

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By
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Design, Characterization, and Applications of Soft 3D Printed Strain
Gauges

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July 2023

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ABSTRACT

DESIGN, CHARACTERIZATION, AND APPLICATIONS OF SOFT 3D PRINTED STRAIN GAUGES

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M.S. in Mechanical Engineering

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The development of soft sensors for integration into untethered miniature robots is significant for improving their environmental perception in physically challenging scenarios, such as collapsed buildings after an earthquake. The primary objective is to design and manufacture reliable soft sensors that serve as structural and sensing elements within the robots, eliminating the need for post-processing methods like data-driven learning and optimization. The soft sensors employ resistive sensing, similar to strain gauges, and are implemented on a Wheatstone bridge to convert resistive changes into voltage changes under mechanical actuation or deformation.

The study explores two categories of soft sensor designs: sheet-type and 3D shaped sensors. Sheet-type sensors are embedded in the C-legs of a soft quadruped robot (SQuad), enabling gait control, while 3D shaped sensors are structurally integrated into the robots to enhance environmental perception. Manufacturing of the soft sensors is made accessible and efficient through 3D printing technology, using conductive Thermoplastic Polyurethane (cTPU) as the printing material.

Challenges arise in integrating the soft sensors into the robots while preserving their soft nature, locomotion, and agility. The thesis addresses these challenges by implementing the soft sensor concept in various robots and their parts, including the C-leg of SQuad, Modular Soft Quadruped (M-SQuad), Suspensionized Soft Quadruped (S-SQuad), Sensorized Collision Resilient Robot (SCoReR), and a tail for Reconfigurable Miniature Modular Robot (ReMBot). The soft sensors enable different functionalities to these robots, such as gait control feedback,

obstacle detection, inclination detection, and collision detection, enhancing the adaptability of the robots in physically challenging environments.

The thesis highlights the potential of soft 3D printed strain gauges. The ease of manufacturing and cost-efficiency of these sensors make them promising for applications in wearable robots and human-computer interfaces. Future directions are highlighted, emphasizing the need for detailed sensor characterization experiments and the development of detection algorithms to improve reliability. Additionally, a dynamic model of the coil-shaped sensors is proposed to simulate resistance changes, streamlining the design process without repetitive manufacturing iterations.

As a result, this thesis presents a reliable soft sensor design, manufacturing, and integration into untethered miniature robots. The outcome of this work demonstrates the effectiveness of soft sensors in enhancing environmental perception, paving the way for innovative solutions in force measurement applications and human-computer interactions.

Keywords: soft robotics, miniature robotics, bio-inspired systems, soft sensing, 3D printing, mobile robots, human-computer interaction, soft sensor, environmental perception.

ÖZET

YUMUŞAK ÜÇ BOYUTLU YAZDIRILMIŞ GERİNİM ÖLÇERLERİN TASARIMI, KARAKTERİZASYONU VE UYGULAMALARI

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Kablosuz minyatür robotlara entegre edilebilen yumuşak sensörlerin geliştirilmesi, özellikle deprem sonrası yıkılmış binalarda çevresel algılamayı artırmak açısından önemlidir. Temel amaç, makine öğrenmesi, yapay zeka veya optimizasyon gibi veri tabanlı yöntemlere ihtiyaç duymadan, robotlarda yapısal ve algısal işlev gören güvenilir yumuşak sensörler tasarlamak ve üretmektir. Yumuşak sensörler, gerilim ölçerlere benzer şekilde direnç ölçümü yaparak mekanik hareket veya şekil değişiklikleri altında direnç değişimini voltaj değişimine dönüştüren Wheatstone köprüsü kullanmaktadır.

Çalışma, iki farklı yumuşak sensör tasarımını araştırmaktadır: levha tipi ve üç boyutlu sensörler. Levha tipi sensörler, bir yumuşak dört ayaklı robotun (SQuad) C-bacaklarına gömülerek yürüme kontrolünü sağlamaktadır. Üç boyutlu sensörler ise robotlara yapısal olarak entegre edilerek çevresel algılamayı artırmaktadır. Yumuşak sensörlerin üretimi, iletken Termoplastik Poliüretan (cTPU) malzemesinin kullanıldığı üç boyutlu (3B) baskı teknolojisiyle kolaylaştırılmıştır.

Yumuşak sensörlerin, robotlara entegrasyonunda yumuşak yapının, hareket kabiliyetinin ve çevikliğin korunması gibi zorluklar ortaya çıkmaktadır. Bu tez, yumuşak sensör kavramını farklı robotlara ve bileşenlerine uygulayarak bu zorluklara çözüm getirmektedir. Uygulanan robotlar ve bileşenler arasında SQuad robotunun C-bacağı, modüler yumuşak dört ayaklı (M-SQuad), süspansiyonlu yumuşak dört ayaklı (S-SQuad), Sensörlü Çarpışmaya Dayanıklı Robot (SCoReR) ve Yeniden Yapılandırılabilir Minyatür Modüler Robot (ReMBot) için bir kuyruk bulunmaktadır. Yumuşak sensörler, bu robotlara yürüme kontrol geri

bildirimi, engel tespiti, eğim tespiti ve çarpışma algılama gibi çeşitli işlevler sağlayarak robotların fiziksel olarak zorlu ortamlarda daha uyarlanabilir olmasını sağlamaktadır.

Tez, 3B baskıyla üretilen yumuşak üç boyutlu gerilme ölçerlerinin potansiyelini vurgulamaktadır. Bu sensörlerin kolay üretilmesi ve maliyet-etkin olması, giyilebilir robotlar ve insan-bilgisayar arayüzleri gibi uygulamalarda umut vaat etmektedir. Gelecek yönelimler, sensör karakterizasyon deneylerinin detaylı olarak yapılması ve güvenilirliği artırmak için algılama algoritmalarının geliştirilmesi gerekliliğine vurgu yapmaktadır. Ayrıca, bobin şekilli sensörlerin dinamik bir modelinin önerilerek, tasarım sürecinin tekrarlayan üretim aşamaları olmadan daha verimli hale getirilmesi hedeflenmektedir.

Sonuç olarak, bu tez, güvenilir yumuşak sensör tasarımını, üretimini ve kablo-suz minyatür robotlara entegrasyonunu sunmaktadır. Bu çalışmanın sonucunda, yumuşak sensörlerin çevresel algılamayı artırmada etkinliği kanıtlanmış ve kuvvet ölçümü uygulamaları ve insan-bilgisayar etkileşimlerinde yenilikçi çözümlere yol açabilecek potansiyeli ortaya konmuştur.

Anahtar sözcükler: yumuşak robotik, minyatür robotik, biyo-ilhamlı sistemler, yumuşak algılama, 3D baskı, mobil robotlar, insan-bilgisayar etkileşimi, yumuşak sensör, çevresel algı.

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Chapter 1

Introduction

1.1 Motivation and Objectives

The primary motivation behind this work is to devise a soft sensor that can be integrated into various untethered miniature robots to increase their environmental perception of physically challenging environments like collapsed buildings after an earthquake incident. It aims to design and manufacture a soft sensor that acts as both a structural and sensing element when integrated into a robot. The main motivation is to devise a reliable soft sensor and use the response of the soft sensor for environmental detection without the need for any postprocessing method like data-driven learning and optimization methods. Using the raw data of a sensor is computationally advantageous for an untethered miniature robot.

To keep the working principle of the soft sensor is inspired by a simple strain gauge. Therefore resistive sensing is preferred as a sensing method. We wanted to use the soft sensor on a Wheatstone bridge to convert the resistive change into the voltage change under a mechanical actuation or a deformation.

Another significant objective is manufacturing the soft sensor easy as possible. 3D printing technology is the most efficient and accessible technology for soft

sensor manufacturing. The conductive Thermoplastic Polyurethane (cTPU) is selected as the printing material to provide resistivity to the sensor.

The most significant part of designing a sensor is categorizing soft sensor designs. We separated the design space into two classes. One is the sheet-type soft sensor, with the other being 3D shape soft sensor. We designed the sheet-type soft sensors to embed them into the C-legs of our lab’s first soft quadruped SQuad [1] to control the robot’s gait whereas, 3D soft shape soft sensors are designed to be structurally integrated into the robot to enhance the environmental perception of the robot.

The challenging part of this work is the design, manufacturing, and characterization process of the soft sensors, which are structurally integrated into the robots. Implementing the soft sensor should be compatible with the design of the robot. In soft robotics preserving the soft nature of the robot is one of the most critical objectives. Therefore, implementation of the soft sensor into the robots is not only important for the performance of the soft sensor on the robot, but it is also significant for preserving the locomotion and agility of the robots.

We have implemented our soft sensor concept on most of the robots created in Bilkent Miniature Robotics Lab, C-legs of Soft Quadruped (SQuad) [2], Modular Soft Quadruped (M-SQuad) [3], Suspensionized Soft Quadruped (S-SQuad), Sensorized Collision Resilient Robot (SCoReR) [4], the tail of Reconfigurable Miniature Modular Robot (ReMBot) for gait control feedback, obstacle detection, inclination detection, and collision detection respectively. We also construct a soft reconfigurable joystick concept using the soft sensor concept to assess the feasibility of using soft sensorized interfaces for Human-Computer Interactions (HCI).

In the future, this work may be a starting point for easy-to-manufacture and cost-efficient soft strain gauges. The sensors may inspire robotic sensing systems and lead creative and innovative solutions for force-measuring applications or soft human-computer interfaces.

1.2 Literature Review on Soft Robotics and Soft Sensing

The soft grippers were the first examples of soft robots in the 1970s [5]. In the early 1990s, flexible microactuators which used fiber-reinforced rubber were the trending topic in soft robotics research [6], [7]. The field of soft robotics has been dormant until the early 2000s. Pneumatically actuated OctArm was the first successful soft robot for grasping and gripping tasks [8]. Soft grippers played a significant role in the transition phase from conventional robotics to soft robotics.

Biology and nature are the primary inspiration sources for a soft robot design [9], [10]. Worm and snake-like robots are one of the most popular robot types in soft robotics. These robots are developed by observing the locomotion of the animals in their habitats. Their locomotion is imitated by designing robots and mechanisms that can move with simple mechanical actuation such as extension, torsion, and bending [11]. Hydraulic, pneumatic, and tendon-driven actuators are commonly preferred for the generation of extension, torsion, and bending. Pneumatic and tendon-driven actuators are commonly used for the gripper mechanism actuated like biological muscles [12], [13].

For miniature untethered robots, it is challenging to use these actuators due to the need to carry pumps, valves, and pressurized reservoirs. Therefore, Shape Memory Alloys (SMA) are generally preferred as actuators to provide the necessary locomotion of the robot on a miniature scale. The soft miniature quadruped SEAQ is an example of SMA usage for the actuation [14]. In our previous robot, a soft miniature quadruped Squad, we used micro brushed DC motors to rotate the C-legs to make Squad walk on terrain [1].

In soft robotics, preserving the soft nature of a soft robot is a critical motivation. Only a few robots are autonomous and entirely soft in literature [15]. Rigid detection sensors can be integrated into soft robots to improve environmental perception, limiting their full potential by making them stiffer. As a rigid obstacle detection sensor, Light Detection and Ranging sensor (LiDAR sensor)

can be used. However, it can potentially ruin the dynamics and kinematics of a miniature soft robot. Soft sensing interferes with the dynamics of a soft robot at the minimum, having the potential to be used for the strain, stress, contact, and roughness estimation on a soft robot body [16].

There are various transducer mechanisms, such as resistive, capacitive, optical, and piezoresistive/piezoelectric used in the development of soft tactile sensors [17]. MagOne is a multi-element magnetic field-based soft sensor used for soft-skin applications. A hall effect module is located at the bottom of the sensor design, with a magnet placed on the top of the soft matrix. [18]. In addition, optical sensing is precise and accurate pressure sensing and localization method. In this sensing method, optical fibers (receivers) detect the change in light intensity in the transparent matrix [19]. Optical sensing has various applications in soft robotics, such as damage detection, since light does not require physical contact for transmission compared to electrical signals [20]. In the resistive sensing method, the resistance of the sensor changes under a deformation. For instance, microchannels on the chip are filled with conductive fluid like eGaIn to construct microchannel strain gauges placed on the tip of the robotic finger. Thanks to this strain gauge, the shear force can be detected [21]. The capacitive sensing method can be used for proximity sensing and localization applications with higher accuracy and precision [22]. These methods require precise sensor manufacturing or a post-process with a data-driven algorithm to overcome reliability issues like non-linearity and non-repeatability [23]. However, in contrast to the literature, we use the raw data for all soft sensor applications instead of post-processing the captured data to save computational power. In addition, since the 3D printing of soft sensors is faster and more practical than manufacturing microfluidic chips, we manufacture our sensors via 3D printing technology.

The soft sensing concept is not only for robotics applications but also for constructing soft human-computer interfaces. For instance, although soft pneumatic sensing is commonly used in the field of soft robotics, it is also used in virtual reality applications and human-robot interactions (HRI) [24]. One of the two primary aims of this concept is to keep the fabrication process of the soft sensor as simple as possible. The other aim is to make the soft sensor compatible

with daily usage. A soft sensor has the potential to be a pen grip for our Apple pencil to control the thickness of the drawing [25]. It is also possible to use 3D printed soft sensors as capacitive transducers. Sensing and regular units are designed to construct new user interfaces the way users want [26]. A soft coil-shape sensor with a magnetic, electrical connection is devised to construct the soft reconfigurable joystick. Thanks to the reconfigurable structure, configurations of the joystick can be changed in seconds. The main difference and the novelty of spring-coil shape sensors are using them on two robots, M-SQuad and SCoReR, and a soft reconfigurable joystick without a need for any filter, optimization, or post-process method. This makes our soft sensor unique in the HCI and soft robotics literature.

1.3 Contributions

As the main contribution, we developed soft sensors that can be integrated into untethered miniature robots, enhancing their environmental perception in physically challenging environments like disaster zones. Additionally, these sensors can be employed in a soft reconfigurable joystick for playing computer games, offering a responsive and adaptable control interface. The functionality of our 3D printed soft sensors also makes them suitable for cost-efficient and practical force-measuring applications.

In addition, this work introduces a new modular soft quadruped M-SQuad, which consists of three modules connected by soft sensors. These sensors serve as sensing elements and structural elements that connect modules. During the locomotion of the robot, the body deforms. Thus, sensors deform as well. Therefore, the resistance of the sensors changes. Obstacles can be both detected and distinguished as scalable or not scalable using these sensors and obstacle detection algorithms. In the case study, it can be observed that the robot can detect and distinguish the obstacles it can climb or not with a success rate of higher than 90%. To the best of our knowledge, this is one of the first times soft sensors are used for environmental detection in mobile robots in literature.

The coil-shape soft sensors are also integrated into the bumpers of an autonomous flying miniature foldable collision resilient quadcopter as sensing elements. The soft sensors allow the robot to sense the impact of the collision with an accuracy of 100% while still preserving the collision resilience of the quadcopter. Through experiments, we show that soft sensors and the detection algorithm are functional. After the detection, the robot can be commanded to preserve its position or to back off from the obstacle. To the best of our knowledge, this is one of the first demonstrations of soft sensors being used as an impact-sensing element on a miniature quadcopter.

Finally, as a part of this work, sensorized C-leg is compared with the commercial encoder used on the robot to assess the soft sensor’s performance. After various experiments conducted on soft sensor-embedded C-leg, it is observed that embedding a soft sensor into the C-leg changes the mechanical properties of the C-leg. Although embedding a soft sensor changes the mechanical properties of the C-leg, it allows us to estimate the rotational speed of the C-leg for both the treadmill and the free rotation cases with an accuracy of %87.5 and %86.7. respectively. We conclude this part as promising to use sensorized C-leg instead of rigid commercial encoders on our robot, SQuad, for angular speed and position feedback of the C-legs.

1.4 Thesis Structure

Chapter 2: This chapter is the part where the design and manufacturing techniques of the soft sensors are explained in detail. The chapter starts with defining sensor types (sheet-type and 3D shaped) and discrete design space. The working principle of the soft sensors, material selection for the sensors, and 3D printing settings are all explained in this chapter. Electronics design (Wheatstone) for converting resistance change into voltage change is explained. The main importance of this chapter is comparing the sensor designs to find the best sensor geometry from the soft sensor design space. First, the experiments are conducted to find the best sensor geometry for sheet-type soft sensors. Then, the best 3D shaped soft

sensor geometry is selected as the soft coil-shaped sensors from another discrete design space. Soft coil-shape sensor geometry is introduced and used on the body of our robot M-SQuad. We hypothesize that the significant resistance decrease occurs because of the coil contact due to the compression. The results of the sensor characterization for 3-coil and 4-coil soft sensors are analyzed. We verify this hypothesis by conducting sensor characterization experiments for constant pitch coil-shaped sensors (sensors with constant coil distance). In order to prove our hypothesis, we devised a new coil-shaped soft sensor with varying pitch. According to our hypothesis, the varying pitch should respond more linearly compared to the constant pitch concept under homogeneous axial compression. Another experiment is conducted to verify our hypothesis by comparing the constant and varying pitch responses under a homogeneous compression. We also introduce the idea of using soft sensors as low-cost and practical force sensors. At the end of the chapter, 3D printing settings and connection types of soft coil-shaped sensors for various applications are explained.

Chapter 3: In this chapter, the case studies conducted with the soft sensor concept are discussed. The chapter starts with introducing the sensorized C-leg design and its application. The sheet-type soft sensor with the optimal geometry is embedded into C-leg to replace the rigid commercial encoders that are used for having the angular feedback and angular speed feedback from each leg of our robot, SQuad. The feasibility and functionality of this idea are discussed and examined. The chapter continues with implementing the soft sensor into the Modular Soft Quadruped (M-SQuad) body to distinguish the relatively small and relatively high obstacles to scale. Soft sensors are used as structural elements to connect to modules of the robots, whereas they are also used as sensing elements to distinguish the obstacles that robots encounter. The Suspensionized Soft Quadruped (S-SQuad) is similar to the concept of M-SQuad, but this time modules are connected via soft sensors in a vertical orientation. The reason for changing the orientation of the soft sensor connection between the modules was to analyze the inclination of the terrain that robot walks. Sensorized Collision Resilient Quadcopter (SCoReR) is a quadcopter in which we implemented soft

sensors on the bumpers. Thanks to the sensorization of the bumpers, the quadcopter is enabled to detect the collision and to measure the impact features such as the duration and the amount. This allows the robot to localize the wall in physically challenging environments like a maze. The soft sensors are also attached to the tails of the robot called ReMBot [27] to detect the inclination amount and obstacle collision. In addition, the sensors are placed on the bumpers of the aerial robot, SCoReR, to detect collisions. This allows the robot to localize the wall in physically challenging environments like a maze. Finally, it is also shown that soft sensors are not only innovative sensing elements for robotics systems but they can also be used in human-computer interaction applications like a soft reconfigurable joystick to play simple computer games like pong.

Chapter 4: Conclusion and Future Directions: This chapter discusses the potential of the soft 3D printed strain gauge concept. Different sensor designs and applications are introduced. The significance of using soft sensors as sensing elements on soft robot bodies to preserve soft nature. It is also highlighted that the performance of soft sensors is inspiring to use on wearable robots and human-computer interfaces as cost-efficient and easy-to-manufacture sensing elements. The initial experiment outcomes are presented with the tail sensorization concept and S-SQuad to assess the functionality of the concepts. However, detailed sensor characterization experiments are required to construct a detection algorithm for detecting the inclination. This is a mandatory requirement to increase the reliability of the soft sensors in both applications. We hypothesize and verify the significant resistance change that occurs when the coils come into contact with each other. A dynamic model of the spring coil-shaped sensor is certainly necessary to simulate the sensor resistance decrease under a homogenous compression or bending. The experimental outcome of this work can be compared with the model outcomes. It also makes the coil-shape soft sensor design process easier without the need for experimental iterations and repetitive manufacturing.

Chapter 2

Devising a Soft Sensor

2.1 Working Principle

The resistive sensing method is preferred since we want to save space on the circuit board of the robots by constructing Wheatstone bridges with four inputs. We are not interested in high-precision applications like proximity. Therefore, resistive sensing methods satisfy our requirements. The working principle of the soft sensors is similar to the basic strain gauges. Under mechanical actuation or deformation, the resistance of the soft sensor decreases. Thanks to this resistance change, we convert the resistance change into a voltage change using a quarter Wheatstone bridge. The working principle is the same for both sheet-type soft sensors and 3D shaped soft sensors.

2.2 Design

2.2.1 Sheet-Type Soft Sensor Design

Sheet-type soft sensor concept is created for embedding these sensors into the C-leg of our robot, SQuad. We are using rigid encoders to provide leg position and speed feedback to the LQR controller which is controlling the gait of the robot. We want to assess the possibility of using soft sensorized C-leg instead of rigid encoders. Another motivation behind this idea is extracting terrain information from the sensorized C-legs.

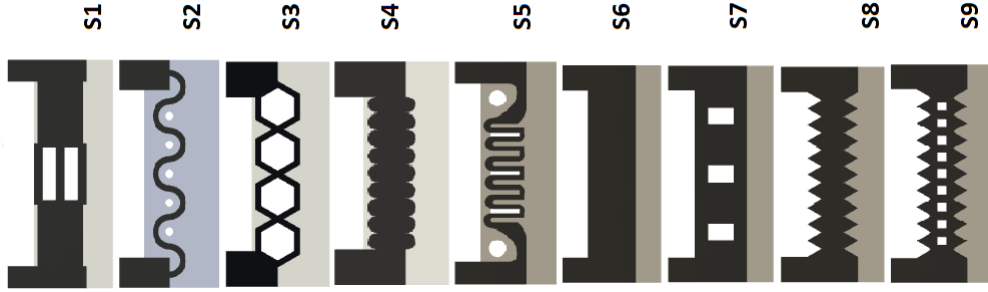


Figure 2.1: Nine different sensor geometries with fixed dimensions. The black parts of the designs show the conductive regions, whereas the non-black part shows the non-conductive regions of the soft sensors.

To assess the different sheet-type soft sensor geometry options, nine different sensor geometries are designed by preserving the dimensions of 26 mm x 9 mm x 1 mm for each geometry, as shown in Fig. 2.1. The dimensions are defined by considering the case of embedding multiple sensors into a C-leg. The dimensions of the SQuad C-leg in the lateral direction, longitudinal direction, and thickness are 36 mm, 40 mm, and 10 mm, respectively. The longitudinal direction represents the direction of gravity, whereas the lateral direction represents the SQuad’s moving direction during locomotion. Sensor geometries are randomly designed with inspiration from basic geometric features like triangles, squares, hexagons, zigzag lines, etc. There is an infinite number of geometries for the soft sensors. Since we cannot assess an infinite number of geometries, we discretized the number of sensor geometries that will be investigated. We have randomly

selected the sensor geometries by considering the various amount of strain each sensor geometry encounters. We cannot guarantee that the best geometry among our trials is the optimum sensor geometry; there can be sensor geometries we could not think of and did not try that may bring better results. The conductive parts of the sensors are 3D printed from conductive Thermoplastic Polyurethane (cTPU), whereas the conductive parts of the sensors are 3D printed from conductive Thermoplastic Polyurethane (cTPU).

To compare the sensor geometries, homogenous and periodic compression is applied on nine soft sensors by controlling compression amount and speed in the axial compression test setup.

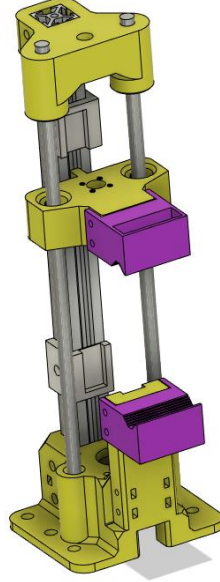


Figure 2.2: The CAD drawing of axial compression test setup.

The compression setup has two fixed ends and a moving module where the C-legs and sensors can be attached. Motion is controlled by stepper motors located at the bottom of the compression test setup. An aluminum beam is integrated into the design to carry the statical load of the assembled test setup. The rest of the parts are 3D printed. There are also aluminum rods with 8-mm diameter to provide alignment and guidance. Linear bearings provide a smooth motion for the moving module. Two limit switches are added for both safety and

calibration. The user inputs a compression amount and compression speed to the microcontroller; the setup compresses the C-leg or the sensor until the input compression is reached, waits for a defined duration, and then decompresses the C-leg or the sensor to the initial position. Users can record the instantaneous sensor response respective to the time as the experiment outcome from this setup. The CAD drawing of the compression test setup can be seen in Fig. 2.2.

The angle of contact between the sensors and the ground is set to 90 degrees in all experiments, which means the contact point is farthest away from the motor mount during the experiments. With the axial compression test setup, experiments are conducted to find the optimum sensor geometry among the nine different geometries listed previously for the sensor-embedded C-leg. For this purpose, nine different sensor geometry was designed by keeping the dimensions 26 mm x 9 mm x 1 mm for each sensor geometry. 6 mm compression, which is almost two times the actual displacement of the leg during the locomotion of the robot, was applied on each soft sensor geometry. Since the cycle time of 5 seconds is sufficient to make both qualitative and quantitative observations, compression speed and release speed were set to 3 mm/s. Each cycle consists of compression of the C-leg, a waiting period of a second, then release of the C-leg, where each experiment consists of 4 cycles. As the experiment result, sensor response in voltage versus elapsed time was gathered from the DAQ system.

Data Acquisition System (DAQ) has a significant role in capturing sensor responses. Wheatstone bridges are constructed to gather data from the soft sensors. Wheatstone bridges are constructed by considering the resistance of the soft sensors at stationary. The sensors form one arm of the bridge, while the other three resistances of the bridge are selected close to the sensor resistance at stationary. The outputs of the Wheatstone bridges are directly connected to the DAQ. In overall, DAQ has eight input channels that can receive signals simultaneously. In the compression test setup, a microprocessor (Arduino Pro Micro) is used to receive and execute commands from the user. The Stepper motor is driven by a stepper motor driver with respect to digital signals coming from the microprocessor.

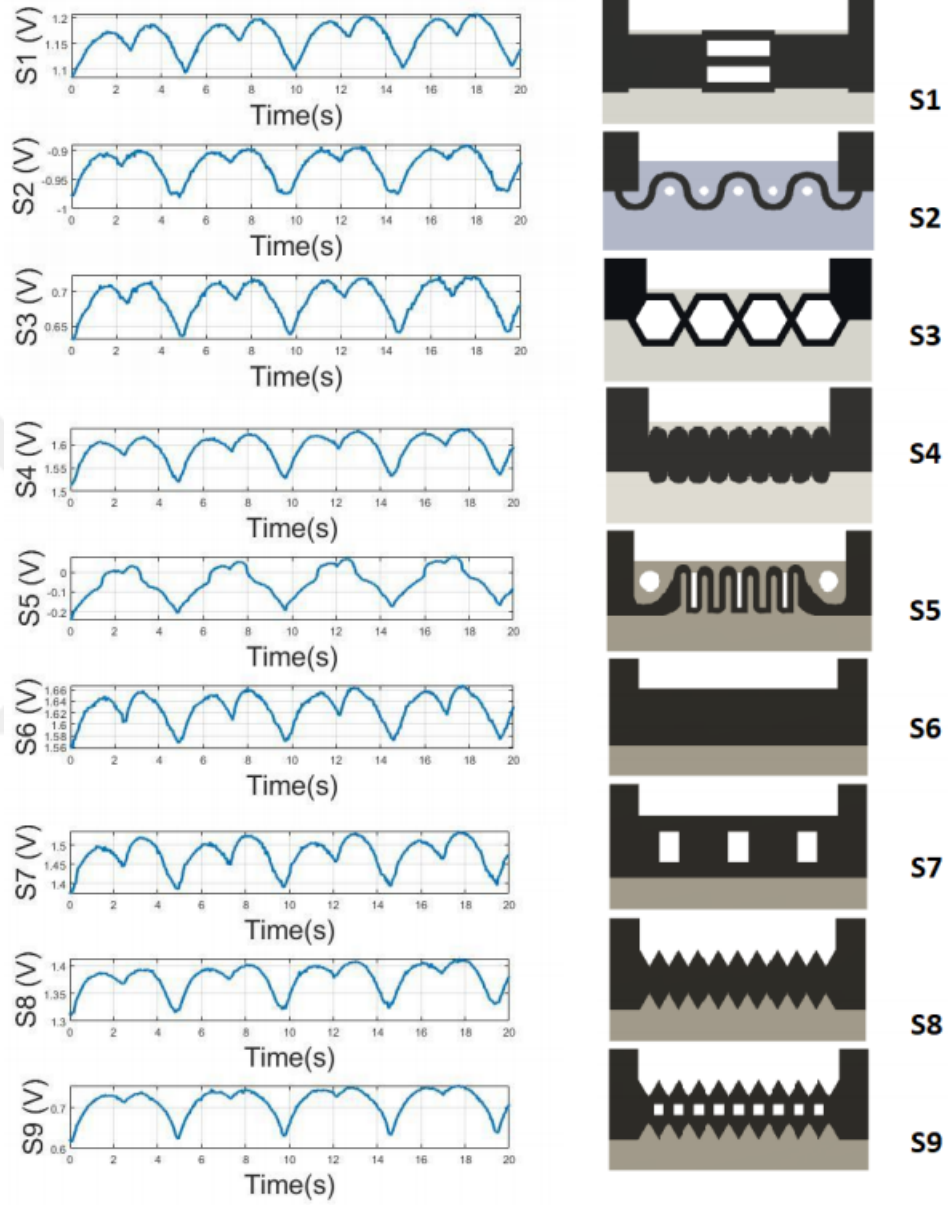


Figure 2.3: The responses of nine sensors with different geometries versus time.

