

DESIGN, CONTROL, MODELING, AND LOCOMOTION ANALYSIS OF A MULTI-LEGGED MODULAR MINIATURE ROBOT WITH SOFT BACKBONES

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By
Nima Mahkam
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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)

Yildiray Yildiz

Evren Samur

Approved for the Graduate School of Engineering and Science:

Ezhan Karaşan
Director of the Graduate School

ABSTRACT

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Nima Mahkam

M.S. in Mechanical Engineering

Advisor: Onur Özcan

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Soft Modular Legged roBot (SMoLBot) is a legged, foldable, modular, miniature robot with soft backbones. SMoLBot's body and locomotion mechanisms are folded out of acetate sheets and its compliant connection mechanisms are molded from Polydimethylsiloxane (PDMS). High maneuverability and smooth walking pattern can be achieved in miniature robots if high stiffness kinematic parts are connected with compliant components, providing the robot structural compliance and better adaptability to different surfaces. SMoLBot is exploiting features from origami-inspired robots and soft robots, such as low weight and low cost foldable rigid structures and adaptable soft connection mechanisms made of PDMS. Every single module in SMoLBot is actuated and controlled by two separate DC motors, that enable gait modification and a higher degree of freedom on controlling the motion and body undulation of the robot in turning and rough terrain locomotion. Each module has 44.5 mm width, 16.75 mm length, and 15 mm height, which is approximately the same size as two DC motors and a Li-Po battery.

The dynamic formulation of SMoLBot is obtained using Newton-Euler formulation and it depends on the physical parameters of the contact and closed-chain kinematic analysis of the feet. The dynamic model framework is proposed by determining the dynamic locomotion parameters of each module as an individual system, as well as, considering the dynamics of the whole robot; i.e. the robot is modeled as one system and modules are considered to be set of flexible links connected to each other, within this system. Kinematic constraints among these modules are obtained by considering the types of backbones integrated in the robot. Various types of backbones are used within the experiments that are

classified into two groups: rigid, and compliant backbones. Experimental results of SMoLBot running/walking with different symmetrical and asymmetrical gates validate the dynamic model presented in this thesis. Additional to the dynamic model, the effect of the backbone stiffness on the locomotion of the legged miniature modular robots with multiple numbers of modules is studied. Analyses comparing the velocity of SMoLBot with different numbers of modules and different types of backbones are presented using the proposed dynamic model. The results indicate that there is an optimum torsional stiffness of the backbone for a legged miniature modular robot that maximizes the robot's translational velocity. Additionally, we can show that, for a given backbone stiffness or a specific range of compliance between the modules, there is an optimum number of feet for the miniature robots.

Furthermore, in this thesis, a locomotion study that investigates the motion patterns of the running/walking multi-legged modular miniature robots with soft module connections, is conducted. The locomotion study is done using the presented dynamic model and results are verified using SMoLBot. The optimum feet sequence and the optimum stride length of a multi-legged robot are derived using the locomotion analyses, and the dynamic and kinematic formulations. The optimum gait analysis of the multi-legged SMoLBots represents different but unique feet contact sequence patterns for each robot with a different module number and diverse ranges of compliance between the modules. Furthermore, analysis considering the effect of various feet failure cases on the locomotion of a multi-legged robot with soft/rigid backbones, is conducted. This study investigates the locomotion behavior of a legged miniature robot with different combinations of the non-functioning feet. Additionally, a case-sensitivity study of an n -legged SMoLBot's locomotion on its individual modules during the operation, is also conducted. This study investigates the modular robot's locomotion with multiple different failure cases where each particular case only considers the effect of an individual module failure on the overall motion of the robot, while the gate is not altered.

Keywords: miniature robotics, foldable robotics, dynamic simulation, multi-legged modular robots, gait analysis, stiffness analysis, soft backbones.

