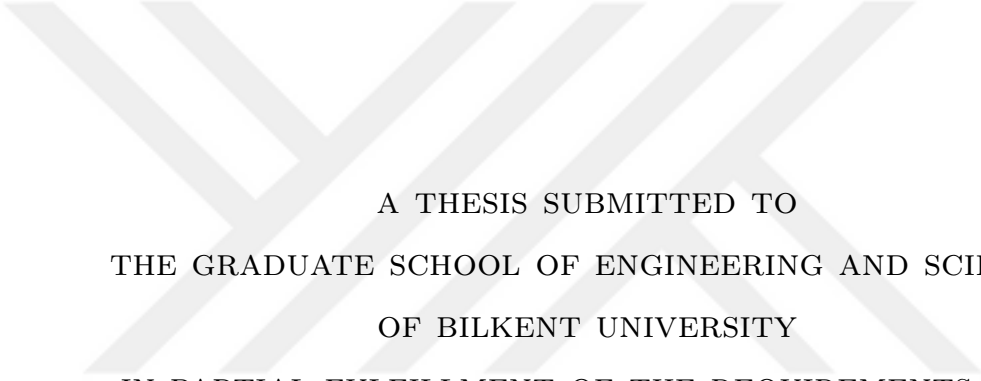


SMOLBOT-VS: A SOFT MODULAR ROBOT WITH VARIABLE STIFFNESS BACKBONES



A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF ENGINEERING AND SCIENCE
OF BILKENT UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF
MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING

By
Muhammed Uygun
September 2024

SMoLBot-VS: A Soft Modular Robot with Variable Stiffness Backbones

By Muhammed Uygun

September 2024

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Onur Özcan (Advisor)

Ali Javili

Ali Emre Turgut

Approved for the Graduate School of Engineering and Science:

Orhan Arıkan
Director of the Graduate School

ABSTRACT

SMOLBOT-VS: A SOFT MODULAR ROBOT WITH VARIABLE STIFFNESS BACKBONES

Muhammed Uygun

M.S. in Mechanical Engineering

Advisor: Onur Özcan

September 2024

This thesis introduces a novel mobile modular C-legged robot featuring a variable stiffness mechanism. The robot's capability to adjust the level of compliance is achieved through a tendon-driven actuation system typically found in continuum robots. This system, in conjunction with 3D-printed soft backbones, forms the core of the robot's modular design. A significant contribution of this work lies in developing and controlling the variable stiffness mechanism for its integration into SMoLBot.

The robot design, in particular the backbone design was iteratively refined through repeated case studies, enhancing the robot's ability to sense obstacles and optimize stiffness quantification using data from conductive backbones. The research also examined the advantages of modulating backbone stiffness, particularly in improving the robot's performance in uneven terrain in rigid and soft configurations.

The work in the thesis is concluded by detailing the implementation of a PI stiffness controller that leverages voltage feedback from the backbones to adjust the robot's stiffness to intermediate levels. This controller allows the robot to autonomously operate variable stiffness mechanisms while demonstrating another potential use of soft sensors for mobile robots. The cyclic load tests established a correlation between voltage data from the backbones and stiffness, with force and displacement measurements confirming the relation across different stiffness levels.

Keywords: Variable stiffness, soft robots, modular robots, miniature robots, mobile robots, legged robots, kirigami-inspired fabrication.

ÖZET

SMOLBOT-VS: DEĞİŞTİRİLEBİLİR SERTLİĞE SAHİP YUMUŞAK MODÜLER ROBOT

Muhammed Uygun
Makine Mühendisliği, Yüksek Lisans
Tez Danışmanı: Onur Özcan
Eylül 2024

Bu tez, değişken sertlik mekanizmasına sahip özgün, mobil, modüler ve C-bacaklı bir robotu tanıtmaktadır. Robotun sertlik seviyesini ayarlama yeteneği, genellikle 'continuum' robotlarda bulunan makara temelli bir lineer aktivasyon sistemi sayesinde sağlanmaktadır. Bu sistem, üç boyutlu baskı ile üretilen yumuşak omurgalarla birlikte robotun modüler tasarımının temelini oluşturur. Bu çalışmanın literatüre temel katkısı, geliştirilen değişken sertlik mekanizmasının kontrol edilmesi ve SMoLBot'a entegrasyonudur.

Robotun ve özellikle omurgaların tasarımı, tekrarlanan vaka çalışmalarıyla iteratif olarak geliştirilmiş, robotun engelleri algılama yeteneğini arttırmak ve iletken omurgalardan elde edilen verilerle sertlik ölçümünü sağlamak üzerine optimize etmiştir. Araştırmada ayrıca omurga sertliğinin modülasyonunun avantajları, özellikle de robotun sert ve yumuşak konfigürasyonlarda engebeli arazide performansını iyileştirmedeki rolü incelenmiştir.

Tezdeki çalışma, omurgalar üzerinden ölçülen voltaj geri bildirimi kullanarak robotun sertliğini uç noktalar arasındaki seviyelere de ayarlayabilen bir PI kontrolcüsünün geliştirilmesini ayrıntılı olarak açıklayarak sonlandırılmaktadır. Bu kontrolcü, mobil robotlarda yumuşak sensörlerin kullanılabileceği yeni bir alan daha göstermekle beraber, robotun harici müdahaleye ihtiyaç olmadan değişken sertlik mekanizmasını denetlemesini sağlamaktadır. Periyodik yük bindirerek yapılan testlerde omurgalardan gelen voltaj verileri ile sertlik arasında bir bağlantı oluşturmuş, farklı sertlik seviyelerinde yapılan kuvvet ve yer değiştirme ölçümleri ile bu ilişki doğrulamıştır.

Anahtar sözcükler: Değişken sertlik, yumuşak robotlar, birimsel (modüler) robotlar, bacaklı robotlar, kirigami esinli üretim.

Acknowledgement

I want to extend my heartfelt gratitude to everyone who contributed to the work presented in this research. First and foremost, I would like to thank my academic adviser, Professor Onur Özcan, for granting me the opportunity to pursue research in the Miniature Robotics Lab. His vision and guidance, with an easy attitude and a constantly tolerant approach, have been the driving force for advancing our research efforts. Working with 'Onur Hoca' has been a great learning experience.

This work would also not have been possible without the support of my lab mates, current and former ones. I was fortunate to have the opportunity to work with Mustafa Uğur, Amiralı Abazari, Alihan Bakır, Doğa Özbek, Yiğit Yaman, Amiralı Aleali, Ömer Çağrı Ergin, Altar Sertpoyraz, Burak Arslan and Haider Raheem, who not only have been colleagues but friends as well. I want to extend a special thank you to Mustafa Uğur, who helped me a great deal in adjusting to the lab in my first year, teaching me necessary technical skills and offering a helping hand whenever needed.

I also would like to mention undergraduate students I worked with, Emre Bulut and Çağın Aydın, who made significant contributions with their efforts. I wish them the best of luck in their future endeavors.

This work was partially funded by TÜBİTAK through grant no: 122E528.

Contents

1	Introduction	1
1.1	Motivation	1
1.2	Literature Review	2
1.3	Research Aims and Contributions	3
1.4	Thesis Structure	4
2	Design and Fabrication	7
2.1	Previous Iterations	7
2.2	SMoLBot-VS Overview	11
2.3	Module Design	12
2.3.1	Body Frame and Motor Casing	13
2.3.2	PDMS C-Legs	14
2.3.3	Tendon-Driven Linear Actuator	16
2.4	Electronics	17

2.4.1	Circuit Components	18
2.4.2	Control and Communication System	20
3	Variable Stiffness Mechanism	22
3.1	Backbone Design Iterations	22
3.1.1	Obstacle Detection Experiments	24
3.1.2	Backbone Design Parameters	29
3.2	Tendon Actuation Mechanism	33
3.3	Experiments and Case Studies	34
3.3.1	Obstacle Climbing	36
3.3.2	Gap Crossing	37
3.3.3	Results and Discussion	38
4	Backbone Sensing and Control	40
4.1	Controller Design	40
4.1.1	Backbone Design Adjustments	40
4.1.2	Data Acquisition	42
4.1.3	Proportional-Integral Controller	43
4.2	Test Setup and Experiments	48
5	Conclusion and Future Works	52

List of Figures

2.1	(a) SMoLBot, (b) body design of a single module, (c) four-bar leg mechanism, (d) PDMS backbones.	8
2.2	(a) SMoLBot-C, (b) C-legs.	9
2.3	(a) ReMBot single module, (b) control of ReMBot via motion capture system (c) 4 module ReMBot configuration.	10
2.4	SMoLBot-VS with TPU backbones.	11
2.5	CAD illustration of a single module with different parts numbered as 1) foldable body frame, 2) backbone docks, 3) circuit board, 4) potentiometer (rotary sensor), 5) PDMS C-leg, 6) motor casing, 7) tendon-driven linear actuator.	12
2.6	AutoCAD design of the body frame, 1) extended motor housings, 2) U-shaped fastener extensions, 3) access holes, 4) backbone dock housings.	14
2.7	(a) Mold assembly, (b) mold assembly exploded view, (c) 26mm diameter C-legs.	15
2.8	(a) Section view of the module: linear actuator (pink), (b) Components of the linear actuator numbered as 1) pulley casing, 2) pulleys, 3) DC motors 4) PVDF strings attached to the pulleys. . .	17

2.9	(a) Custom-designed PCB of SMoLBot-VS, (b) PCB with soldered components numbered as 1) ESP32 module, 2) 5V step-up/step-down voltage regulator, 3) ESP32 serial connection pins, 4) ESP32 enable and reset buttons, 5) power switch, 6) resistive sensor connection pins, 7) DC motor connection pins, 8) motor driver, 9) 3.3V LDO voltage regulator 10) dual operational amplifier.	18
2.10	Other components connected to the PCB numbered as 1) 3.7V battery, 2) potentiometers, 3) 136:1 gear ratio DC motors, 4) 700:1 gear ratio DC motors.	19
2.11	Control and Communication System.	20
3.1	(a) M-SQuad: Modular Soft Quadruped, (b) spring-shaped resistive soft sensor.	23
3.2	(a) Spring-shaped resistive soft sensor design, (b) resistive soft sensor with rectangular layers	23
3.3	SMoLBot with dual sensors/backbones.	24
3.4	(a) The robot climbing 27mm obstacle, (b) voltage data from the backbones with 1.25mm layer gap	25
3.5	(a) The robot climbing 54mm obstacle, (b) voltage data from the backbones with 1.25mm layer gap	26
3.6	(a) The robot climbing 27mm obstacle, (b) voltage data from the backbones with 0.75mm layer gap	27
3.7	(a) The robot climbing 54mm obstacle, (b) voltage data from the backbones with 0.75mm layer gap	28

3.8	Effect of the nominal backbone compliance: (a) the backbones are unable to support the module's weight, (b) the backbones push the module against obstacles to enhance climbing ability.	29
3.9	Backbone parameters and connection parts numbered as 1) PVDF strings, 2) pins securing connection of backbones to the module. .	30
3.10	Backbone samples with single parameter variation: (a) decreasing layer thickness, (b) increasing gap between the layer, (c) decreasing layer height.	31
3.11	Backbone load and deflection results.	32
3.12	(a) Soft configuration, (b) rigid configuration	33
3.13	(a) Relaxed tendons, layers are free to bend, (b) actuated tendons, layers are compressed	34
3.14	Obstacle climbing in (a) rigid mode, (b) and soft mode	37
3.15	Gap crossing in (a) soft mode, (b) and rigid mode	38
4.1	(a) Constant pitch design, (b) variable pitch design.	41
4.2	(a) Wheatstone bridge, (b) differential amplifier.	42
4.3	Controller performance at $K_P = 0.50$	44
4.4	Controller performance at $K_P = 0.25$	44
4.5	Controller performance at $K_P = 0.10$	45
4.6	Controller performance at $K_P = 0.10$ and $K_I = 0.50$	46
4.7	Controller performance at $K_P = 0.10$ and $K_I = 0.25$	46

4.8	Controller performance at $K_P = 0.10$ and $K_I = 0.10$	47
4.9	Controller performance at $K_P = 0.10$ and $K_I = 0.10$, integral limit = 500.	47
4.10	Controller performance at $K_P = 0.10$ and $K_I = 0.10$, integral limit = 50.	48
4.11	Stiffness measurement test setup.	49
4.12	Mean stiffness values calculated at different input voltage levels shown with standard deviation.	50
4.13	Force vs deflection results for 2400mV-3000mV range.	50
4.14	Force vs deflection results for 1000mV, 2000mV and 3000mV input voltage levels.	51

List of Tables

3.1	Bending Stiffness Measurement Results	32
3.2	Obstacle Climbing and Gap Crossing Performance of SMoLBot-VS	35
3.3	Success Rate of SMoLBot-VS at Limit Values	35

Chapter 1

Introduction

1.1 Motivation

Miniature robots have significant advantages over their larger counterparts due to their small size and low weight, making them ideal for exploring tight spaces and areas prone to sinking or breaking under heavy loads [1], [2]. These benefits make them particularly useful for discovery, search, surveillance, and communication in confined spaces such as natural disaster zones, narrow tunnels, and delicate structures [3]. Additionally, modular miniature robots can be quickly and inexpensively produced using additive manufacturing [4] and origami-inspired planar fabrication [5], allowing them to adapt to various tasks.

As the scale decreases, navigating rough terrain becomes increasingly challenging for miniature robots. Their low weight and surfaces with low friction coefficients make climbing inclines and obstacles particularly difficult, especially for robots with standard wheels. Additionally, gaps in the terrain can severely impact the robot's operation. While control algorithms can mitigate these issues by finding alternative paths around obstructions, this comes at the expense of time and increased sensing and computational demands. Alternatively, the

robot’s design can be optimized to better handle rough terrain without significantly compromising its locomotion.

The solution to many challenges requiring adaptability is often introducing compliance to the system via soft materials or alternative actuation schemes such as dielectric and pneumatic actuators. However, these methods have feasibility and reliability problems, especially for untethered mobile systems. Electrical and pneumatic actuation requires high power systems with large dimensions, making them practical only as a base of tethered systems such as vine robots. Although soft materials are effective for durability against external forces, they are equally ineffective when applying force, making them slow in operation and useful only in completing niche tasks that require minimum load capability. Developing hybrid systems that can utilize the benefits of soft robots without suffering drawbacks is an important goal moving forward for the emergence of commercially utilized systems.

1.2 Literature Review

Several miniature robot designs in the literature employ innovative locomotion methods to navigate unstructured environments. Some robots use jumping mechanisms [6] and adhesion techniques [7, 8] to climb over obstacles. Additionally, modular robots have been developed in the past decade that can be assembled from multiple units and reconfigured to perform tasks such as crossing gaps [9], reaching high points, and forming unique structures [10].

The incorporation of compliance in miniature robots with bio-inspired soft designs allows for even greater adaptability to complex environments [11], enabling behaviors such as crawling, walking, running, or swimming [12]. Examples of progress in soft robotics include robots with pneumatic actuators that can burrow into granular terrain [13], grasp branches and climb [14]; legged soft-hard hybrids that traverse naturally confined environments [15], [16, 17]; and snake robots with backbone modulation suitable for tunnels and narrow passages [18, 19].

While soft robots offer better environmental adaptability than their rigid counterparts, their compliance can limit their ability to perform tasks that require large forces, such as carrying payloads without deformation [20]. Stiffness modulation mechanisms bridge the gap between rigid and soft materials, providing greater control over the robot and enhancing its overall functionality [21].

Soft robot arms and grippers utilizing antagonistic actuation [22,23], fiber jamming [24], and shape memory materials [25] can handle higher loads with minimal disruptions. Rigid robots that need natural compliance for activities like walking and running can benefit from adjustable torque outputs provided by variable stiffness actuators (VSAs) [26]. These actuators employ lever mechanisms [27], series elastic configurations [28], tendon-driven antagonistic mechanisms [29,30], or magneto-rheological fluids [31].

Various robots in the literature leverage compliant actuators and joint mechanisms to enable different locomotion modes. For example, EduBot, introduced by Galloway et al., enhanced the dynamic running efficiency of a C-legged robot by adjusting leg stiffness [32]. Buckley et al. incorporated tail stiffness modulation in a quadruped, stabilizing its gait cycle and increasing the slope it can climb [33]. Chen et al. used origami-inspired variable stiffness joints to reconfigure leg shapes, enabling transitions between inching, crawling, and walking gaits [34]. Labazanov et al. designed variable stiffness joints between reconfigurable rigid modules using Field’s metal, which melts at low temperatures, allowing the robot to conform to curved structures [35]. While these robots accomplish impressive tasks independently, their functioning requires more sophisticated mechanisms with increased complexity. Additionally, some designs hinder the robots’ mobility on various terrains, while others add unnecessary weight.

1.3 Research Aims and Contributions

In this thesis, we present a mobile modular C-legged robot with adjustable backbone stiffness, incorporating the origami-inspired body design of SMoLBot [36].

The robot can switch between rigid and soft modes through a tendon-driven actuation system commonly used in continuum robots [37], along with 3D-printed soft backbones connecting the modules. One of the key contributions of this work is the design of the variable stiffness backbones and their integration into SMoLBot.

We have iteratively improved the backbones' design by repeated case studies with the robot to accommodate better environmental sensing of obstacles in the terrain and optimize quantification of stiffness with the data from conductive backbones for the stiffness controller without the updated design of the backbones disrupting the robot's locomotion, resulting in unpredictable gait patterns.

We have finalized the backbone design, characterizing the design's three main parameters to adjust the backbones' compliance, allowing us to rapidly manufacture backbones with different effective base stiffness without interfering with material properties. Additionally, we explored the benefits of modulating backbone stiffness by evaluating the robot's performance in climbing obstacles and crossing gaps in both rigid and soft modes.

Finally, we have implemented a simple PI stiffness controller for the variable stiffness mechanism that allows the robot to change stiffness to intermittent values using the voltage feedback from the backbones. This shows an additional utility for soft sensors in mobile robots. We have demonstrated the effectiveness of the stiffness controller via cyclic load tests, showing the correlation between voltage data from backbones and stiffness by getting force and displacement measurements for increasing stiffness levels.

1.4 Thesis Structure

The work done in this thesis is distributed into four main chapters, and the contents of each chapter are as follows:

Chapter 2 - Design and Fabrication: This chapter serves as the backbone of the thesis, outlining the essential steps toward developing SMoLBot-VS. The chapter begins by examining previous SMoLBot versions and how SMoLBot-VS improves upon their design. The module design section details the development and construction of a single module, covering body design, C-legs, the cable-driven linear actuator, and electronics. Each design stage is thoroughly described, with CAD images, 3D printed molds, and the fabricated PDMS components. The final section discusses the robot’s electronics and provides information on the custom-printed circuit board and its components. The control method for operating the motors connected to the C-legs, managing the variable stiffness mechanism, and communication between the server and the robot are briefly outlined.