To conduct the experiment set, nine sensors with the same dimensions are compressed in the axial compression test setup by keeping compression speed and compression amount fixed. Each sensor response can be observed in Fig. 2.3. Sensors 1-6 and 8 have peak-to-peak amplitudes less than 10 mV, whereas sensors 5, 7, and 9 have peak-to-peak amplitudes higher than 15 mV. Therefore, by investigating the amplitude of the responses, sensors 5, 7, and 9 are selected due to their relatively large amplitudes. The same response trend (the “m” shape)

is observed for all sensors. Compression continues until the first peak of the m shape, whereas after the second peak of the m shape, the release period starts. A waiting period of one second is observed between two peaks of m shape. Therefore, the m shape response of the soft sensors expresses the experiment phase. To select the optimum geometry, the clarity of detecting the waiting period in a cycle was chosen as the criterion since, for an angular position determination algorithm, this would give the greatest number of features. By considering this criterion, sensor 7 is selected to continue with.

2.2.2 3D Shaped Soft Sensor Design

3D shaped soft sensors concept is initiated by using the soft sensors both as a structural and as a sensing element for M-Squad. Therefore, there are two critical points for the sensor design. First, the sensor should be stiff and durable enough that it can connect a pair of modules without the main module sagging all the way to the ground. Additionally, the sensor should be soft enough and should deform considerably so that it is capable of sensing the obstacles and distinguishing the scalable obstacles.

Since the soft nature of M-Squad will mostly be due to the sensors' compliances, conductive Thermoplastic Polyurethane was preferred as the main material of the sensors. This is because Thermoplastic Polyurethane is a flexible material, and it has conductive versions which are available on the market as a 3D printer filament.

In order to determine which sensor geometry is suitable for our case, different geometries were designed and tried, such as zigzag-shaped, leaf-spring shaped, cantilever shaped, and coil-spring shaped as is shown in the Fig. 2.4. To understand which geometries perform better in our case, all the geometries are tested separately. All the dimensions of the sensors are kept the same to have a fair comparison between different experiments. The width, length, and thickness of the sensors are chosen as 7 mm, 26.4 mm, and 3.5 mm, respectively. Especially the lengths of the sensors are dictated by the C-leg motion and how close two

modules can be placed without the legs hitting each other during locomotion.

Coil-spring shaped sensor, shown in Fig. 2.4(d), provides the clearest output compared to other geometries because when the sensor is compressed or bent, the adjacent rings touch each other and cause a significant resistance decrease. The nominal resistance of the coil-spring shaped sensor is around 3.5-5 k Ω , whereas the other geometry sensors we tried have nominal resistances in the range of 1-2 k Ω . When the other sensors are bent or compressed, resistance decreases in the range of 10-30%, whereas the resistance of coil-spring shaped sensors decreases 81% under compression or bending.

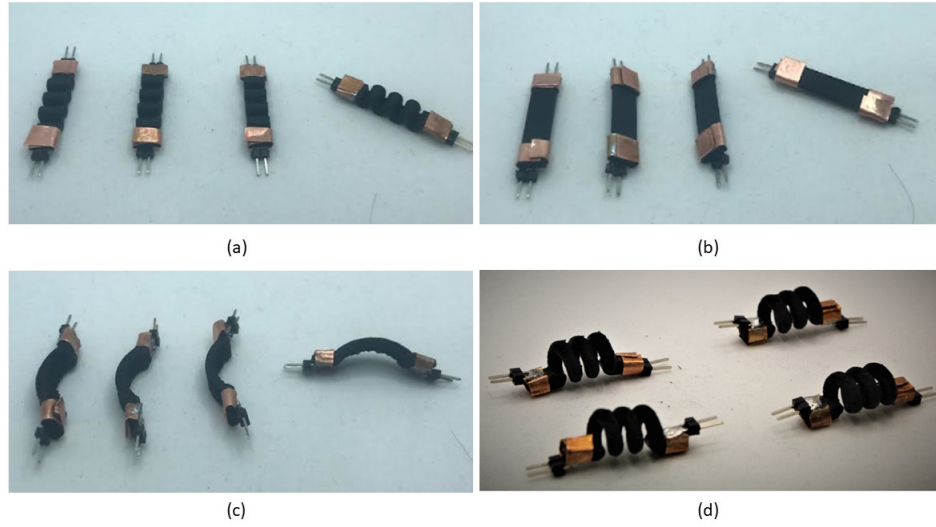


Figure 2.4: (a) Zigzag shaped, (b) Cantilever beam shaped, (c) Damper-leaf, (d) Coil-shaped sensor.

$$R = \rho L / A \quad (2.1)$$

$$\Delta = \rho / \Delta d_c \quad (2.2)$$

After coil-spring shaped sensor is selected as the main sensor geometry, we investigate the properties of the sensor. As the sensor is compressed, the coils get

closer to each other until, eventually, they contact and are further compressed into each other. We hypothesize that the contact between coils significantly reduces the resistance of the sensor during compression. As more coils contact each other and as the coils are pressed more against each other, the resistance decreases more. This can also be related to Eq. (2.1), where resistance is directly related to the length of the conductor (L) but inversely related to the cross-section area (A).

Eq. (2.1) can be written as Eq. (2.2), where d_c is defined as a characteristic dimension (A/L) and is a function of the sensor's compression amount (x). In Eq. (2.1) and (2.2), ρ is the constant resistivity of the sensor's material. When the sensor is compressed, the characteristic dimension increases. As a result, the sensor's resistance decreases. However, the function that defines the relation between characteristic dimension d_c and the compression amount x is expected to be nonlinear and non-smooth because the electrical contact between coils forms stochastically due to the electrical break-down phenomenon. A more detailed model of the sensor is planned for future work.

In order to verify the validity of this hypothesis, the electrical responses of two different spring sensors (one with three coils and one with four coils) are analyzed on a compression test setup. These two sensors are 3D printed under the same conditions and the design parameters such as length, thickness, width, and cross-sectional area. Each sensor is examined under 10 mm of compression and decompression. Eight trials are conducted for each sensor response; in total, sixteen trials are conducted. Sensor resistance and displacement data are gathered via a data acquisition device with a sampling frequency of 5 kHz. Collected data can be seen in Fig. 2.5.

The sensor response has three different regions, which we called no coil-contact response, coil-collapsing response, and fully-collapsed response, respectively. These three different regions should be investigated and analyzed separately from each other. A line is fit to each region separately and the line equations are also shown in Fig. 2.5. These equations can be used to provide a linear estimate for the function between d_c and x . On the other hand, the

coil-collapsing response shows nonlinear and non-smooth behavior, which supports our hypothesis of contact between coils significantly affecting the sensor response.

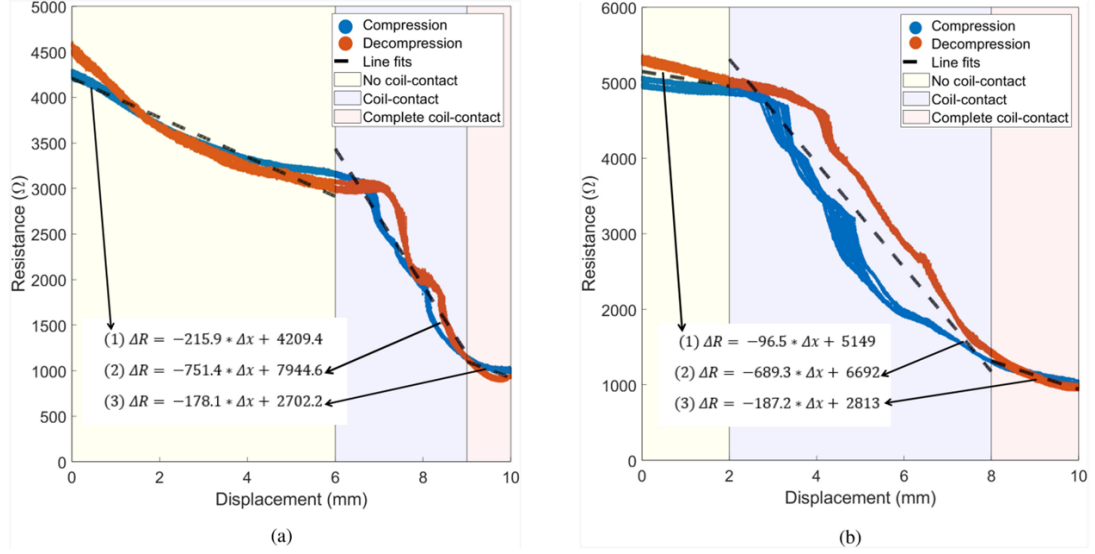


Figure 2.5: The resistance change for 10 mm compression of (a) 3 coil-spring shaped sensor, (b) 4 coil-spring shaped sensor.

It should also be noted that the nonlinearity of the coil-collapsing regions is more dominant in 4-coils spring sensors compared to 3-coils spring sensors. The maximum nonlinearity and the maximum hysteresis for both sensors as a percentage of full-scale deflection are reported in Table 2.1.

Sensor	Max. Non-Linearity (%)	Max. Hysteresis (%)
3 coil-spring	13.51	15.54
4 coil-spring	19.51	30.92

Table 2.1: The maximum non-linearity and hysteresis as a percentage of full-scale deflection.

3-coil sensors are preferred for the robot experiments because of their lower max. nonlinearities and max. hysteresis. The sensor has a nominal resistance (resistance without deformation) in the range of 4.2-4.6 kΩ. When the sensor experiences mechanical deformations such as bending, compression, tension, or

twisting, the resistance of the sensors drops significantly. When the resistance of the sensor drops significantly, the output of the bridge becomes quite large, and when amplified, becomes saturated at 3.3 V since the maximum voltage reading is 3.3 V for our controller board. The relation between the compression amount and the sensor response can be observed from Fig. 2.6.

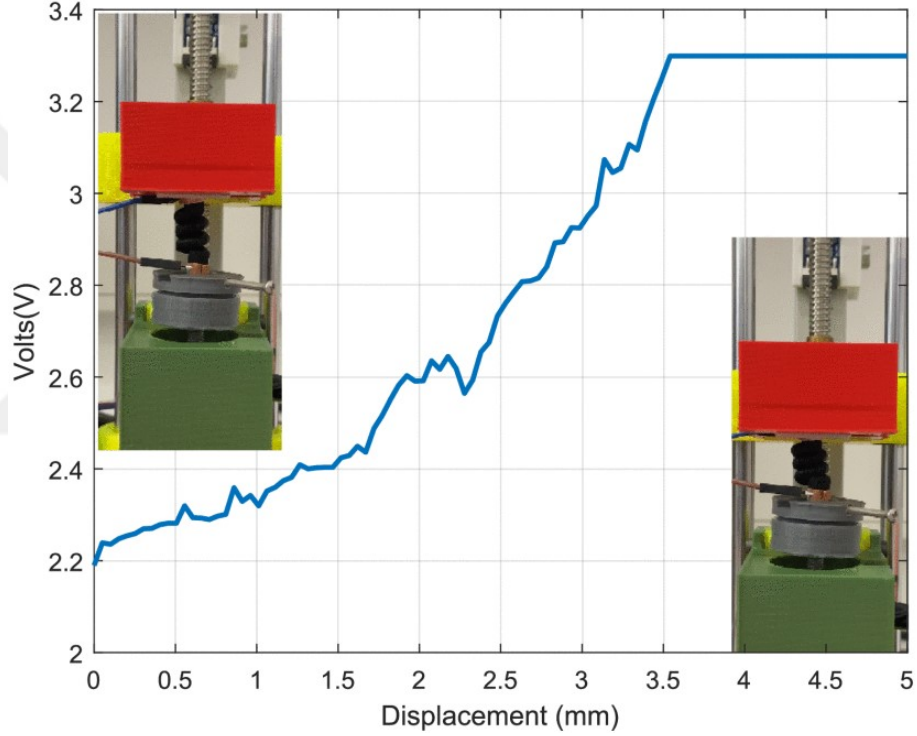


Figure 2.6: The compression test of the coil-spring shaped soft sensor.

2.2.2.1 Coil-Shape Sensor with Constant Pitch

We observe that when the coils of the soft coil-shaped sensors contact each other, the resistance of the soft sensor decreases significantly due to electrical breakdown phenomena. For the constant pitch soft sensors, we hypothesize that since the distance between the coils is kept the same as it is shown in Fig. 2.7(a), the coils should contact each other at the same time under a homogenous axial compression. However, we noticed that because of the manufacturing error due to the resolution of FDM 3D printing and the plastic deformation over time, the

distance between the coils slightly varies. As a result, the coils are not contacting each other at the same time during the characterization experiments. Although constant pitch soft sensor performance was already enough for simple environmental detection tasks, there were still reliability problems with the sensor.

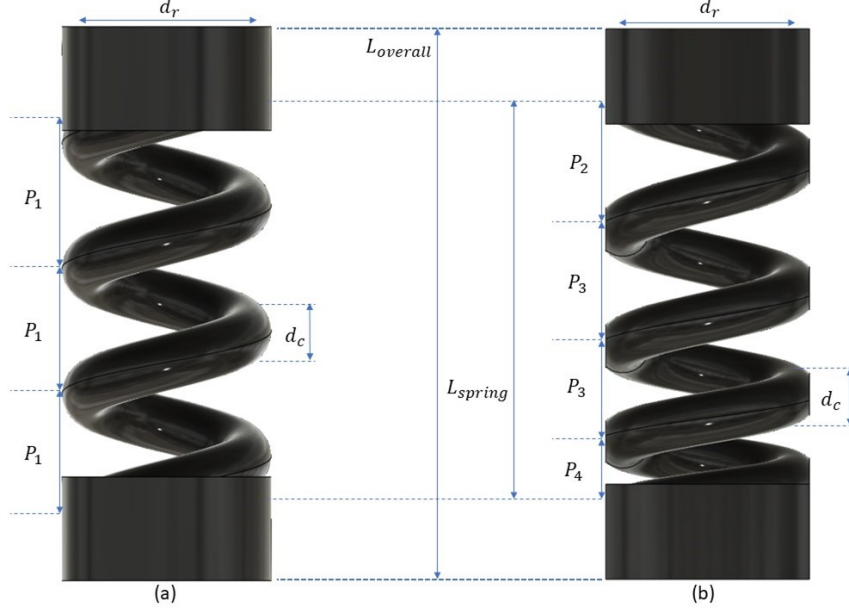


Figure 2.7: (a) Constant pitch, coil-shape design parameters: longitudinal length of the sensor (L_{sensor}), the longitudinal length of the spring (L_{spring}), the pitch of coil ($P_{1,2,3,4,5}$), the diameter of the spring base (d_r), the diameter of the spring cross-section (d_c), (b) varying pitch.

2.2.2.2 Coil-Shape Sensor with Varying Pitch

We update the soft sensor design by using a varying pitch, as can be observed in Fig. 2.7(b). Thanks to the varying pitch feature, we expect the coils to contact each other in a sequence. Since the major resistance change occurs because of the contact of coils, under a homogenous axial compression, the sensor resistance should decrease more linearly compared to a constant pitch soft sensor. In the constant pitch soft sensor design, we already observed that the resistance of the sensor does not change significantly until the sensor becomes almost fully compressed. In order to relate the compression amount to the soft sensor resistance, using varying pitch design is critical. Thanks to this design we could

observe certain resistance changes due to compression before the sensor became fully compressed.

2.2.2.3 Comparing the Response of Varying Pitch Sensor and Constant Pitch Sensor

The longitudinal length of the sensor (L_{sensor}), the longitudinal length of the spring (L_{spring}), the diameter of the spring base (d_r), the diameter of the spring cross-section (d_c) are kept constant at 65 mm, 50 mm, 10 mm, and 3 mm respectively for both varying pitch sensor and constant pitch sensor. Constant pitch sensor has a pitch of 7 mm, whereas varying pitch has a starting pitch of 3.5 mm which is increased by 1.5 mm at each coil pair. The sensors examined on the force sensor embedded compression test setup are shown in Fig. 2.8. An attached soft sensor to the compression test setup can be seen in Fig. 2.9.



Figure 2.8: 3D printed coil-shaped soft sensors with varying pitch and constant pitch for comparison experiments.

The varying pitch sensor is compressed starting from zero compression until the compression of 30.5 mm is reached, whereas the constant pitch sensor is compressed up to 28 mm. The compression amounts are determined by calculating the total gap between the coils for both sensors. Because, unlike the characterization experiment we conducted for the M-SQuad sensor, we are not interested in

the fully-compressed region of the sensor responses in this experiment. We want to analyze the effect of varying pitch on soft sensor response. We also measure the compression force applied on the soft sensor since a force sensor is embedded in the compression test setup shown in Fig. 2.9.

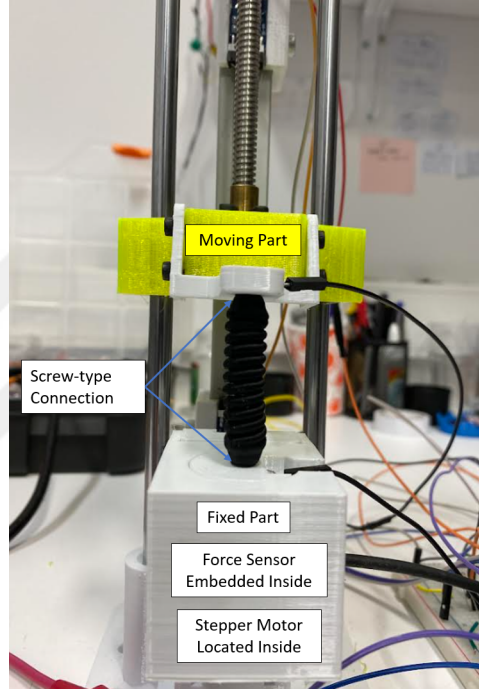


Figure 2.9: The axial compression test setup for comparison experiments of varying pitch and constant pitch soft sensors.

We post-processed data to find the response interval of varying pitch and constant pitch sensors under the compression starting from zero to 30.5 mm and 28 mm, respectively. The response interval as a function of compression amount is presented in Fig. 2.10. We observe that the response interval is larger for the constant pitch sensor than for the varying pitch sensor. As the size of the response interval increases, the hysteresis increases. Therefore, we decrease the effect of the hysteresis problem on our soft sensor response by devising the varying pitch concept. The varying pitch sensor also detects the compression earlier than the constant pitch sensor at the compression of 7.5 mm. In contrast, the response of the constant pitch sensor remains stationary until the compression amount reaches 22-23 mm.

In addition, we hypothesize that ideally, under homogeneous compression, all the coils of the soft sensors with constant pitch contact each other simultaneously. We expect to see a step response when the compression amount reaches the overall gap size (28 mm) between the coils. We see a sharp increase in the response earlier than our expectations, between the 22 mm and 28 compression amounts, as shown in Fig. 2.10. Due to manufacturing errors and plastic deformations, it happens earlier, not being as sharp as the step response.

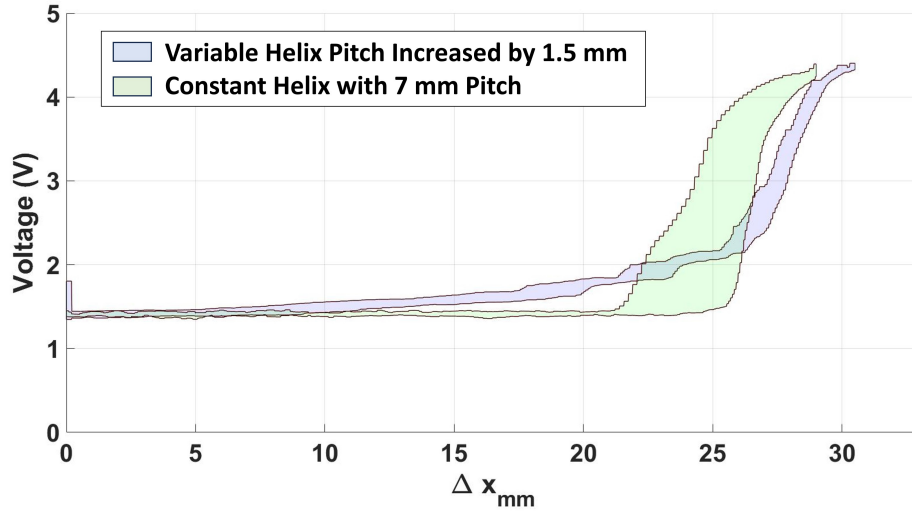


Figure 2.10: The response interval of soft coil-shaped sensors with varying pitch and constant pitch versus compression amount.

We notice that the varying pitch sensor has a more linear response compared to the constant pitch sensor. Between 0 mm and 26 mm compression amounts, it stays linearly with a tolerable amount of hysteresis. After that, the sensor response behaves linearly with a higher slope up to a saturation value of 4.25 V, as shown in Fig. 2.10.

Since we use constant pitch sensors during M-SQuad sensor characterization tests, we observe a certain hysteresis in the soft sensor response. These results show we improve the soft sensor response by decreasing the hysteresis in no-coil and coil-contact regions using varying pitch sensors. In the no coil-contact case, sensor resistance decreases since the helix deforms, although there is no coil contact until the compression of 3.5 mm. The slope of the resistance decrease

remains constant due to the coil contact in order. We design the order of coil contact by increasing the pitch with the step of 1.5 mm. Therefore we conclude that varying pitch concept linearizes the sensor response. The average of the sensor response interval for both sensors is presented in Fig. 2.11.

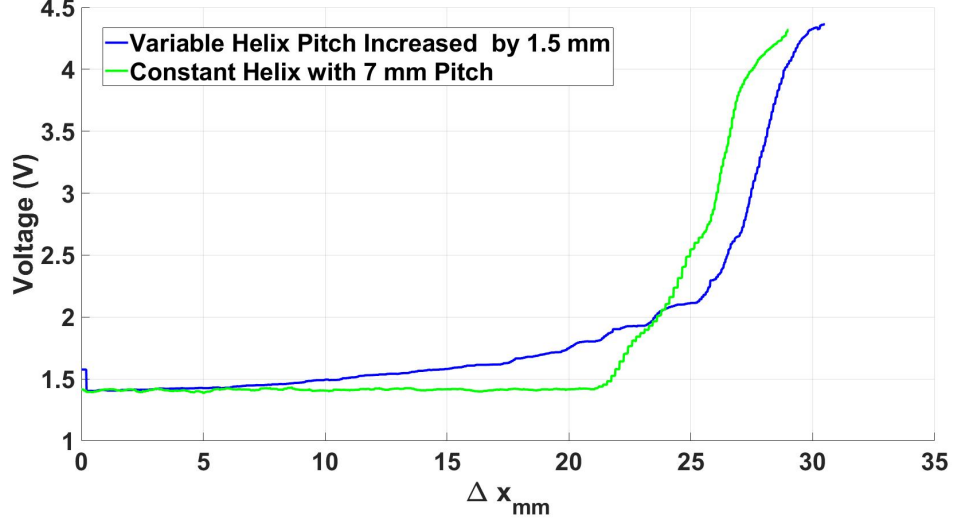


Figure 2.11: The average response of soft coil-shaped sensors with varying pitch and constant pitch versus compression amount.

Using coil-shape soft sensors as low-cost and practical force sensors have been one of our main motivations since the beginning. We linearize the soft sensor response by devising the varying pitch feature for our soft sensor. Then we compare the varying pitch and constant pitch soft sensor responses with the force sensor outcome under homogeneous compression since we simultaneously record the force and soft sensor data in all experiments. The force sensor is embedded into the axial compression test setup as shown in Fig. 2.9, measuring the force starting from the beginning of the experiments as shown in Fig. 2.13 and Fig. 2.12. From the force data versus soft sensor response, we noticed that compared to constant pitch soft sensor response, varying pitch soft sensor response is more appropriate to be mapped into the force data taken for linear force measuring applications. This is because varying pitch detects the compression amount earlier than the constant pitch soft sensor. We also observe that when the coils become fully collapsed, the measured force increases more rapidly compared to the coil-contacting phase shown in Fig. 2.13. The constant pitch soft sensor is more

appropriate for measuring the impact force since it can respond to the compression until the compression amount reaches the total gap between the coils (between 22 mm and 28 mm). Although the force sensor measures the compression force acting on the constant pitch soft sensor before the coils become fully collapsed, the soft sensor does not detect the compression. Both the soft sensor and force sensor detects the fully collapsed coils instant and the rest of compression as shown in Fig. 2.12.

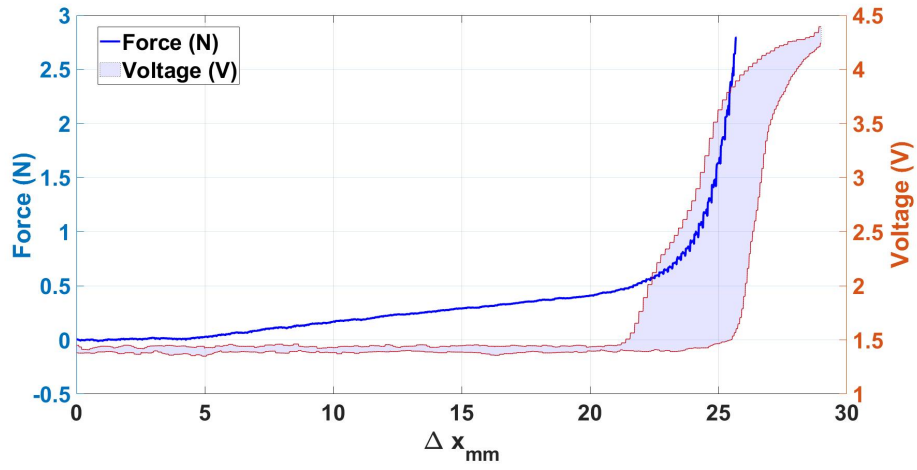


Figure 2.12: The response interval of soft coil-shaped sensors with constant pitch and measured compression force versus compression amount.

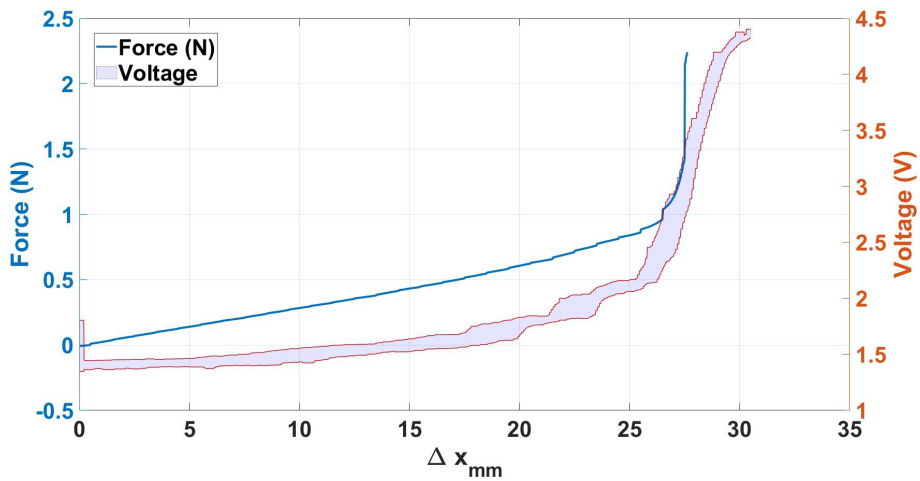


Figure 2.13: The response interval of soft coil-shaped sensors with varying pitch and measured compression force versus compression amount.

2.2.3 Manufacturing and Connection Types

2.2.3.1 Material Selection

In our soft robot project, the primary material we initially used was PDMS (polydimethylsiloxane). We explored incorporating carbon black as a conductive filler into the PDMS mixture to make the PDMS conductive. The goal was to manufacture soft sensors using a carbon black-filled PDMS mixture through the molding technique. However, we encountered several challenges throughout the process.

One of the major problems we faced was limited conductivity in the resulting material. The addition of carbon black did not provide the desired level of electrical conductivity, resulting in high resistance values. Stationary resistance measurements of the soft sensors indicated values in the megaohm scale. Moreover, any mechanical actuation or deformation caused a further increase in the sensor resistance, reaching the ohm scale. This conductivity inconsistency hindered the soft sensors' reliability and consistent performance.

Another issue we encountered was the inhomogeneous distribution of carbon black within the PDMS. Achieving a uniformly dispersed mixture of PDMS and carbon black proved challenging. As a result, each manufactured soft sensor responded differently to the same mechanical actuation, even though we used the same mixture ratio of PDMS and carbon black for all sensors. This lack of uniformity in the distribution of conductive particles affected the overall performance and repeatability of the soft sensors.

Additionally, incorporating carbon black negatively impacted the stretchability of the PDMS. PDMS is known for its high stretchability, but with the addition of carbon black, the material exhibited reduced flexibility, becoming more brittle and prone to deterioration. These changes in mechanical properties were undesirable for our soft robot application.

Considering all these factors, we decided to explore alternative approaches for manufacturing our soft sensors. We used Fused Deposition Modeling (FDM) 3D printing technology with a conductive thermoplastic polyurethane (TPU) filament called NinjaTek Eel.

Conductive TPU filaments, like NinjaTek Eel, incorporate conductive particles, including carbon black, into the printing material. This provides the desired electrical conductivity for the printed objects. NinjaTek Eel filament offers exceptional elongation properties, boasting an elongation capability of 355%. This feature was crucial for our project as it allowed for repeated mechanical actuation and deformation without wear or cracking, ensuring higher reliability and repeatability for our soft sensors.

By transitioning to NinjaTek Eel and utilizing FDM 3D printing, we aimed to overcome the limitations we encountered with carbon black-filled PDMS, ensuring more consistent conductivity, improved stretchability, and enhanced performance for our soft sensors.