ÖZET

YUMUSAK OMURGALI ÇOK BACAĞLI MODÜLER MİNYATÜR ROBOTUN TASARIMI, KONTROLÜ, MODELLENMESİ VE LOKOMOSYON ANALİZİ

Nima Mahkam

Makine Mühendisliği, Yüksek Lisans

Tez Danışmanı: Onur Özcan

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Yumuşak Modüler Bacaklı Robot (Soft Modular Legged roBot - SMoLBot), minyatür, modüler, katlanabilir ve yumuşak-sert karışık olan ve esnek omurgaya sahip bacaklı bir robottur. SMoLBot'un gövdesi ve hareket mekanizmaları asetat kağıtlarından katlanır ve esnek bağlantı mekanizmaları Polidimetilsiloksandan (PDMS) kalıplanarak üretilir. Yüksek direngenliğe sahip kinematik parçalar esnek bileşenlerle bağlandığında, robotun yapısal esnekliği artar ve farklı yüzeylere daha iyi uyum sağlar dolayısıyla minyatür robotların manevra kabiliyeti artar ve daha düzgün bir yürüme şekli elde edilebilir. SMoLBot, düşük ağırlıklı ve düşük maliyetli katlanabilir sert yapılar ve PDMS'lerden yapılmış esnek bağlantı mekanizmaları gibi hem origamiden ilham alan robotların hem de yumuşak robotların özelliklerini kullanıyor. SMoLBot'taki her bir modül, iki ayrı DC motor ile hareket ettirilir ve kontrol edilir; bu durum, yürüme şeklinin değiştirilmesini ve robotun dönüşü ve engebeli arazide hareketi sırasında robotun hareketini ve gövde salınımını kontrol etme konusunda daha yüksek bir serbestlik derecesi sağlar. Her modül 44.5 mm genişliğe, 16.75 mm uzunluğa ve 15mm yüksekliğe yani yaklaşık olarak iki DC motor ve bir Li-Po pil ile aynı boyuta sahiptir.

SMoLBot'un dinamik modellemesi Newton-Euler formülleri kullanılarak elde edilir ve ayakların temas parametrelerine ve kinematik analizinin fiziksel parametrelerine bağlıdır. Dinamik modelin altyapısı, tüm robotun dinamik yapısı göz önünde bulundurulurken aynı zamanda da her bir modülün ayrı birer sistem olarak değerlendirilmesiyle, yani robotun tümüyle bir sistem olup modüllerin ise bu sistemin içinde birbirine bağlı esnek birer bağlantılardan ibaret olduğu

düşünülmüş ve oluşturulmuştur. Modüllerin kinematik kısıtlamaları robotta kullanılan omurganın tipine göre bulunmuştur. Deneylerde kullanılan omurgalar sert ve esnek omurgalar olmak üzere iki gruba ayrılır. Farklı simetrik ve asimetrik yürüme şekilleriyle koşan ya da yürüyen SMoLBot'un deneysel sonuçları bu tezde sunulan dinamik modeli doğrulamaktadır.

Dinamik modele ek olarak, omurga direngenliğinin çok sayıda modüle sahip bacaklı minyatür modüler robotların hareketi üzerindeki etkisi incelenmiştir. SMoLBot'un hızının farklı sayıda modül ve farklı omurga tiplerine sahip olan SMoLBotlar ile karşılaştırıldığı analizler, önerilen dinamik model kullanılarak sunulmuştur. Sonuçlarımız, ayaklı minyatür modüler robotlar için robotun hızını en üst düzeye çıkaran optimum bir burulma direngenliğine sahip omurganın var olduğunu göstermektedir. Ek olarak, belirli bir omurga direngenliği veya modüller arasında belirli bir esneklik aralığı için minyatür robotlarda optimum bir ayak sayısının olduğunu gösterebiliriz. Ayrıca, bu tezde, koşan ya da yürüyen yumuşak modül bağlantılarına sahip çok bacaklı modüler minyatür robotların hareket şekillerini araştıran bir hareket çalışması yürütülmektedir. Hareket çalışması sunulan dinamik model kullanılarak yapılır ve sonuçlar SMoLBot kullanılarak doğrulanır. Çok bacaklı bir robotun optimum adım sayısı ve optimum adım uzunluğu, hareket analizleri, dinamik ve kinematik denklemler kullanılarak elde edilir. Çok bacaklı SMoLBot'ların optimum yürüyüş analizi, farklı modül sayılarına ve modüller arasında çeşitli esneklik aralıklarına sahip her robot için farklı olup benzersiz ayak teması sırası modellerini temsil eder. Ayrıca, ayakların çeşitli arıza vakalarının, esnek ya da rijid omurgalı çok bacaklı bir robotun hareketi üzerindeki etkisini göz önünde bulundurarak analiz yapılır. Bu çalışma, arızalı ayakların farklı kombinasyonlarına sahip bacaklı bir minyatür robotun hareketini araştırmaktadır. Ek olarak, n-bacaklı bir SMoLBot'un çalışması sırasında kırılan bacakların hangi modülün üzerinde bulunmasının robotun hareketini nasıl etkilediği de araştırılmıştır. Bu çalışma, modüler robotun hareketini, her bir vakanın yalnızca tek bir modül arızalandığındaki etkisini birçok farklı arıza vakasıyla ve yürüme şekli değiştirilmeden araştırmaktadır.