Chapter 3 - Variable Stiffness Mechanism: This chapter covers the working principle of variable stiffness and evaluates its benefit for miniature modular robots. The first section begins with an in-depth overview of the backbone design procedure and how initial designs were refined to enhance the robot’s capabilities. Results of experiments testing the backbone’s design and the influence of dimensional parameters on obstacle detection are presented. Lastly, design parameters to adjust backbone stiffness and related tests are provided. The following section briefly describes how the variable stiffness mechanism implemented in SMoLBot-VS utilizes tension in the linear actuator cables to adjust stiffness between the modules. The final section concludes with the case studies conducted with SMoLBot-VS to assess the advantages of the variable stiffness mechanism on uneven terrain. Obstacle-climbing and gap-crossing experiments are repeated for different difficulty levels for the robot in rigid and soft modes. Additionally, the effect of gait pattern is observed, and the results are displayed as success rates.

Chapter 4 - Backbone Sensorization and Control: This chapter explores the development of the feedback controller for the variable stiffness mechanism. The first section outlines the reasoning behind the variable pitch design approach in the latest iteration of the backbones. Additionally, the circuit design for data acquisition from the sensors and integration of the PI (Proportional-Integral) controller for the variable stiffness mechanism with the ESP32 microcontroller

is discussed. The final section of this chapter provides a detailed explanation of the test setup used to measure the bending stiffness of the backbones at different reference voltage levels adjusted by the controller. The design of the test setup for data collection is outlined, and the results of the force-displacement measurements from the experiments conducted are presented. The results regarding the calculated bending stiffness are analyzed in relevant discussions.



Chapter 2

Design and Fabrication

2.1 Previous Iterations

SMoLBot, standing for **S**oft **M**odular **L**egged **R**obot, is a series of miniature, modular, soft-hybrid robots designed in Bilkent Miniature Robotics Laboratory (MRL). The two key distinctive characteristics of the SMoLBot series are the use of cheap, lightweight materials with the kirigami-inspired 2D to the 3D folding method as the primary method of fabrication that allows rapid prototyping and the compliant connection between the n number of modules that provides a greater degree of mobility for the robot, especially in uneven terrain. A common problem among different versions of the robots is slippage due to insufficient traction, which stems from the low weight of the robot and the limited torque output of sub-micro DC motors used for actuation.

The first SMoLBot model shown in 2.1(a), was designed primarily for gait and locomotion analysis to understand the effect of backbone compliance on the overall motion and speed of the robot [38].

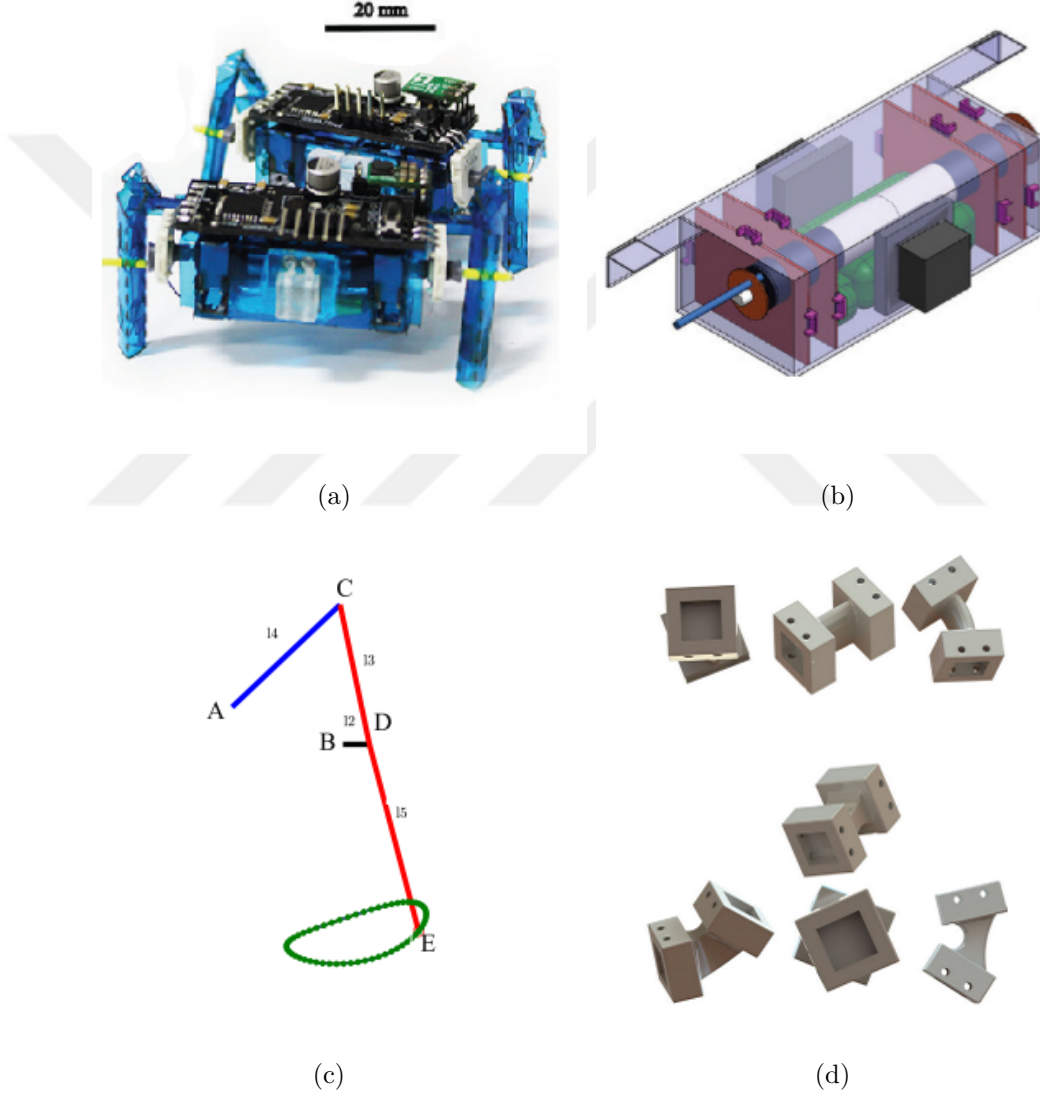


Figure 2.1: (a) SMoLBot, (b) body design of a single module, (c) four-bar leg mechanism, (d) PDMS backbones.

For the body of a single module (Fig. 2.1(b)), a 2D acetate sheet encases the battery and the two sub-micro DC motors, which are connected to a four-bar mechanism that creates the stepping motion of the legs highlighted by green in Fig. 2.1(c). The legs synchronized based on voltage readings across the potentiometers attached to the DC motors.

I-beam-shaped and elliptical PDMS (Polydimethylsiloxane) backbones (Fig. 2.1(d) between the modules introduce a compliant connection between the modules that allows smoother motion by reducing the yaw and roll of the modules. This also causes a considerable increase in translational velocity for the same leg frequencies compared to the rigid connection.

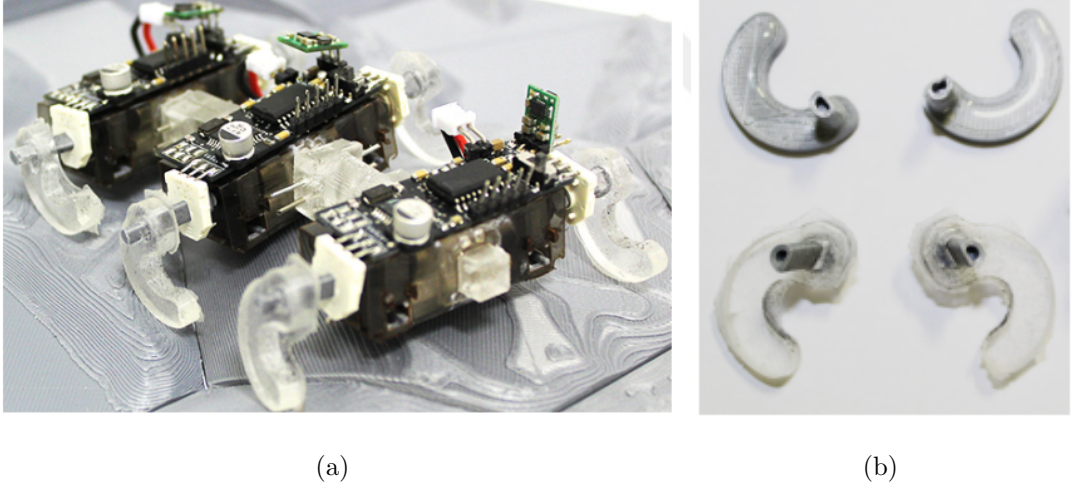


Figure 2.2: (a) SMoLBot-C, (b) C-legs.

The following iteration, SMoLBot-C, featured C-shaped PDMS legs directly connected to DC motors instead of the folded four-bar mechanism to improve the robot’s performance on inclined and rough terrain [36]. The use of C-legs forms better support and traction at the rear modules, allowing SMoLBot with two modules to climb obstacles 1.6 times the robot’s module height, getting up to 2 times the module height with the use of a soft tail [36].

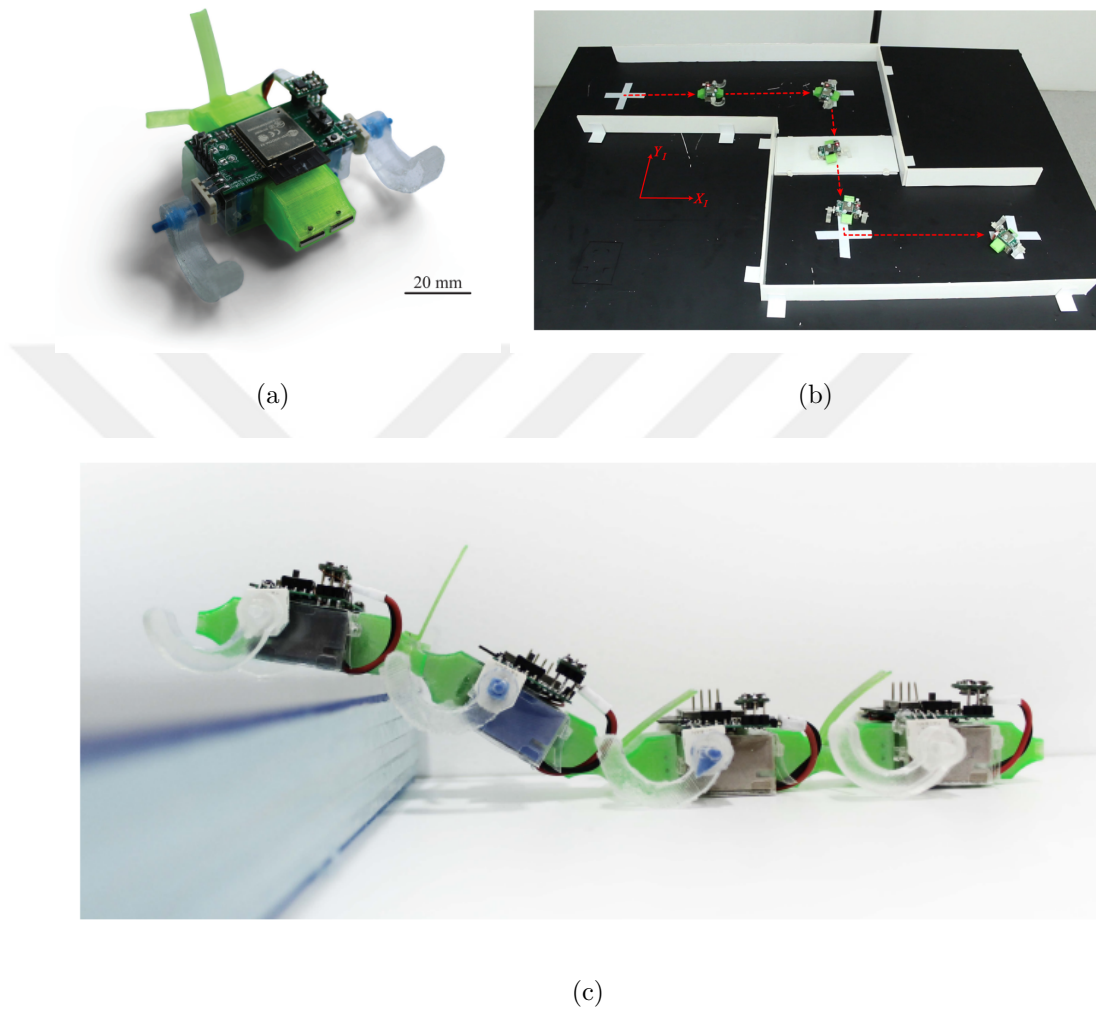


Figure 2.3: (a) ReMBot single module, (b) control of ReMBot via motion capture system (c) 4 module ReMBot configuration.

ReMBot (**R**econfigurable **M**odular **R**obot) utilized SMoLBot-C modules with permanent magnets for compliant connection instead of PDMS backbones to allow separation and merging of the modules [39]. Using positional feedback from the motion capture system, the modules could move separately to different tasks and join at a designated position with a simple path-tracking algorithm to climb over obstacles that single modules could not overcome and separate again with reverse rotation of the C-legs.

2.2 SMoLBot-VS Overview

Our main goal with SmoLBot-VS (**Soft Modular Legged Robot with Variable Stiffness**) was utilizing the kirigami-inspired design of SMoLBot that allowed cheap and rapid manufacturing and enhance operation range with the implementation of a mechanism to regulate the relevant motion between the modules by controlling the backbone behavior.

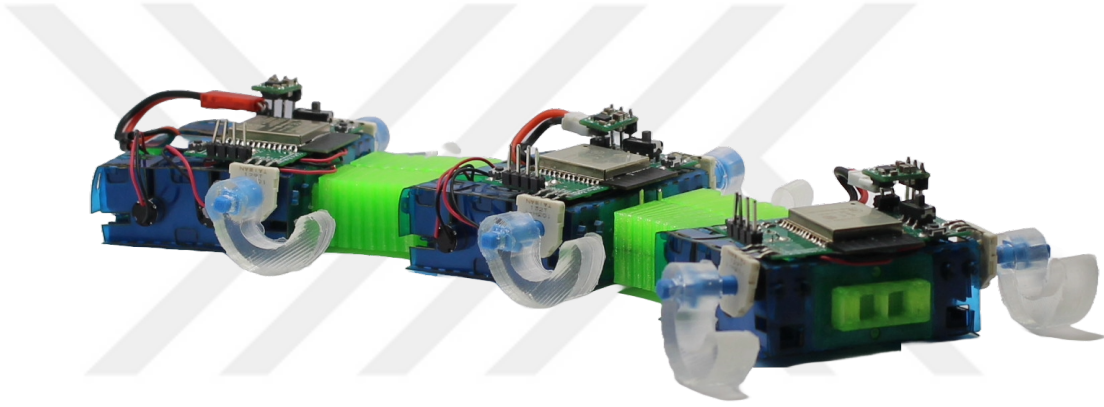


Figure 2.4: SMoLBot-VS with TPU backbones.

This mechanism would allow the robot to complete tasks requiring compliance and load-bearing capabilities [40]. To achieve that, we needed an actuation mechanism for the backbones to control stiffness. Among the methods mentioned for stiffness modulation in Section 1.2, we focused on series-elastic configurations as the backbones connecting the modules could already be modeled as springs.

Using the same type of DC motors to drive a linear actuator was viable for the size of our robot and ease of integration to the existing circuit on board. The addition of a tendon-driven actuation mechanism required more space since the SMoLBot-C module design was too small to encase the addition of two DC motors, and the switch from PDMS backbones to 3D-printed TPU (Thermoplastic Polyurethane) backbones resulted in a considerable increase in the mass and size of the robot.

To compensate, the design of the body frame and the motor casings were changed, and in the later versions of the robot, 136:1 gear ratio DC motors connected to the C-legs were replaced by 700:1 gear ratio. Including three modules and two sets of backbones, the robot weighs a total of 125.8 grams. When backbones are relaxed and compliant, the robot’s nominal length is 223mm, extendable to 260mm under external forces. In a completely rigid configuration, its length is 215mm. Although the earlier implementations of SMoLBot-VS required the robot to conclude its task to change stiffness by the user, the addition of the stiffness controller in the later stages allowed the robot to change stiffness with wireless communication automatically.

2.3 Module Design

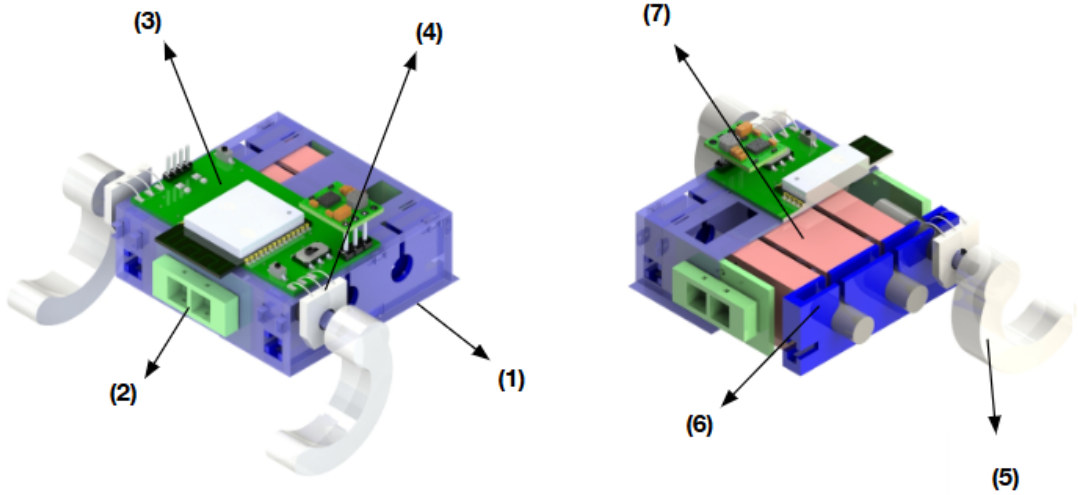


Figure 2.5: CAD illustration of a single module with different parts numbered as 1) foldable body frame, 2) backbone docks, 3) circuit board, 4) potentiometer (rotary sensor), 5) PDMS C-leg, 6) motor casing, 7) tendon-driven linear actuator.