2.2.3.2 3D Printing Settings

During the 3D printing of sheet-type soft sensors, the number of wall perimeter layers is set to one except for the top and the bottom layer wall perimeters, which are set to three. Furthermore, the first layer height is set at 0.27 mm, whereas the other layer heights are kept at 0.18 mm. Thus, there was no need to set the infill rate since the 1 mm thickness of the sensors was considered. The nozzle temperature is set to 230°C, and the heat bed temperature is set to 65°C. A second extruder combines cTPU and regular, non-conductive Thermoplastic Polyurethane (TPU) to manufacture the sensor geometries.

The 3D shaped sensors are also 3D printed using only conductive TPU filament with 80% infill. Similarly, the first layer height is set at 0.27 mm, with the other layer heights being kept at 0.18 mm. The nozzle and heat bed temperatures are again set to 230°C and 65°C, respectively. The number of wall perimeter, top

layer, and bottom layer also remains the same, with the number preferred for sheet-type soft sensor printing. The only difference between the 3D printing of 3D shaped soft sensors and sheet-type soft sensors is that the 3D shaped sensors are printed using a single extruder fed by the cTPU.

2.2.3.3 Bent Copper Plate Type Electrical Connection

The coil-spring shaped sensors attached to M-Squad have extensions at both ends to provide an area for proper electrical and mechanical connection. The connection is achieved with a double male header soldered copper plates, as shown in Fig. 2.14(a). The copper plate is necessary since it is not possible to solder headers to conductive TPU. Male headers are soldered to copper plates before wrapping the copper plates around the sensor extension. To prevent connection loss, the copper plate is compressed using pliers. Sensors are then attached to the screw terminals embedded in each robot module using the double male header.

2.2.3.4 Screw-Type Electrical Connection

The screw-type electrical connection is designed for the soft sensors attached to SCoReR to prevent noise caused by the vibration during the flight and the airflow from the propellers. To fabricate the screw-type electrical connectors, threaded M3 inserts are placed on both ends of the soft sensor, as shown in Fig. 6. The connection cables for the sensors are soldered to these inserts. Using the holes created on the bumpers, soft sensors can be attached to the foldable bumpers using screws, as shown in Fig. 2.14(b).

2.2.3.5 Magnetic Type Electrical Connection

The focus is making the soft sensors easily attachable and detachable to a soft reconfigurable joystick system by devising a magnetic connection shown in Fig. 2.14(c). We tightly fit 5 mm-diameter and 4 mm-thickness cylinder magnets into

both ends of the sensors. These ends are cylinders with an outer diameter, inner diameter, depth of the inner hole, and cylinder height of 10.5 mm, 4.85 mm, 2 mm, and 5 mm, respectively. This was designed according to the dimensions of the most miniature magnet we could find in the local market. The dimensions given for the cylinder ends of the sensors are constrained by the FDM 3D printing resolution of our 3D printer, such as a minimum layer height of 0.2 and a minimum number of layers between the surfaces (5) to prevent degeneration on the surfaces. Since the magnets needed to be tight-fitted to the sensors without the need for conductive superglue, we kept the thickness between the outer diameter and inner diameter of the cylinder at 2.825 mm. This minimum thickness value prevents the magnet from tilting in any direction and holds the magnet concentric. Since we push the magnet until the magnet surface reaches the bottom surface of the end cylinder hole, the bottom surface should be stiff enough to preserve the magnet level embedded into the soft sensor. Therefore, the distance between the cylinder end's outer surface and the hole's bottom is kept at 3 mm.

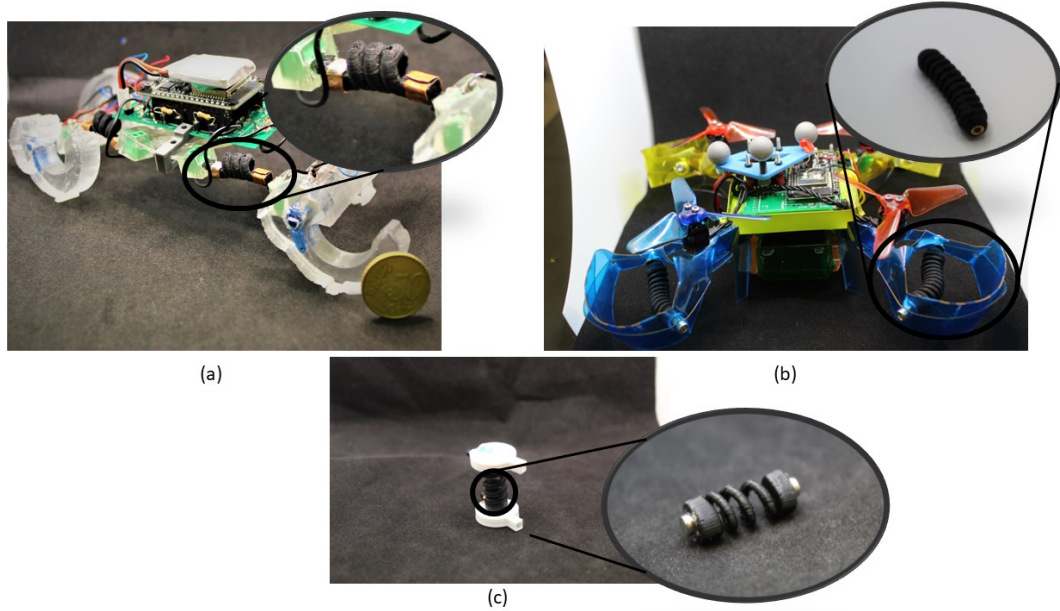


Figure 2.14: The connection types: (a) bent copper plate connection, (b) screw connection, (c) magnetic connection.

Chapter 3

Application of Soft 3D Printed Sensors

3.1 Soft Sensor Embedded C-legs

In this concept, we aim to assess the feasibility of implementing soft sensor technology into the C-legs of SQuad. The motivation behind this idea is to assess the terrain information and replace hard commercial encoders with soft sensors by embedding soft sensors into the C-legs. To assess the feasibility of this idea, two experimental test setups are developed. In the axial loading test setup, a soft sensor embedded C-leg can be compressed axially by controlling the speed of compression and the amount of compression as shown in Fig. 2.2 and explained in section 2.2.1. In the treadmill test setup, C-leg is inserted into a tower with a miniature slipring specially designed to acquire data from the rotating C-leg. Sensorized C-leg is simulated in robots' locomotion in this test setup. Sensor responses are acquired in both test setups. Additionally, encoder data is also acquired in the treadmill test setup. The design of sensorized C-legs has two significant milestones which are finding the optimal sensor geometry and the optimal position for the sensor implementation. These are both within a discrete design

space by assessing the experimental data obtained from both test setups. Methods for finding the optimal sensor geometry are explained in section 2.2.1, and the optimal sensor geometry is selected before designing the soft sensor embedded C-legs.

3.1.1 Design

3.1.1.1 Slipring Mechanism

An electrical connection mechanism is designed to receive a continuous electrical reading from the embedded soft sensor located at the rotating C-leg. The working principle of this mechanism is somewhat similar to a commercial slipring. However, there are not many miniature commercial sliprings available. The mechanism can be observed in Fig. 3.1. The design mainly consists of two hollow tubes and two bearings next to each other. Each hollow tube mechanically connects to one of the bearings. The long and smaller diameter hollow tube connects the motor to the leg. The outsides of the bearings do not rotate with the leg and are used for electrical connections. A polyimide film is placed between the two hollow tubes to isolate the tubes electrically and, therefore, the sensor connections. The bearings provide the bedding for the rotating shaft in the treadmill test setup. They are also pinouts where the cables from the DAQ are soldered to.

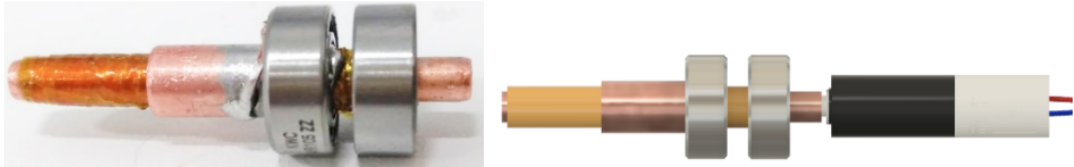


Figure 3.1: The assembled version of the slipring mechanism and its CAD drawing.

3.1.1.2 Treadmill Test Setup

The treadmill test setup is designed to simulate the C-leg behavior during SQuad's locomotion on the ground. It consists of two towers and one treadmill. Encoder, which is used to have angular position feedback and angular speed feedback from the C-leg, is placed into one tower. The slipping mechanism which is specially designed to have a soft sensor response from rotating C-legs is placed into the other tower. These two towers are connected to each other via an extended camshaft which also carries the rotating C-leg. C-leg runs on the treadmill which imitates the ground contact of the C-leg while the SQuad is walking. Because the SQuad body's vertical position changes during locomotion, the treadmill is fixed to the setup through four soft springs, one for each corner, which acts as a soft suspension for the ground. Using this suspension system, the motor's relative distance to the ground can change. Users can input the angular speed of the rotating C-leg and the initial height of the treadmill and record soft sensor response and the encoder data simultaneously via the data acquisition system. CAD drawing of the treadmill test setup and its fully assembled version can be seen in Fig. 3.2.

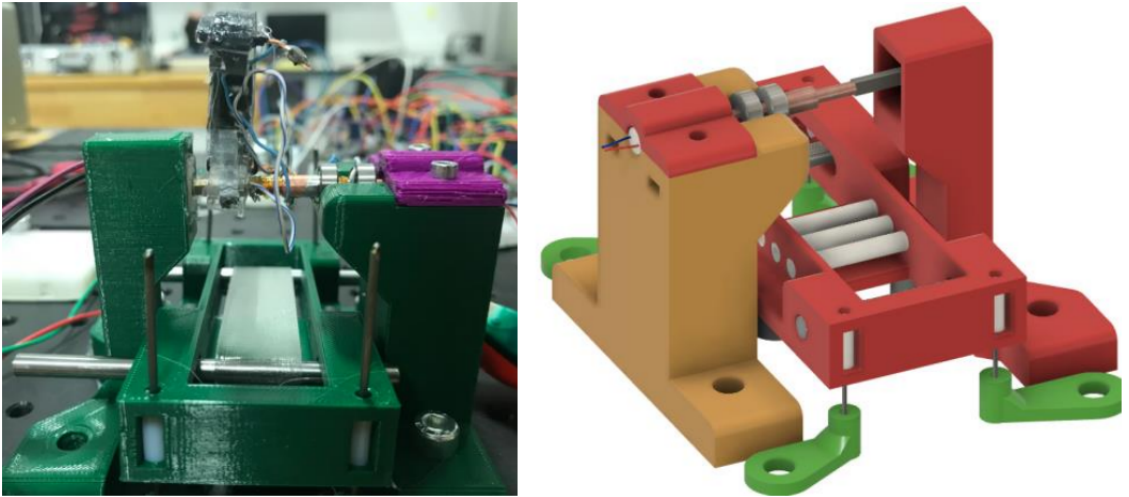


Figure 3.2: The fully assembled version of treadmill test setup and its CAD drawing.

3.1.1.3 Sensorized C-legs

Soft sensor embedded C-legs are manufactured with almost the same technique used in the manufacturing of SQuad's C-legs. Since the main material is PDMS, the molding technique is utilized. Molds are 3D printed using 3D printer filament, Polylactic Acid (PLA). Then, PDMS Sylgard 184 is mixed in a 5:1 ratio of a pre-polymer and cross-linker, and the mixture is poured into the mold. To embed the 3D printed soft sensors, channels are created in the mold to place the soft sensors before pouring PDMS into the mold. The number and position of the soft sensor channels differ in the molds according to the experiments. We aim to assess the optimum position for the soft sensor placement in the C-leg and the effect of the embedded sensor on the longitudinal stiffness of the C-leg. Thus, we designed two different types of C-leg molds. One mold contains a single channel, as shown in Fig. 3.3(a).

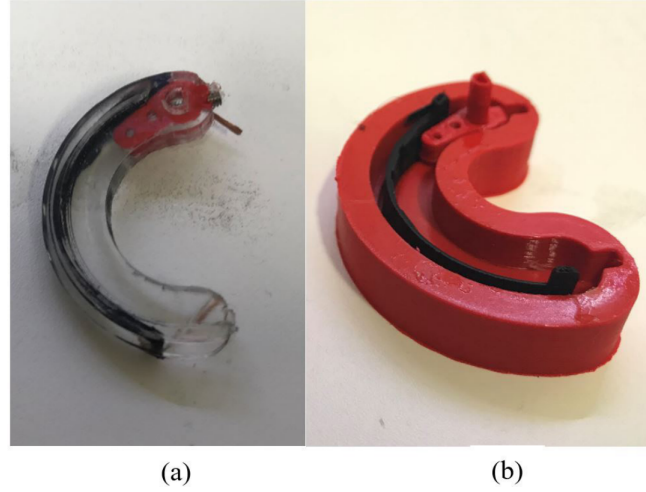


Figure 3.3: The soft sensor embedded C-leg (Composite C-leg) and its mold.

In contrast, the other mold contains two additional channels with an equal distance of 1.5 mm to the channel located in the middle of the mold, as shown in Fig. 3.4(a). The second mold enables us to place eight soft sensors in a single leg at different positions within the leg. The channel width and length were kept the same at 1 mm and 50 mm, respectively, for both designs. The molds of the soft sensor embedded C-legs (composite C-legs) can be observed in Fig. 3.3(a),

and the manufactured composite C-legs can be observed in Fig. 3.3b. The mold of eight soft sensors embedded C-leg can be observed in Fig. 3.4(a), and the manufactured multisensory embedded C-leg is shown in Fig. 3.4(b).

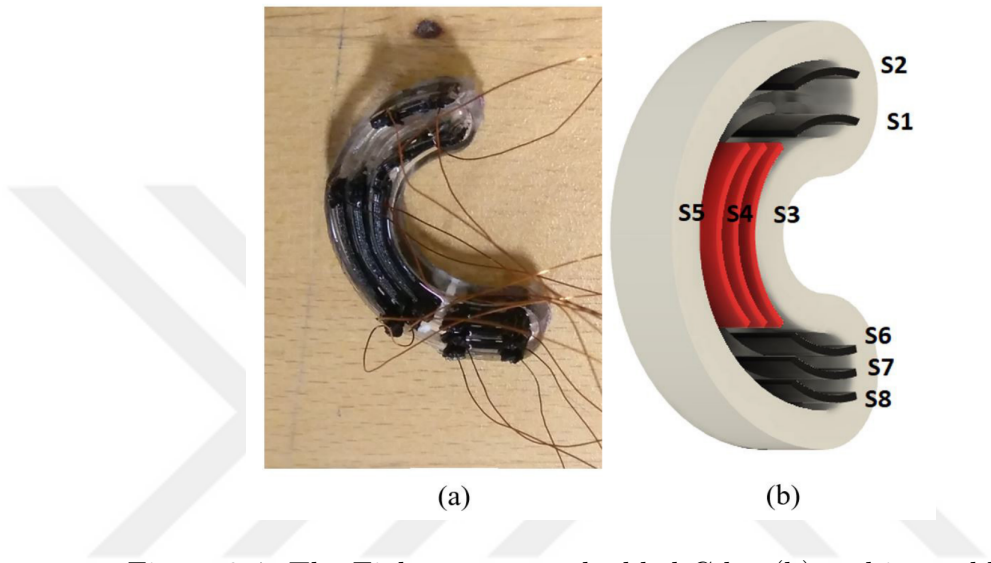


Figure 3.4: The Eight sensors embedded C-leg (b) and its mold (a).

3.1.2 Methods

3.1.2.1 The Experiments to Find the Optimum Sensor Position

Experiments to find the optimum position for a soft sensor in the C-leg were conducted using the axial compression test setup shown in Fig. 2.2. This was necessary after deciding on the optimal geometry of the sensor. In these experiments, eight identical sensors are embedded into a soft C-leg, which is attached to the moving module of the axial compression test setup. Each of the sensors was embedded into different locations in the soft C-leg. Most experiment parameters (compression speed, release speed, content of one cycle) were kept the same as the experiments conducted to find the optimum sensor geometry. As the experiment outcome, the sensor response of all eight sensors in voltage with respect to the elapsed time was gathered simultaneously from the DAQ system. A snapshot from one of the sensor position experiments is shown in Fig. 3.5.

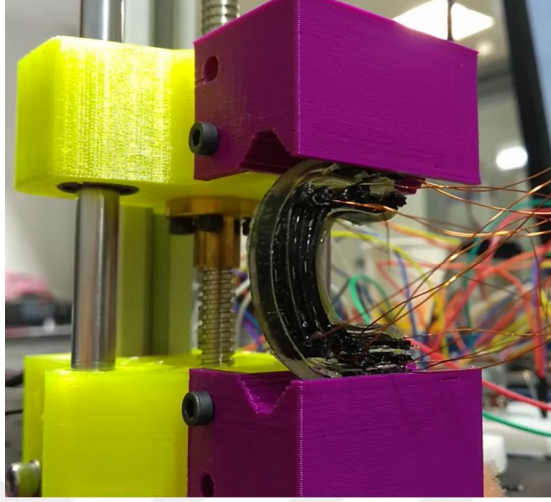


Figure 3.5: The compression of eight sensors embedded C-leg in axial compression test setup.

3.1.2.2 The Experiments to Assess the Soft Sensor Performance

Experiments to assess the soft sensor performance is conducted using the treadmill test setup. In this setup, C-legs are simulated as they are attached to SQuad's body during locomotion. By rotating the C-legs freely at 0.3 Hz in air, with no treadmill contact, a baseline for the embedded soft sensor detecting the inertial effects of a freely rotating C-leg is established. C-legs are also rotated on the treadmill test setup to observe how the sensor would behave during the locomotion of SQuad. For both cases, the sensor response is captured via the slipping mechanism developed and the DAQ system.

3.1.2.3 The Finite Element Analysis to Determine the Stiffness of the C-legs

Finite Element Analysis (FEA) is conducted to evaluate the stiffness values of both the soft sensor embedded C-leg and the regular C-leg (without the soft sensors) in the simulation environment. The linear elastic material assumption is used for all structural analyses. The magnitude of the force applied for both the regular C-leg and the soft sensor-embedded composite C-leg is set to 1 N. For

setting the boundary conditions of FEA, fixed surfaces are selected as the bottom surface of the C-leg. An automatic contact tool is used to preserve the composite structure of the soft sensor embedded C-leg. Embedded sensors are considered as fibers, whereas the PDMS is considered as the matrix for the composite C-leg. The tolerance for the automatic contact tool is set to 0.01 mm.

3.1.2.4 The Experiments to Evaluate the Stiffness of Soft Sensor Embedded C-leg

Experiments to evaluate the stiffness of the soft sensor embedded C-leg is conducted using a custom-made compression test setup. The regular C-leg and the soft sensor embedded C-leg are placed into the test setup in this experiment. The bottom end of the C-legs is attached to the bottom fixed end of the compression test setup, where a force sensor is located. The amount of compression is set to 12 mm for both the soft sensor embedded C-leg and the regular C-leg, where the compression rate is set to 0.8 mm/s. The 12-mm-compression amount is almost four times the actual displacement amount that occurs during the locomotion of the robot. Compression occurs in only the longitudinal direction of the C-leg up to 12 mm; hence this compression amount is chosen. Compression speed is preferred as the slowest speed possible since we want to make both qualitative and quantitative observations. The setup provides force versus displacement data for the C-leg attached. The data gathered is post-processed using MATLAB to find the stiffness of the attached C-leg along the longitudinal direction. The test setup can be observed in Fig. 3.6. This setup slightly differs from the compression test setup shown in Fig. 2.2, since the force sensor is embedded into the bottom fixed part of the setup.

In the compression tests, the main goal is to investigate the change in the stiffness of the leg in the longitudinal direction when the sensors are embedded. Our hypothesis is that embedding a soft sensor into a C-leg would create a composite structure for the C-leg; thus, the stiffness of the C-leg would change. However, if the stiffness change is not large, this change would not affect the locomotion much and would be acceptable.

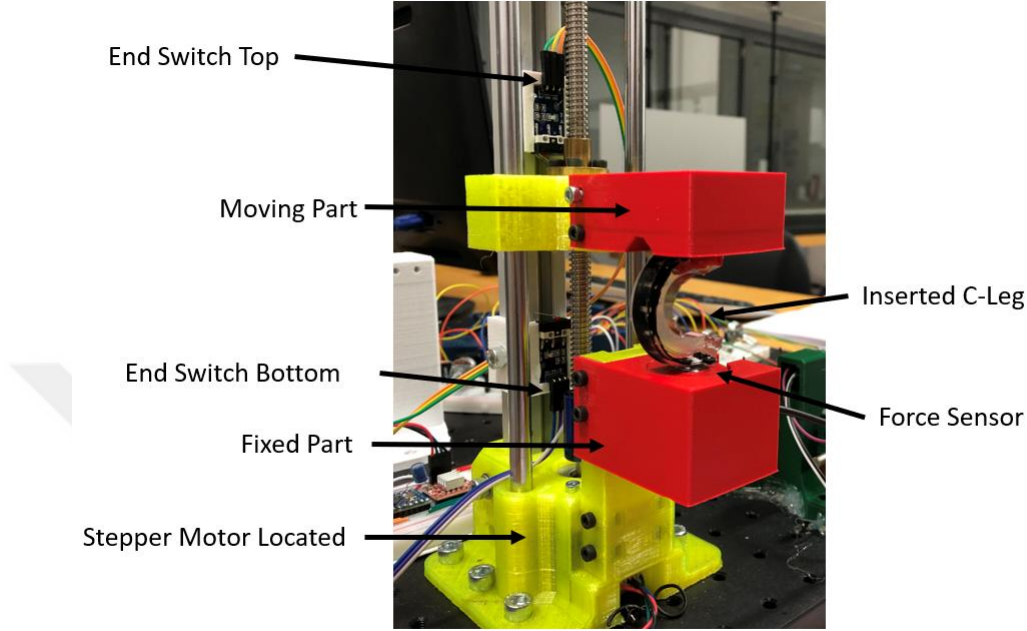


Figure 3.6: The axial compression test setup for the C-leg stiffness analysis experiments.

3.1.3 Results

3.1.3.1 The Experiments to Find the Optimum Sensor Position

It is possible to place only eight sensors in a C-leg without causing significant cracks. Sensors are labeled as shown in Fig. 3.4. Each soft sensor response inside the C-leg can be observed in Fig. 3.7. To assess the optimum sensor position, the clarity of detecting the sensor response regime and peak-to-peak amplitude of the soft response was set as the criteria. By considering these criteria, the performance of sensors located at both the top and bottom ends of C-legs was better. Sensors located in the middle of the C-leg were not affected a significant amount. This was expected since we had observed upper ends of the C-legs deflect the most in FEA analysis of the C-legs. The bottom ends of C-legs were not affected that much since it is assumed as the fixed end in structural analysis. At the end of this experiment, although it is observed that both the bottom and upper ends of C-legs are affected by the compression, we preferred a longer

and continuous sensor along the channel located at the middle since peak-to-peak amplitude is much higher for sensors located at the middle. Furthermore, increasing the length of the sensor will provide more mechanical deflection for the sensor. Thus, it will provide a sensor response with a higher peak-to-peak amplitude.

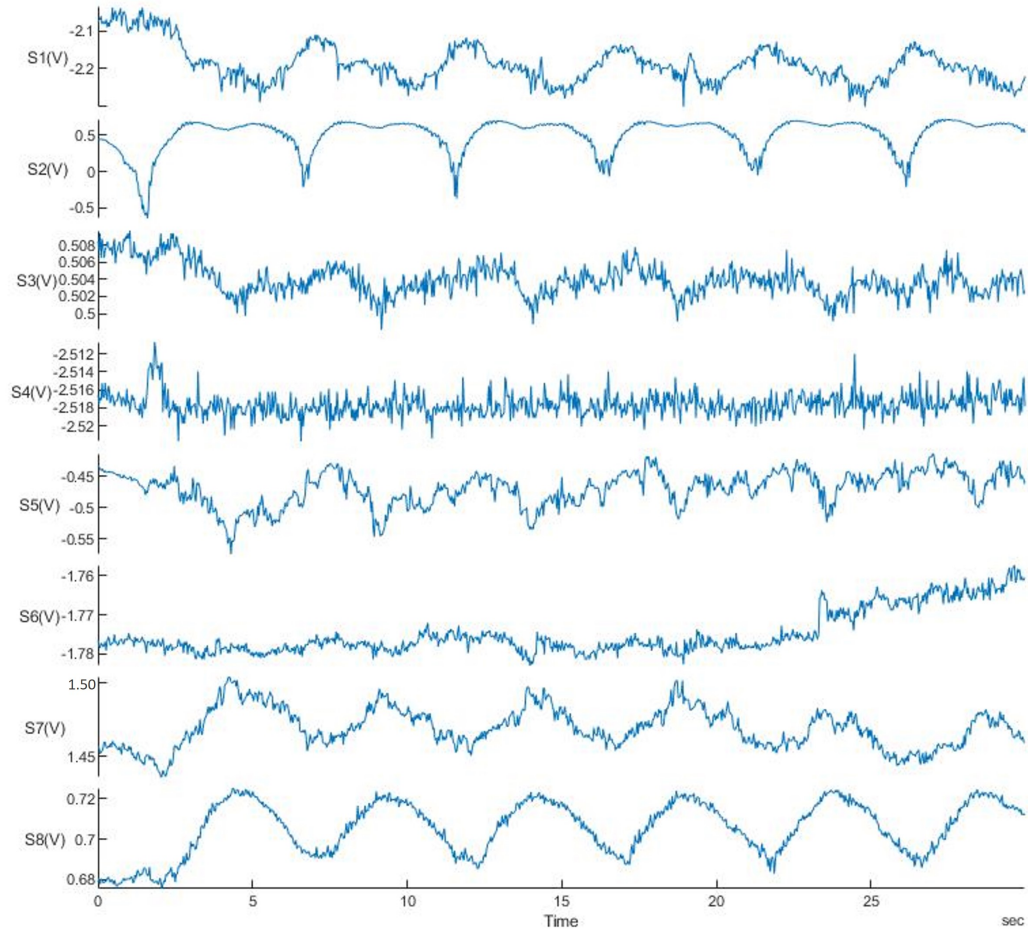


Figure 3.7: The response of eight soft sensors embedded into the C-leg respective to the elapsed time.

3.1.3.2 The Experiments to Assess the Soft Sensor Performance

In this experiment, we aim to compare the soft sensor performance to the commercial encoder currently used on SQuad. C-leg is attached to the treadmill test setup and rotated at 1 Hz for 30 seconds. Free rotation and rotation on treadmill cases are investigated. Three clear peaks of triangular-shaped commercial encoder signal can be observed in Fig. 3.8 and Fig. 3.9 for both cases. Three respective responses can be observed in the soft sensor responses for both cases. A promising observation of the experiment was that the soft sensors even captured the inertial forces due to the rotation of the C-leg, as shown in Fig. 16. When the C-leg is placed onto the treadmill, the amplitude of the soft sensor response increases since the cyclic load applied from the ground is increased as can be observed from Fig. 3.9.

The soft sensor response’s peak amplitude is much smaller than the encoder response. Despite this, the soft sensors seem to be following a trend that could be correlated with the stepping pattern. On the other hand, the sensor response cannot be used to distinguish the C-leg’s angular position without any postprocessing such as filtering, fitting a function, or potentially some machine learning methods. Also, as future work, instead of using symmetrical sensor geometries shown in Fig. 2.1, we consider using unsymmetrical sensor geometries to extract information about the C-leg’s angular position. Instantaneous, non-delayed angular position and rotational speed information are needed to control the robot’s gait. Thus, even if a simple moving average filter is applied to the robot, the gait control of the robot may be broken due to the time delay introduced by the filter. We only eliminate the dead zone for the commercial encoder by simple thresholding without introducing time delay. At this point, acquiring instantaneous angular position information does not seem possible with the current soft sensor response. Hence the sensor is not applicable for gait control under the current control scheme.

However, it is possible to capture the rotational speed of the leg with these soft sensors in both free rotation and on treadmill cases. In the first three seconds,

three repeating patterns were expected to be observed in the soft sensor response since the rotation speed of the C-leg was set to 1 Hz. In both Fig. 3.8 and Fig. 3.9, three repeating patterns exist in the first three seconds of the experiment. We constructed an algorithm that counts how many times soft sensor responses reach or pass a defined threshold. A timer is also used to capture the elapsed time during the counting process. For instance, the threshold is set to be between -0.2 V and -0.15 V for free rotation, whereas it is set to be between 0.45 V and 0.46 V for the treadmill case. For the commercial encoder, the threshold is set to be between -0.55 V and -0.45. The counter is divided into four because we observed in each pattern that soft sensor response creates an “m shape,” meaning almost two symmetrical peaks exist.