Anahtar sözcükler: minyatür robotlar, katlanabilir robotlar, dinamik simülasyon, çok-bacaklı modüler robot, gait analizi, yürüme şekli analizi, sertlik analizi, esnek omurga.

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Chapter 1

Introduction

1.1 Research Aims and Objectives

While robots working in highly predictable industrial environments are well developed and identified, attaining real-world environments that require creativity and adaption remains a huge challenge. Different applications require various scales of robotic systems, whereas large-scaled robots are mainly used in automotive assembly lines, miniature robots are exploited in dangerous tasks that require navigation in small and complex environments such as search and rescue missions, exploring hazardous environments, and surveillance. Operational conditions that are recognized individually for miniature robots require them to perform different gaits and to be highly maneuverable to traverse a variety of terrains. Additionally, the unpredictability of these applications and real-world environments oblige miniature robotics platforms to be inexpensive, low-weight, robust, easily-programmable, and safe to interact.

Apart from the useful applications and practical environments that small-scaled robots can operate in, miniature robots' locomotion analysis can provide an insight into biological motions at small scales. Animals modify their locomotion trends concerning their speeds and terrain characteristics; However, for the

robots, especially small ones, generating a dynamically stable feet cycle trend to deal with different environments is still a challenge. This is due to the fact that for a given gait, feet landing point is dependent mainly on the robot’s orientation such as roll and pitch angles. For large-scaled robots, the feet movement cycle is controlled using contact sensors, however, for the miniature robots, these sensors are not feasible, due to the limitation on the size, payload capacity, and power. As a result, the requirements to control the robot’s gait for improved locomotion mostly reduces down to controlling the orientation of the robot, which is a function of the geometry, the compliance between the modules, and the number of legs. Similarly, despite the advances in the design and fabrication techniques of miniature and micro-robots, their design techniques are relatively limited compared to the conventionally manufacturing methods of the large-scaled robots. There is a need for studies to investigate alternative design and fabrication techniques for the next generations of miniature robots.

The research presented here has contributed to the goal of developing a legged modular miniature robot with soft module connections for understanding and analyzing the locomotion behavior of the multi-legged robots in small-scale. This research primarily focuses on the fabrication method, design, development, and operation of Soft Modular Legged roBot (SMoLBot). SMoLBot’s design incorporates a fabrication method, that exploits features of origami-inspired foldable robots, such as low weight, low cost, easy to manufacture, high structural integrity, and simple replaceable structures. Additionally, with the use of Polydimethylsiloxane (PDMS) connection mechanisms, SMoLBot turns to be soft-hybrid and modular at the same time. Each module is made out of a single acetate sheet with optimized fold-locks resulting in a highly resilient assembly, holding motors, electrical components, and connection locks. PDMS connection mechanisms make it possible to connect individual modules while having the possibility of imposing different values of stiffness to the system. Additionally, with the aim of performing gait studies in miniature robots, SMoLBot is designed with independent leg actuation and control, which makes it capable of running/crawling with different gaits.