A single module of the SMoLBot-VS shown in 2.5 consists of a Polyethylene Terephthalate (PET) body, which is folded into a 3D shape from a 2D design,

C-shaped soft legs, a custom electronics board, and a linear tendon-driven actuation mechanism that connects adjacent modules. Although a single module can wirelessly operate by itself, a longer chain of modules allows greater operational capability while handling challenging terrain. 3D-printed TPU backbone docks are positioned at the front and back of the module to attach the soft backbones. The backbones are secured to these docks using metal pins. Using the metal pins for connection allows us to detach and attach modules in a few seconds while also being used as a connection point when backbones are utilized as sensors. A single module measures 45mm in length, 80mm in width, and 19mm in height and weighs 30.1 grams, excluding the backbones.

2.3.1 Body Frame and Motor Casing

The exterior of SMoLBot-VS modules is created by laser cutting 100 μm thick acetate sheets into a 2D body frame shown in Fig. 2.6, which folds into a 3D structure that encases the backbone docks, DC motors, battery, and tendon-driven connection mechanism. The enclosure is locked in using the U-shaped out-of-plane fastener extensions highlighted in the top left of Fig. 2.6.

Compared to the body frame in the previous versions, the length of the robot is roughly doubled, and the number of access holes is increased to ease the frame’s folding process. The circular cuts for the motors are connected with a 1mm thick line to form a gap on top of the motor housing highlighted in the top right of Fig. 2.6. Two 3D-printed polylactic acid (PLA) motor casings originally intended to reinforce the module structure also house two DC motors connected to the tendon-driven linear actuator.

Due to the cylindrical shape of the motors, they need to be tight-fitted into housing to prevent motor slippage. The 1mm gap above the housing allows the body frame and the PLA piece to stretch at that location, making tight-fitting possible while accounting for tolerance issues.

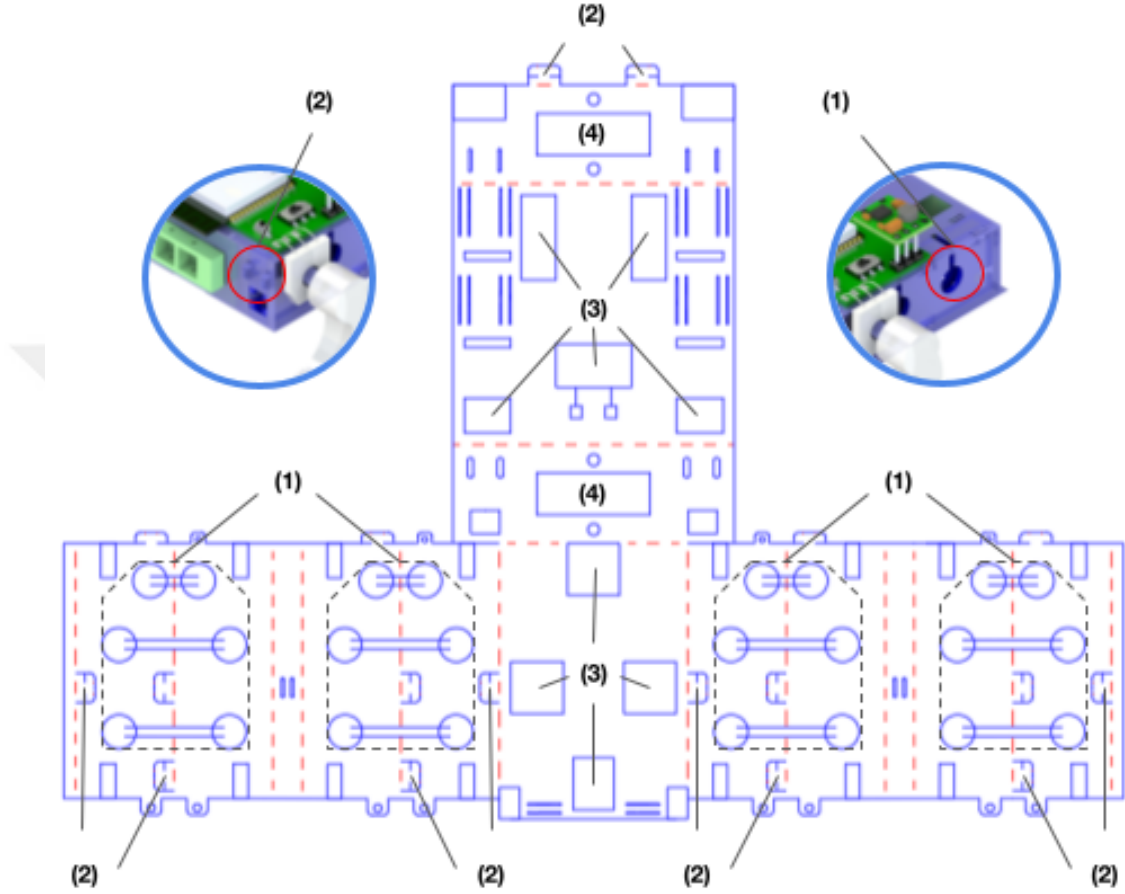
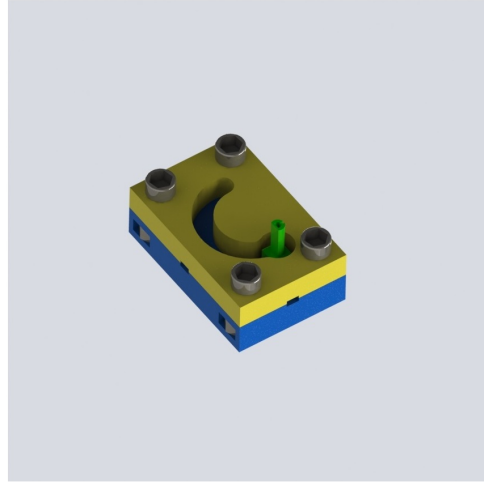


Figure 2.6: AutoCAD design of the body frame, 1) extended motor housings, 2) U-shaped fastener extensions, 3) access holes, 4) backbone dock housings.

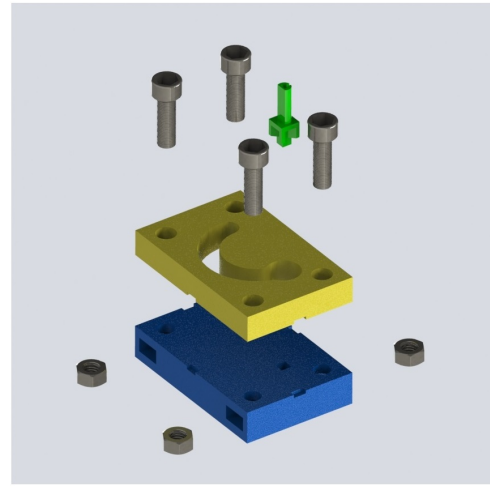
2.3.2 PDMS C-Legs

Compared to the four-bar mechanism utilized in the first version of the SMoLBot, C-shaped wheel-legs (whegs) [41] allow faster locomotion, better steerability, and better handling of rough terrain with obstacles. The C-shaped leg design enables the body to adjust to varying surface conditions with minimal control effort. The adaptability can be further improved with the use of soft materials, which reduce the undulation of the body, resulting in a smoother body motion.

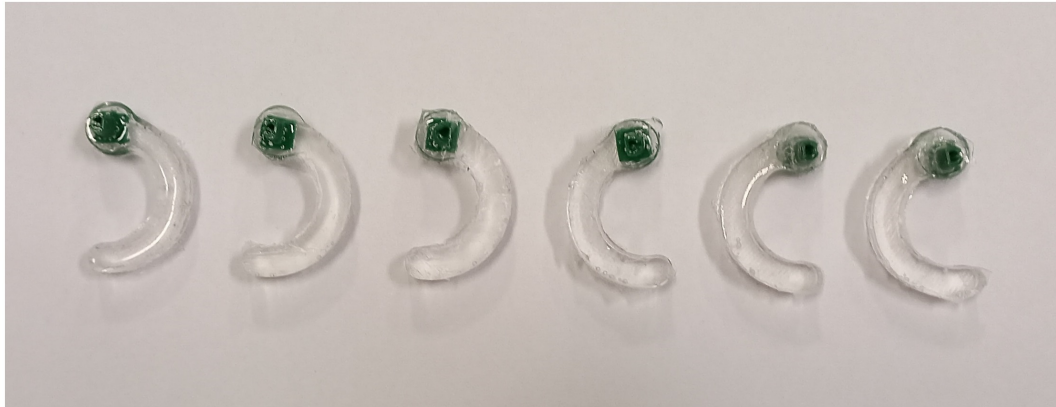
Another quality that makes PDMS an ideal material for the C-legs is that we can adjust the stiffness by changing the ratio of the active chemical in the mixture. We use a 7:1 ratio between PDMS and the catalyst for the C-legs.



(a)



(b)



(c)

Figure 2.7: (a) Mold assembly, (b) mold assembly exploded view, (c) 26mm diameter C-legs.

For the fabrication of the PDMS C-legs, we use 3D-printed molds. The top part of the mold, shown in yellow, is bolted on firmly to the bottom part of the mold, shown in blue in Fig. 2.7(a), via the hex nuts embedded into the bottom part to prevent hex bolts connecting top and bottom parts from eroding the PLA pieces. The camshaft, shown in green, is loosely connected to the bottom part and is removed as part of the C-leg once the molds are left in the oven at 60° Celcius temperature for three hours for the curing process. For SMoLBot-C and earlier iterations of SMoLBot-VS, we utilized C-legs 18mm in diameter; however, as the size of the modules increased due to the placement of the cable-driven linear actuator, we also increased the diameter of the C-leg to 26mm (2.7(c)) as it became difficult for the robot to climb obstacles.

2.3.3 Tendon-Driven Linear Actuator

We needed to implement a linear actuator in our robot to control backbone behavior. Many studies in the literature employ large commercial linear actuators to drive tendon mechanisms for robotic arms, hands, and grippers, which necessitates a complex system. An alternative is to use shape memory alloy (SMA) springs to overcome size constraints. However, their heat-based activation through passing current requires relatively high power and has the added disadvantage of slow response times for tendon relaxation.

To address the drawbacks of these alternative actuation schemes, we designed a custom linear actuator that we integrated into the module shown in Fig. 2.8(a). Although placing the actuator inside the module doubles the module’s length compared to the regular SMoLBot, it prevents jamming caused by friction when tendons need to make multiple 90-degree turns to run parallel to the backbones if the actuator is placed on top of the module. The pulley mechanism inside the linear actuators is powered by sub-micro DC motors, chosen because their size and power requirements matched the existing circuit. While two 136:1 gear ratio DC motors are sufficient to pull the modules together, they can be easily back-driven without continuous input.

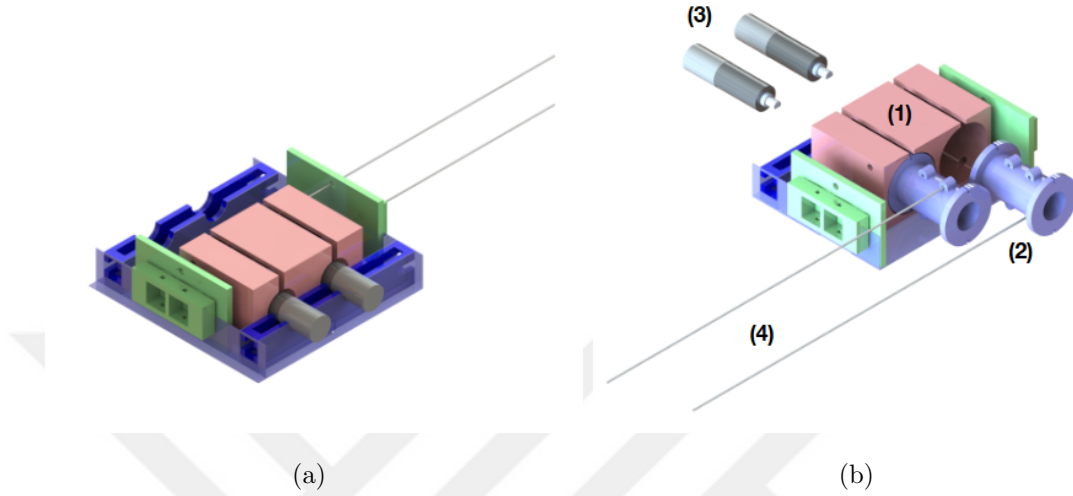


Figure 2.8: (a) Section view of the module: linear actuator (pink), (b) Components of the linear actuator numbered as 1) pulley casing, 2) pulleys, 3) DC motors 4) PVDF strings attached to the pulleys.

To address this, the system uses two 700:1 gear ratio sub-micro DC motors, which are much harder to back-drive, eliminating the need for constant input. The DC motors' outputs are connected to two separate 3D-printed pulleys shown in Fig. 2.8(b), with one end of each polyvinylidene fluoride (PVDF) tendon attached. These pulleys can rotate side by side in separate chambers of the 3D-printed actuator casing.

2.4 Electronics

For SMoLBot-VS, we have three primary tasks to achieve with the electronics on board: synchronization of the C-legs, control of the variable stiffness mechanism, and communication with the server to receive commands. To undertake these tasks, the Arduino Pro Micro microcontroller utilized for the previous versions of SMoLBot was replaced with an ESP32 microcontroller, and the circuit board was changed accordingly.

2.4.1 Circuit Components

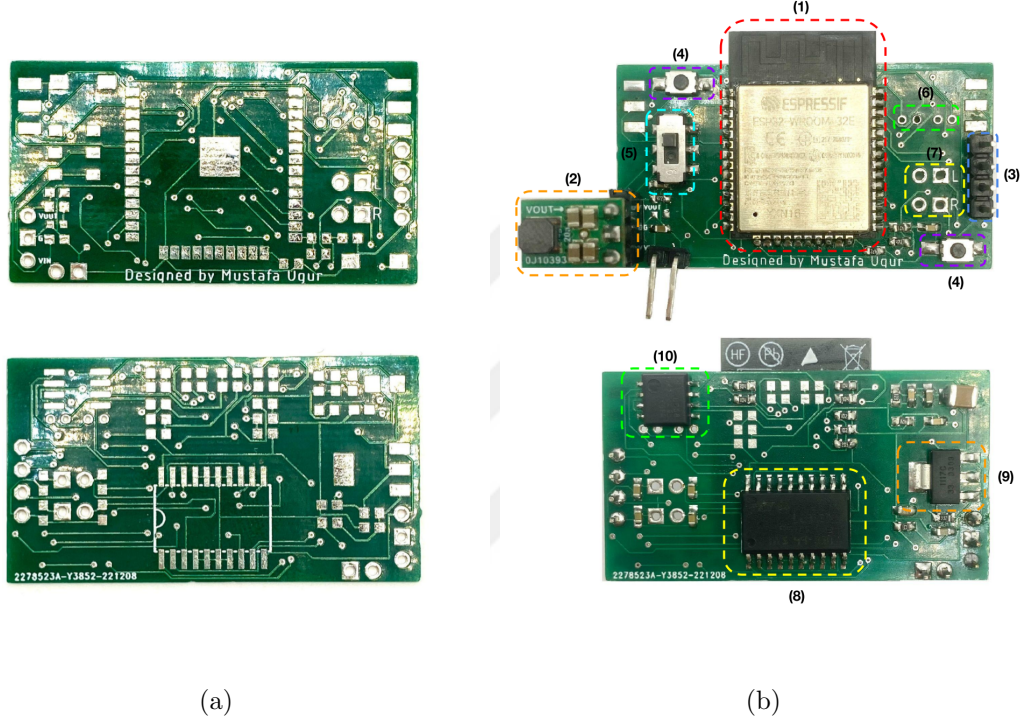


Figure 2.9: (a) Custom-designed PCB of SMoLBot-VS, (b) PCB with soldered components numbered as 1) ESP32 module, 2) 5V step-up/step-down voltage regulator, 3) ESP32 serial connection pins, 4) ESP32 enable and reset buttons, 5) power switch, 6) resistive sensor connection pins, 7) DC motor connection pins, 8) motor driver, 9) 3.3V LDO voltage regulator 10) dual operational amplifier.

The microcontroller module utilized for this board is an ESP32-WROOM-32 with a built-in antenna for wireless communication. Several protocols can be used to send messages to and from the robot; however, the ESP-NOW protocol has been more reliable and easier to use for our implementation than protocols like WebSocket. All electronics on board draw power from a 3.7V and 150mAh single-cell LiPo battery; therefore, we use two voltage regulators to adjust the voltage. The first is a 3.3V LDO (Linear Drop-Out) voltage regulator (Onsemi, NCP1117) connected to WROOM-32 as ESP32 modules are powered at 3.3V and utilize the same value for "HIGH" compared to commonly used 5V in Atmega chips.

The second is a 5V step-up/step-down voltage regulator (Pololu, S7V7F5) connected to the L293DD motor drivers, rotary potentiometers (Bourns 103H-1), dual operational amplifiers (Texas Instruments, LM358P), and the Wheatstone bridge circuit for soft sensor data acquisition. Since the circuit board has to be as small as possible, there is no room for a USB Micro B connection in the ESP32 breakout boards. The microcontroller is programmed with a serial connection via the pins connected to the Universal Asynchronous Receiver/Transmitter (UART).

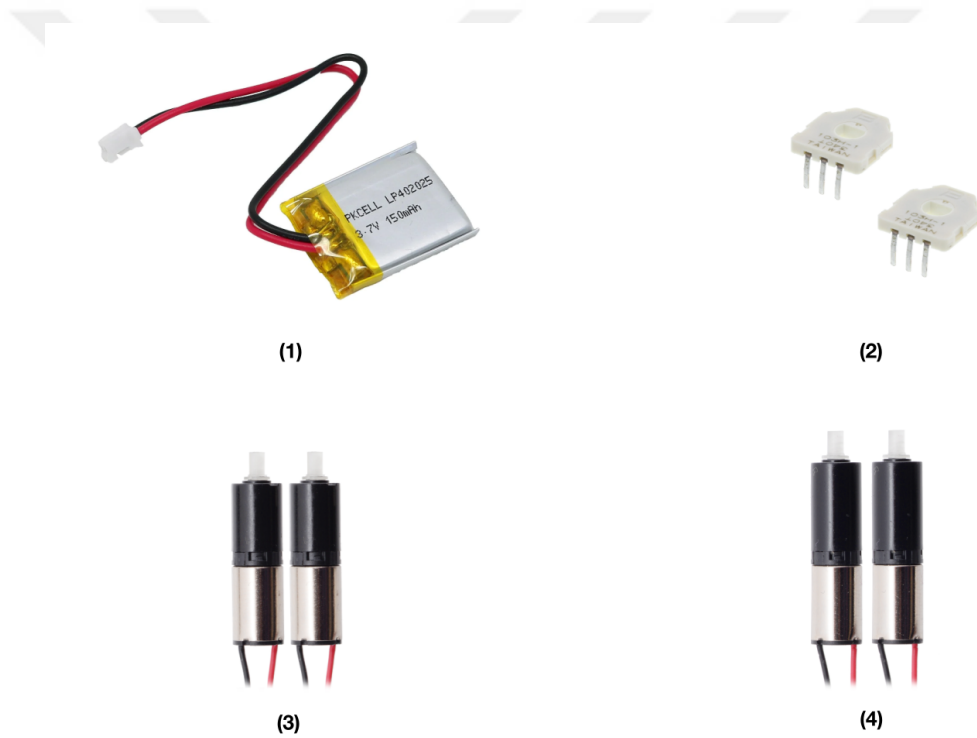


Figure 2.10: Other components connected to the PCB numbered as 1) 3.7V battery, 2) potentiometers, 3) 136:1 gear ratio DC motors, 4) 700:1 gear ratio DC motors.