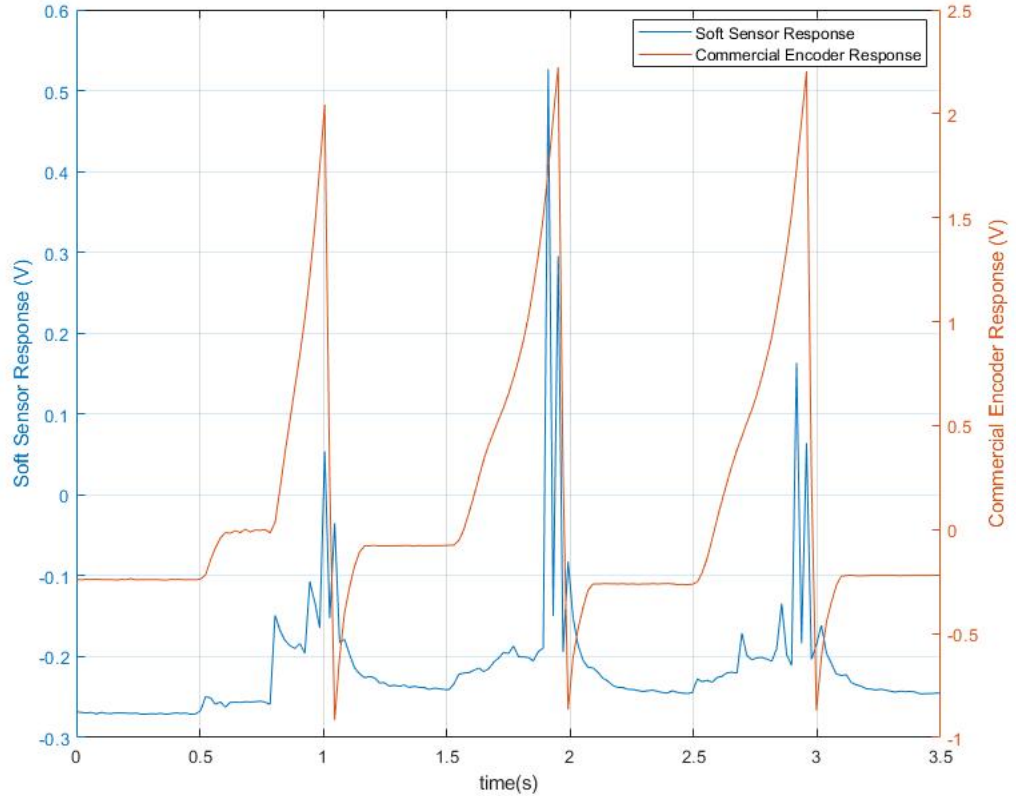


Figure 3.8: The soft sensor and commercial encoder responses under free rotation.

On the other hand, to estimate the rotation speed with commercial encoders, the counter is divided into two since each pattern consists of a single peak. After

the division, we have the number of revolutions and time elapsed. By using these two features, the rotational speed can be calculated respectively.

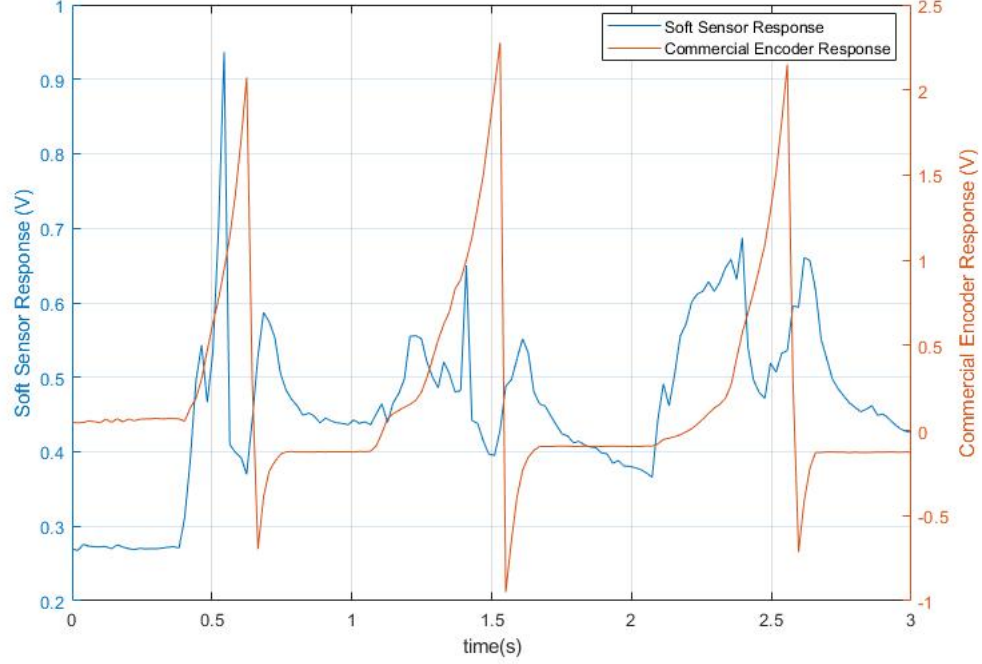


Figure 3.9: The soft sensor and commercial encoder responses on treadmill.

Furthermore, one of the significant observations was the connection loss due to slipping reliability issues. Although it rarely happened, it affected the results of some experiments, as shown in Fig. 3.10. Connection loss directly affects the error percentage in estimating the rotational speed of the C-leg. Once a connectivity issue occurs in the slipping mechanism, it continues to affect the sensor response unless it is manually fixed, as can be observed in Fig. 3.10. If there are no connectivity issues in the slipping mechanism, we found that the algorithm can detect the rotational speed with an accuracy of 86.7% for the free rotation case. Moreover, the accuracy of detecting the rotational speed is 87.5% for the treadmill case. We cannot claim any accuracy on the rotational speed estimation when a connectivity issue occurs because estimating rotational speed is almost impossible before manually fixing the connectivity issue.

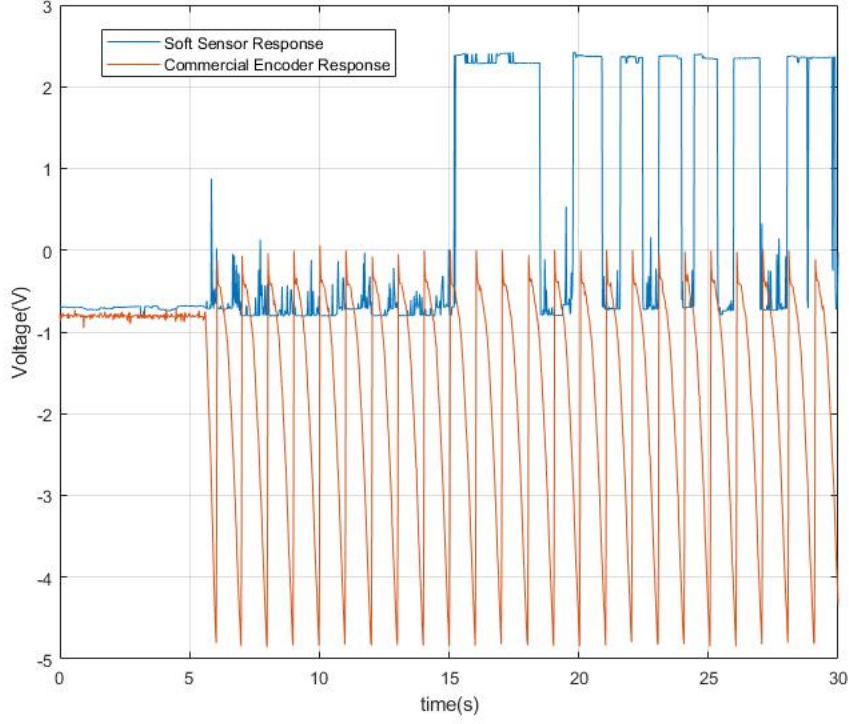


Figure 3.10: The connection loss sample of soft sensor response.

3.1.3.3 Finite Element Analysis to Determine the Stiffness of the C-legs

In this analysis, 1 N is applied in the y-direction for both cases. Distributed displacement along the longitudinal direction on both the regular C-leg and composite C-leg can be observed in Fig. 3.11 and Fig. 3.12, respectively. Maximum displacement along the longitudinal axis is found as 5.49 mm for the regular C-leg whereas it is found as 2.95 mm for the composite C-leg. Since the compression amount and applied force are known, it is possible to apply Hooke's law to determine the stiffness of each C-leg. For the regular C-leg, stiffness is found as 182.15 N/m, whereas it is found as 338.87 N/m for the composite C-leg. Embedding the soft sensor into C-leg increased the stiffness by almost twice, by 85.6%.

$$E_c = fE_f + [1 - f]E_m \quad (3.1)$$

Where E_c is Longitudinal Young's Modulus of composite, f is fiber to volume ratio, E_f is the Young's Modulus of the fiber, E_m is the Young's Modulus of the matrix.

The longitudinal Young's modulus of the composite material is calculated as 5.8 MPa via using Eq. (3.1) [28] since Young's modulus of the PDMS and TPU is 1.5 MPa and 2.3 MPa, respectively. However, the change in leg stiffness is only found to be from 338.87 N/m to 182.15 N/m. The main reason for this discrepancy is that the composite mechanic's calculation is made by considering unit volumes sampled from the upper end, the middle, and the bottom end of the C-leg. From the upper end to the bottom end, the longitudinal direction and the transverse direction of the sampled unit volume do not match with the longitudinal direction and transverse direction of the C-leg. Therefore, it is not possible to evaluate the change in leg stiffness with respect to the longitudinal Young's modulus of the composite material in this case. These composite mechanics calculations are made to approximate the mechanical properties of the composite material created with PDMS and cTPU sensors.

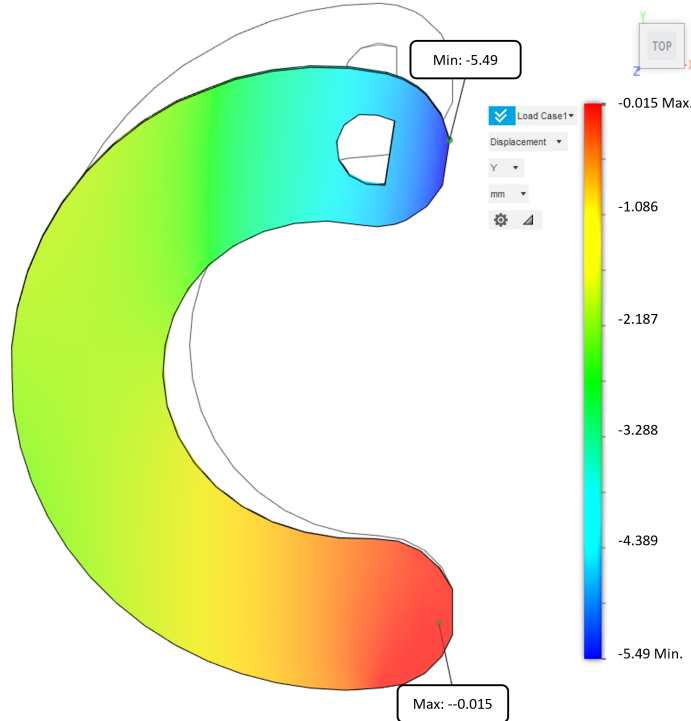


Figure 3.11: The structural analysis of the regular C-leg.

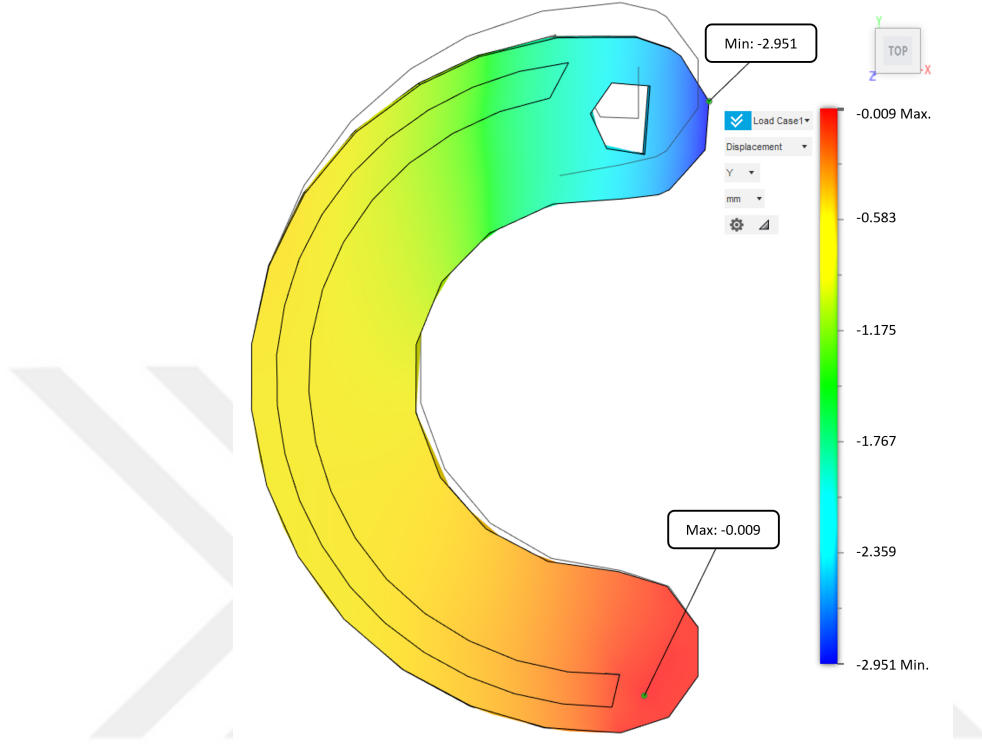


Figure 3.12: The structural analysis of the composite C-leg.

3.1.3.4 Experiments to Evaluate the Stiffness of Soft Sensor Embedded C-leg

In this experiment, compression amount versus applied force data is gathered for both the regular C-leg and the soft sensor embedded C-leg. Data is represented in Fig. 3.13 and Fig. 3.14, respectively. By finding the slope of these two plots, the experimental stiffness of both legs can be found. The results of this experiment are compared to the FEA conducted before. The outcome of this comparison can be observed in Table 3.1.

Leg Type	Stiffness from FEM	Stiffness from Exp.	Error (%)
The regular C-leg	182.15 N/m	229.72 N/m	20.7
The composite C-leg	338.87 N/m	295.90 N/m	12.7

Table 3.1: The comparison of stiffness experiment results and FEA results.

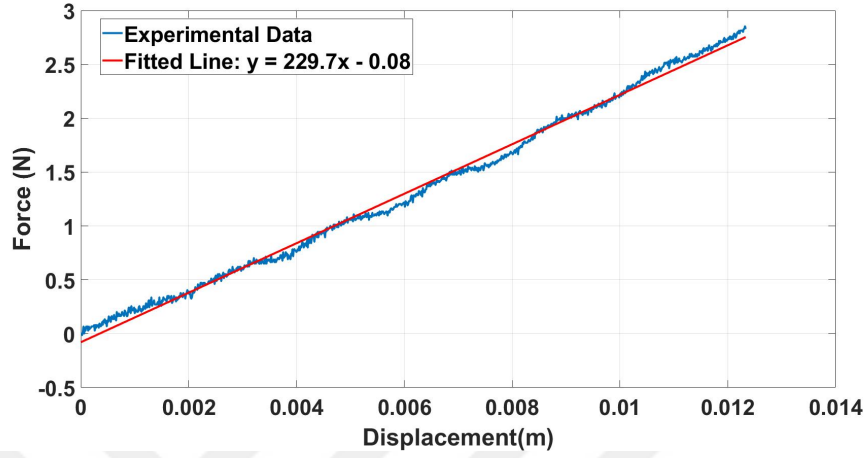


Figure 3.13: The structural analysis of the regular C-leg.

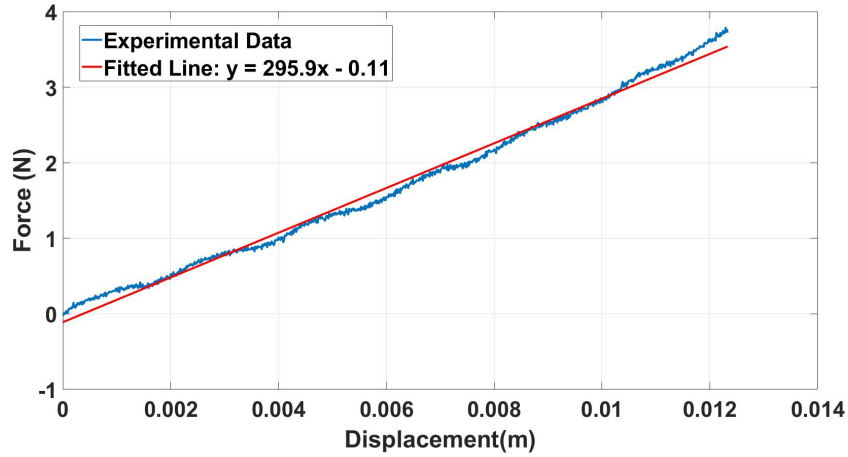


Figure 3.14: The structural analysis of the composite C-leg.

The stiffness values are found by using FEM and conducting experiments. Percentage errors are calculated for both legs. Small manufacturing errors, the D shaft housings located in the PDMS matrix for connection purposes, or even a small mismatch between the reported Young's Moduli of the materials used and their actual values can account for the small mismatch between the FEA results and the experimental findings. Either case, composite nature of the sensorized C-legs does not change the stiffness value of the legs in an amount that would significantly alter locomotion characteristics, i.e., the legs are still expected to deflect a significant amount during locomotion and cause the robot to walk like a soft robot, rather than a rigid one.

3.2 Modular Soft Quadruped (M-SQuad)

3.2.1 Design

When we design M-SQuad shown in Fig. 3.15, our main aim is to improve our soft miniature C-shaped legged quadruped SQuad shown in the Fig. 3.16, by giving it the ability to recognize if an obstacle is scalable. To achieve this, we have modified SQuad and divided it into three modules: back, middle, and front.

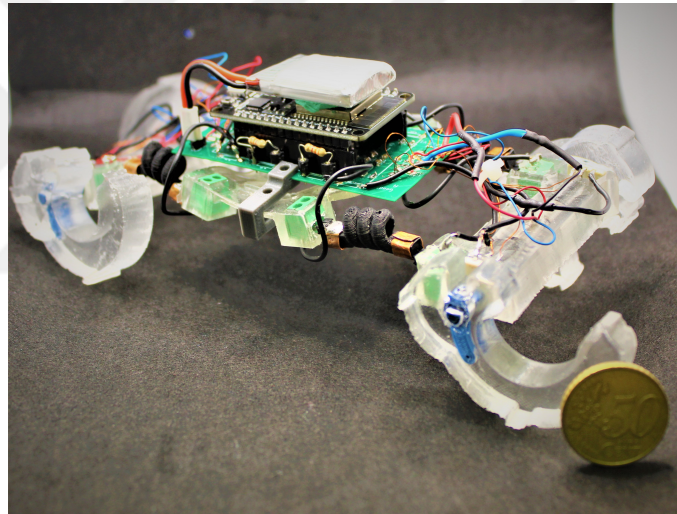


Figure 3.15: M-SQuad: Modular soft quadruped.

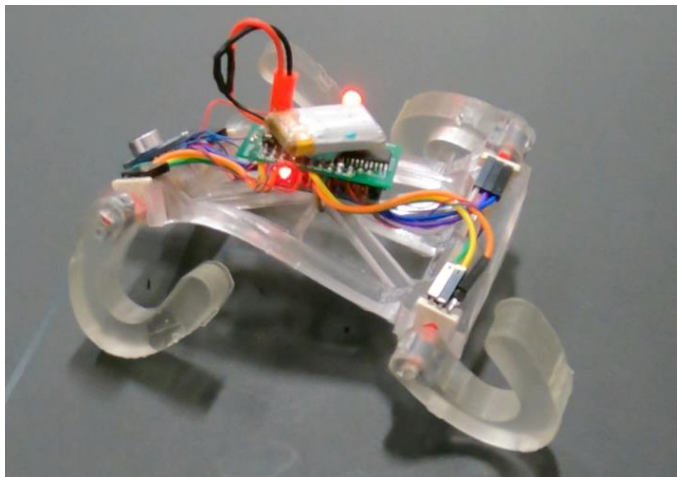


Figure 3.16: SQuad: Soft quadruped.

3.2.1.1 Body Design

The main inspiration behind the M-Squad's body design is to soften the sensorized parts of the robot body to maximize the bending amount the soft sensors experience during locomotion. On the other hand, we don't want the robot's body touching down during locomotion in order to avoid unnecessary forces caused by dragging. As a result, we ended up designing a more rigid motor mounting part and a middle electronics carrier module, but softer module connecting sensors, compared to M-Squad's brother Squad Fig. 3.15.

The M-Squad's body design consists of three modules, which can be listed as the back module, middle module, and front module. The front and back modules are identical modules. Since they carry the motors, they are both called motor end modules. The middle part is designed to carry PCB and battery; all the wires are distributed from this module to the motor end modules. Thus, this module is called the main module. The motor end modules are mechanically connected to the main module via two soft sensors. A schematic of the robot's body is shown in Fig. 3.17.

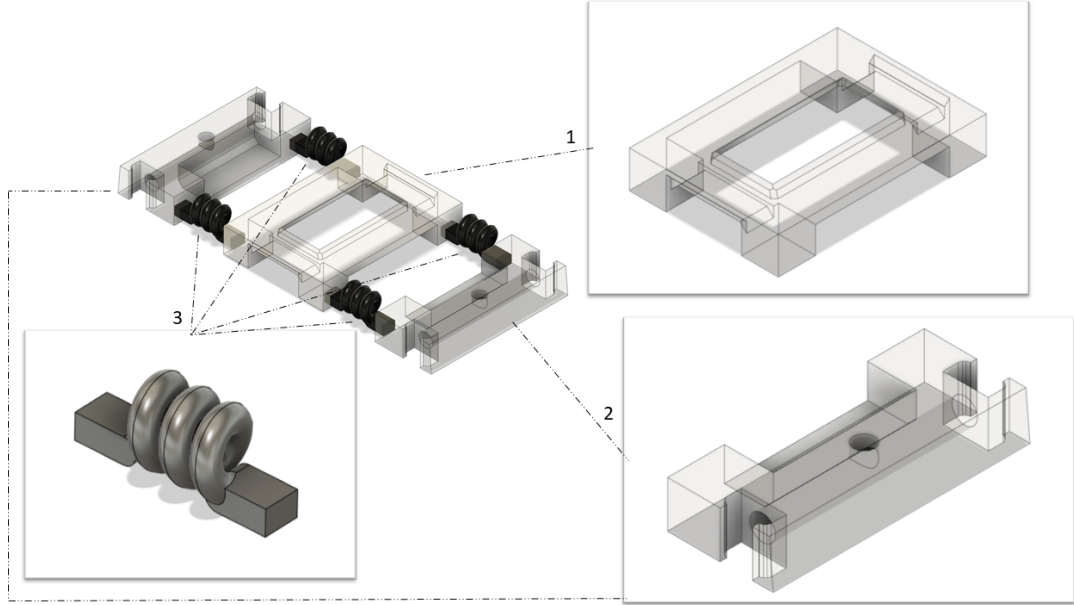


Figure 3.17: The CAD drawing of the body of the M-Squad together with sensors. (1) Main module (2) Motor end module (3) Soft sensors.

In order to provide necessary electrical connections between the sensors and the microcontroller, double-row PCB screw terminals are used. Four of these screw terminals are embedded in the middle module, and two screw terminals are embedded in each motor end module during the curing of the PDMS in the module molding step. Sensor connections are prepared with respect to these double-row PCB screw terminals with dimensions of 5 mm x 5 mm x 6 mm. The used screw-in terminals can be seen at the locations where the soft sensors are connected to the body modules in Fig. 2.14(c).

Each module has a width of 60 mm, where motor ends have a length of 25 mm, and the middle module has a length of 44.5 mm. The motor end module has a weight of 15 grams, and the middle module has a weight of 10 grams. Overall, the assembled body has a length of 154 mm, a width of 60 mm, a height of 30 mm, and a mass of 123 grams.

Similar to the SQuad's design, PDMS is the main material used in M-SQuad's body modules and C-legs. For fabrication, first, the molds necessary for manufacturing the body modules and C-legs are prepared. In total, 3 different types of molds are designed and prepared, one for the middle module, one for the motor, end modules, and one for the C-legs. PDMS Sylgard 184 was mixed in a 10:1 ratio of a pre-polymer and cross-linker and mixed for body modules, for the C-legs ratio is kept at 5:1. PDMS is poured into the mold and placed in the oven for 4 hours at 70°C. Then the modules are removed from the mold.

Different from SQuad's C-legs, C-legs used in M-SQuad have an expanded circular width at the locations where the legs are attached to the motors in order to raise M-SQuad's body from the ground. These expanded C-legs can be seen in Fig. 3.15. Raising the robot's body modules was critical to prevent dragging problems. Compared to the SQuad's C-legs, the only significant difference is the expansion of the C-legs.

3.2.1.2 Electronics Design

In the Squad's circuits, an Arduino Pro Micro and two L293DD H-bridges are used to drive four DC motors. The main components can be summarized with these components. In addition, there are some passive components located on the circuit board in order to prevent any instantaneous voltage fluctuations. Also, a switch and a 3.7-5 V regulator were used on the PCB. M-Squad also has a similar circuit board architecture.

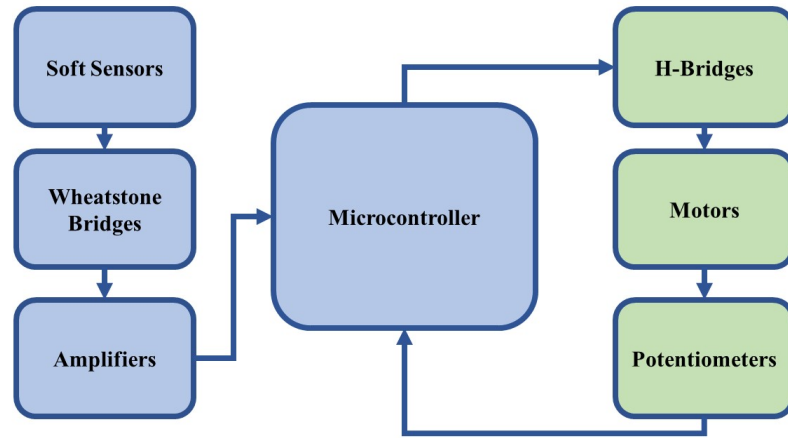


Figure 3.18: The architecture of the electronics board of M-Squad.

The electronic design of Squad differs from M-Squad mainly because of the four-sensor located on the M-Squad's body. In order to transmit the responses of these four sensors to the microcontroller, four extra analog read pins are needed. Thus, different from the Squad, in M-Squad's circuit board, an ESP-32 was utilized instead of the Arduino Pro Micro because the ESP-32 has more general-purpose input/output pins. Furthermore, unlike Arduino Pro Micro, it has its own embedded Bluetooth module, which is used to transfer the data of the sensors during experiments. Furthermore, for each pair of sensors, an LM358P Op-Amp and two wheat-stone bridges are used on the circuit board.

Wheatstone bridges are used to convert the soft sensor response to a voltage change. The bridges are supplied with 5 V. Wheatstone bridge is formed with 1 k Ω , 3 k Ω , 3.3 k Ω resistors, and the actual sensor as the fourth leg. However,

the voltage output was very low, and amplification was essential. Thus, for this purpose, LM358P Op-Amps are preferred. A single Op-Amp differential amplifier configuration is used. By using the amplifier circuit, sensor signals are amplified with the desired gain (set to 2.14) by adjusting the resistance with respect to the gain. The general architecture of the electronics is shown in Fig. 3.18.

3.2.2 Detection Algorithm

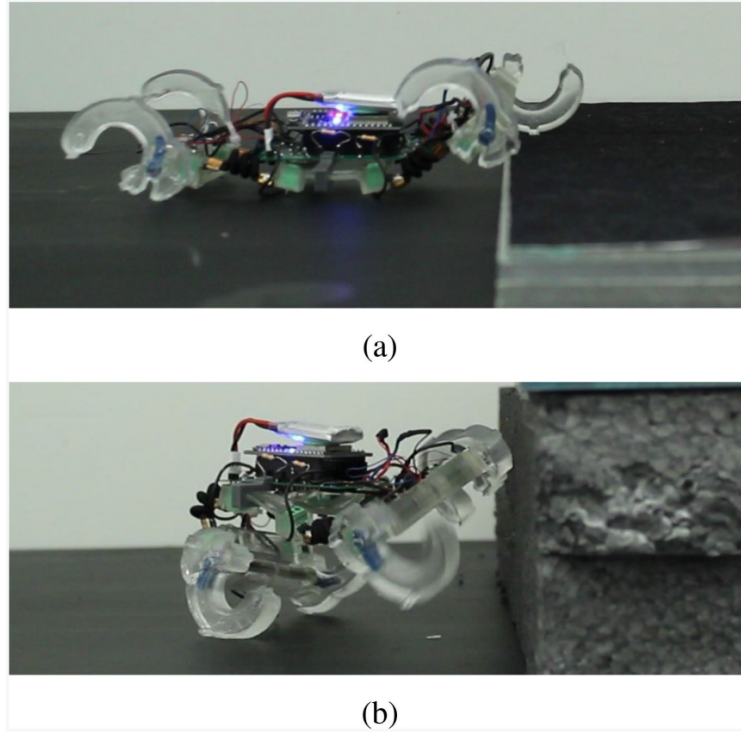


Figure 3.19: Photos of M-Squad when it encounters (a) scalable obstacle (b) non-scalable obstacle.

In order to detect whether an obstacle is scalable or not, sensors on the robot are used. Data gained from the soft coil-spring-shaped sensors are used and reported as raw data. The data is not filtered in any way. We observed that when the robot hits an obstacle that it cannot scale, sensors on the back of the robot compress until the rings of the spring are touching each other. When this happens, the resistance of the sensors connecting the rear motor end module and

the main module drops to a very low resistance value, and the measured voltage from the sensors saturates at 3.3 V.