The foremost contribution of this thesis is the locomotion study that gives a

better understanding of the many-legged miniature robots' locomotion behavior with a lack of control on feet placement. In the interest of studying the legged miniature robots' locomotion characteristics with various range of compliance between modules and analyzing the possible achievable gaits during the operation, a comprehensive three-dimensional dynamic model of the body rotations and out-of-plane dynamics is developed. Presented dynamic model and the locomotion study analysis predicts the locomotion trends of the robot at a terrain and give better insight understanding the multi-legged robot's motion behavior at a small scale with multiple degrees of freedom. Furthermore, the presented dynamic model is utilized to investigate the effect of compliance between the modules on the robot's locomotion and to understand the underlying factors that can contribute to an optimized locomotion. Additionally, a gait analysis study of the multi-legged robots with various ranges of compliance between the modules is conducted, which investigates the actual achievable gaits and the optimum gaits of a multi-legged robot during the locomotion. The validity of the model and the locomotion study results are confirmed using SMoLBot's experimental data such as roll and pitch angles and the robot's translational velocity.

1.2 Structure of the Thesis

The work done in this thesis are illustrated by the following highlights and organized as follows.

Chapter 2 (Design): Design and fabrication of SMoLBot with passive soft backbones to use as a platform for studying multi-legged robots' locomotion at small scales. This chapter focuses on the design of SMoLBot, a multi-legged robot with soft backbones. SMoLBot's modules are inspired by origami, the traditional Japanese art of subsequent folding of a two-dimensional sheet into a three-dimensional functional structure. Folding is an efficient and simple method to fabricate a flexible three-dimensional structure, and can be considered as an alternative fabrication method for the traditional machining or complex and expensive composite manufacturing processes. On the other hand,

with the use of the fabrication methods of manually assembled modular robots and soft robots, un-tethered SMoLBot represents properties of soft and modular robotic classes at the same time. Backbones and locks as connection mechanisms are manufactured using PDMS, which makes it possible to add multiple DOF to the system based on the type and the shape of the backbone that is used in the robot.

Chapter 3 (Operation): Discover the body morphology and the locomotion behavior of SMoLBot, while the compliance between the modules ranges from rigid to soft. This chapter briefly introduces the control procedure and compares the dynamic locomotion parameters of the multi-legged SMoLBot with various types of backbones. First, the control procedure of a single DC motor is introduced. Then, the locomotion parameters of SMoLBot with rigid/soft backbones are presented that show the particular features of each robot during the operation. A comparison study of the robot’s dynamic locomotion parameters is conducted that highlights the soft backbones’ effect on the robot’s dynamic behavior, while the module number is increasing.

Chapter 4 (Dynamic modeling): A formulated dynamic model to describe the motion of SMoLBot. This chapter formulates a three-dimensional model to describe the locomotion of SMoLBot with different module numbers and various ranges of compliance between the modules. Model is developed in a manner that can predict the locomotion of an under-actuated multi-legged robot with passive module connections. Robot’s dynamic locomotion parameters and motion trends are dependent on the physical properties of the contact and the backbone’s physical characteristics.

Chapter 5 (Model verification): Dynamic model verification using SMoLBot’s experimental data. In this chapter, experimental data of rigid/soft multi-legged SMoLBots operating with a trot gait or continuous form of the trot gait, are extracted from raw videos; and then the results are compared with the simulations to verify the model’s validity and discussions presented in this work. It is observed that the simulation successfully predicts the trends of the robot in locomotion on terrain.

Chapter 6 (Stiffness and gait study): An investigation on the locomotion of SMoLBot to maximize the locomotion velocity and to understand the actual walking/running trends of the multi-legged robots during the operation. Chapter 6 gives an insight into how the dynamic model can be used to identify the optimum stiffness values that result in a maximum translational velocity. Additionally, this chapter represents the gait study results that shows the actual gaits of the robot during the operation. This study considers the locomotion patterns, feet landing points, stride period, and slip length of the multi-legged SMoLBot with different backbone types to show the effect of different sets of design parameters on the overall motion of the robot. The studies show that robots with different backbone types (different ranges of compliance between the modules) have different locomotion patterns while operating with a similar gait. This is due to the effect of the body orientations (roll and pitch angles) on the robot's motion and feet landing points.