The empty pins, pads, and holes seen in Fig. 2.9(a) are connection points for the battery, potentiometers, 700:1 and 136:1 gear ratio DC motors (Pololu, Sub-Micro Plastic Planetary Gearmotor).

The size of the DC motors is ideal for a miniature robot, and the 136:1 gear ratio allows faster leg motion, ranging up to 4 Hz with PDMS legs attached; however, they can quite easily be backdriven. Therefore, we used the 700:1 gear ratio model for the variable stiffness mechanism. The circuit board is designed on Autodesk EAGLE and fabricated by third-party manufacturers. The motor driver utilized by the variable stiffness mechanism is connected externally to the circuit board as the mechanism was designed at a later stage.

2.4.2 Control and Communication System

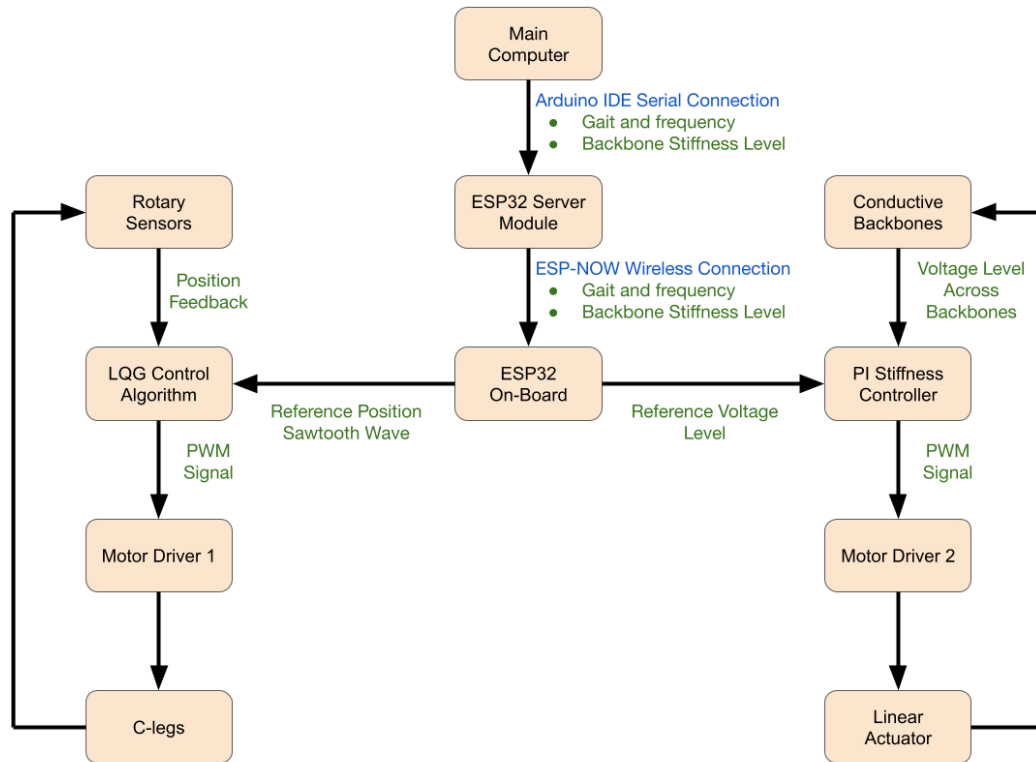


Figure 2.11: Control and Communication System.

As mentioned in the previous section, we switched from Arduino Pro Micro to the ESP32 microcontroller to wirelessly control the robot during the experiments. ESP32 on each module is registered as a receiver and is connected to a server ESP32 module via ESP-NOW protocol and receives input for robot gait, frequency, and backbone stiffness levels. The inputs are entered by the user on the main computer with a serial connection to the ESP32 server module registered as the sender. The ESP32-WROOM-32 kits have two processing chips, allowing us to run two separate algorithms on each module of SMoLBot-VS simultaneously.

The LQG (Linear-Quadratic Gaussian) control algorithm controls the robot's gait by controlling the C-legs' rotational speed and phase difference [42]. First, a live reference signal in the shape of a sawtooth wave is generated for the angular position of the C-leg based on the desired rotational frequency, the phase difference. Using the position data and the estimated rotational speed from the position data, the algorithm generates and adjusts a PWM (Pulse-width Modulation) signal for the motor driver to follow the reference signal. For all our experiments regarding SMoLBot-VS, we used trot or pronk gait where the right and left legs of a module rotate with 180° and 0° phase difference, respectively.

While controlling the variable stiffness mechanism, the stiffness of the backbones is not directly measured. However, using the conductive backbones with a layered structure, we can detect changes in stiffness by measuring the resistance drop that occurs when the backbone layers contact each other. Using the feedback from the conductive backbones, the PI controller implemented in the secondary processing core can adjust the stiffness level by following a reference voltage. The variable stiffness mechanism and the stiffness controller are explained in detail in Chapter 3 and Chapter 4, respectively.

Chapter 3

Variable Stiffness Mechanism

3.1 Backbone Design Iterations

SMoLBot-VS backbones are produced from TPU using an FDM (Fused Deposition Modeling) 3D printer. 3D printing enables rapid production and testing of complex designs that would be challenging to create with the PDMS molding techniques used in earlier versions of SMoLBot [36]. Fabrication of complex design was relevant as one of our primary goals with the new SMoLBot was the implementation of soft resistive sensors as backbones to add an environmental sensing component similar to M-SQuad (**M**odular **S**oft **Q**uadruped) [43].

The soft robot could sense scalable and unscalable obstacles using spring-shaped resistive soft connectors attached to the robot’s body shown in Fig. 3.1(a) and pursue or retreat from advancing based on sensor reading alone. The core idea behind the use of the spring shape for the resistive sensors (Fig. 3.2(a)) was to utilize the drop in resistance that occurs when the spring contracts due to external forces and layers of the spring contacting each other. The change in resistance can be measured by a simple voltage divider or a Wheatstone bridge circuit designed and commonly used for strain gauges.

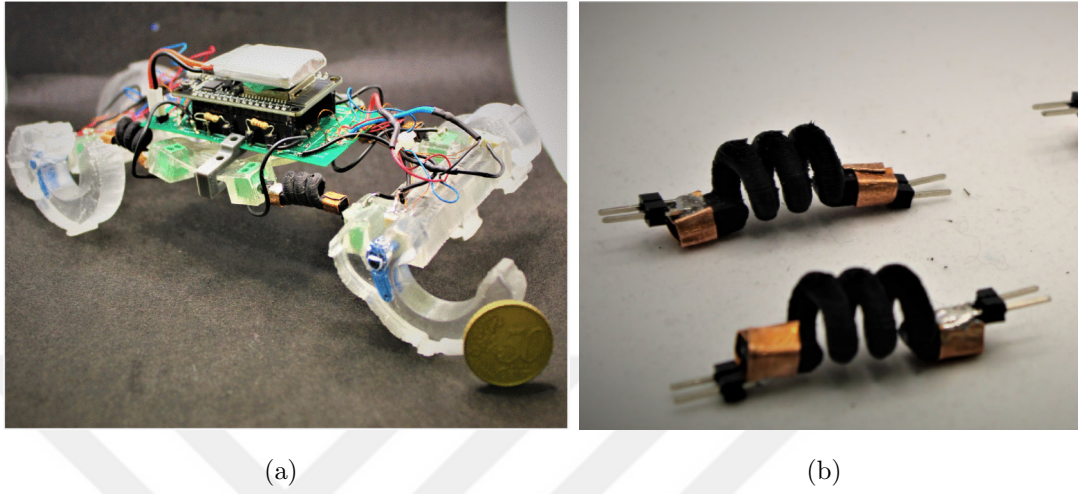


Figure 3.1: (a) M-SQuad: Modular Soft Quadruped, (b) spring-shaped resistive soft sensor.

Although the design was ideal for axial compression, it allowed endpoints to rotate and bend in any direction relative to each other, resulting in unstable motion that undermined the gait controller. A rectangular cross-section with a strain gauge pattern shown in Fig. 3.2(b) was preferred for SMoLBot over a circular spring shape to restrict the motion and increase the contact area between the layers for better sensing.

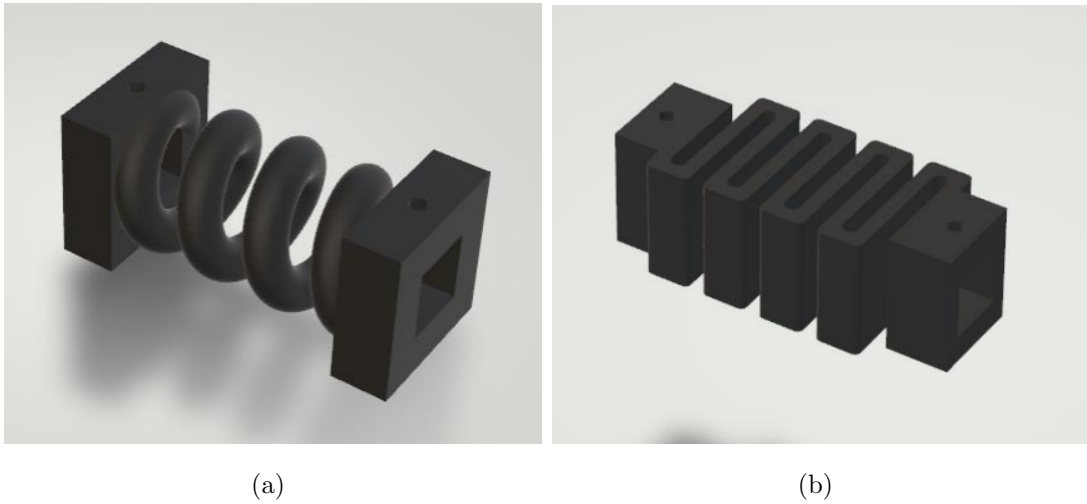


Figure 3.2: (a) Spring-shaped resistive soft sensor design, (b) resistive soft sensor with rectangular layers

Two sensors/backbones were connected between each module pair as shown in Fig. 3.3 to see if the sensors could provide data on the relative yaw angle between the modules and the terrain and obstacle data. Using a pair between modules also helped minimize the roll and yaw caused by the motion of the C-legs. To adjust to the size of the new circuit board with ESP32 controllers, the length of the modules was increased to 1.5 times that of SMoLBot-C modules, while other dimensions remained the same.

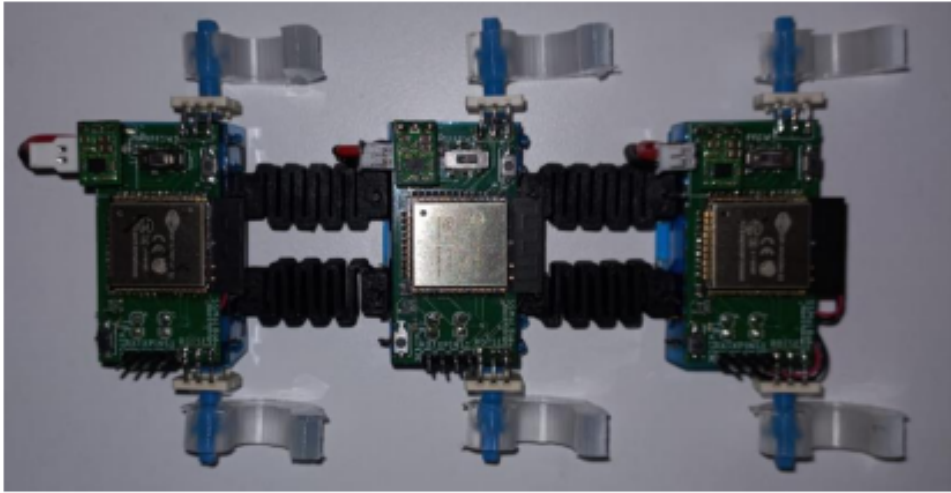


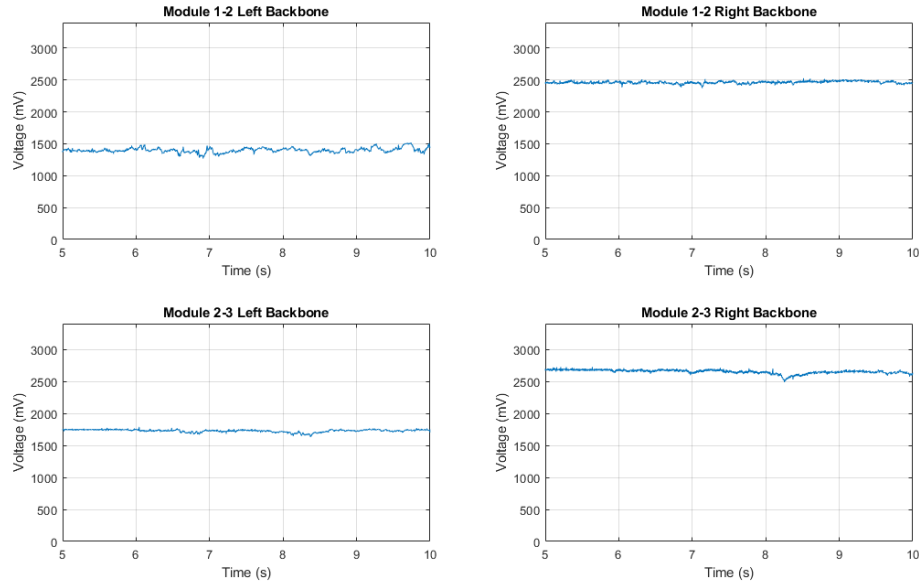
Figure 3.3: SMoLBot with dual sensors/backbones.

3.1.1 Obstacle Detection Experiments

For the early design of the backbones, our priority was to test sensor response during obstacle climbing and ensure that the results from M-SQuad were repeatable. We wanted to adjust the design parameters so that we would be able to collect data about the obstacle from the conductive backbones.



(a)



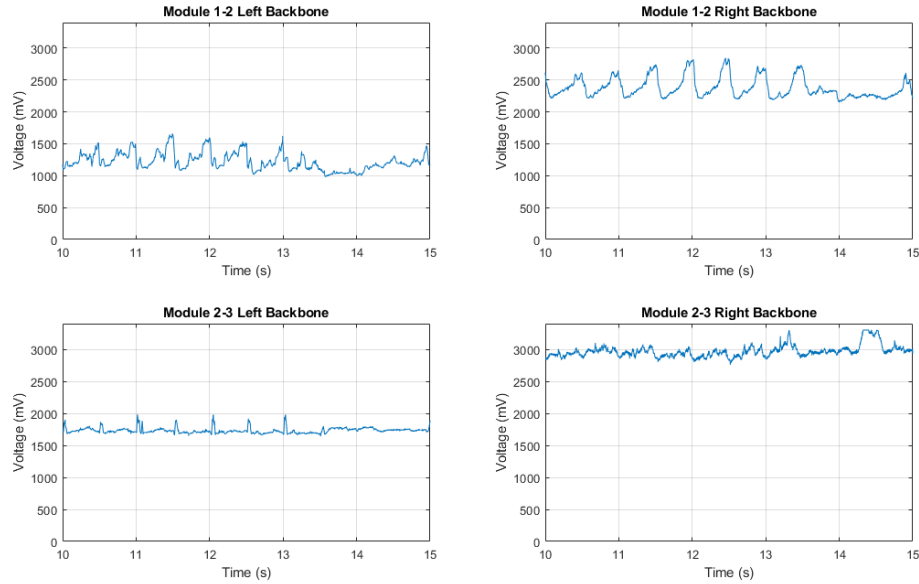
(b)

Figure 3.4: (a) The robot climbing 27mm obstacle, (b) voltage data from the backbones with 1.25mm layer gap

Our goal was to see if the data could be used to discern whether the robot could or could not climb the obstacle. We tested two cases with 27mm obstacles the robot could climb and a 54mm obstacle the robot could not. The initial design of the backbones had a 1.25mm layer thickness and a 1.25mm layer gap with a 10mm backbone thickness or layer height. We have collected data via separate Wheatstone bridge circuits on a breadboard for each sensor, amplifying the signal with a differential amplifier.



(a)



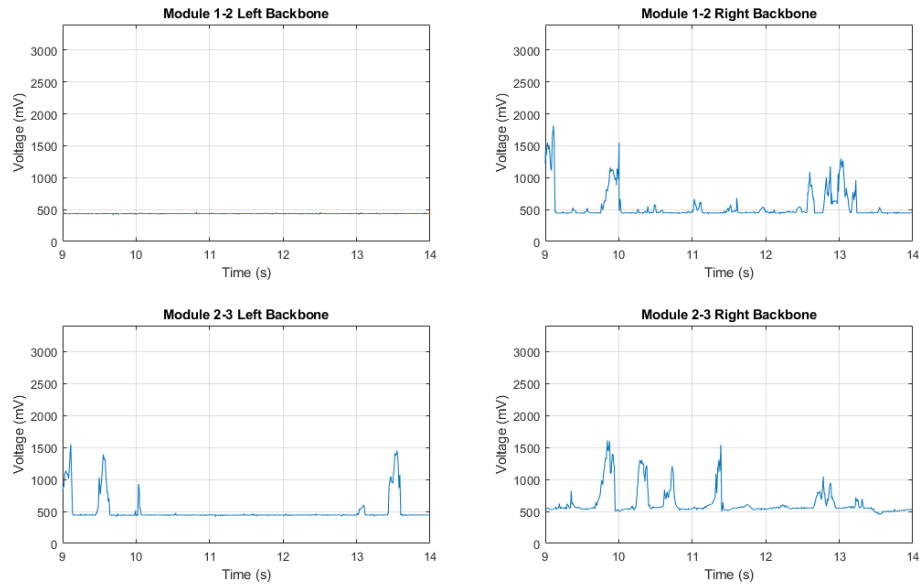
(b)

Figure 3.5: (a) The robot climbing 54mm obstacle, (b) voltage data from the backbones with 1.25mm layer gap

For the 27mm step obstacle, The robot would consistently climb the obstacle; however, as seen in Fig. 3.4, no discernible change in voltage across the backbones was observed despite adjustments in amplification. The backbones were unable to detect the existence of the obstacle. On the other hand, we detected an oscillatory signal for the 54mm obstacle (Fig. 3.5) from the backbones between the first and second modules as the front module of the robot bent backward, collapsing the backbone layers.