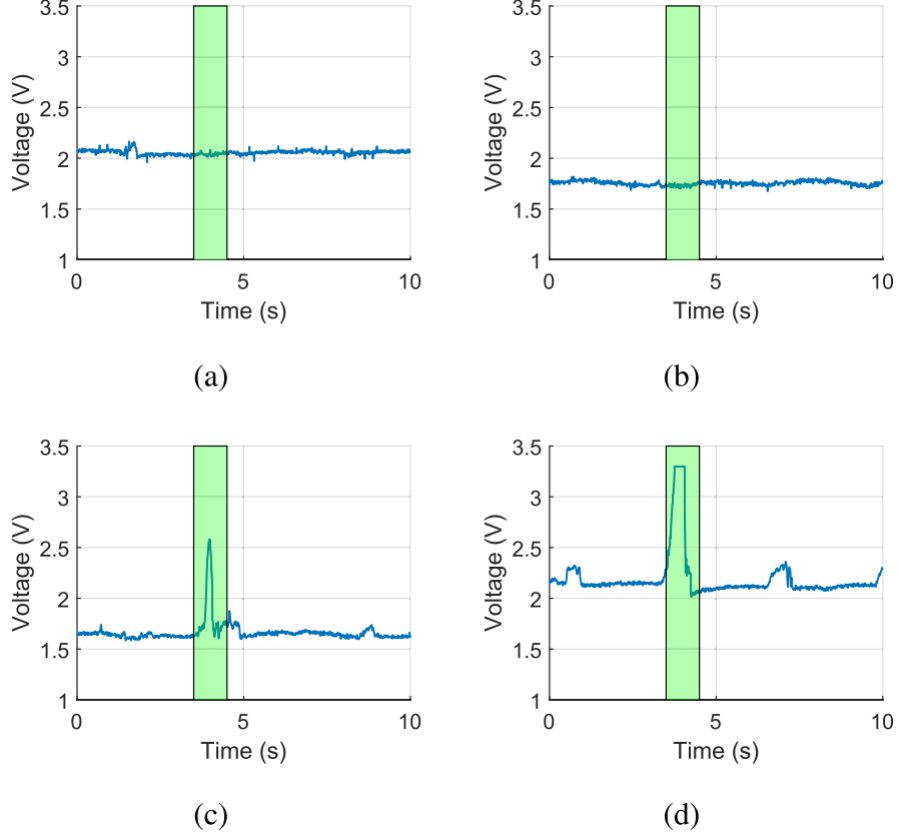


Figure 3.20: The data obtained from the sensors, when M-SQuad hits a scalable obstacle: (a) front left sensor, (b) front right sensor, (c) rear left sensor, (d) rear right sensor.

We developed an algorithm so that the robot can respond to obstacles beyond its scaling capabilities. If the sensors on the back of the robot saturate simultaneously and for more than a given threshold of time (selected as one second), the robot understands that it is facing an obstacle that it cannot scale. Then, the robot stops, and the directions of the actuators are reversed so that the robot climbs down and starts to move in the opposite direction.

In Fig. 3.19(a), the robot encounters a relatively small obstacle that it can scale. From Fig. 3.20, we can see that only the rear right sensor readings shown in Fig. 3.20(d) reach the saturation value for a very short duration. The rear left

sensor reading shown in Fig. 3.20(c) reaches a high value yet does not saturate. Such a sensor response is typical during climbing over scalable obstacles.

In Fig. 3.19(b), the robot encounters an obstacle that it cannot scale. In Fig. 3.21(c) and (d), we can observe that, while the robot tries to climb the obstacle, there are first small peaks for a short duration at first. Eventually, when the front of the robot starts to climb and the robot bends significantly, the readings from the rear sensors saturate for a significant time. So, the robot evaluates this as trying to climb over an unscalable obstacle, stops, and moves backward.

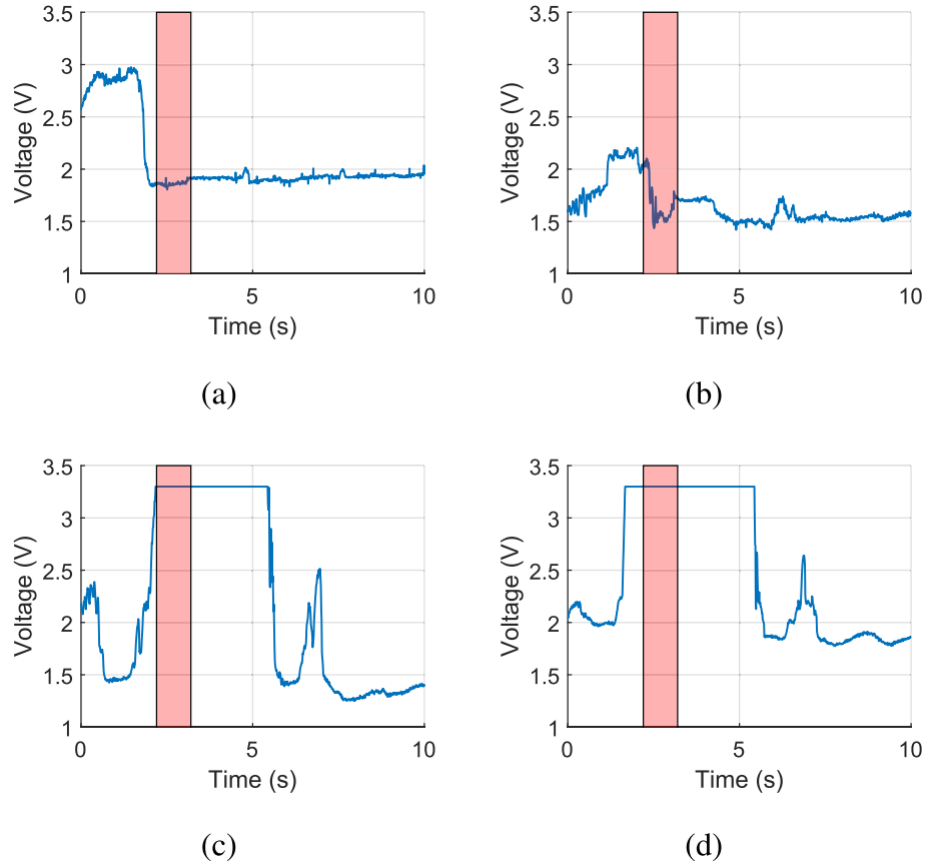


Figure 3.21: The data obtained from the sensors, when M-SQuad hits a non-scalable obstacle: (a) front left sensor, (b) front right sensor, (c) rear left sensor, (d) rear right sensor.

In order to evaluate the reliability of the robot's decision-making (if an obstacle is scalable or not), twenty-six trials are conducted with a relatively small obstacle

that the robot is expected to scale easily. In only one of the twenty-six trials, M-SQuad failed to identify the obstacle as scalable. However, after investigating the video footage of the experiment, we observed that the tip of the sensor terminal was stuck on the obstacle while scaling, and the robot got stuck. This caused the sensors to get compressed more than the threshold, and the robot labeled the obstacle unscalable. Even though this was a valid concern for the robot, and if continued, the robot might have gotten broken, we considered this case to be a failure. After twenty-six trials, the success rate of distinguishing the scalable obstacle is higher than 96% (25 out of 26).

Additionally, we conducted twenty-seven trials with an obstacle that the robot could not scale. In total, the robot labeled the obstacle as not scalable correctly, with a success rate of higher than 92% (25 out of 27). In each trial, the time elapsed during detection was gathered from the videos. The average time between obstacle contact and decision-making is found as 3.81 seconds, with a standard deviation of 1.56 seconds.

3.2.3 Case Study

To demonstrate the scalable obstacle detection capabilities of the robot, a simple parkour is prepared. We placed two obstacles back-to-back, where the first obstacle is 20 mm in height and the second one is around 150 mm, which is much higher than M-SQuad can climb over. The robot was expected to detect and pass the first obstacle, detect the second obstacle as non-scalable, move backward, and scale the first obstacle again.

Fig. 3.22 illustrates the data obtained from the soft sensors on the robot during the demonstration. Green sections represent the successful obstacle scaling of the robot, while the red sections represent where the robot fails to scale the obstacle and reverse the moving direction. The first green section shows where the robot encounters the first obstacle, and Fig. 3.23(a) shows a screenshot from the video of the experiment. It can be seen in the first green section in Fig. 3.22(c) and (d) that sensor readings reach a peak value instantaneously during the climbing.

The time threshold is not exceeded before the sensor levels drop, so the robot continues the mission.

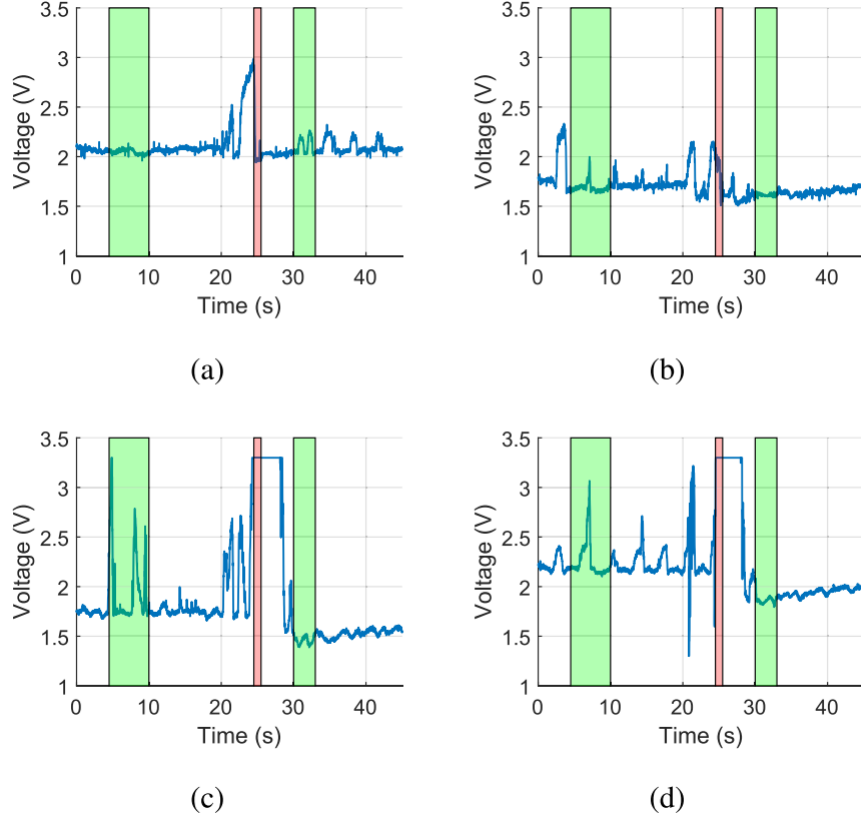


Figure 3.22: The sensor data obtained from the sensors during the case study. M-Squad first hits a scalable obstacle, then a nonscalable obstacle, returns, and hit the scalable obstacle again. (a) Front left sensor, (b) front right sensor, (c) rear left sensor, (d) rear right sensor.

After that, the robot encounters the second obstacle, for which a screenshot is shown in Fig. 3.23(b), and fails to scale it. The red section in Fig. 3.22(c) and (d) shows the one-second period of saturated reading of the rear sensors. As the saturated readings from the rear sensors exceed one-second duration, the robot waits for another second and reverses the directions of the motors to move backward. While moving backward, the robot encounters the first obstacle again, which is illustrated by the second green section for the rear sensors in Fig. 3.22(c) and (d). However, this time as the robot is moving backward, front sensors are the focus of interest for detecting the obstacles and there are no significant changes in the sensor readings as can be seen in Fig. 3.22(a) and (b). As a result, the robot

continues to move in the same direction. The moment that the robot encounters the scalable obstacle while moving backward is shown in Fig. 3.23(c). It should also be noted here that the locomotion of the robot in the forward direction and reverse direction may differ from each other in trot gait because of the C-shaped legs used in the M-SQuad design. Therefore, it is expected to see different sensor behaviors. However, it is not a significant difference since the sensors still can detect the obstacles and distinguish them as scalable or non-scalable.

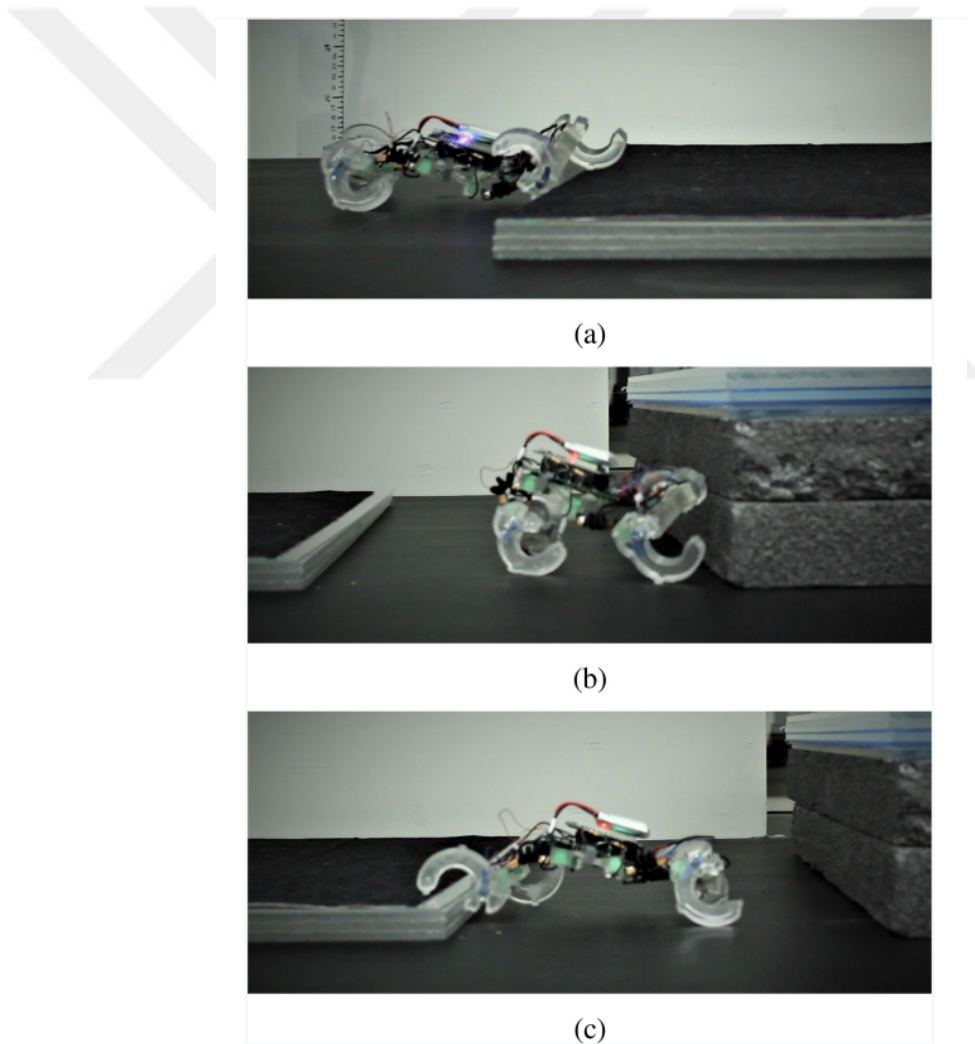


Figure 3.23: Photos from case study video when M-SQuad hits the (a) scalable obstacle while moving forward, (b) non-scalable obstacle, (c) scalable obstacle while moving backward.

3.3 Suspensionized Soft Quadruped (S-SQuad)

Suspensionized soft quadruped (S-SQuad) is a modified version of the robot, M-SQuad shown in Fig. 3.24. The primary motivation of M-SQuad is detecting the obstacles and distinguishing the obstacles as scalable and non-scalable, whereas S-SQuad is designed to detect the softness of the terrain and the inclination amount of the surface where the robot walks. We completed the design process of S-SQuad. We are currently analyzing the functionality of the robot for the specified tasks. There is a detailed explanation of the S-SQuad design in the design section and some initial experiments conducted, and the results will be evaluated.

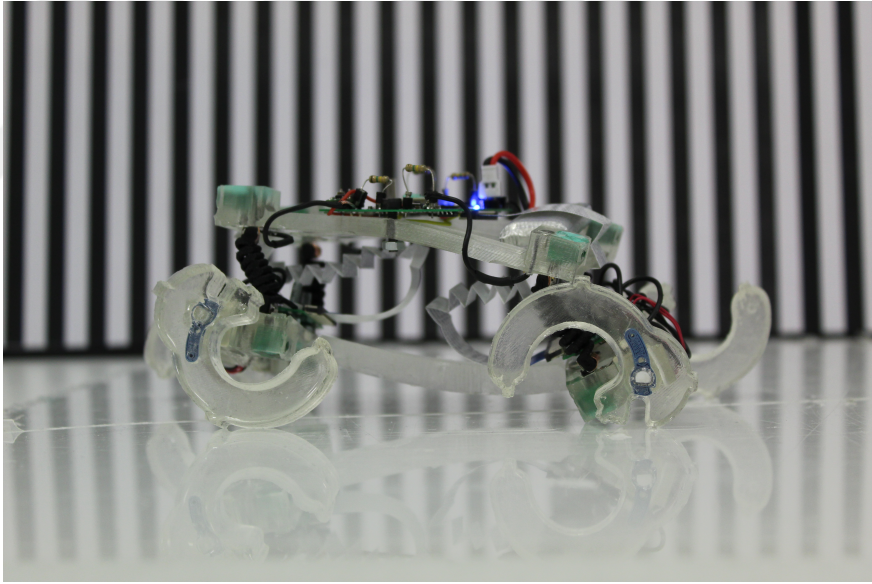


Figure 3.24: S-SQuad: Suspensionized soft quadruped.

3.3.1 Design

3.3.1.1 Body

Overall, the body design of the robot is similar to M-SQuad. The robot body consists of two end modules, one main module, and four sensors. The end module design is the same as the end module design of M-SQuad. Unlike the M-SQuad

design, an extra part called the backbone connects two end modules shown in Fig. 3.25. This is necessary to complete the bottom chassis of the robot 3.26. The backbone prevents orientation shifts during the locomotion of the robot. We observe that the robot circles around without the backbone connecting two end modules. The main module design differs from the M-SQuad since the soft sensors are placed in the vertical direction between the main module and the end module. The main module is raised by four soft sensors on the top of the bottom-end modules, as it is shown in Fig. 3.24. The expectation behind this design is the tilt of the main module when the robot is walking on an inclined surface. The tilted main module creates some compression on some soft sensors carrying the main module. By analyzing the compressed soft sensor responses and compressed soft sensor location, we expect to quantify the inclination amount and the orientation.

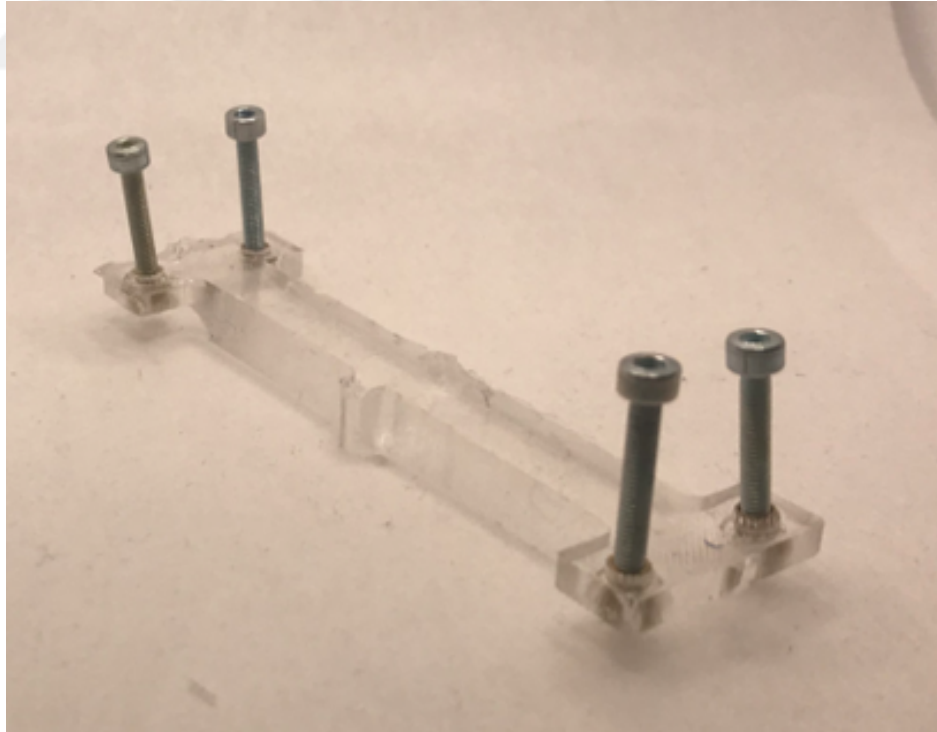


Figure 3.25: The backbone of S-SQuad.

Soft coil-shape sensors are integrated into the S-SQuad design. The sensor design should be stiff enough to carry the main module. However, when the main module is tilted because of the inclination of the surface, the soft sensor

should be elastic enough so that the coil contact should occur on some sensors to detect the orientation and the amount of the inclination of the surface. The robot can roll over on an inclined surface if the height of the main module from the bottom module is increased by the length of the soft sensors. Therefore, the sensor dimensions are given as a length of 24.5 mm, a width of 6 mm, a coil-to-coil distance of 0.35 mm, and a thickness of 2 mm. These dimensions are found by design iterations. Iterations are continued until we satisfy our design requirements.

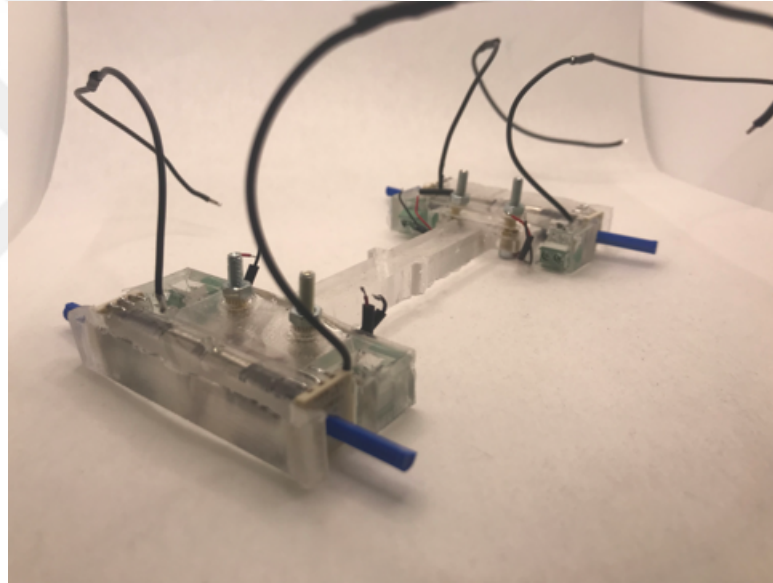


Figure 3.26: The assembled version of end modules via backbone.

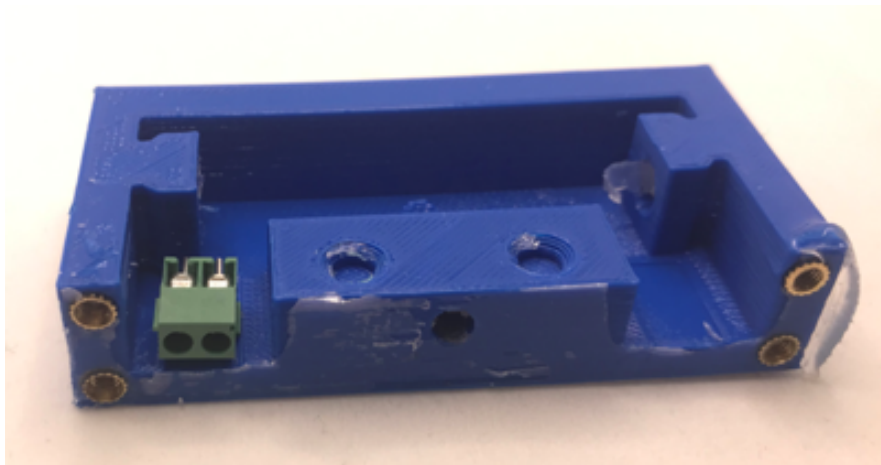


Figure 3.27: The screw terminal placement in the vertical direction.

Furthermore, the soft coil-shape sensor with bent copper plate-type connectors is preferred. To connect soft sensors and the modules to each other, screw terminals are embedded into the modules with respect to the soft sensor placement in the vertical direction, as shown in Fig. 3.27. Thanks to this design, the soft sensors are used as both structural and sensing elements on the robot body, like the M-SQuad design.

Similar to the M-SQuad's design, PDMS is the main material used in S-SQuad's body modules and C-legs. For fabrication, firstly, the molds necessary for manufacturing the body modules and C-legs are designed and prepared. In total, four different types of molds are designed and prepared, one for the middle module, one for the end modules, one for the backbone, and one for the C-legs shown in Fig. 3.28. PDMS Sylgard 184 was mixed in a 10:1 ratio of a pre-polymer and cross-linker and mixed for body modules, for the C-legs, and the backbone ratio is kept at 5:1. PDMS is poured into the mold and placed in the oven for 4 hours at 70°C. Then the modules are removed from the mold.

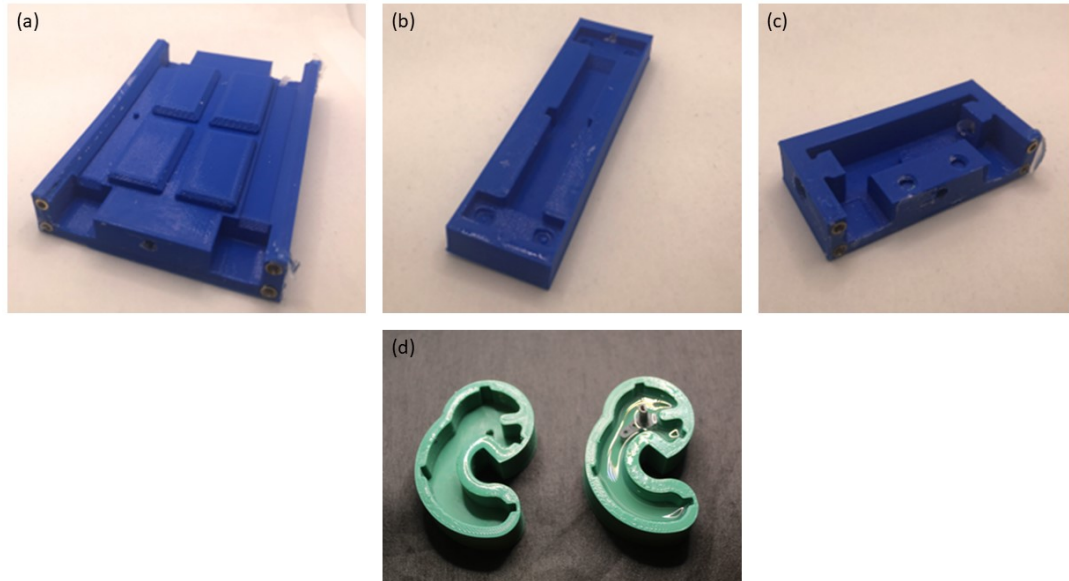


Figure 3.28: (a) Main module mold, (b) Backbone mold, (c) End module mold, (d) C-leg mold.

3.3.1.2 Electronics

The general architecture of the electronics design is the same as the electronics design of the M-Squad shown in 3.18. However, the printed circuit board (PCB) design differs from M-Squad PCB. M-sQuad carries the PCB on the top of the main module, and all the cables that come from the encoders, soft sensors, and motors are soldered to this PCB as shown in Fig. 3.29. In the PCB design of the S-Squad, we split the PCB into three PCBs. There are two types of PCBs which are main module PCB and end module PCB. The main module PCB involves the microprocessor (ESP 32), data-capturing circuits (Op-Amps and Wheatstone bridges), and FPC connectors. The motor drivers, encoder pinouts, and motor pinouts are located on end module PCBs. It also has FPC cable connectors similar to the main module PCB. The modules are connected to each other via a flexible FPC cable. Thanks to this design, the soldering process is reduced. The soldering process is required only for the connection of the motor and encoder pinouts to the end modules. The robot modules can be connected to each other. In addition, since the FPC cable is flexible, it does not ruin the soft nature of the robot.

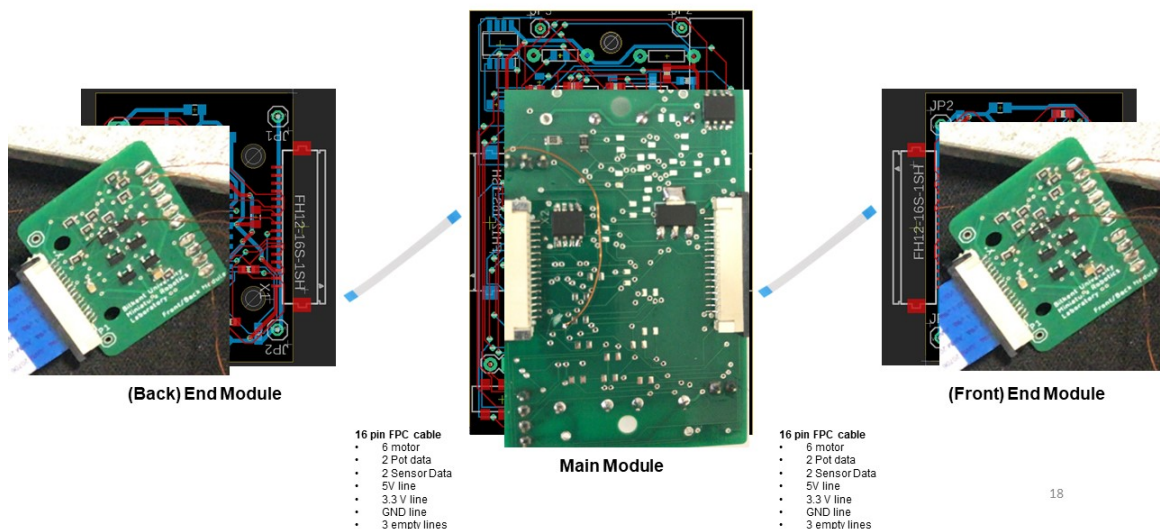


Figure 3.29: The connection diagram of splitted PCB concept.