Chapter 7 (Locomotion study): Demonstration of the graceful degradation of the locomotion performance due to feet failures and an optimization study to find the optimum walking/running patterns for individual multi-legged SMoLBots with different backbone types. First, this chapter investigates the possible operational optimum gaits of the multi-legged robot, that result in a maximum velocity. This optimization study considers the locomotion behavior and the translational velocities of SMoLBot with different backbone types and module numbers, individually. Next, a locomotion study that considers multiple feet failure cases in an n -legged robot is conducted as well, which shows the effect of multiple random feet failure cases on the robot's operational capabilities and its translational velocity, while the gait is not altered.

Chapter 2

Design and Fabrication

This chapter presents the design and the development of SMoLBot, a multi-legged soft-hybrid modular miniature robot, explaining in detail the fabrication, and the assembly of the robot's body and the electronics. SMoLBot's modules and leg mechanisms are originally inspired by origami art, which consists of a subsequent folding of a two-dimensional sheet into a three-dimensional complex functional structure. Module connections of SMoLBot are molded from Polydimethylsiloxane using 3D-printed molds with diverse shapes that make it possible to achieve various ranges of compliance between the modules. Each leg of the robot is actuated and controlled individually with an aim of performing gait and locomotion studies in modular miniature robots. Discussion on operation, modeling, locomotion, and gait analysis are given in the following chapters. The content of this chapter is published in [1].

2.1 Miniature Robotics Literature

Small modular robots, that are easily manufactured inexpensively, and can be utilized in applications such as inspection, surveillance or search and rescue, where small size is important. High maneuverability, agile locomotion, and surface

adaptation due to the body undulation enable small modular miniature robots to access confined and hazardous spaces or to perform explorations in small and complex environments [2]. However, despite their advantages, miniature robots have challenges regarding design, actuation, and power, which affect the body stiffness and maneuvering capabilities

There are numerous techniques in design and fabrication of miniature robots including 3D printing [3], MEMS fabrication [4, 5], Inverse-Flow Injection (IFI) and Dip-Cure-Repeat (DCR) [6], photo-lithography [7], laser cutting and creating multilayer composite structures with smart composite manufacture (SCM) [8] techniques. HAMR [9] and RoACH [10] are examples of such robots fabricated using SCM fabrication method. Similarly, various types of materials, such as hydrogels, polymeric elastomers [11], and PET films [12] are used to fabricate small-scale miniature robots. Origami-inspired robot fabrication [13, 14], which consists of transforming a two-dimensional paper sheet into a three-dimensional complex design with subsequent foldings, is another method to manufacture miniature robots [15, 16]. Following the early works reported in [17], origami-inspired fabrication method was first developed by researchers in Harvard University and MIT [18] and was later employed by many researchers in designing miniature grasping [19, 20], flying [21], and crawling robots [22, 23] as well as some legged versions [24]. Soft Modular Legged roBot (SMoLBot), shown in Fig. 2.1, whose main modules, as the fundamental base structures of the robot body, are fabricated using the same method of laser cutting and folding.

Studies on modular robots, classifies them into manual or autonomous reconfigurable robots [25]. Both types preserve some advantages of modular robots, including but not limited to modifiable size scale, low weight, and low cost production. There have been various studies on self-reconfigurable robots autonomously changing shape to various configurations such as a quadruped or a snake [26], in which each module is provided with computational and communication capability. Similarly, there have been a tendency to use the reconfiguration capabilities of these robots as a locomotion mechanism for crawling-walking movement. Such robots use optimized shape change patterns to maximize the speed [27–29]. On the other hand, modular robots assembled by the operator have the advantage