(a)



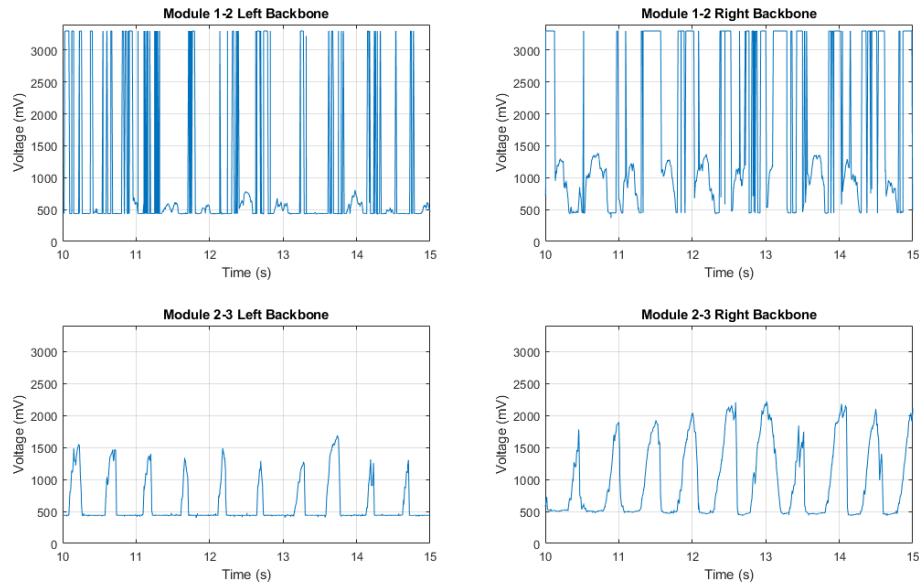
(b)

Figure 3.6: (a) The robot climbing 27mm obstacle, (b) voltage data from the backbones with 0.75mm layer gap

To increase the sensitivity, we decreased the distance between the layers to 0.75mm and repeated the tests for obstacle detection. By just reducing the gap between the layers of the backbones by 0.5mm, we could detect the 27mm step obstacle (Fig. 3.6). While the robot was trying for the 54mm obstacle, oscillation in the voltage was more visible and easier to detect (Fig. 3.7), with data from the first and second modules' backbones saturating at the maximum value.



(a)

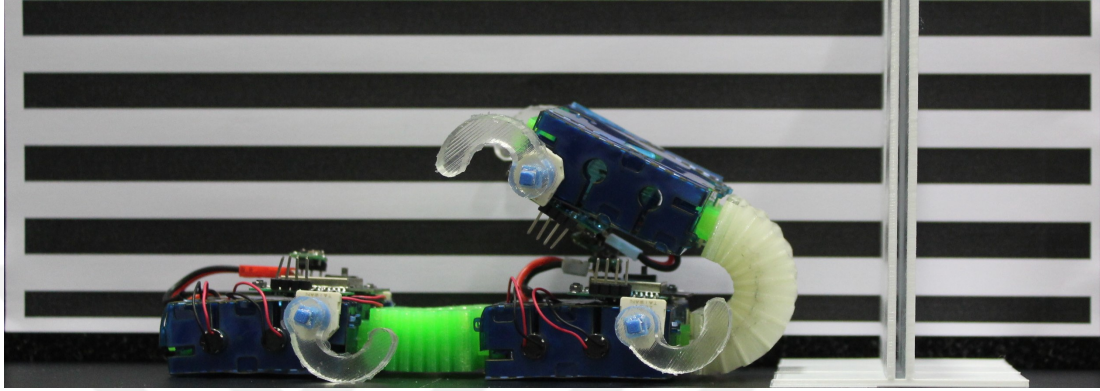


(b)

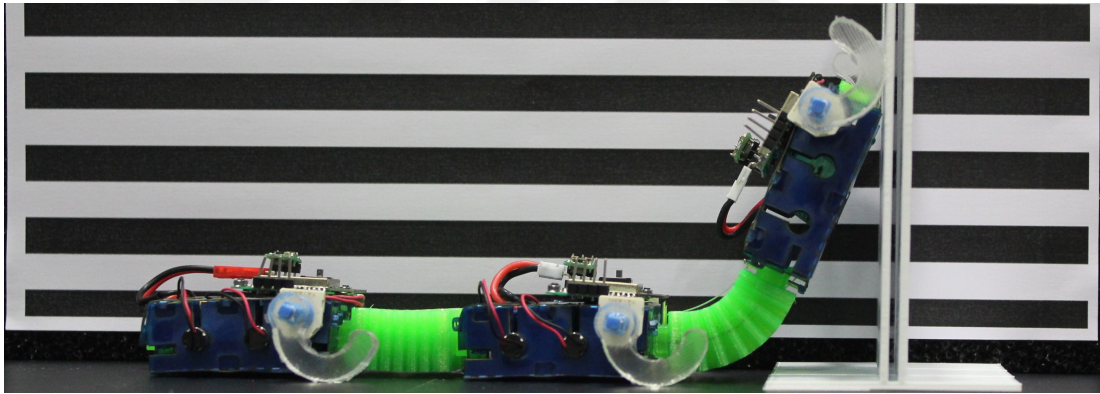
Figure 3.7: (a) The robot climbing 54mm obstacle, (b) voltage data from the backbones with 0.75mm layer gap

The amplitude of the oscillatory data for the 54mm obstacle experiment was roughly two times of the 27mm obstacle experiment. Setting a threshold to differentiate between scalable and unscalable obstacles was possible.

3.1.2 Backbone Design Parameters



(a)



(b)

Figure 3.8: Effect of the nominal backbone compliance: (a) the backbones are unable to support the module's weight, (b) the backbones push the module against obstacles to enhance climbing ability.

When the tendons of the connection mechanisms are inactive, the base stiffness of the backbones determines the robot's motion. Although this base stiffness can be optimized for different tasks, ideally, the robot should have the vertical mobility to bend around obstacles without folding back to 180 degrees to maintain the contact of the C-legs with the surface, as illustrated in Fig. 3.8.

The bending resistance of the backbones can be modified without altering the material by adjusting three dimensions of the repeating backbone pattern: layer thickness, layer height, and the gap between layers (Fig. 3.9). Increasing the layer thickness and height enhances the bending resistance while increasing the gap between layers reduces it.

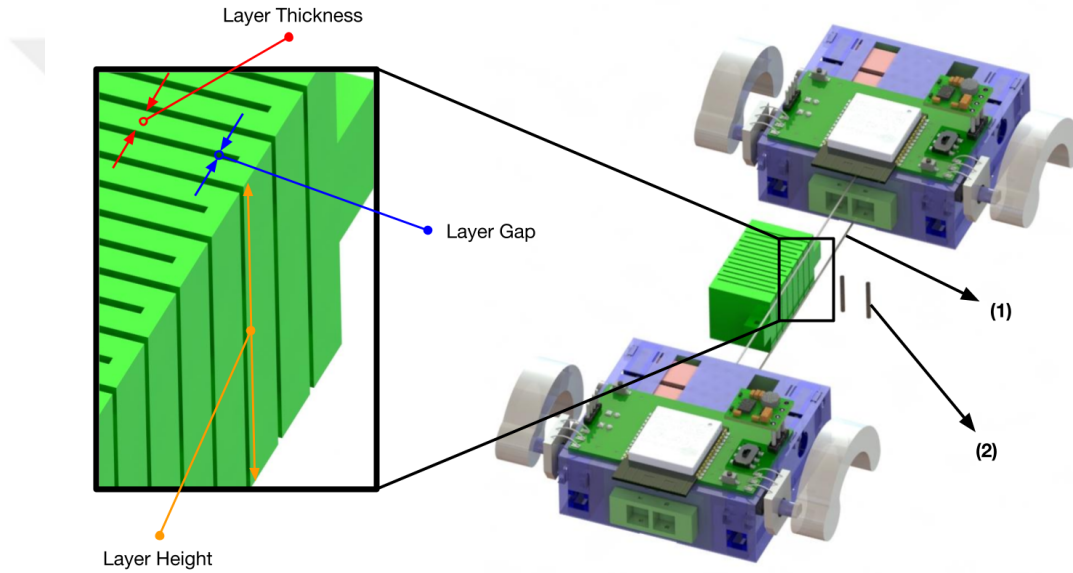


Figure 3.9: Backbone parameters and connection parts numbered as 1) PVDF strings, 2) pins securing connection of backbones to the module.

To get an approximate measure of how each parameter affects the stiffness of the backbones, we printed backbones with different parameters and measured their bending stiffness. We printed seven in total, adjusting a single parameter twice for each backbone parameter (Fig. (3.10)). The first backbone printed had a 15mm layer height, 1.8mm layer thickness, and 0.6mm gap between the layers. The backbones' length and width were kept constant for the following samples. However, we reduced the thickness by 0.6mm, increased the layer gap by 0.6mm, and finally reduced the layer height by 3mm.

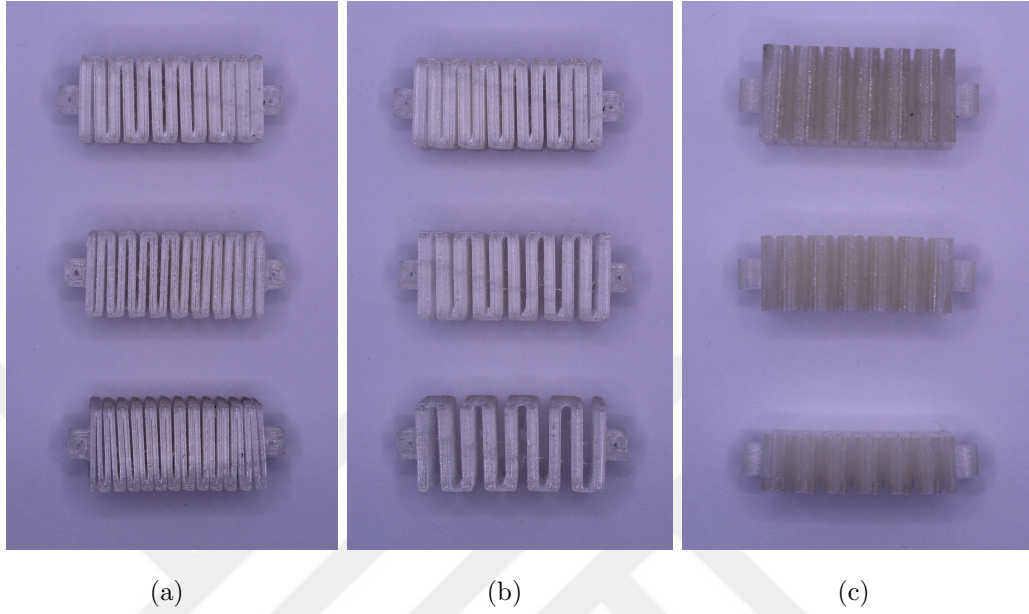


Figure 3.10: Backbone samples with single parameter variation: (a) decreasing layer thickness, (b) increasing gap between the layer, (c) decreasing layer height.

We fixed one end of the backbones and attached loads to the other. We measured the displacement from the free tip's nominal position, repeating to increase the weights for each sample.

The results shown in Fig. 3.11 suggest an approximately linear relation between each parameter and the deflection under the force applied by free-hanging loads. Decreasing the layer thickness is the most effective way to reduce the bending stiffness of the backbone compared to adjusting the other parameters. Increasing the gap between the layers affects the stiffness minimally and thus can be adjusted to vary the backbone dimensions without detrimental changes to the stiffness of the backbone.

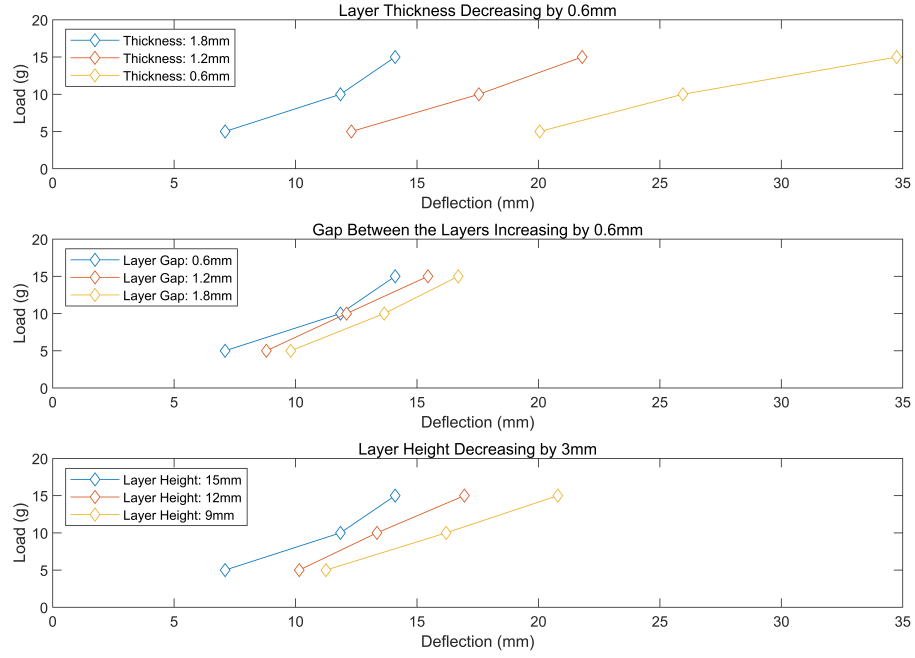


Figure 3.11: Backbone load and deflection results.

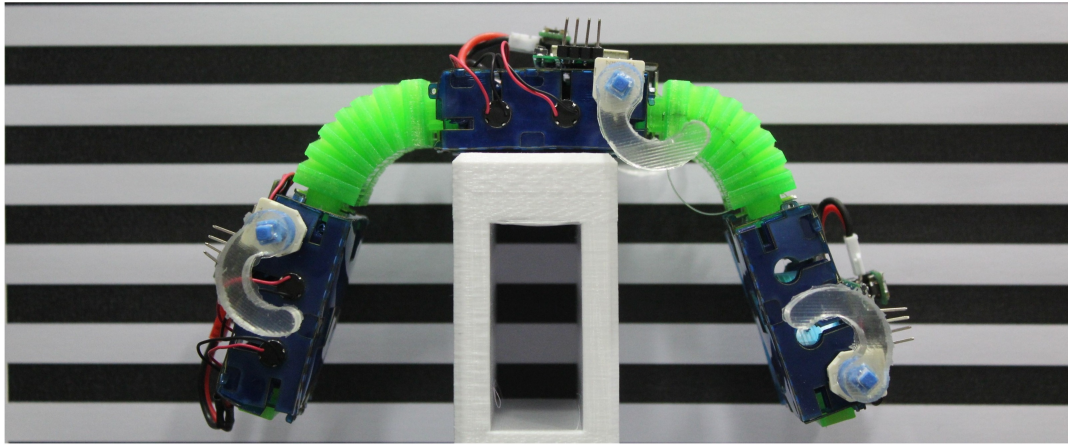
Bending stiffness is calculated at 5g, 10g, and 15g loads, and the results for the calculated average bending stiffness can be found in Table 3.1.

Table 3.1: Bending Stiffness Measurement Results

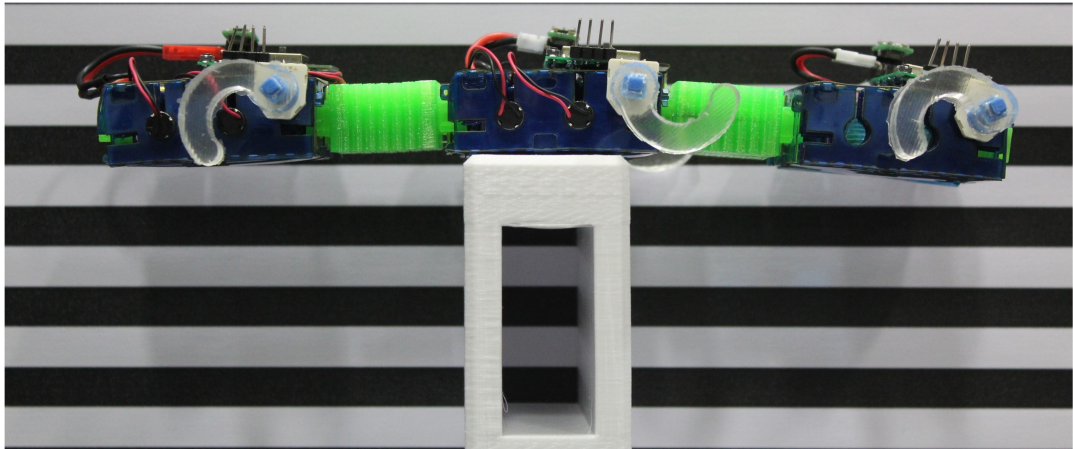
Layer Thickness (mm)	Layer Gap (mm)	Layer Height (mm)	Calculated Bend. Stiffness N/m
1.8	0.6	15	8.53
1.2	0.6	15	5.43
0.6	0.6	15	3.48
1.8	1.2	15	7.72
1.8	1.8	15	6.99
1.8	0.6	12	6.94
1.8	0.6	9	5.82

3.2 Tendon Actuation Mechanism

The tendon-driven mechanism linking the modules operates on the same principles as the antagonistic actuation used to bend soft robotic arms. In our design, tendons pull the modules towards each other, counteracting the compression stress on the backbones that are connected in parallel, as shown in Fig. 3.13.



(a)



(b)

Figure 3.12: (a) Soft configuration, (b) rigid configuration

To enable the robot to switch to rigid mode, the backbone layers must be compressed with enough force to minimize deformation from external forces, the robot’s weight, and ground reaction forces during movement.