3.3.2 Experiments and Results

The initial experiments are conducted to analyze soft sensor responses when the S-Squad is walking on the non-incline surface and inclined surfaces. We tested the robot's performance on different inclination amounts (7, 9, and 19 degrees). In total, we captured three different data sets. The experiment starts with dropping the robot off to the ground as shown in Fig. 3.30(a).

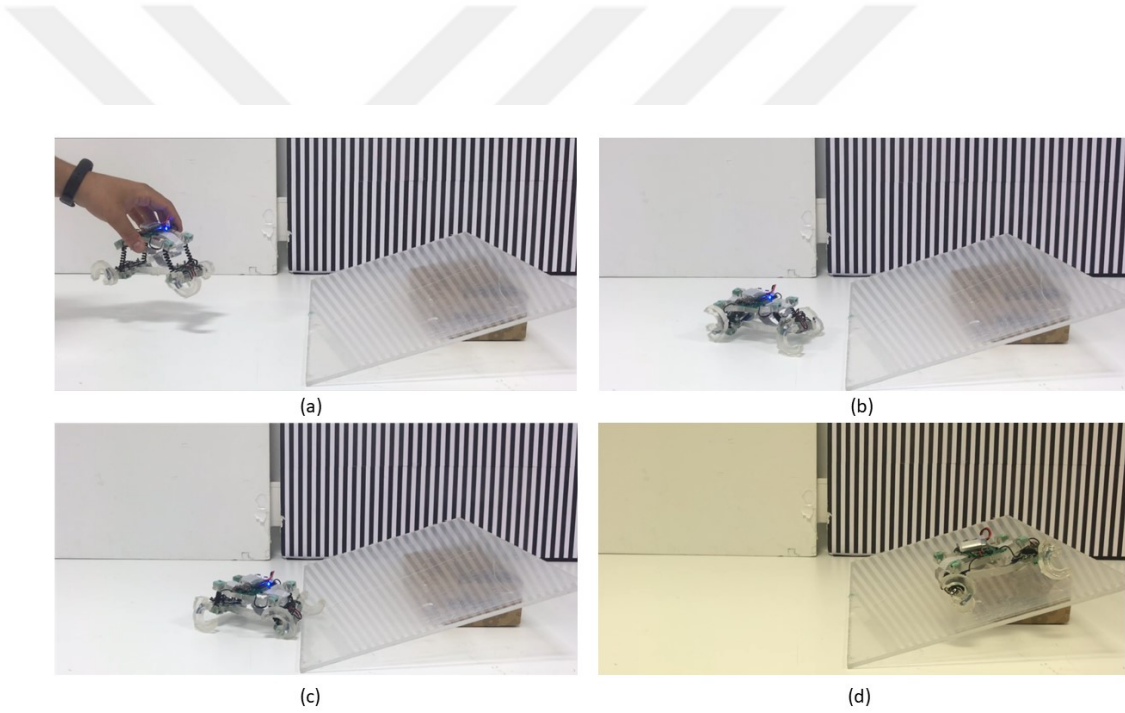


Figure 3.30: (a) The beginning of the experiment, (b) S-Squad is dropped to the ground and walking, (c) left front C-leg first touches the inclined surface when it is scaling the misalignment, (d) S-Squad is walking on the inclined plane.

This is necessary to match the video recording and the data taken from the soft sensors because when the robot touches the ground, all the sensors are actuated simultaneously. A significant decrease or increase is observed in the soft sensor responses depending on the way of falling shown in Fig. 3.31, 3.32, and 3.33. The robot starts to walk on the ground (non-inclined surface), reaching the inclined plane placed on the setup as shown in Fig. 3.30(b). There is a misalignment between the inclined surface and the ground.

When the robot is scaling the misalignment, since the robot walks in trot gait, one of the front C-legs makes contact with the inclined plane surface earlier, as shown in Fig. 3.30(c). After the robot scales the misalignment, it continues to walk on the inclined plane until the end of the experiment 3.30(d). One of the qualitative observations of the robot's walk on the inclined terrain is that the main module of the robot slipped in the direction of the slope. As the slope increases, we observe that the slippage of the main module increases.

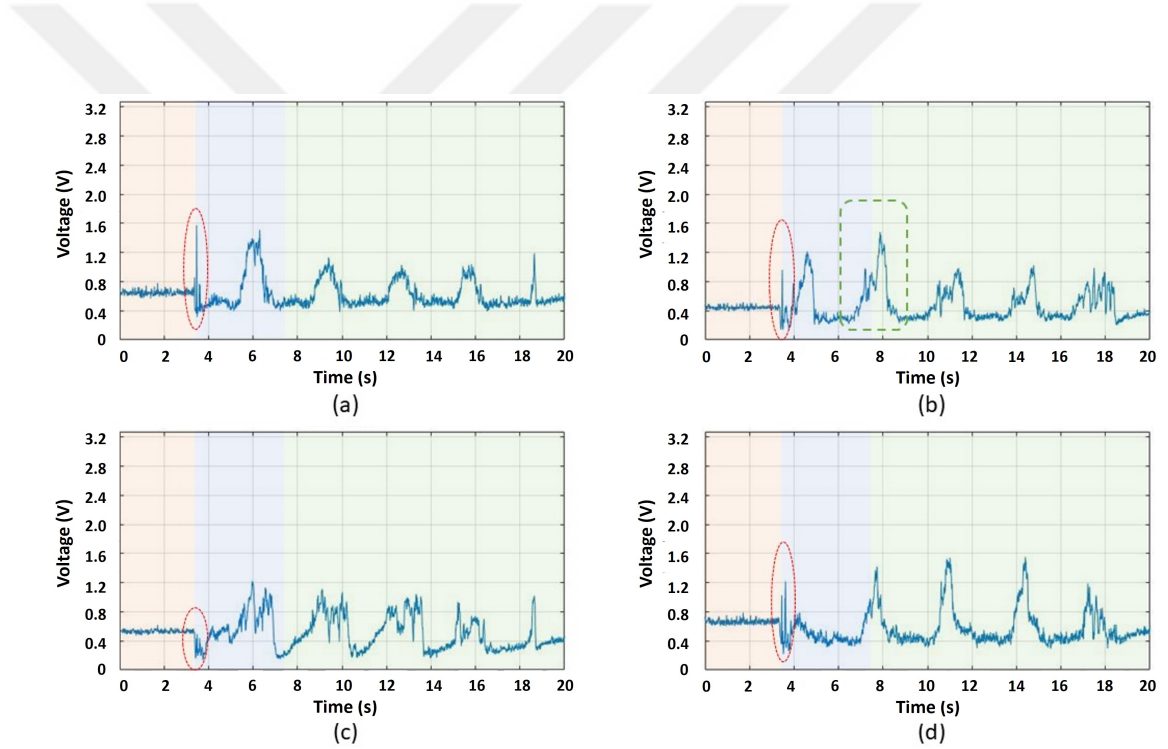


Figure 3.31: Soft sensor responses during the experiment with 7-degree inclination. (a) Front left sensor, (b) front right sensor, (c) rear left sensor, (d) rear right sensor. (Green dashed: the maximum peaks occurred when the robot is scaling the misalignment, red dashed: robot first touches the ground.)

Due to the slippage, the sensors at the front are tensed, whereas the sensors at the back are compressed. Therefore we expect to see an increase in the amplitude of the signals received from the back sensors and a decrease in the amplitude of the front sensors' signals. The taken data supports the decrease in the amplitude of the front sensors' signals. When the robot walks on the inclined surface, the amplitude of each sensor response decreases compared to signals received during walking on the ground and scaling the misalignment stages of the experiments.

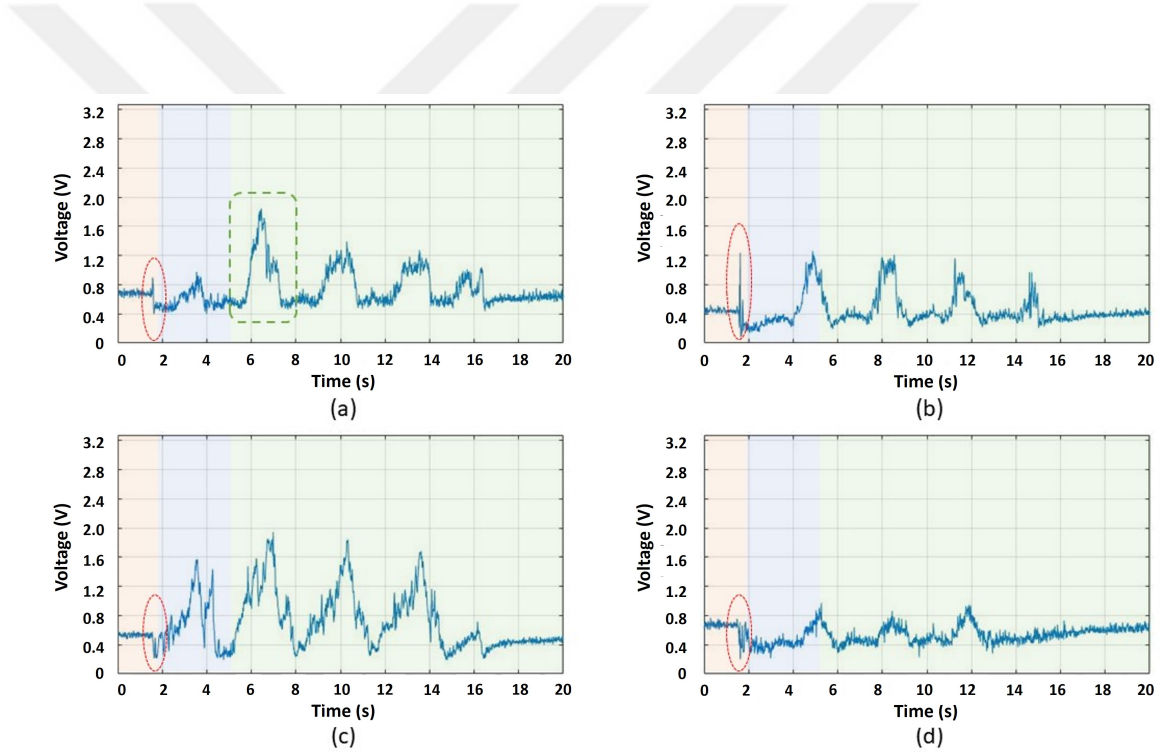


Figure 3.32: Soft sensor responses during the experiment with 10-degree inclination. (a) Front left sensor, (b) front right sensor, (c) rear left sensor, (d) rear right sensor. (Green dashed: The maximum peaks occurred when the robot is scaling the misalignment, red dashed: robot first touches the ground.)

The maximum peak of the front sensors occurs when the robot makes the first contact with the inclined surface by a front C-leg. This is because, at that moment, the sensor located on the top of that C-leg is actuated most compared to the other sensors. The maximum peaks are shown in Fig. 3.31, 3.32, and 3.33. These peaks are observed when the robot finishes walking on the ground and starts to scale the misalignment.

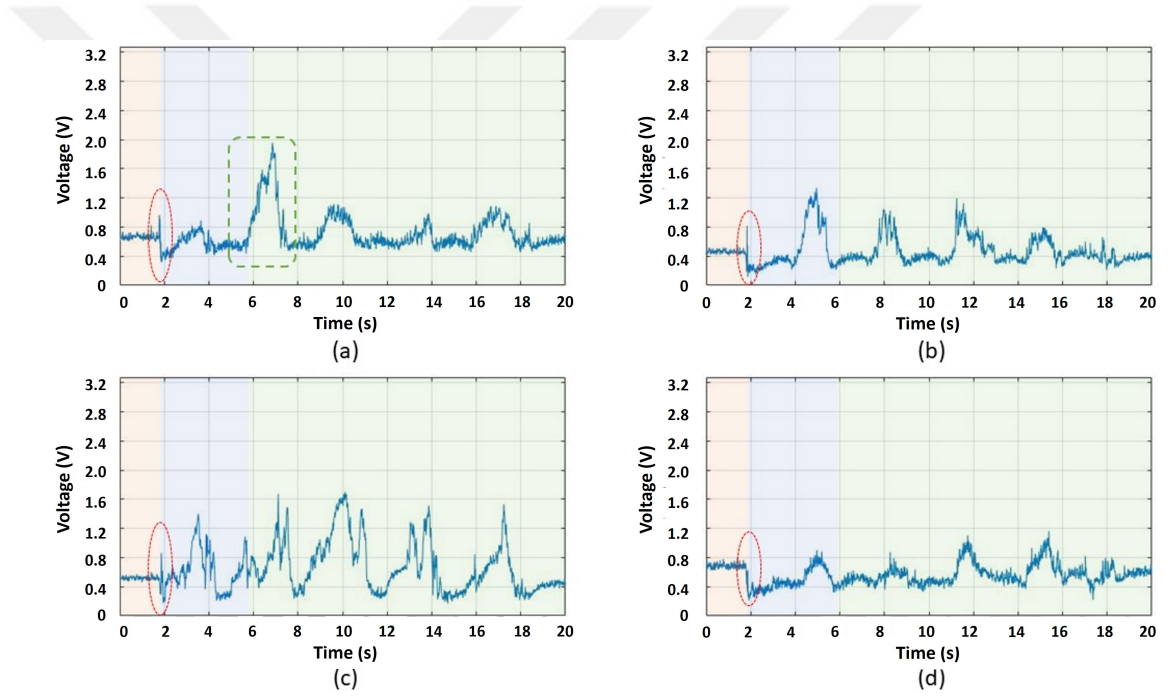


Figure 3.33: Soft sensor responses during the experiment with the 19-degree inclination. (a) Front left sensor, (b) front right sensor, (c) rear left sensor, (d) rear right sensor. (Green dashed: The maximum peaks occurred when the robot is scaling the misalignment, red dashed: robot first touches the ground.)

3.4 Sensorized Collision Resilient Robot (SCoReR)

The SCoReR is an origami-inspired collision-resilient robot based on one of our previous works in Bilkent Miniature Robotics Laboratory, miniature, foldable, collision-resilient quadcopter, MiniCoRe shown in Fig. 3.34. The most significant update on the design of SCoReR is the soft sensor attached bumpers, as

shown in Fig. 3.35. Thanks to these bumpers, We experimentally evaluate and demonstrate that SCoReR is capable of passively resisting the impacts, detecting the contact and impact with surrounding obstacles, and maintaining its hovering while it avoids further contact or keeps hovering at the contact point.

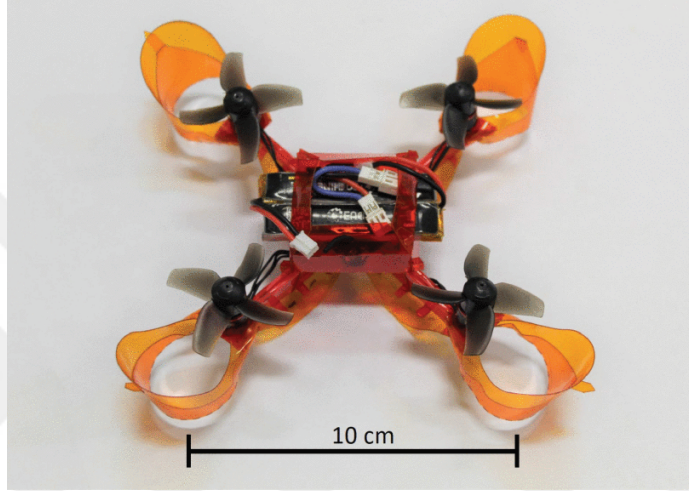


Figure 3.34: The miniature, foldable, collision resilient quadcopter, MiniCoRe.

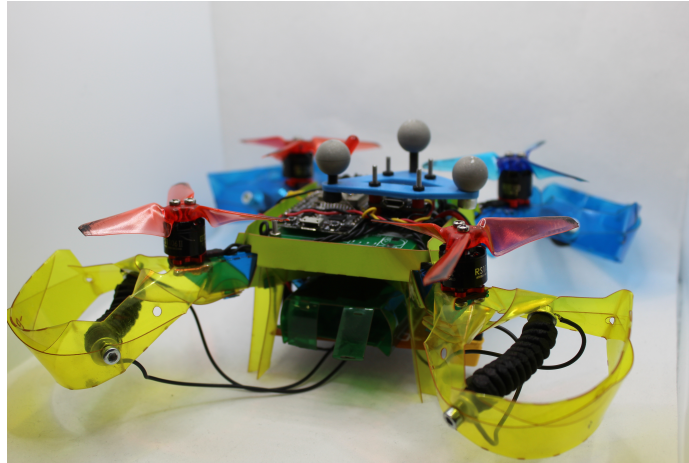


Figure 3.35: The sensorized collision resilient foldable aerial robot (SCoReR).

3.4.1 Design

The soft sensors are placed on the foldable bumpers on SCoReR to detect the possible obstacles the drone may encounter. We expected to capture the impact of the collision with the soft sensors.

Selecting the soft sensor orientation and position on the bumper was the first step in designing the soft sensor. An experiment is designed with a non-sensorized robot, in which the drone hits the wall with a speed of 1 m/s when a high-speed camera is recording the collision. The bumper's reaction to the collision is investigated frame by frame. During the collision, the two points that came closest to each other on the bumper were approximated and shown in Fig. 3.36.

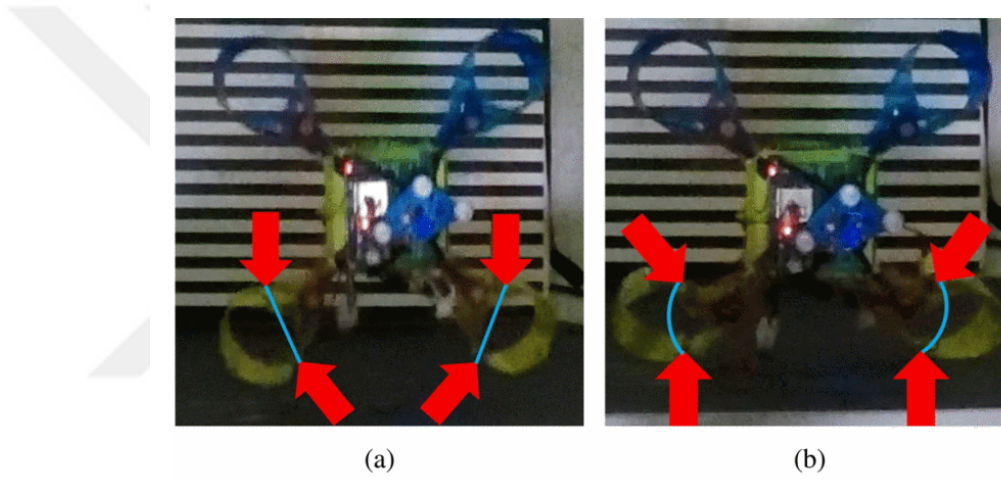


Figure 3.36: (a) An instant before the collision during an impact between a non-sensorized robot and a wall. (b) During the collision.

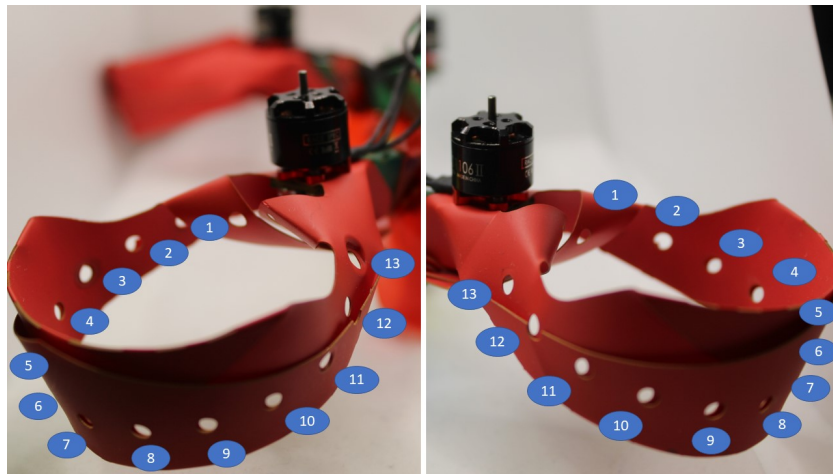


Figure 3.37: The labeling of the equally spaced holes on the bumpers. Left-hand side: left bumper, right-hand side: right bumper.

To estimate the location of these points more precisely on the bumpers, equally

Hole	1	2	3	4	5	6	7	8	9	10	11	12	13
1	-	-	-	-	1.02	1.12	1.19	1.27	1.3	1.34	1.23	1.05	1.03
2	-	-	-	-	-	1.12	1.16	1.21	1.22	1.23	1.14	0.98	0.98
3	-	-	-	-	-	-	1.08	1.09	1.09	1.09	1.01	0.88	0.89
4	-	-	-	-	-	-	-	1.07	1.06	1.05	0.98	0.86	0.89
5	1.02	-	-	-	-	-	-	-	1	1	0.93	0.83	0.88
6	1.12	1.12	-	-	-	-	-	-	-	0.98	0.91	0.82	0.9
7	1.19	1.16	1.08	-	-	-	-	-	-	-	0.92	0.84	0.97
8	1.27	1.21	1.09	1.07	-	-	-	-	-	-	-	0.85	1.04
9	1.3	1.22	1.09	1.06	1	-	-	-	-	-	-	-	1.17
10	1.34	1.23	1.09	1.05	1	0.98	-	-	-	-	-	-	-
11	1.23	1.14	1.01	0.98	0.93	0.91	0.92	-	-	-	-	-	-
12	1.05	0.98	0.88	0.86	0.83	0.82	0.84	0.85	-	-	-	-	-
13	1.03	0.98	0.89	0.89	0.88	0.9	0.97	1.04	1.17	-	-	-	-

Table 3.2: Represents the ratio of undeformed length to deformed length for each hole pair combination.

spaced thirteen holes were created on the strip of the bumpers. The labeling of the equally spaced holes on the bumpers can be seen in Fig. 3.37. We used image processing to measure the distance between each pair of holes on both undeformed and deformed bumpers before and after the collision. The ratio of undeformed to deformed hole pair lengths is calculated and recorded in Table 3.2. The width and thickness of the soft sensors were chosen as 8 mm and 2.5 mm, respectively. Since we are embedding metal threaded inserts into the sensors for both structural and electrical connection, the width and thickness of the soft sensors are kept at a minimum by considering the manufacturing limitation of this process. Furthermore, the distance between the coil pairs is kept at 0.0375 mm since, below this distance, the coils of the sensor stick to each other during the 3D printing process. Below the sensor length of 30 mm, although we tried the brim and raft options in the 3D printing process, the print still did not homogeneously stick to the printing plate. Due to the adhesion problems, some coils stuck to each other. As a solution, we selected hole pairs with at least four holes between them since the gap between the hole pairs with four holes is measured as 30 mm. By considering this approach, we observed that the amount of deformation between the first and the tenth hole is the largest compared to the other combinations. The gap between the first and tenth holes is measured

as 40.8 mm. As a result, the number of coils between the two ends of the sensor becomes 10.5 by considering the minimum coil distance.

When the soft coil-spring sensor coils collapse, we know that a significant drop in sensor resistance because adjacent coils of the sensor contact each other. As a result, keeping the distance between the coils of the coil-spring-shaped soft sensors as low as possible makes the sensor more sensitive to impact forces.

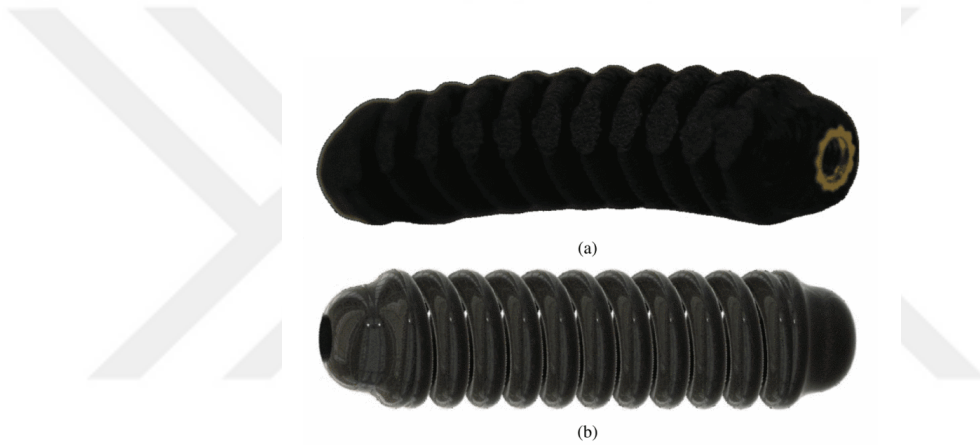


Figure 3.38: (a) Picture of the soft sensor, (b) the CAD model of the soft sensor.

A screw-type electrical connection is designed for the soft sensors to prevent noise caused by the vibration during the flight and the airflow from the propellers. To fabricate the screw-type electrical connectors, threaded inserts are placed on both ends of the soft sensor, as shown in Fig. 3.38. The connection cables for the sensors are soldered to the nuts. Using the holes created on the bumpers, soft sensors can be attached to the foldable bumpers using screws, as shown in Fig. 3.35.

The nominal resistance of the soft sensor (in the non-compressed form) is in the range of 130-150k Ω . The sensors buckle and compress when the bumpers deform, as in Fig. 3.39. As a result, the resistance of the sensor decreases by 75%. The sensors are 3D printed using settings explained in section 2.2.3.1. The number of perimeter layers is set to three.

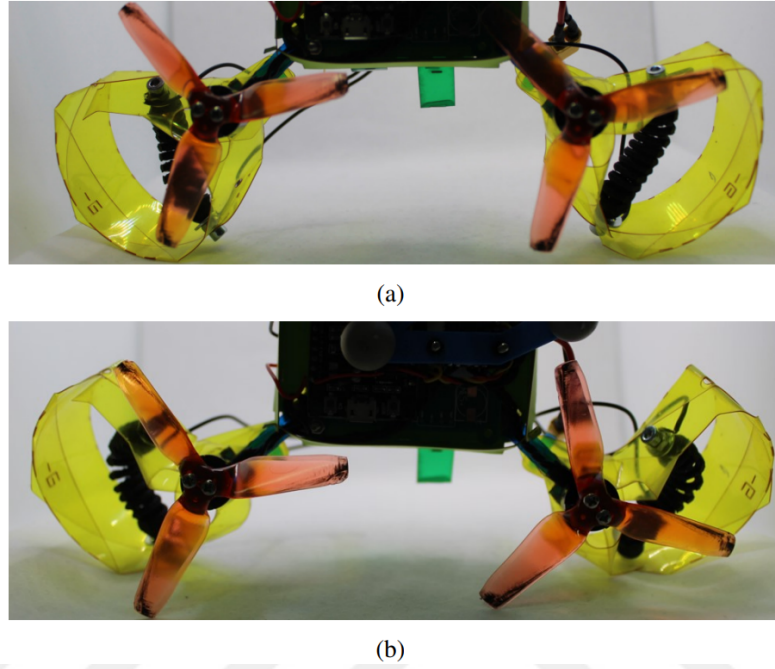


Figure 3.39: (a) Undeformed bumper, (b) fully deformed bumper.

3.4.2 Detection Algorithm

For detection, the soft sensors attached to the bumpers are used. The raw (un-filtered) data obtained from the sensors is processed live. After the drone takes off, the responses of the soft sensors are recorded for a second to determine the average of the soft sensors' responses in the hovering position of the drone. This process has to be done in hovering conditions to compensate for the noise caused by the airflow and the vibration caused by the motors. Adding a predefined value to the average responses sets the threshold for obstacle detection. The detection algorithm checks whether any soft sensors exceed the threshold in each control loop. If the threshold is exceeded, the robot understands that it has contacted an obstacle.

In Fig. 3.40, all the steps of the detection procedure are shown. First, SCoReR hovers, and the variation of the soft sensor data is relatively low. Soft sensor output increases above the threshold value at the impact, which can be seen in the red-labeled regions shown in Fig. 3.40. When the drone detects such a sudden

increase in the output of any of the soft sensors located at the front bumpers, the drone is commanded either to turn back to its initial position or to wait at the contact position.

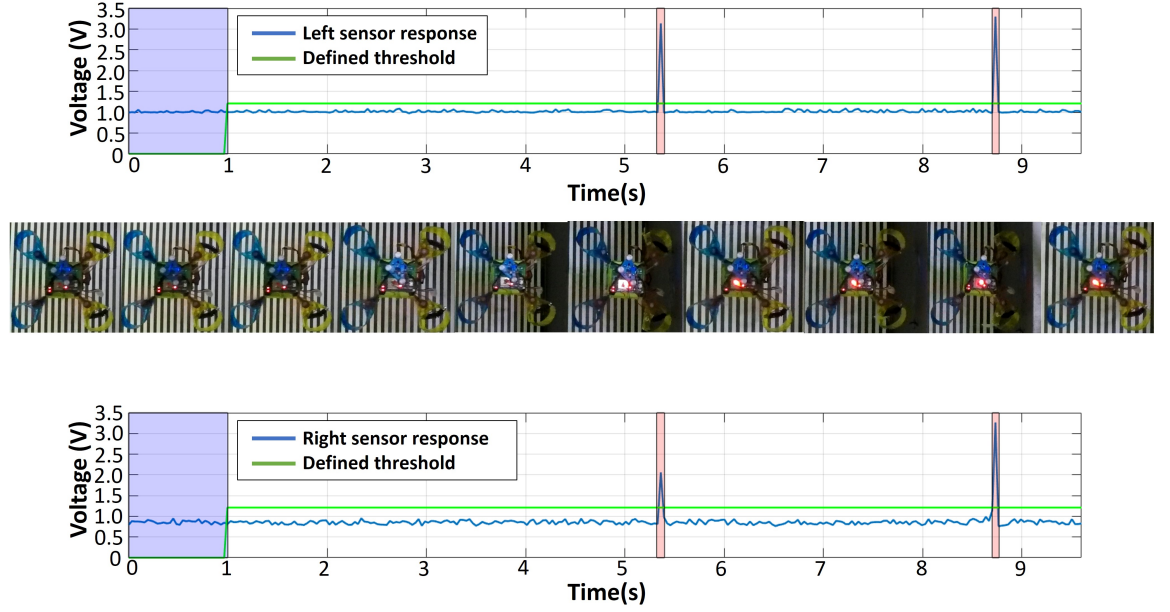


Figure 3.40: The step by step demonstration of the obstacle detection system.