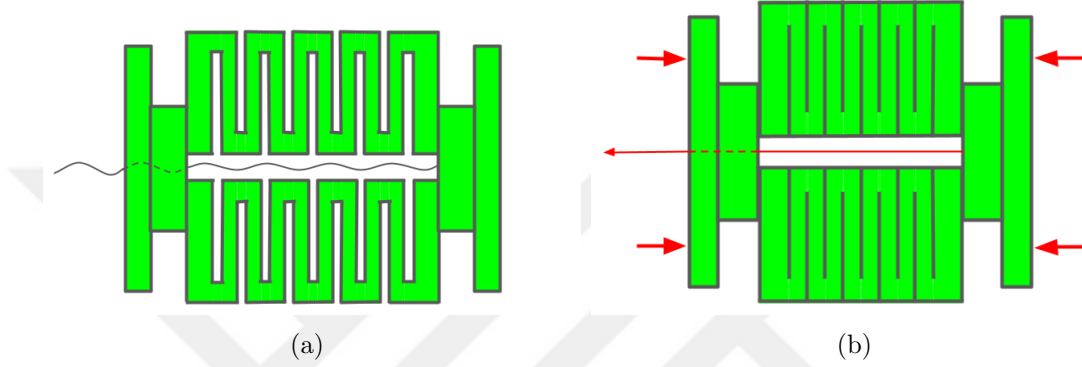


Figure 3.13: (a) Relaxed tendons, layers are free to bend, (b) actuated tendons, layers are compressed

While various linear actuators can accomplish this, several constraints must be considered to keep the robot modular and untethered. The cable-driven linear actuator described in Section 2.3.3 provides sufficient force for the robot’s weight while being powered and controlled using the single battery and the circuit board utilized in SMoLBot-C. As illustrated in Fig. 3.12, the backbones are soft in their nominal state, enabling the robot body to bend and adapt to its surroundings. When the tendons are activated, the compression in the backbone layers maintains the robot’s posture and increases load capacity without causing body deformation.

3.3 Experiments and Case Studies

Two sets of experiments were conducted to evaluate the robot’s performance in both rigid and soft modes while navigating unstructured environments, specifically testing its obstacle-climbing and gap-crossing capabilities. The key factors influencing the robot’s ability to climb higher obstacles and cross wider gaps were, apart from compliance of the backbones, its gait, and the diameter of the C-legs.

The results, expressed as a percentage of body length (%BL) and body height (%BH), are summarized in Table 3.2, with the body height of 45mm, the body length of 215 mm in rigid mode and 223 mm in soft mode.

Table 3.2: Obstacle Climbing and Gap Crossing Performance of SMoLBot-VS

Stiffness Mode	Maximum Step Height	Maximum Gap Length
Rigid	44.3 %BH	48.8 %BL
Soft	66.9 %BH	24.7 %BL

The gap-crossing and obstacle-climbing experiments were performed using two different gaits: the pronk gait, where all six legs move together, and the trot gait, where diagonally opposite legs move together while the others move with a 180-degree phase difference. While the pronk gait is ideal for movement on flat surfaces, it was observed during the obstacle-climbing experiments in soft mode that this gait caused the front module to slide back during the simultaneous non-contact period of the C-legs.

Table 3.3: Success Rate of SMoLBot-VS at Limit Values

Case Studies	Pronk Gait Succ. Rate	Trot Gait Succ. Rate
Soft Mode - 24.7 %BL Gap	20%	90%
Soft Mode - 66.9 %BH Step	40%	90%
Rigid Mode - 48.8 %BL Gap	10%	50%
Rigid Mode - 44.3 %BH Step	80%	40%

Additionally, in the gap-crossing experiments, the success of the pronk gait was highly dependent on the robot’s initial position, as the front module’s legs sometimes failed to contact the opposite side of the gap before falling in, or vice versa. In contrast, the trot gait allowed the robot to maintain constant ground contact during climbing. It eliminated the dependency on initial positioning for gap crossing, as either the left or right leg would always contact the edge of the gap. The success rates for both gaits in the ten experiments conducted at the limit values are presented in Table 3.3.

In the obstacle-climbing experiments, the primary reason for failure with the pronk gait was the legs losing contact with the ground. In contrast, for the trot gait, failures typically occurred when the robot veered left or right before beginning the climb. In the gap-crossing experiments, a similar issue was observed, along with another factor: the robot losing balance after crossing the gap. The trot gait generally resulted in a higher success rate than the pronk gait, except during obstacle climbing in rigid mode.

Larger C-leg diameters improve the success rate for obstacle-climbing and gap-crossing. However, as the diameter increases, so does the legs' weight. At a diameter of 30mm, it becomes challenging for DC motors to rotate the legs at frequencies of 1.5Hz or higher. Therefore, 20mm diameter C-legs were chosen for the experiments.

3.3.1 Obstacle Climbing

A simple step obstacle was prepared to evaluate the robot's vertical mobility, starting with a 5mm step and increasing the height by 5mm increments. Each height was tested in ten trials. It was observed that beyond the limit values shown in Table 3.2, the robot could not overcome the obstacle within the ten trials.

The robot could climb a maximum step height of 20mm in rigid mode. As illustrated in Fig. 3.14(a), at a 25mm step height, the C-legs of the first and third modules barely made contact with the surface during movement, leading to foot slippage due to the robot's unfavorable pitch angle while the middle module completely lost contact, significantly reducing the force needed to push the modules over the step.

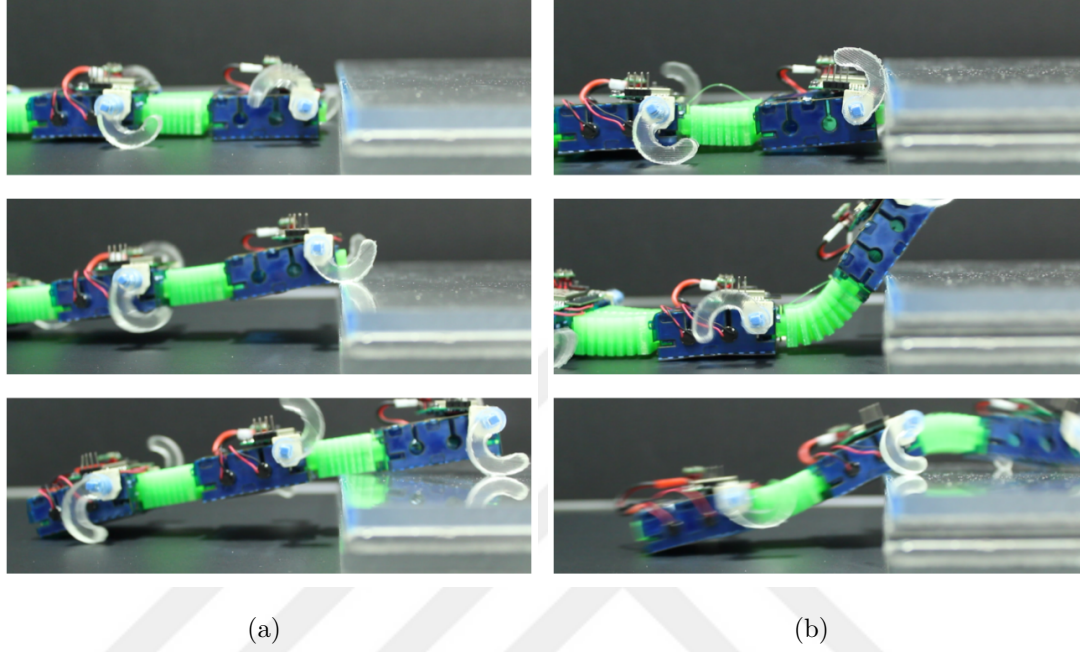


Figure 3.14: Obstacle climbing in (a) rigid mode, (b) and soft mode

In contrast, in soft mode, the bending allowed by the backbones enables the robot to adapt its shape around the step. Upon first contact with the obstacle, the front module bends upward, allowing the C-legs of the following modules to maintain sufficient ground contact (Fig. 3.14(b)). After the first module reaches the top of the step, the subsequent modules continue to bend around the step to maintain motion. In this soft mode, three-module configuration, the robot can reliably climb obstacles up to 30mm in height.

3.3.2 Gap Crossing

The second set of experiments evaluated the robot's ability to cross gaps. Starting with a 50mm gap, roughly equivalent to the length of a single module, the process was repeated with a 5mm increase in gap length each time until the robot could no longer cross it. The maximum gap lengths crossed in both rigid and soft modes are shown in Table 3.2.

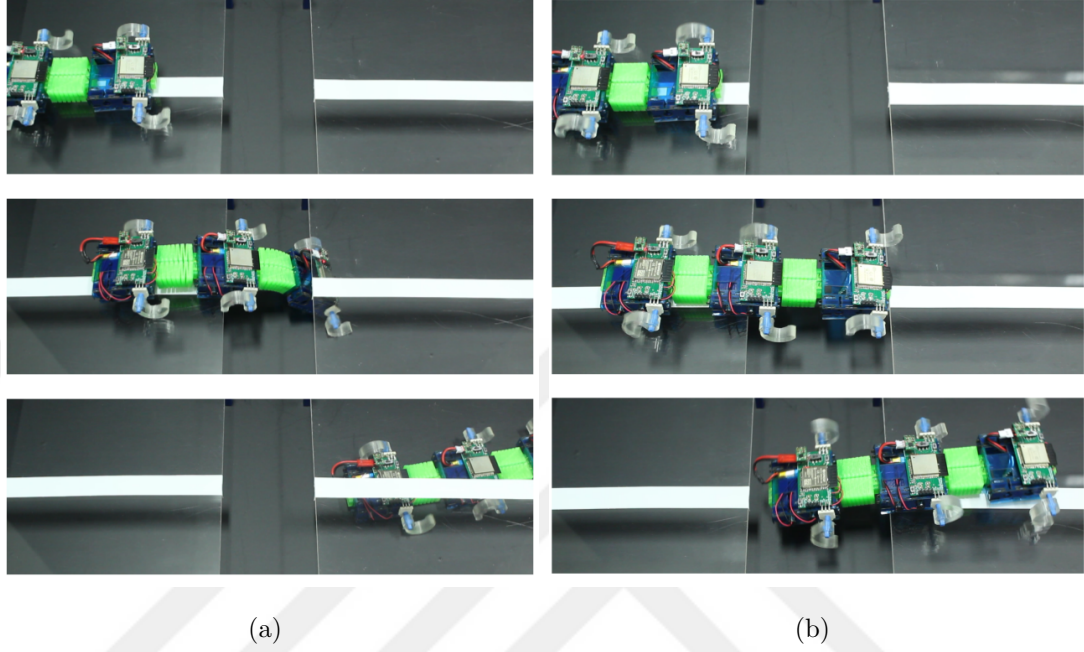


Figure 3.15: Gap crossing in (a) soft mode, (b) and rigid mode

In soft mode, the robot can cross a gap of up to 55mm, which aligns with expectations, as the combined maximum length of a module with the C-leg is 55mm. At greater gap lengths, the front module bends before reaching the opposite side, as shown in Fig. 3.15(a), causing the robot to slide into the gap and continue its motion. In contrast, the robot maintains its posture in rigid mode, keeping a straight configuration after leaving the edge until its center of gravity passes beyond the edge, as seen in Fig. 3.15(b). This enables the robot to consistently cross gaps up to 105mm in length until its center of gravity is no longer supported by the edge.

3.3.3 Results and Discussion

In this study, we examined how backbone compliance impacts the locomotion of our robot, SMoLBot-VS, when navigating rough terrain. We explored the benefits of adjusting backbone stiffness between fully rigid and soft modes by testing the robot’s performance in obstacle-climbing and gap-crossing scenarios.

By incorporating a variable stiffness backbone mechanism with tendon-driven actuation, we could alter the robot’s compliance by applying stress to its naturally soft backbones using a 3D-printed linear actuator powered by sub-micro DC motors.

In our experiments to evaluate the effectiveness of the rigid and soft modes, parameters related to the robot’s gait and C-legs were kept constant. The trot gait used in the experiments enhanced the robot’s performance in both obstacle climbing and gap crossing, in both rigid and soft configurations, by providing better ground contact than the alternative pronk gait. Likewise, the diameter of the C-legs positively influenced performance, although it was limited by the power needed for rotation.

The results of our experiments with SMoLBot-VS demonstrated that the robot’s soft configuration is better suited for obstacle climbing than its rigid mode. In rigid mode, the C-legs tend to lose ground contact, restricting the climbing threshold to 20mm. However, the soft backbones enable the robot’s modules to bend relative to each other around the obstacle, maintaining ground contact for the C-legs, which allows the robot to climb the barriers up to 30mm high.

Gap-crossing experiments revealed that in rigid mode, the robot can maintain a straight posture longer than in soft mode, enabling it to cross a maximum gap of 105mm, compared to 55mm in soft mode. The experiments also demonstrated that switching between the two modes allows the robot to enter or cross openings and selectively enhances its performance in climbing obstacles or traversing gaps.

Chapter 4

Backbone Sensing and Control

4.1 Controller Design

The experiments with the variable stiffness mechanism for obstacle climbing and gap crossing were conducted for two extremes achievable with the mechanism: rigid and soft modes. Additionally, the switch between the two modes required human interference between tasks. Therefore, we decided to develop a controller for the variable stiffness mechanism to change stiffness on the command during the robot's operation and be able to set the stiffness to intermediate values to enhance adaptability to different situations.

4.1.1 Backbone Design Adjustments

Using conductive TPU filament for 3D printing, the backbones allow us to utilize them as a sensing element and a structural component of the actuator. When layers contact each other, the current path gets shorter, resulting in a drop in resistance. However, for the regular backbones with constant layer thickness and layer gap, layers collapse simultaneously, resulting in a sharp decline in resistance followed by a slight decrease with increasing pressure on the layers.

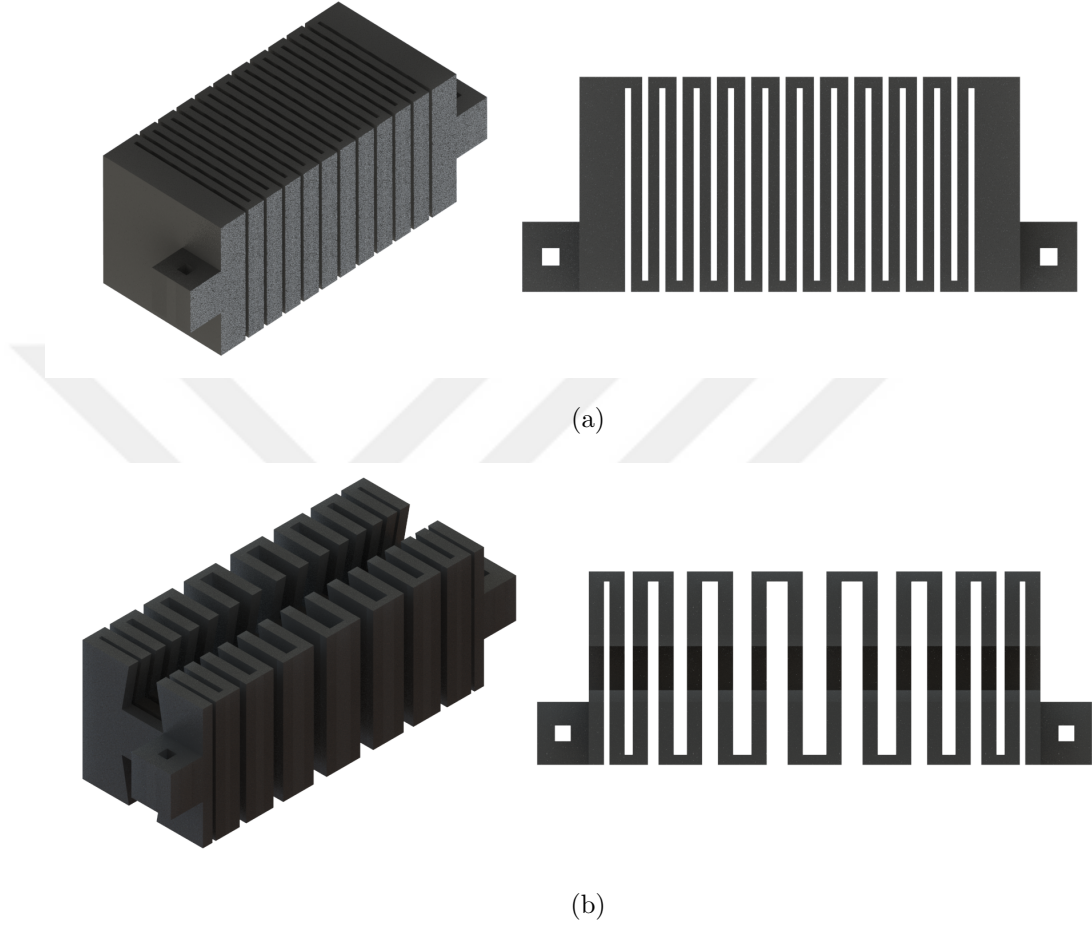


Figure 4.1: (a) Constant pitch design, (b) variable pitch design.

We altered the backbone design to have a linear decrease in resistance during the collapsing, so we increased the layer gap with each layer toward the center. The comparison between the constant and variable pitch can be observed in Fig. 4.2. The gap between the layers for variable pitch design starts at 0.2mm at the edges and increases by 0.2mm towards the center. Some part of the middle section was removed from the backbone to increase the resistance and meet the circuit requirements.

4.1.2 Data Acquisition

We use a Wheat stone bridge to detect the change in backbone resistance and amplify the signal with a differential amplifier circuit. The amplifier output is connected to an analog reading pin on ESP32. For the Wheatstone bridge shown in Fig. 4.2(a), R2 and R3 resistors are low and equal value usually chosen to be $1k\Omega$. The nominal resistance RS for design presented in Fig. 4.1(b) is $38k\Omega$. The fabrication with an FDM printer does not produce consistent results regarding backbone resistance due to imperfections. The nominal resistance for the same design parameters varies roughly in the order of 5-10%. Additionally, the curing process for the resistors after printing continues, and nominal resistance changes over time.

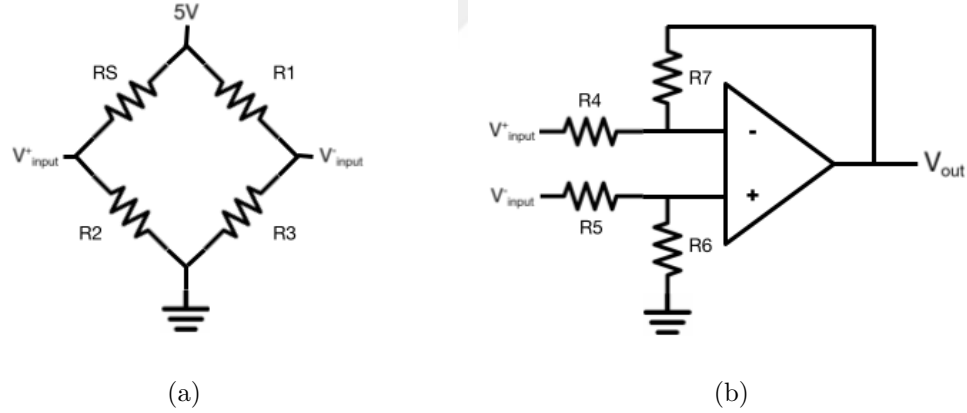


Figure 4.2: (a) Wheatstone bridge, (b) differential amplifier.

The resistor R1 is chosen to be either equal or slightly greater in value compared to the nominal resistance of the backbone to keep the difference between input voltages in the positive range so that the ESP32 can constantly measure the voltage difference. We can adjust the amplification level in the differential amplifier circuit as shown in Fig. 4.2(b) by changing the ratio of the resistors relative to each other.

$$Gain = \frac{R7 = R6}{R4 = R3} \quad (4.1)$$

An important thing to remember while adjusting the resistor values is that the Wheatstone bridge affects the differential amplifier circuit. Thevenin-equivalents of the Wheatstone bridge resistance are added to the R4 and R3 resistor values. Thus, when the resistance of the sensor changes, it can also affect the amplification. To reduce the effect to a minimum, values of the resistors to adjust gain are kept an order of magnitude high compared to Wheatstone bridge resistance values. The gain is adjusted to avoid saturation before the complete collapse of the backbone layers.

4.1.3 Proportional-Integral Controller

Using the voltage readings from the backbones, we designed and implemented a proportional-integral (PI) controller for the ESP32 to control the variable stiffness mechanism. We collect data from the two backbones with two separate Wheatstone bridges and differential amplifier circuits via the ESP32 analog to the digital converter. For each backbone, the ESP32 collects 100 voltage measurements over 1 ms and uses the average as feedback at each step of the controller loop. This provides smoother data for the controller and prevents bias towards the left or right side backbone.

In each loop iteration, the controller compares the data with the desired voltage level input and outputs the duty cycle for the motor driver connected to the cable-driven linear actuator. If the calculated output of the controller is negative, an if condition is checked to reverse the direction of the DC motors. We started developing the controller with just a proportional term:

$$P = K_P * (V_i^{Desired} - V_i^{measured}) \quad (4.2)$$

$$Duty\ Cycle = |P| \quad (4.3)$$

The $K_P = 0.50$ results are shown in Fig. 4.3 as follows:

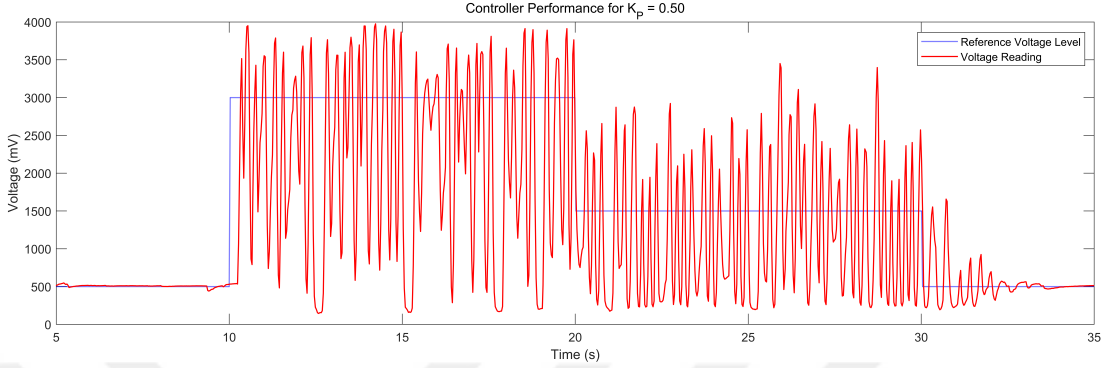


Figure 4.3: Controller performance at $K_P = 0.50$.

At $K_P = 0.50$, the controller reacted too strongly to the small errors, either overshooting or undershooting the target voltage level, resulting in back-and-forth oscillation of the variable stiffness mechanism. We dropped K_P to 0.25 and later 0.10 to increase stability.

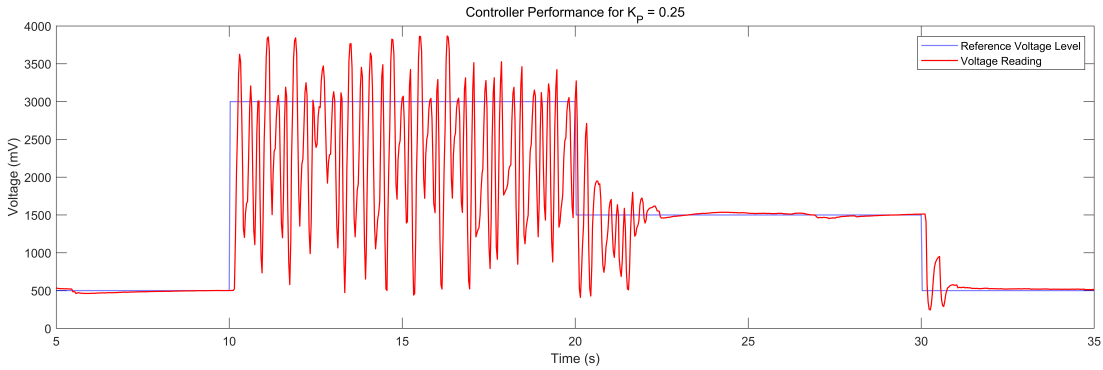


Figure 4.4: Controller performance at $K_P = 0.25$.

$K_P = 0.25$, the controller performance was acceptable for certain voltage ranges, but the controller failed to settle to other thresholds, as seen from Fig. 4.4. The main reason was that errors drastically changed with small inputs when layers contacted each other, which often happened at high voltage reference levels. Therefore, we dropped the proportional constant further down to 0.1.

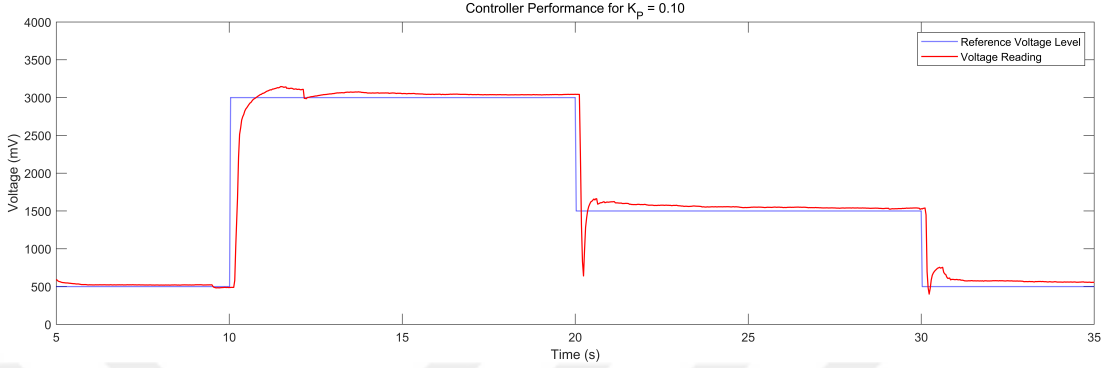


Figure 4.5: Controller performance at $K_P = 0.10$.

Reducing the proportional constant further solved the instability problem. Still, we observed that settling to the desired level within the 10mV error range was impossible as the controller's PWM output was too small to register the action of the variable stiffness mechanism. Therefore, we decided to add an integral term to the controller:

$$I = K_I * \sum_1^i (V_i^{Desired} - V_i^{measured}) * (t_i - t_{i-1}) \quad (4.4)$$

$$Duty\ Cycle = |P + I| \quad (4.5)$$

Where $t_i - t_{i-1}$ is the time elapsed between two iterations of the controller loop. An if condition to set an upper and lower limit for the error summation was implemented to prevent excessive error accumulation. The initial limit was set to 1000 mV. Without the limit implementation, abrupt and instantaneous changes in the desired voltage level would result in excessive instability, making it impossible for the controller to reach the desired level within 10 seconds. Still, even with the addition of the limit, oscillations were present albeit in lower amplitude, as seen in Fig. 4.6.

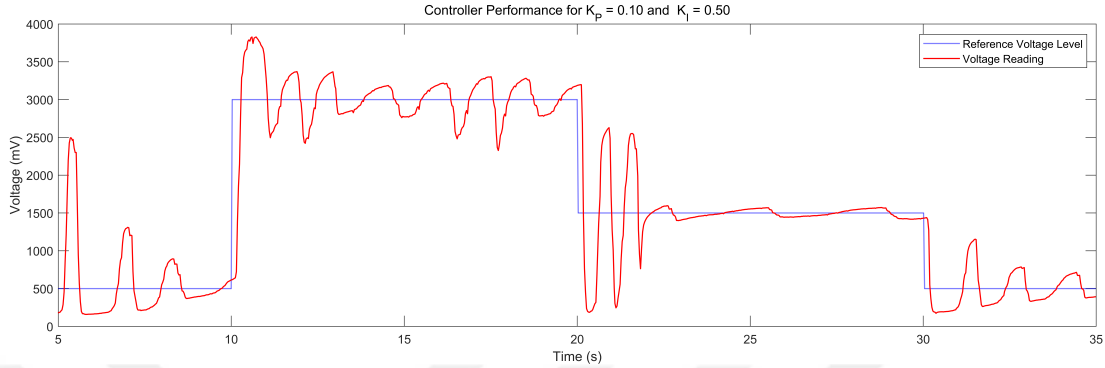


Figure 4.6: Controller performance at $K_P = 0.10$ and $K_I = 0.50$.

Like the proportional constant, The integral constant was reduced to 0.25 and 0.10 afterward. With the reduction of the integral term constant, there was a significant decrease in the amplitude of the oscillations. The final adjustments for the controller were made for the integral limit to decrease the overshoot and undershoot that occurred with an abrupt change of reference voltage level.

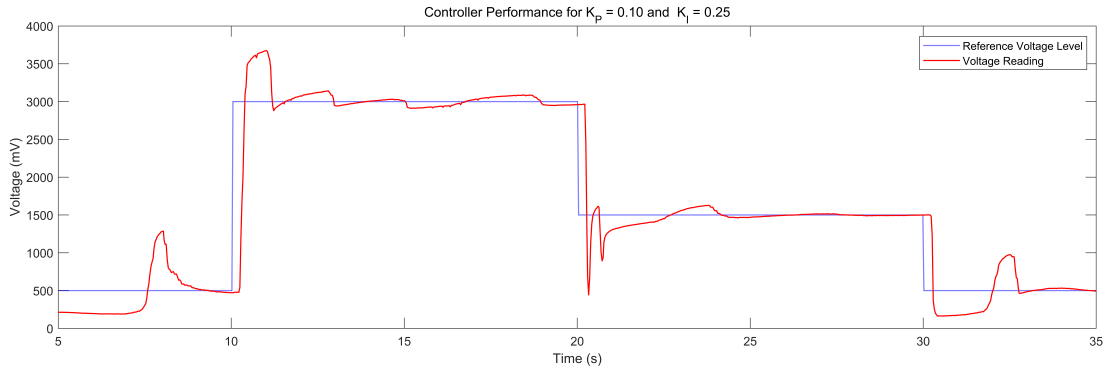


Figure 4.7: Controller performance at $K_P = 0.10$ and $K_I = 0.25$.

The integral limit was reduced to 500 mV and 50 mV. The data collection was repeated to make comparisons between the controller performance.

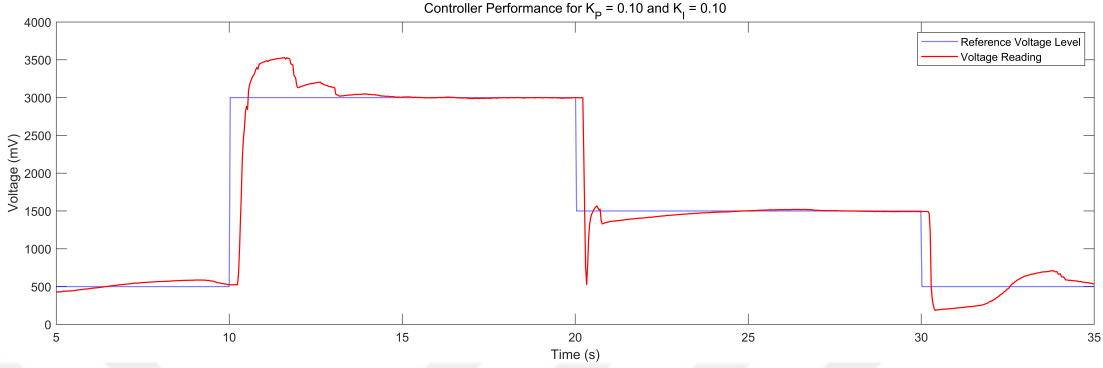


Figure 4.8: Controller performance at $K_P = 0.10$ and $K_I = 0.10$.

The overshoot was minimized to an acceptable level, with the integral limit set to 50 mV. However, no improvement was observed for the undershoot. When the cable-driven linear actuator starts compressing the layer, the resistance drops slowly with increasing pressure, even with all layers in contact.

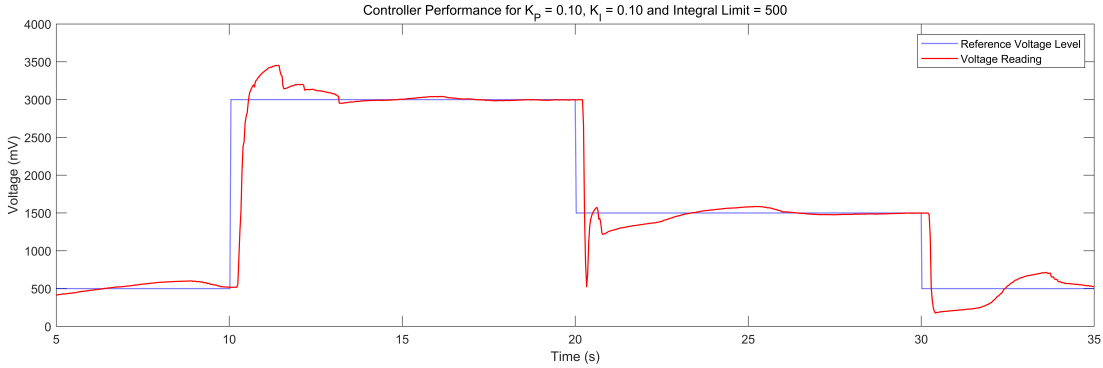


Figure 4.9: Controller performance at $K_P = 0.10$ and $K_I = 0.10$, integral limit = 500.

However, when the tendons are released, the increase in resistance occurs instantaneously, with the layers losing contact, which makes it harder for the actuator to compensate.

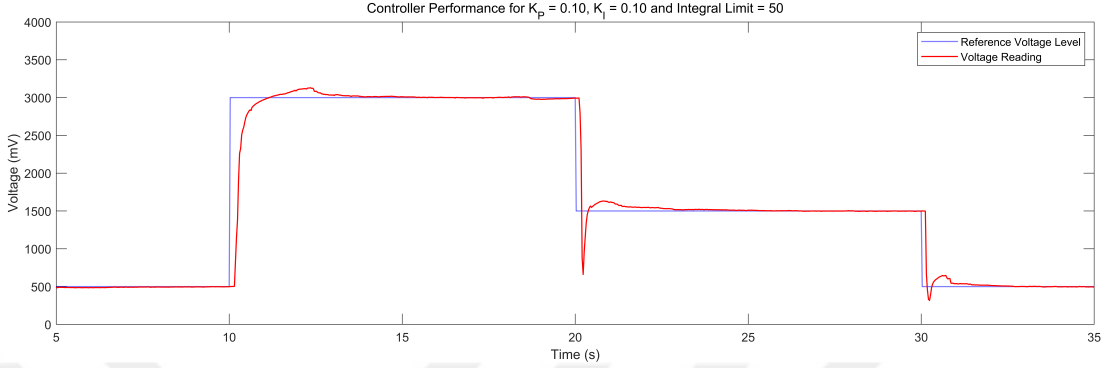


Figure 4.10: Controller performance at $K_P = 0.10$ and $K_I = 0.10$, integral limit = 50.

4.2 Test Setup and Experiments

To derive the relation between the voltage level measured by the backbones and the stiffness of the backbones, we connected the variable stiffness mechanism to a force measurement setup shown in Fig. 4.11.

The load cell is connected to the tip of the variable stiffness mechanism with a PVDF string to measure the tension when the linear actuator driven by a stepper motor moves the load cell in the Z axis. The force is measured by the load cell, amplified, and data is transferred to the computer via a data acquisition device. The displacement is provided as input to the stepper motor.

In this setup, we set the input voltage level with the PI controller we developed and measured the stiffness by setting an increasing displacement at 0.5mm increments. We started the measurements at 200mV and repeated the process at increasing increments of 200mV. During the measuring process, the controller was inactive to prevent interference with the force measurement.

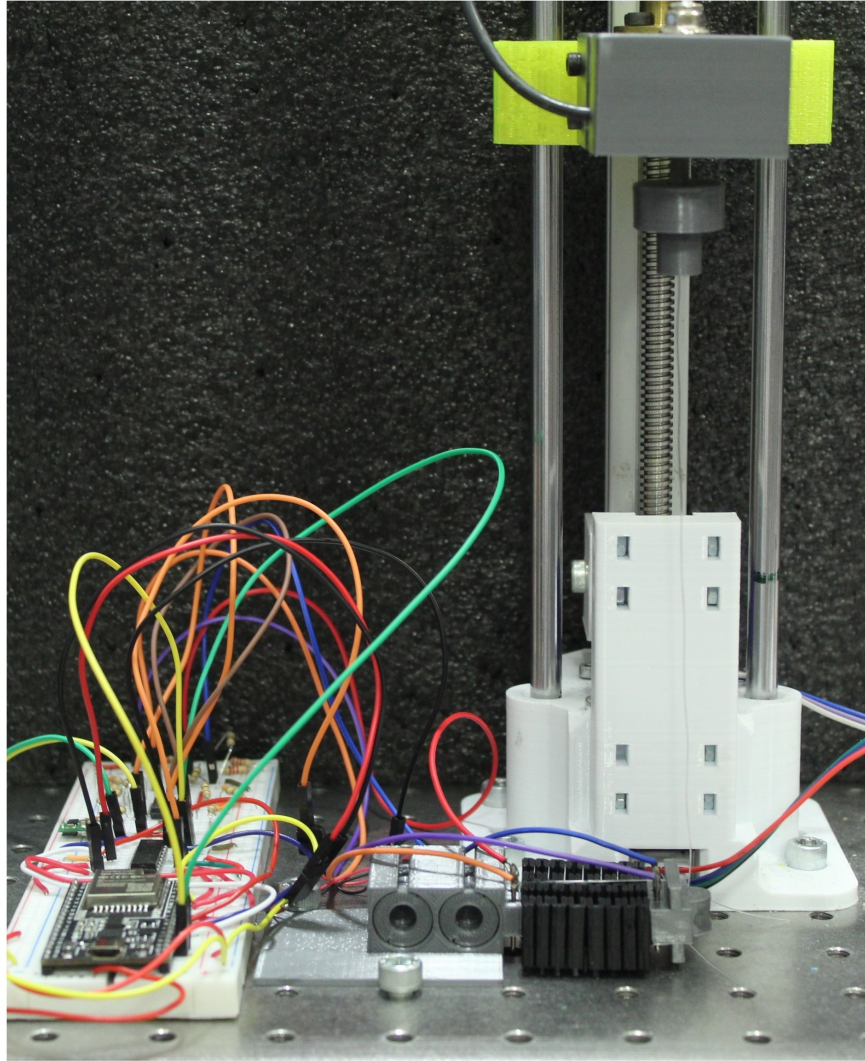


Figure 4.11: Stiffness measurement test setup.