To test the functionality of the obstacle detection algorithm, we flew the drone toward the wall at different speeds, starting from 0.1 m/s up to 1 m/s with 0.1 m/s increments. Five trials were conducted for each speed. Soft sensors managed to detect the impact in all the trials. Therefore, the accuracy of the detection is 100%.

However, at very low speeds, such as 0.1 m/s, it takes more time for the drone to detect the wall. Sometimes the impact cannot exceed the threshold, and the drone continues towards the wall until the soft sensor output, directly correlated to the contact force, exceeds the threshold. This is not a big problem for SCoReR, as its compliant nature ensures that the robot can sustain such low-speed impacts quite easily.

3.4.3 Case Studies

We conducted a series of impact tests at different speeds to demonstrate the capabilities of the sensor embedded in SCoReR. The experimental setup involved several components, including a black rigid wall intended for SCoReR to collide with, a striped plate positioned below the flight path to enable impact analysis through a camera, a high-speed camera for detailed observation, and the SCoReR vehicle itself. The black wall is positioned vertically to the ground, while the striped plate is a visual reference. An overhead camera is placed on the top of the black wall to record the impact experiments.

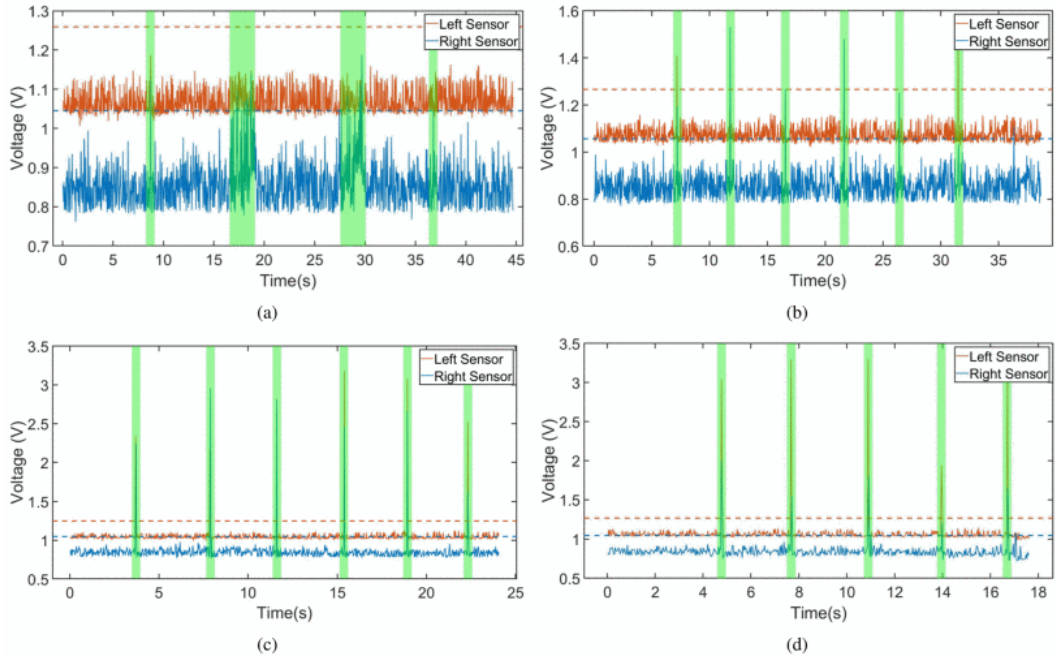


Figure 3.41: The results of sensor readings during the test flights with different speeds. Dashed lines represent the thresholds for corresponding sensors. (a) 0.1 m/s, (b) 0.2 m/s, (c) 0.5 m/s, (d) 0.9 m/s.

Fig. 3.41 presents the voltage readings from the sensor during some of the controlled crash flights. The green segments on the plots indicate the regions where SCoReR's sensors detected the wall. Before the test flights, SCoReR armed itself, collected sensor readings for one second, and averaged them. It then initiated the takeoff sequence, maintaining its position at the initial point until reaching the

designated altitude. Once the takeoff sequence was completed, SCoReR awaited a user command to begin the impact tests. The user sent the command, prompting SCoReR to move toward the wall at a predefined velocity. Upon contact with the wall, SCoReR detected the impact and returned to its initial position. It then awaited further commands, either to perform another impact test or to land. This procedure was repeated at least five times for each test. Throughout all the experiments, SCoReR successfully detected the wall.

The plots in Fig. 3.41 reveal the collision moments through sudden jumps in the sensor data, indicated by the green regions. Based on initial experiments, we determined that a threshold of 0.2 V was suitable, as the impact data consistently exceeded this threshold while the noise caused by robot vibrations and airflow remained below it.

Following the impact experiments, we conducted a case study in which SCoReR updated its position references upon detecting the impact using the sensor. It then maintained its position at the edge of the wall.

One of the main challenges encountered during the tests was detecting impacts during low-speed flights. In these instances, the bumper absorbed most of the impact, resulting in minimal deflection, as depicted in Fig. 3.36. However, thanks to the sensor design, we can detect impacts at 0.2 m/s instantaneously. Even for the 0.1 m/s trials, although the sensor did not detect the impact immediately, SCoReR was able to detect the wall after a few seconds. In such cases, SCoReR exerted additional effort to move forward and apply extra force until a sensor detected the wall.

3.5 Human-Computer Interfaces (HCI)

Thanks to the working principle and functionality of the soft coil-shaped 3D printed sensors, the sensors can be used for various applications such as physical

human-computer interfaces. By using the new magnet type connection and varying pitch soft sensors, we designed a soft reconfigurable joystick with a maximum dimension of 76.7 mm x 76.7 mm x 33.6 mm shown in Fig. 3.42.



Figure 3.42: The soft reconfigurable joystick for HCI applications.

3.5.1 Design



Figure 3.43: The soft reconfigurable joystick pack.

The soft joystick pack consists of four soft sensors, two middle nodes, eight corner nodes, and four stationary connectors shown in Fig. 3.43.

3.5.1.1 Node

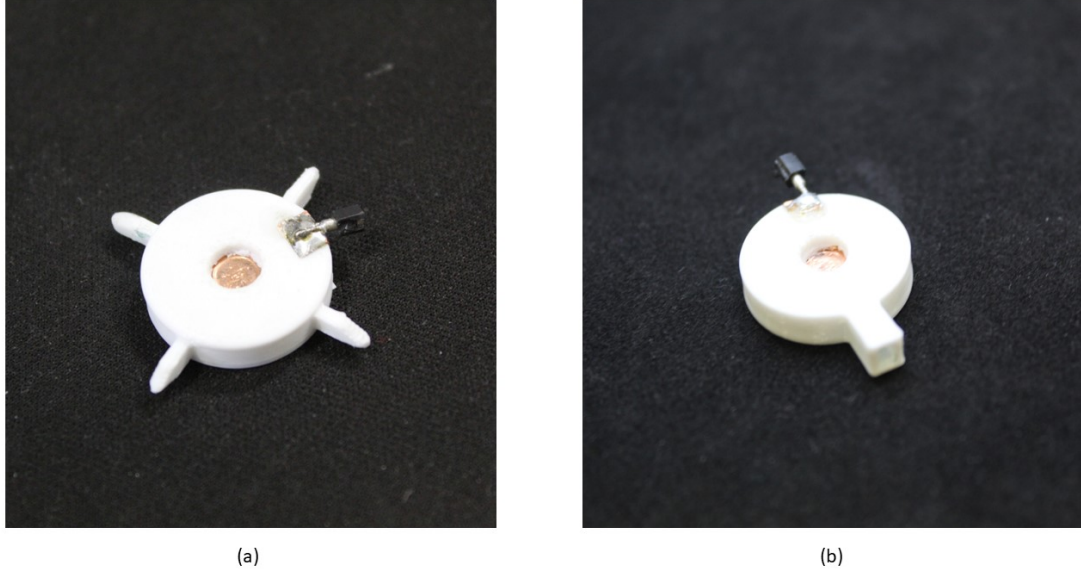


Figure 3.44: (a) Male node, (b) female node.

Nodes involve cable connection ports that are directly connected to a magnet inside the node merging with a soft sensor connection magnet. Since both magnets are contacting each other, an electrical connection is provided. Magnets are coated with thin copper tape, with the copper tape surrounding some part of the upper surface of the node where female cable connection ports are soldered to, as shown in Fig. 3.44. Both the main node and corner node involves the same features in their design. However, the main nodes consist of four male mechanical connections, whereas the corner nodes consist of a single female mechanical connection. Node pairs can be constructed by connecting a single soft sensor between two same-type nodes. Corner node pairs can be placed to the male mechanical port of the middle node pair, as it is shown in Fig. 3.42. Both main and corner nodes are 3D printed using Polylactic acid (PLA) with 20% infill. During 3D printing, the first layer height is set at 0.25 mm, with the other layer heights being kept at 0.2 mm. The bed temperature and nozzle temperature are set to 60°C and 210°C. In addition, the number of top, bottom, and wall perimeter layers is set to three.

3.5.1.2 Soft Sensors with Varying Pitch



Figure 3.45: The soft coil-shape sensor with varying pitch and magnetic electrical connection.

Soft sensors are the components that provide the soft nature to the joystick, connected between a node pair that is from the same node type. Since magnets are embedded into the soft sensors, nodes magnetically attract each other without the need for any other actions. Therefore, the polarity of the soft sensor magnet and node sensor selected is opposite to each other. Soft sensors that are designed for soft joysticks have varying pitches as it is shown in Fig. 3.45. There are 4 coils with pitches of 3.5 mm, 4.5 mm, 5.5 mm, and 6.5 mm, whereas end ports are 10.5 mm-diameter and 5 mm-thickness cylinders. The overall length, the diameter of the cross-sectional area, and the width of the spring base are set to 26 mm, 2.5 mm, and 8 mm respectively. The magnets embedded in the end ports are in the shape of 5 mm-diameter and 4 mm-thickness cylinders.

3.5.1.3 Stationary Connectors

Stationary connectors shown in Fig. 3.46 are only for connecting one corner pair to another, not being designed to connect the middle node pair. They are used to splitting the joystick into two different control tools, as it is shown in Fig. 3.47. Connecting one corner pair to another requires two stationary connectors, with

two corner pairs having the option to be attached to each other or detach from each other, thanks to the magnets located at one of the surfaces of the stationary connectors. Stationary connectors are also 3D printed by using the same settings that are used for 3D printing the nodes. The magnets are attached to the back surface of the stationary connectors by using a simple, super glue.

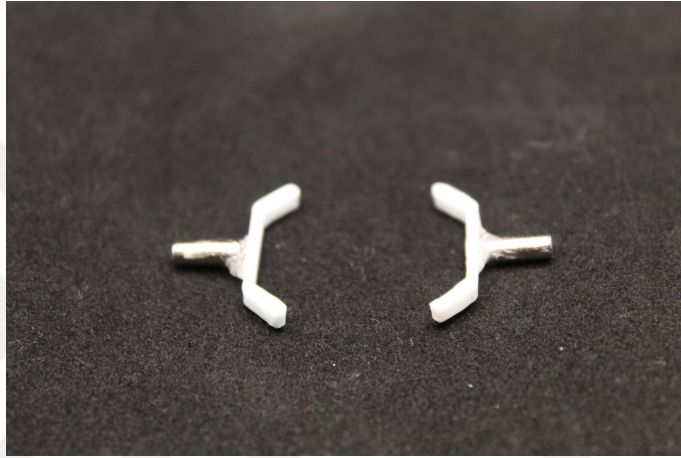


Figure 3.46: A photo of the stationary connector.

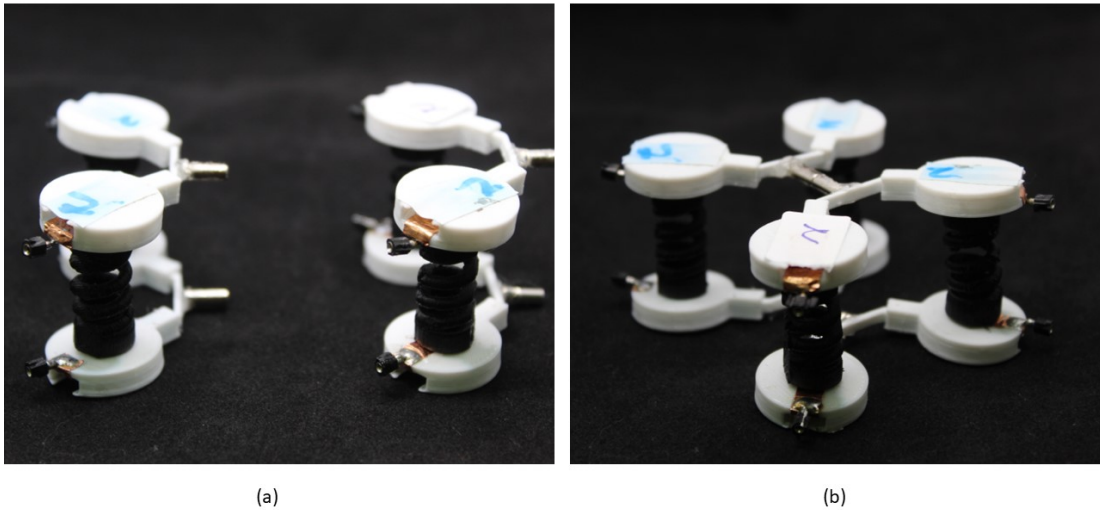


Figure 3.47: (a) Splitted mode, (b) merged mode.

3.5.1.4 Electronics

In M-Squad's circuit board, there were two LM358P Op-Amp and four wheatstone bridges used for converting resistance change of soft sensors into voltage change and amplifying it. In the electronic design of the soft joystick, similarly, these components and single Op-Amp differential amplifier configuration are used.

However, the formation of the Wheatstone bridge and the amplification value is slightly changed. The bridges are again supplied by 5V, whereas resistors of the bridge are selected as 1 k Ω , 3 k Ω , 3.3 k Ω , and the actual resistor as the fourth leg. Amplification gain is set to 10 by adjusting the resistors with respect to the gain. Similarly, ESP 32 (version 2.0) is preferred as the microcontroller for capturing data and transferring data to the computer via Bluetooth.

3.5.2 Reconfigurations

A single node pair configuration, shown in Fig. 3.48, consists of single soft sensors and two nodes, whereas the node type can be main or corner. It is the simplest and the most basic configuration of the joystick.

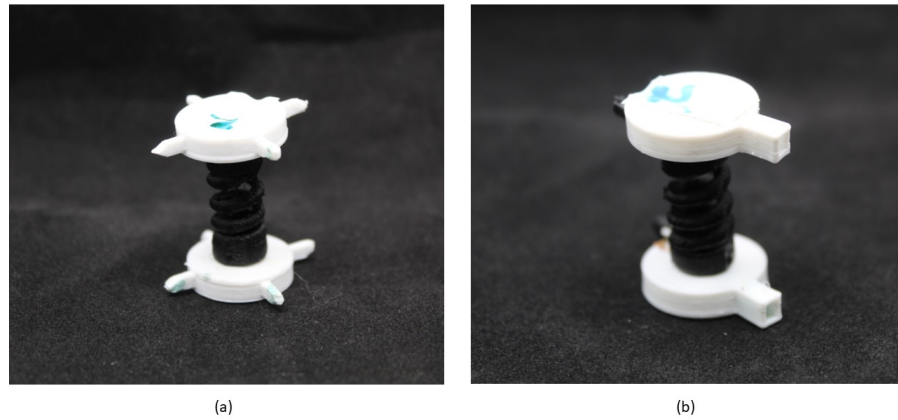


Figure 3.48: (a) Single node pair with two main nodes, (b) single node pair with two corner nodes.

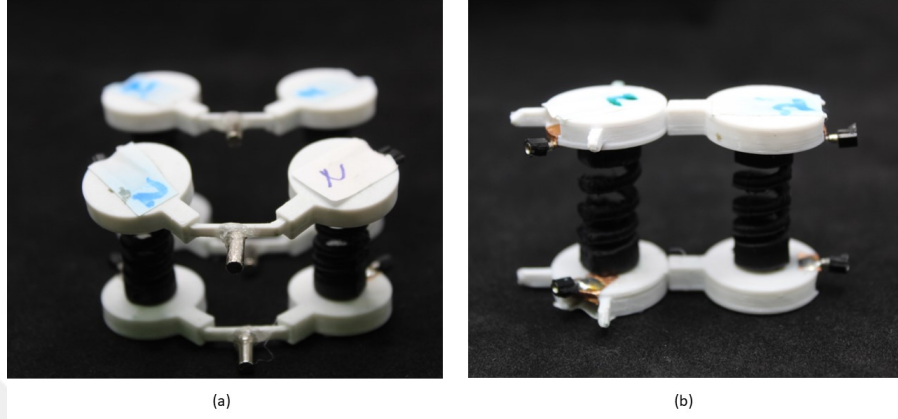


Figure 3.49: (a) Double node pair with two stationary connectors and two corner nodes, (b) double node pair with two main nodes and two corner nodes.

A double-node pair configuration requires two soft sensors and four nodes, whereas there are different variations to construct this type of pair. A single main node pair and a single corner node pair can be preferred, as it is shown in Fig. 3.49(b). In this case, the corner node pair is connected to the main node pair mechanically. Another option is to construct this pair by using stationary connectors. Two corner node pair can be connected to each other, as it is shown in Fig. 3.49(a).

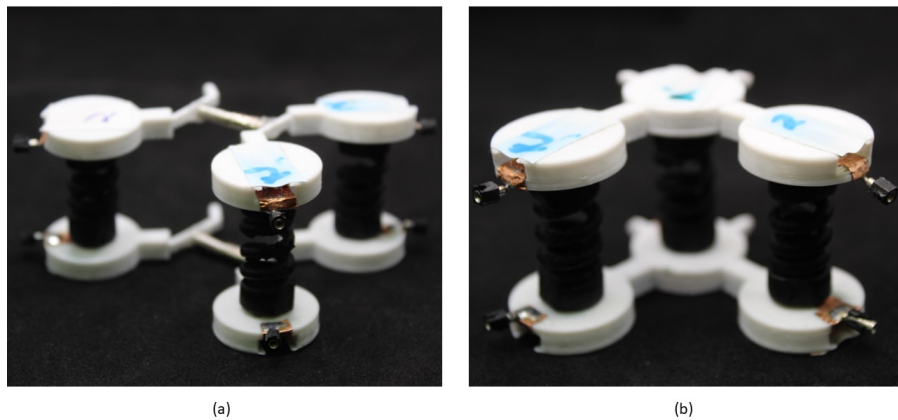


Figure 3.50: (a) Triple node pair with four stationary connectors and six corner nodes, (b) triple node pair with two main nodes and four corner nodes.

To construct a triple node pair, a middle node pair, two corner node pair, and three soft sensors are needed to be connected, as it is shown in Fig. 3.50(a). Alternatively, by using four stationary connectors and six corner nodes, a triple node pair can be constructed as shown in Fig. 3.50(b).

There are two options for the formation of a tetra node pair. Four soft sensors are used in both options. One of the options is using four corner node pairs which are connected to each other via stationary connectors. With magnets placed on the stationary connectors, two double node pairs can be merged to form a single tetra node pair, as shown in Fig. 3.51(b). Another option for this formation is using a single middle node pair to mechanically connect four corner node pairs around the main node pair, as shown in Fig. 3.51(a). In this configuration, the maximum size of the joystick is reached.

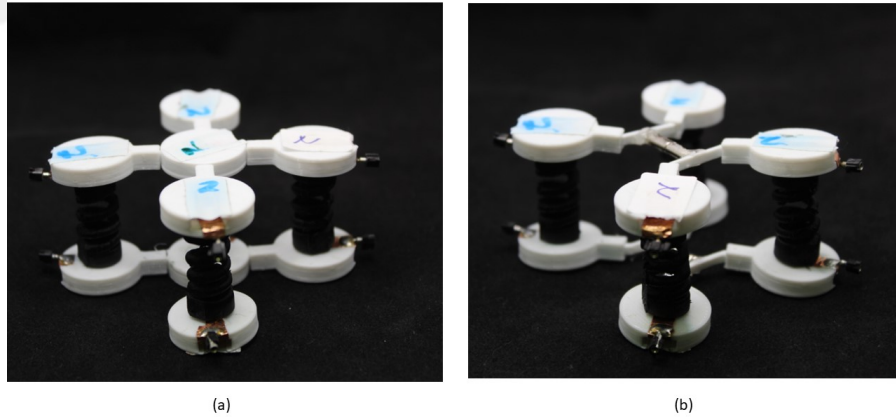


Figure 3.51: (a) Tetra node pair with two main nodes and eight corner nodes, (b) tetra node pair with four stationary connectors and eight corner nodes.

3.5.3 Applications

3.5.3.1 Visualization Program

We send the soft sensor data from the joystick to the computer, with ESP 32 sending the data at the rate of 100 Hz via Bluetooth Serial. Before the game or

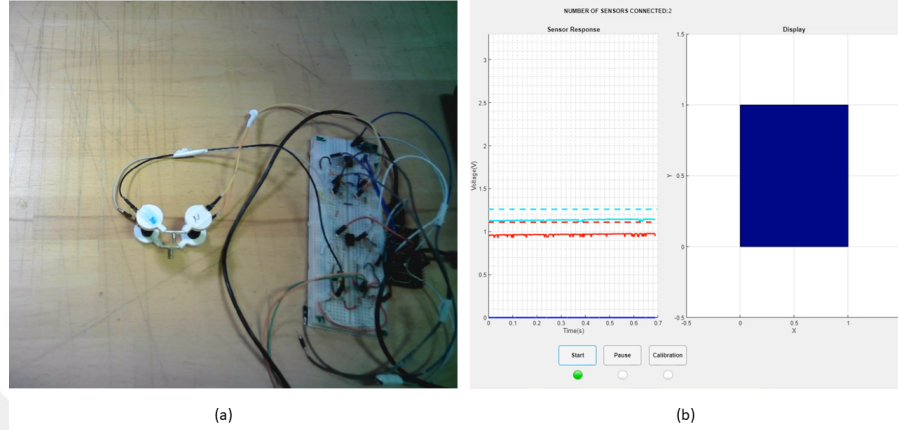


Figure 3.52: (a) Current configuration (double node pair), (b) application panel, the live plot of the soft sensor responses with calibrated minimum reading (dashed lines) on right, corresponding geometric shape (a square).

the application starts, the joystick is left stationary for the calibration process. The data is captured from the sensors for 5 seconds, with the average of the captured data being captured to define the thresholds of the soft sensors.

The thresholds are the minimum readings that can be had from the soft sensors. The minimum readings are used for on/off applications. If a soft sensor exceeds its thresholds, that sensor is labeled as actuated. In this application, we use soft sensors as a simple keyboard key that can only send binary data (pressed or not pressed) to the computer. Rather than an on/off application, since the maximum voltage that ESP32 reads from the soft sensor is 3.3 V, with the minimum reading of each sensor being known, it is possible to map soft sensor data for some continuous visualization applications. An application is designed to demonstrate some samples of these applications via using MATLAB app designer. Furthermore, we modified some traditional four-input and two-input computer games to show the performance of the soft sensors for the on/off applications.

The application waits until the user sends a start input by clicking the start button. After the application starts, automatic calibration is done to record the stationary sensor readings, lasting in the first 5-6 seconds.

After the algorithm checks if any soft sensor is reading zero since it is necessary to detect the number of node pairs. Zero reading indicates the disconnected number of soft sensors. This information is processed further to decide what kind of three-dimensional geometric shape is necessary to construct in the right-side plot display panel, whereas, on the left-side plot display panel, real-time sensor responses can be observed, as shown in Fig. 3.52.

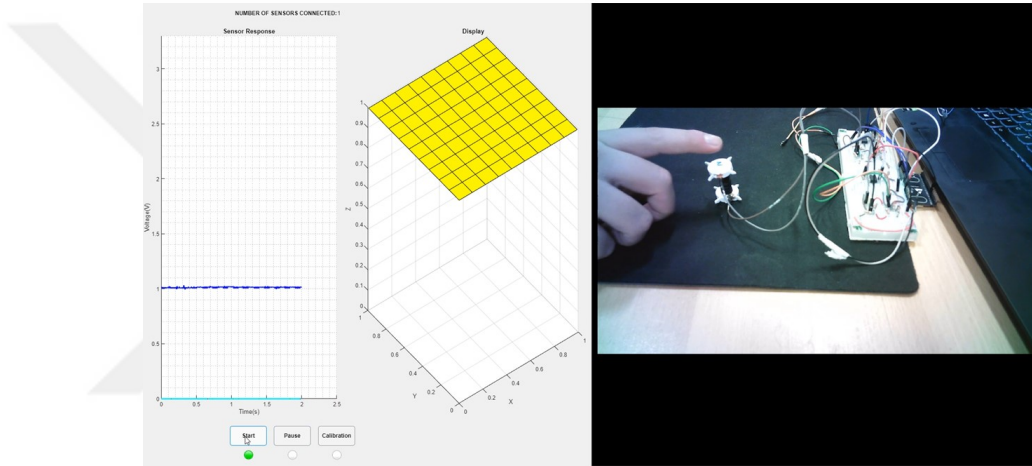


Figure 3.53: The initial program display when the configuration of single node pair is used.

A meshed plane appears if the soft joystick configuration is single node pair. The meshed plane is defined in 3D space, with corners of the plane located at points $(1,1,1)$, $(1,0,1)$, $(0,0,1)$, and $(0,1,1)$ as shown in the Fig. 3.53. When the soft sensor is pressed, the plane is deformed as shown in Fig. 3.54. The amount of deflection is linearly mapped according to changes in the soft sensor response. The side of the plane remains undeformed, whereas the maximum deformation occurs in the middle of the plane. The deformation distribution from the side to the middle is approximated by using a logarithmic function.

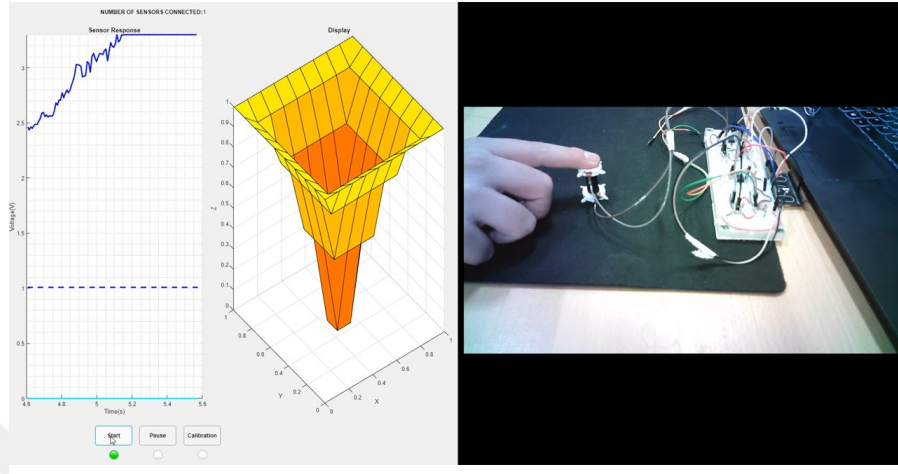


Figure 3.54: The deformation of the meshed plane with respect to the response of the soft sensor.

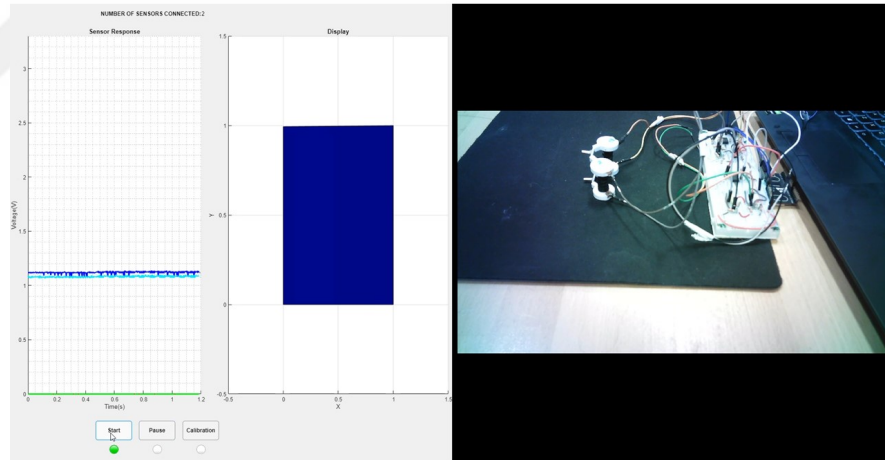


Figure 3.55: The initial program display when the configuration of double node pair is used.

In case the number of node pairs is two, a square with corners $(0,0)$, $(1,0)$, $(1,1)$, and $(0,1)$ in 2D space is observed in the program display shown in Fig. 3.55. In this demonstration, the vertical side (sides between $(0,0)$, $(0,1)$ and sides between $(1,0)$ and $(1,1)$) of the square deforms linearly according to the soft sensor actuation as shown in the Fig. 3.56.