We can observe the overall variation in the stiffness with the increasing voltage input by examining the stiffness values presented in Fig. 4.12, which are calculated by taking the average values of stiffness at every deflection point. Although a direct linear relation between the input voltage level and effective bending stiffness is absent, we observed a positive relation consistent with our expectations of up to 2400mV input voltage.

Above that threshold, even though the resistance of the backbones continues to decrease with increasing pressure from the actuator, stiffness remains the same, as can be seen from Fig. 4.13.

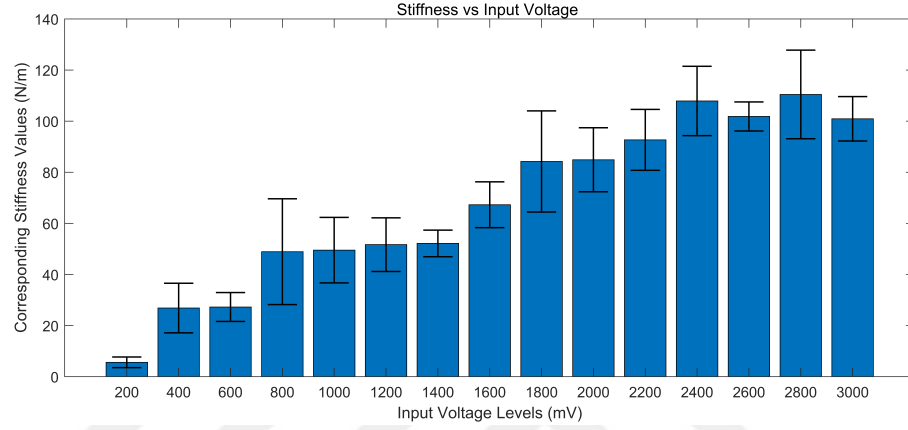


Figure 4.12: Mean stiffness values calculated at different input voltage levels shown with standard deviation.

Additionally, for small deflections up to 2mm, the variable stiffness mechanism makes little difference in bending stiffness, as seen in Fig. 4.14.

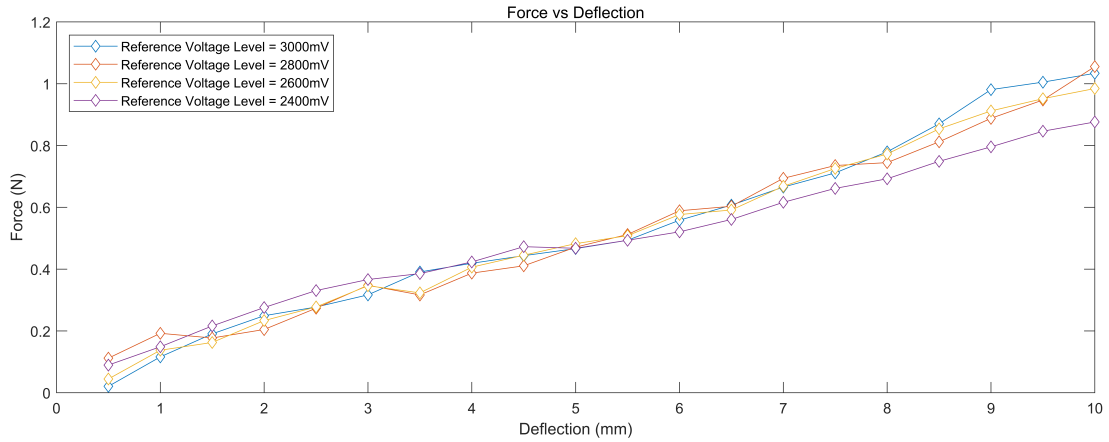


Figure 4.13: Force vs deflection results for 2400mV-3000mV range.

For the same deflection values, the variation of the generated force between the 1000mV, 2000mV, and 3000mV input voltage levels is less than 0.05N. At higher deflection of the backbones, the effect of the mechanism becomes increasingly clear.

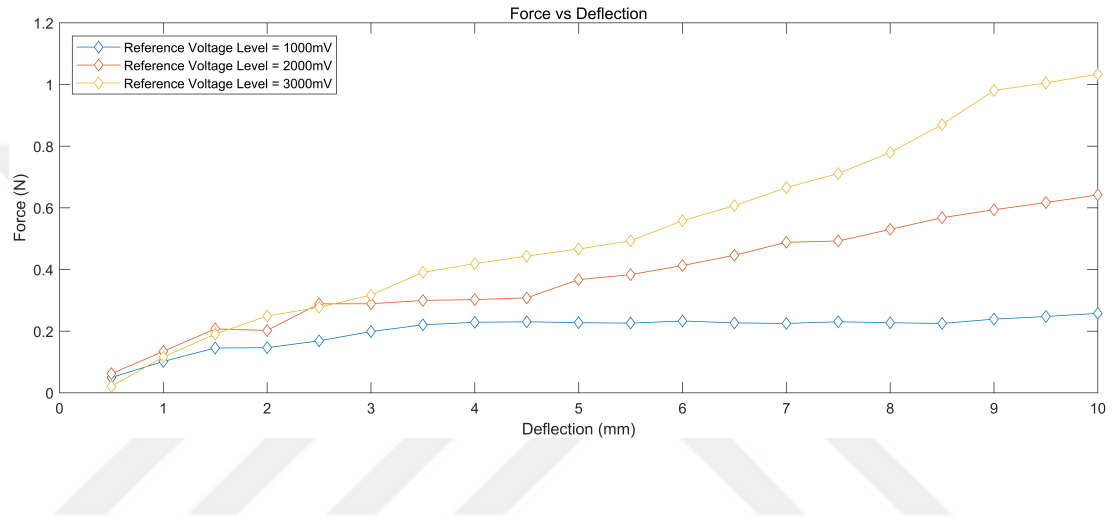


Figure 4.14: Force vs deflection results for 1000mV, 2000mV and 3000mV input voltage levels.

Chapter 5

Conclusion and Future Works

This thesis presents a comprehensive study of the design control and testing of SMoLBot-VS, a modular miniature soft robot with a variable stiffness mechanism capable of modulating the compliance between the modules by a cable-driven linear actuator. Implementing the variable stiffness mechanism to a mobile robot provides an advantage over rigid and soft robots by allowing adaptation to different types of challenging terrain with stiffness modulation.

The module design of the robot allows rapid fabrication and assembly using kirigami-inspired body design and 3D-printed body components. While the materials utilized for manufacturing the robot are cheap, they introduce a limited level of compliance to the body structure, increasing the robot's durability. The control of the C-legs, the main actuator for the SMoLBot's motion, and the variable stiffness mechanism added for SMoLBot-VS are integrated into the same circuit, enabling easy control and communication with a single microcontroller. The backbone design allows adjustment of the base level of compliance between the modules by changing one of the three dimensions, making redesigning for different implementations relatively quick.

Throughout the development of SMoLBot-VS components of the variable stiffness mechanism, the linear actuator, and the backbones are iteratively improved to account for sensing capabilities and terrain handling. Compared to other executions of stiffness modulation in mobile robots, which require complex mechanisms with increased weight, power consumption, and performance limitations, the linear actuation scheme is seamlessly implemented into SMoLBot-VS with minimal change in dimension and weight of the robot. Case studies regarding the robot’s performance in terms of operational capability and environmental sensing are conducted to optimize the design of the backbones and test how the design parameters affect sensibility and stiffness. The advantages of the variable stiffness mechanism for a mobile robot are observed with a series of obstacle-climbing and gap-crossing experiments.

Finally, a stiffness controller for the variable stiffness mechanism is implemented, enabling the robot to adjust the compliance between the modules to intermediate levels using voltage feedback from the backbones that highlight an additional application of soft sensors in mobile robots. We validated a positive relation between the input voltage adjustment of the controller and the actual stiffness measurements through cyclic load tests by obtaining force and displacement measurements at different input voltage levels of the controller.

We plan to further enhance the capabilities of the SMoLBot-VS by adjusting the design of the backbones/sensors to allow active direction control in the backbones. With dual-material 3D printing, we can measure the voltage from the backbones’ upper and lower parts separately, providing data about which direction the modules are bending. Based on the voltage level we can adjust the relative angle between the modules by using an estimation from the voltage measurements. Controlling the posture of the longer chain of modules can be utilized to grab onto objects for target recovery tasks.

Bibliography

- [1] A. T. Baisch, O. Ozcan, B. Goldberg, D. Ithier, and R. J. Wood, “High speed locomotion for a quadrupedal microrobot,” *The International Journal of Robotics Research*, vol. 33, no. 8, pp. 1063–1082, 2014.
- [2] S. A. Rios, A. J. Fleming, and Y. K. Yong, “Miniature resonant ambulatory robot,” *IEEE Robotics and Automation Letters*, vol. 2, no. 1, pp. 337–343, 2017.
- [3] P. Birkmeyer, K. Peterson, and R. S. Fearing, “Dash: A dynamic 16g hexapedal robot,” in *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 2683–2689, 2009.
- [4] Z. Patterson, D. Patel, S. Bergbreiter, L. Yao, and C. Majidi, “A method for 3d printing and rapid prototyping of fieldable untethered soft robots,” *Soft Robotics*, vol. 10, 07 2022.
- [5] D. Rus and M. Tolley, “Design, fabrication and control of origami robots,” *Nature Reviews Materials*, vol. 3, p. 1, 05 2018.
- [6] J. Zhao, W. Yan, N. Xi, M. W. Mutka, and L. Xiao, “A miniature 25 grams running and jumping robot,” in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 5115–5120, 2014.
- [7] A. Sirken, G. Knizhnik, J. McWilliams, and S. Bergbreiter, “Bridge risk investigation diagnostic grouped exploratory (bridge) bot,” in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 6526–6532, 2017.

- [8] K. A. Daltorio, T. E. Wei, A. D. Horchler, L. Southard, G. D. Wile, R. D. Quinn, S. N. Gorb, and R. E. Ritzmann, “Mini-whegs tm climbs steep surfaces using insect-inspired attachment mechanisms,” *The International Journal of Robotics Research*, vol. 28, no. 2, pp. 285–302, 2009.
- [9] S. Yi, Z. Temel, and K. Sycara, “Puzzlebots: Physical coupling of robot swarms,” in *2021 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 8742–8748, 2021.
- [10] J. W. Romanishin, K. Gilpin, and D. Rus, “M-blocks: Momentum-driven, magnetic modular robots,” in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 4288–4295, 2013.
- [11] S. Kim, C. Laschi, and B. Trimmer, “Soft robotics: A bioinspired evolution in robotics,” *Trends in biotechnology*, vol. 31, 04 2013.
- [12] Y. Sun, A. Abudula, H. Yang, S.-S. Chiang, Z. Wan, S. Ozel, R. Hall, E. Skorina, M. Luo, and C. D. Onal, “Soft mobile robots: a review of soft robotic locomotion modes,” *Current Robotics Reports*, pp. 1–27, 2021.
- [13] J. Tao, S. Huang, and Y. Tang, “Sbor: a minimalistic soft self-burrowing-out robot inspired by razor clams,” *Bioinspiration Biomimetics*, vol. 15, 04 2020.
- [14] S. Rozen-Levy, W. Messner, and B. Trimmer, “The design and development of branch bot: a branch-crawling, caterpillar-inspired, soft robot,” *The International Journal of Robotics Research*, vol. 40, p. 027836491984635, 05 2019.
- [15] Y. Ozkan-Aydin, B. Chong, E. Aydin, and D. I. Goldman, “A systematic approach to creating terrain-capable hybrid soft/hard myriapod robots,” in *2020 3rd IEEE International Conference on Soft Robotics (RoboSoft)*, pp. 156–163, 2020.
- [16] K. Jayaram and R. Full, “Cockroaches traverse crevices, crawl rapidly in confined spaces, and inspire a soft, legged robot,” *Proceedings of the National Academy of Sciences of the United States of America*, vol. 113, 02 2016.

- [17] A. M. Hoover, E. Steltz, and R. S. Fearing, “Roach: An autonomous 2.4g crawling hexapod robot,” in *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 26–33, 2008.
- [18] Z. Wan, Y. Sun, Y. Qin, E. Skorina, R. Gasoto, M. Luo, J. Fu, and C. Onal, “Design, analysis, and real-time simulation of a 3d soft robotic snake,” *Soft Robotics*, vol. 10, 08 2022.
- [19] C. Branyan, C. Fleming, J. Remaley, A. Kothari, K. Tumer, R. L. Hatton, and Y. Mengüç, “Soft snake robots: Mechanical design and geometric gait implementation,” in *2017 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, pp. 282–289, 2017.
- [20] M. Manti, V. Cacucciolo, and M. Cianchetti, “Stiffening in soft robotics: A review of the state of the art,” *IEEE Robotics Automation Magazine*, vol. 23, no. 3, pp. 93–106, 2016.
- [21] F. Stella, J. Hughes, D. Rus, and C. Della Santina, “Prescribing cartesian stiffness of soft robots by co-optimization of shape and segment-level stiffness,” *Soft Robotics*, vol. 10, 01 2023.
- [22] D. Bruder, M. A. Graule, C. B. Teeple, and R. J. Wood, “Increasing the payload capacity of soft robot arms by localized stiffening,” *Science Robotics*, vol. 8, no. 81, p. eadf9001, 2023.
- [23] A. Stilli, H. Wurdemann, and K. Althoefer, “Shrinkable, stiffness-controllable soft manipulator based on a bio-inspired antagonistic actuation principle,” pp. 2476–2481, 09 2014.
- [24] S. Jadhav, M. Majit, B. Shih, J. Schulze, and M. Tolley, “Variable stiffness devices using fiber jamming for application in soft robotics and wearable haptics,” *Soft Robotics*, vol. 9, 02 2021.
- [25] E. Lerner, H. Zhang, and J. Zhao, “Design and experimentation of a variable stiffness bistable gripper,” in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 9925–9931, 2020.

- [26] R. Van Ham, T. Sugar, B. Vanderborght, K. Hollander, and D. Lefeber, “Compliant actuator designs,” *Robotics Automation Magazine, IEEE*, vol. 16, pp. 81 – 94, 10 2009.
- [27] N. G. Tsagarakis, I. Sardellitti, and D. G. Caldwell, “A new variable stiffness actuator (compact-vsa): Design and modelling,” in *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 378–383, 2011.
- [28] H. vu, H. Hauser, D. Leach, and R. Pfeifer, “A variable stiffness mechanism for improving energy efficiency of a planar single-legged hopping robot,” 01 2014.
- [29] F. Petit, M. Chalon, W. Friedl, M. Grebenstein, A. Albu-Schäffer, and G. Hirzinger, “Bidirectional antagonistic variable stiffness actuation: Analysis, design implementation,” in *2010 IEEE International Conference on Robotics and Automation*, pp. 4189–4196, 2010.
- [30] C. Yigit, E. Bayraktar, and P. Boyraz, “Low-cost variable stiffness joint design using translational variable radius pulleys,” *Mechanism and Machine Theory*, vol. 130, pp. 203–219, 09 2018.
- [31] D. Zhang, H. Yuan, and Z. Cao, “Environmental adaptive control of a snake-like robot with variable stiffness actuators,” *IEEE/CAA Journal of Automatica Sinica*, vol. 7, no. 3, pp. 745–751, 2020.
- [32] K. Galloway, J. Clark, and D. Koditschek, “Variable stiffness legs for robust, efficient, and stable dynamic running,” *Journal of Mechanisms and Robotics*, vol. 5, 01 2013.
- [33] J. Buckley, N. Chikere, and Y. Ozkan-Aydin, “The effect of tail stiffness on a sprawling quadruped locomotion,” *Frontiers in Robotics and AI*, vol. 10, 2023.
- [34] Z. Chen, B. Tighe, and J. Zhao, “Origami-inspired modules enable a re-configurable robot with programmable shapes and motions,” *IEEE/ASME Transactions on Mechatronics*, vol. 27, no. 4, pp. 2016–2025, 2022.

- [35] L. Labazanova, S. Peng, L. Qiu, H.-Y. Lee, T. Nanayakkara, and D. Navarro-Alarcon, “Self-reconfigurable soft-rigid mobile agent with variable stiffness and adaptive morphology,” 2022.
- [36] N. Mahkam, T. B. Yılmaz, and O. Özcan, “Smooth and inclined surface locomotion and obstacle scaling of a c-legged miniature modular robot,” in *2021 IEEE 4th International Conference on Soft Robotics (RoboSoft)*, pp. 9–14, 2021.
- [37] R. III and B. Jones, “Design and kinematic modeling of constant curvature continuum robots: A review,” *I. J. Robotic Res.*, vol. 29, pp. 1661–1683, 11 2010.
- [38] N. Mahkam, A. Bakir, and O. Özcan, “Miniature modular legged robot with compliant backbones,” *IEEE Robotics and Automation Letters*, vol. 5, no. 3, pp. 3923–3930, 2020.
- [39] M. Ugur, “Rembot: A reconfigurable, miniature, modular robot with soft connection mechanisms,” Master’s thesis, Bilkent University, 2023.
- [40] M. Uygun and O. Ozcan, “Smolbot-vs: A soft modular robot capable of modulating backbone stiffness,” in *2024 IEEE 7th International Conference on Soft Robotics (RoboSoft)*, pp. 34–39, 04 2024.
- [41] R. D. Quinn, G. M. Nelson, R. J. Bachmann, D. A. Kingsley, J. Offi, and R. E. Ritzmann, “Insect designs for improved robot mobility,” in *Proceedings of 4th International Conference on Climbing and Walking Robots*, pp. 69–76, Germany, 2001.
- [42] M. Askari, M. Ugur, N. Mahkam, A. Yeldan, and O. Ozcan, “Control and study of bio-inspired quadrupedal gaits on an underactuated miniature robot,” *Bioinspiration Biomimetics*, vol. 18, 01 2023.
- [43] D. Özbek, T. B. Yılmaz, M. A. Kalın, K. Şentürk, and O. Özcan, “Detecting scalable obstacles using soft sensors in the body of a compliant quadruped,” *IEEE Robotics and Automation Letters*, vol. 7, no. 2, pp. 1745–1751, 2022.