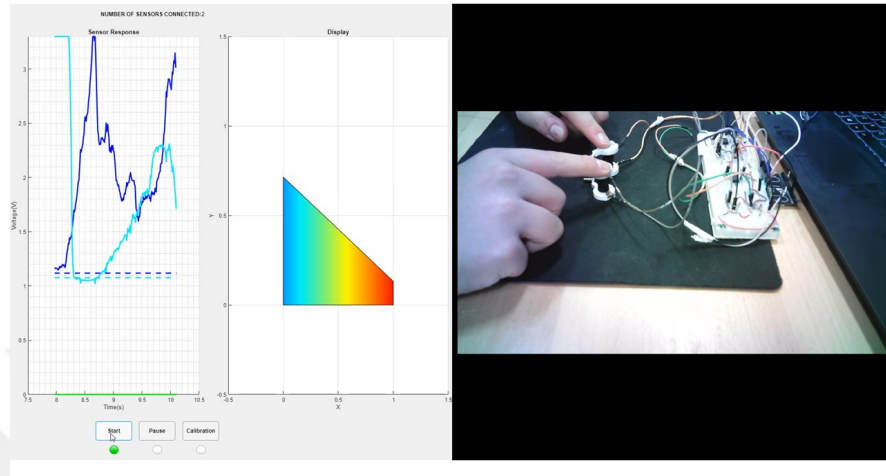


Figure 3.56: The deformation of the square with respect to the response of the soft sensors.

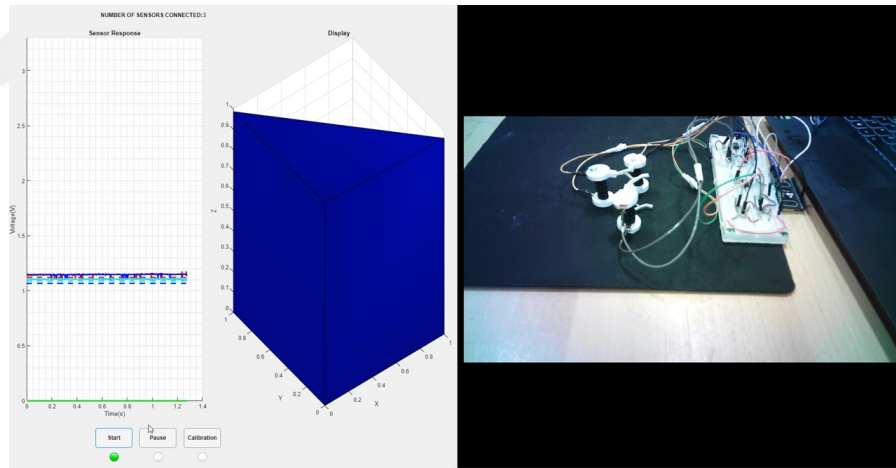


Figure 3.57: The initial program display when the configuration of triple node pair is used.

A triangular prism is used to demonstrate three node pair case. Since there are three soft sensors used, there are three length-varying sides. These sides are the vertical sides of the triangular prism between the points $(0,0,0) - (0,0,1)$, $(0,1,0) - (0,1,1)$, and $(1,0,0) - (1,0,1)$ shown in Fig. 3.57. A three-node pair configuration of the joystick should be used to control the deformation of these sides. Similarly, the deformation amount is linearly mapped to the soft sensor responses shown in Fig. 3.58.

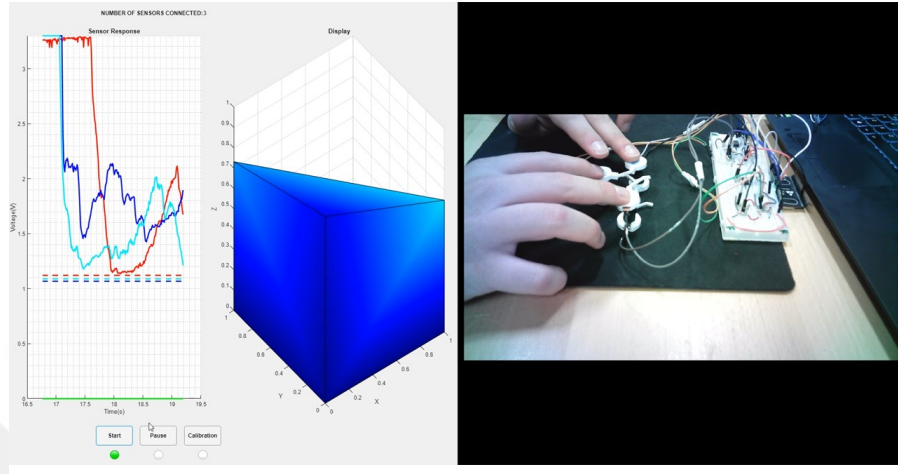


Figure 3.58: The deformation of the triangular prism with respect to the response of the soft sensors.

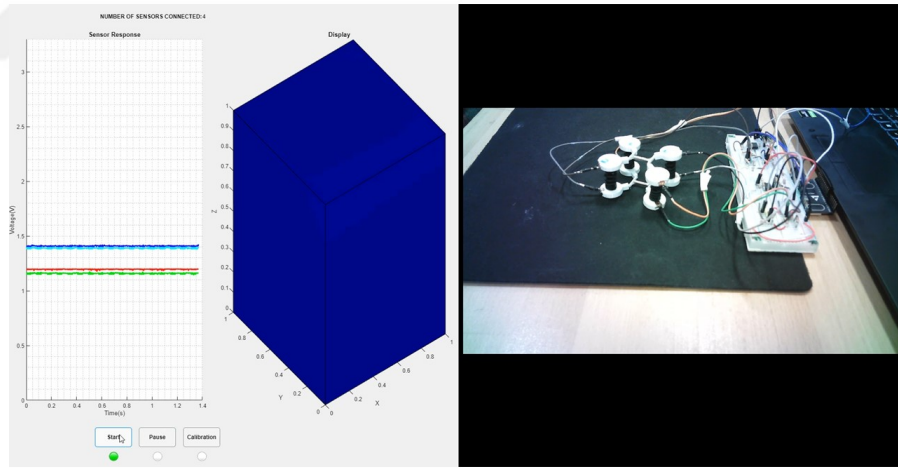


Figure 3.59: The initial program display when the configuration of tetra node pair is used.

If a tetra node pair configuration is set, a cube can be seen in the right plot display panel as shown Fig. 3.59. A cube consists of four vertical sides $(0,0,0) - (0,0,1)$, $(0,1,0) - (0,1,1)$, $(1,1,0) - (1,1,1)$ and $(1,0,0) - (1,0,1)$, the deformation along each side is linearly related to each soft sensors in the configuration of tetra node pair shown in Fig. 3.60.

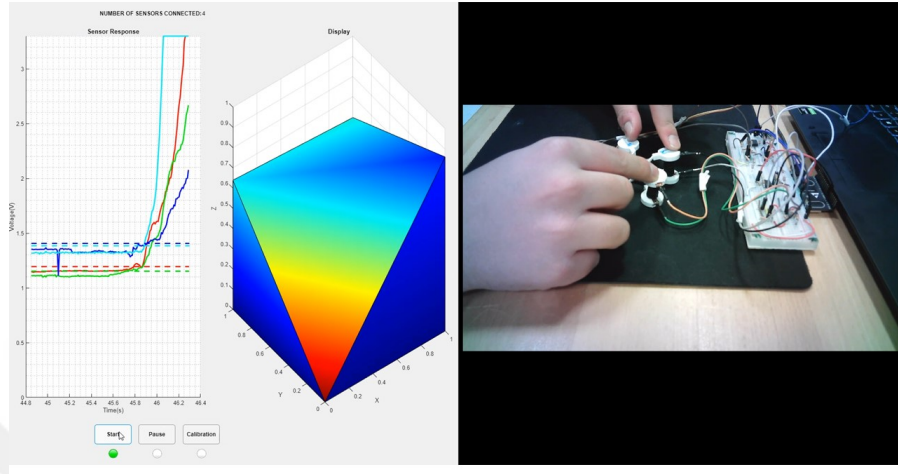


Figure 3.60: The deformation of the cube with respect to the response of the soft sensors.

3.5.3.2 Control Tool for Computer Games

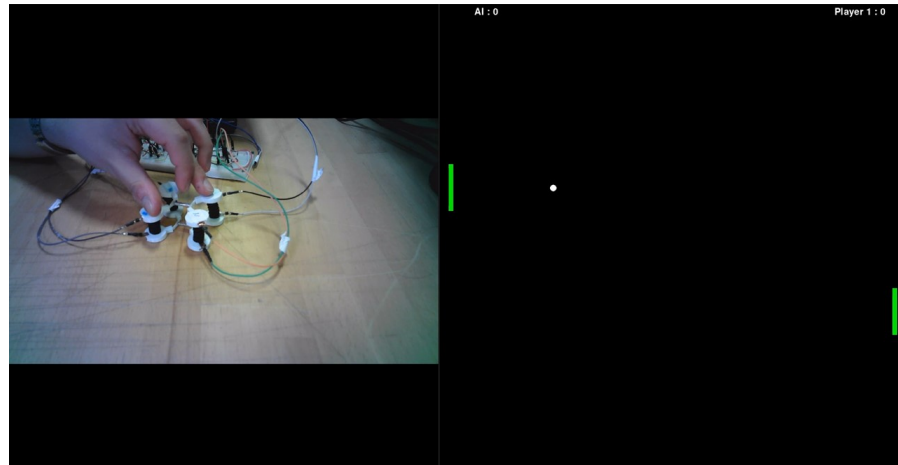


Figure 3.61: User plays the pong game in the configuration of tetra node pair.

Pong game is a basic computer game that can be played with the W and S keys or PgUp and PgDn of a computer. We accessed a version of the game written via using the PyGame library, slightly modifying the game to use our soft joystick as a control tool instead of the computer keys. We also added a simple AI to provide a single-player option to the game, as shown in Fig. 3.61. If the user wants to go for the multiplayer option, the only thing that the user needs to do

is to split the soft reconfigurable joystick up into two, as it is previously shown in Fig. 3.62.

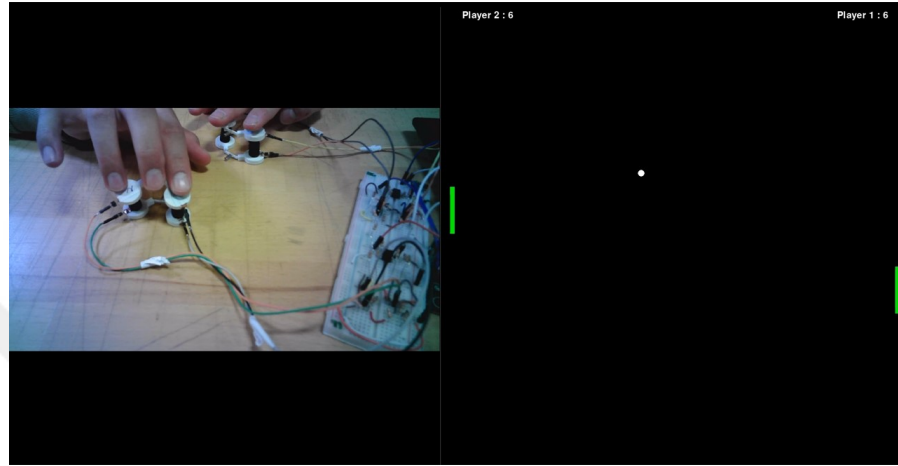


Figure 3.62: User plays the multiplayer pong game with a friend by splitting the configuration of tetra node pair into two double node pairs.

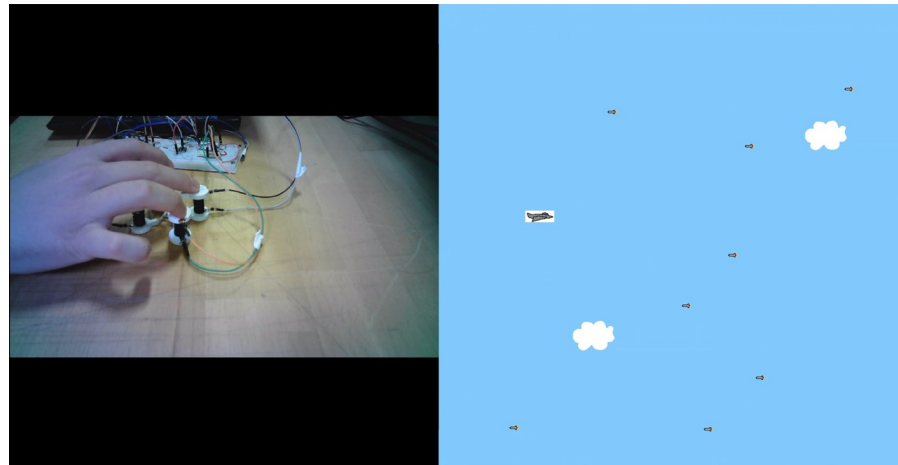


Figure 3.63: User plays a hawk game.

Hawk game is another traditional computer game that is built via PyGame Library. The game has a two-dimensional display, being played by four keyboard keys (PgUp, End, PgDn, and Home). The only thing different compared to the pong game setup and play is side motions which are triggered by pressing the End and Home buttons. We modified the game to use a soft sensor joystick to control the game as shown in Fig. 3.63. Sensors which are located at the up

corner, right corner, down corner, and left corner, have the same functions as the keyboard keys, PgUp, End, PgDn and Home, respectively.

3.5.4 Sensorized Tail for Robots

We implement a soft tail to our robot SMoLBot-C, with the results showing that the robot with the compliant tail gains the capability of walking on surfaces with higher inclination angles compared to the same robot without a tail. The tail also provides an extra capability for the robot to scale larger obstacles compared to the robot without a tail [29]. The main motivation behind the sensorization of the tail is enhancing the environmental perception of the upgraded version of SMoLBot-C, ReMBot. We place a soft coil-shape sensor with a screw connection on the tail, updating the tail design used for SMoLBot-C as shown in Fig. 3.64. The objective of sensorized tail concept is to give robots an exteroceptive sensing element for detecting and distinguishing the inclination and the obstacles.

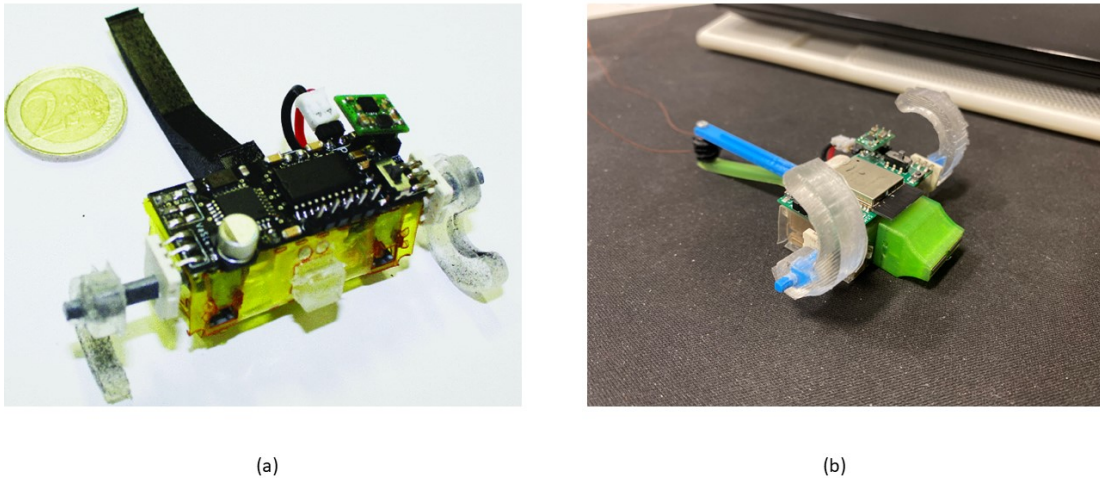


Figure 3.64: (a) SMoLBot-C with non-sensorized tail, (b) ReMBot with sensorized tail.

3.5.4.1 Design

ReMBot consists of modules with green TPU magnetic connectors in both the front and back. A single module of ReMBot has 82 mm x 60 mm x 29 mm in size and 29.25 grams in weight. It is one of the smallest and lightest robots in Bilkent Miniature Robotics lab. Thanks to the connectors, a module can be attached or detached from another module of ReMBot by sending the necessary commands to the robot. Since ReMBot has a modular and reconfigurable nature, we want to test the sensorized tail concept on this robot by implementing the soft sensor into a single module. The module which carries the sensorized tail is responsible for tagging the locations where an obstacle or an inclination exists on the terrain.

The tail consists of three parts: rigid extension, soft extension, and coil-shaped soft sensor with a constant pitch as shown in Fig. 3.65. Rigid extension provides a rigid connection to the module, whereas the soft part of the tail contacts with the ground when the robot encounters an inclination or an obstacle, and it deforms in the direction which is normal to the ground. The soft sensor can convert this deformation into a resistance change.

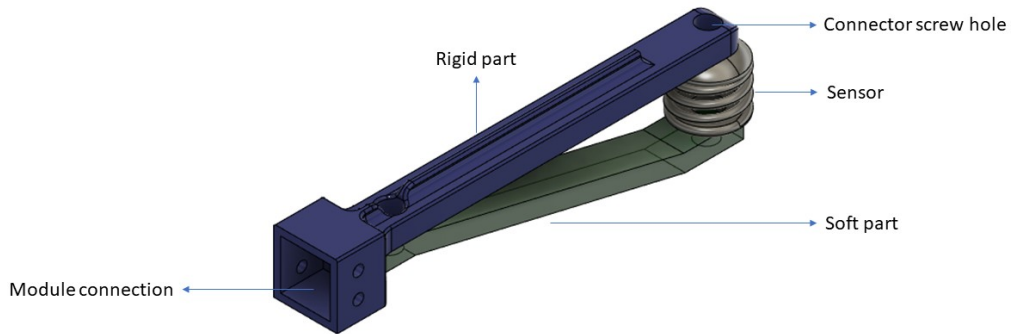


Figure 3.65: The soft sensorized tail of ReMBot.

In the first stage, we preferred constant pitch since we want to detect the surrounding inclination and obstacles in the on/off stage. In addition, the sensor is located between the rigid part and the soft part, with the gap between these two being limited by the height of the robot. To prevent contact between the tail and the surface at stationary, we keep the maximum distance between the top surface of the rigid part and the bottom surface of the soft less than half of the height, roughly 15 mm. By keeping the thickness of the rigid part and soft part 3 mm, the height of the soft sensor cannot exceed 9 mm. Under these size limitations, using varying pitch concept or constant pitch concepts would not differ, and manufacturing of varying pitch soft coil-shape soft sensors require a height higher than 9 mm. The section diameter, constant pitch, diameter of the spring, and number of coils are selected as 1 mm, 1.7 mm, 8 mm, and 3, respectively. The reason behind using screw-type connections is to eliminate noise during the locomotion of the robot by tightening the screw. The length and the width of the sensorized tail are kept at 53 mm and 5 mm, respectively, with these dimensions being roughly the same as the tail used on SMoLBot-C.

3.5.4.2 Experiments and Results

Since sensorized tail concept is one of the most recent applications with our soft sensors, we are still designing and iterating the experiments we conduct to analyze the sensorized tail performance in detecting the obstacles and the inclinations on a terrain. The initial experiments are explained in this section, with the results being discussed.

The initial experiments generally start with saturating sensor response manually to match video and soft sensor response. In some experiments, since the data capturing and the video starts synchronically, we do not need to saturate the soft sensor response. The experiments are conducted to assess the robot’s performance in detecting the inclinations and non-scalable obstacles it encounters in the parkour. A 30 mm-height obstacle and a 30-degree inclination are used as non-scalable obstacles and non-scalable inclinations, respectively. We also tested the performance of the robot on a surface with an inclination of 17 degrees.

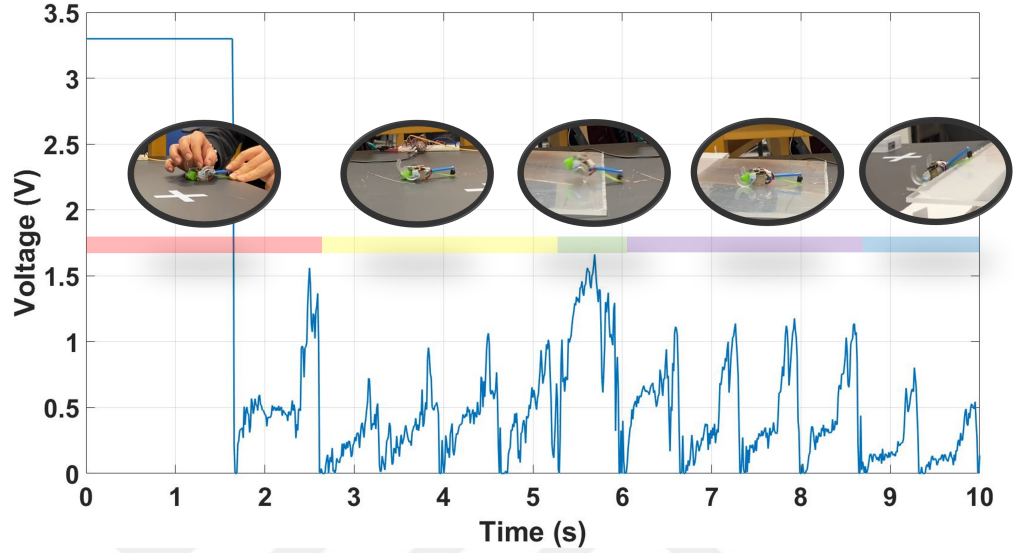


Figure 3.66: ReMBot with the sensorized tail encounters with 17-degree inclined surface. Red: soft sensor response is manually saturated manually, yellow: the robot is walking on the ground, green: the robot encounters the misalignment, purple: the robot walks on an inclined surface, blue: the robot falls off.

Before the robot encounters the inclinations, we observed that the soft sensor response reaches the maximum peak. This is because of the misalignment between the inclined surface and the ground. When the robot is scaling the misalignment, These maximum peaks can be observed in Fig. 3.66 and 3.67.

After the robot scales the misalignment, walking on an inclined surface, the robot starts leaning on the tail. The normal force applied to the tip of the tail increase. As a result, balancing torque also increases. On the ground, the peaks of the sensor response are around the level of 1V. However, when the robot starts to walk on the inclined surface, the peaks exceed the 1V threshold. When the robot sticks on the 30-degree inclined surface, the peaks continue to exceed 1V, as shown in Fig. 3.67.

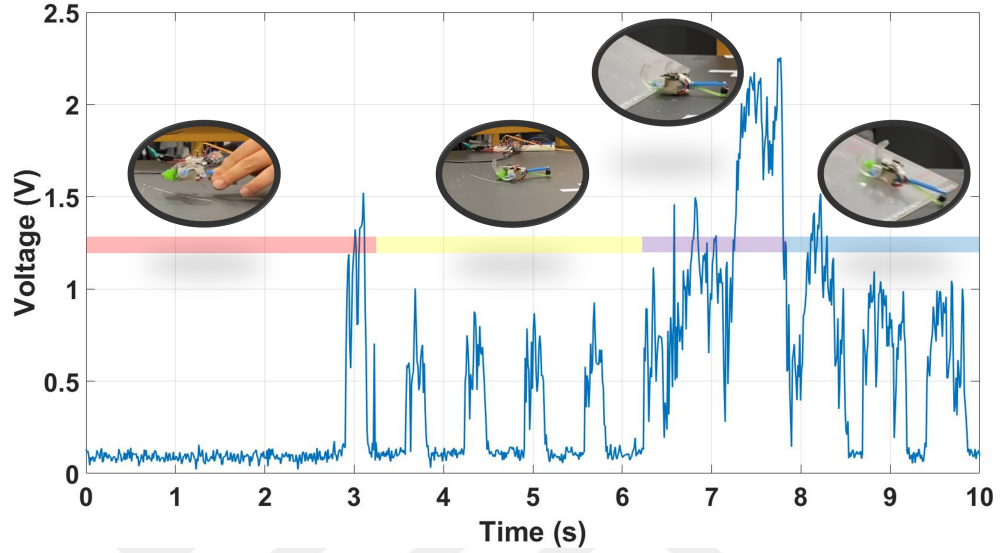


Figure 3.67: ReMBot with the sensorized tail encounters with 30-degree inclined surface. red: the robot is placed on the ground, yellow: the robot is walking on the ground, purple: the robot encounters the misalignment, blue: the robot struggles to walk on the inclined surface.

When the robot encounters a non-scalable obstacle, the impact of the collision is sensed by the soft sensors. The peaks reach the threshold of 1.5 V when the robot collides with the obstacle. When the robot is walking on the ground, peaks are close to the level of 1V. In addition, the soft sensor response pattern comes from the contact of the tail and the ground also ruined since the obstacle prevents the robot's locomotion as shown in Fig. 3.68.

These are the initial experiments conducted with the sensorized tail concept to obtain first thoughts about the feasibility and functionality of this concept. As the first step, We wanted to distinguish non-scalable obstacles and non-scalable obstacles with the tail. We have further plans to extract information from the obstacles and inclination such as the height of obstacles, the inclination amount, and the scalability information. Therefore, we are aware that we need more data and experiments to progress.

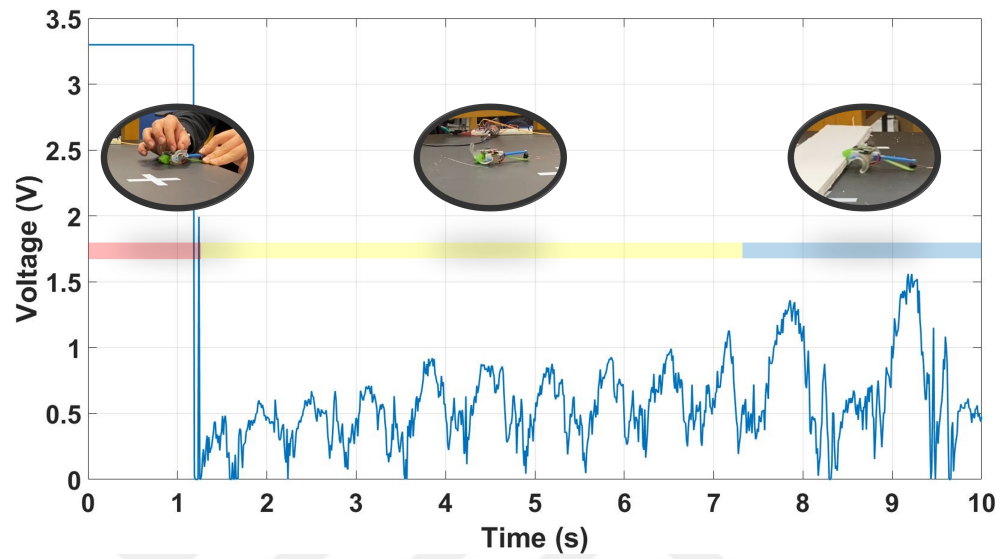


Figure 3.68: ReMBot with the sensorized tail encounters with 30-degree inclined surface. Red: the soft sensor response is manually saturated manually, yellow: the robot is walking on the ground, blue: the robot encounters the non-scalable obstacle.

Chapter 4

Conclusion and Future Direction

4.1 Summary and Conclusion

In conclusion, this thesis presents the design and manufacturing techniques of soft sensors, along with their practical applications. The design space for soft sensors was investigated, encompassing two types, sheet-type, and 3D shaped sensors. The working principle of these two types of soft 3D printed sensors can be summarized as basic strain gauges in the system. The conversion of resistance change into voltage change is made through Wheatstone electronics design was explained.

The primary objective of the thesis is to identify the optimal sensor geometry within the created design space. The best sensor geometry for sheet-type sensors was determined with systematic experiments, followed by selecting soft coil-shaped sensors as the best geometry in the 3D shaped sensors. The hypothesis of significant resistance decrease due to coil contact during compression is verified through sensor characterization experiments using constant pitch and varying pitch coil-shaped sensors. The 3D printing settings and connection types for soft coil-shaped sensors have been introduced in various robotics and human-computer interaction applications.

Devising the coil-shaped soft sensors initiates new application fields for the implementation of soft sensors. These studies encompassed diverse scenarios, including embedding soft sensors into the C-leg of a robot (SQuad) to replace the rigid commercial encoders, utilizing soft sensors in the body of the Modular Soft Quadruped (M-SQuad) to distinguish different obstacles, and integrating soft sensors into Suspensionized Soft Quadruped (S-SQuad) to analyze terrain inclination. Moreover, the Sensorized Collision Resilient Quadcopter (SCoReR) was equipped with soft sensors on its bumpers to detect collisions, while soft sensors were attached to the tails of the ReMBot robot for inclination and obstacle collision detection. The applications extend beyond robotics, as soft sensors are used to construct novel human-computer interfaces for playing games like pong.

4.2 Future Directions

The potential of soft 3D-printed strain gauges is emphasized. The utilization of soft sensors as sensing elements on soft robot bodies is highlighted for preserving their soft nature. Furthermore, the cost-efficiency and ease of manufacturing soft sensors made them promising candidates for wearable robots and human-computer interfaces. While the initial experiments on both S-SQuad and the sensorized tail concepts yielded promising results, further research is needed to develop detection algorithms and dynamic models for more accurate and reliable sensor performance. The experimental outcome shows that these concepts can be used for inclination detection. However, more research is needed to detect the roughness and the softness of the surfaces with these concepts. Constructing the dynamic model of the soft coil-shape sensor and simulating the electrical breakdown phenomena reduces the need for manufacturing iterations for sensor design and implementation, providing a better understanding of the working principle of the soft coil-shape sensor.

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