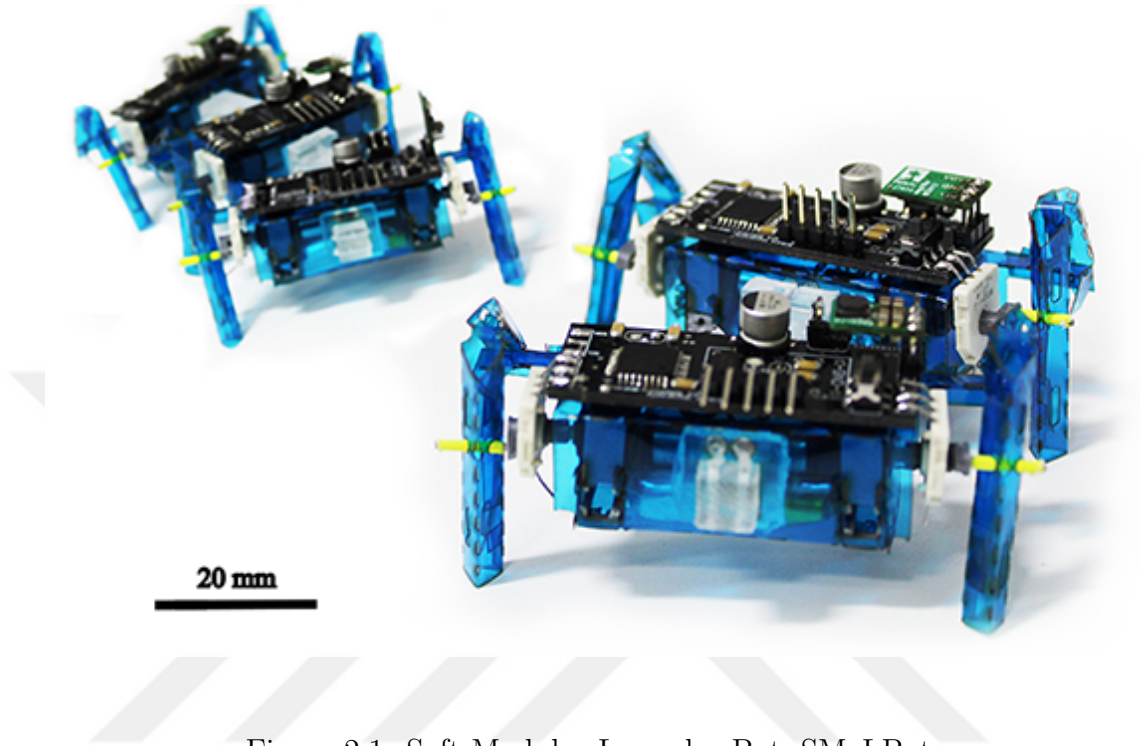


Figure 2.1: Soft Modular Legged roBot, SMoLBot.

of utilizing connection mechanisms that don't need to be turned on or off. These connection mechanisms keep the manufacturing process of bigger structures simple, straightforward, and time and cost efficient, and make it feasible to utilize various types of connection mechanisms such as electromagnetic connections [30] and electrostatic connections [31] in modular robot's design.

Adaptability through mechanical compliance is an inherent advantage of soft robots, however, untethered actuation of soft miniature robots remains a challenge. The Prospect of assembling soft and hard units in a modular concept can be a way to overcome challenges regarding the actuation and locomotion of the soft robots [32]. In a few researches, magnetic connections are used in soft complex robots connecting hard-driving units to the soft portion of the robot [33,34] in a modular concept. Assembling soft and hard units, have granted the possibility of manufacturing bio-inspired robot designs. For instance, an octopus inspired robot, which locomotes by pushing itself from the sea bed uses the same modular and soft-hybrid concept to mimic a pattern that is similar to its biological counterpart [35].

Despite the evolution of modular robots, there exists a space for the development of a robot that carries features of different classes of robots as to be soft, foldable, and modular, simultaneously. SMoLBot is a foldable modular robot with soft connection mechanisms. SMoLBot’s design incorporates a fabrication method, that exploits features of origami-inspired foldable robots, such as low weight, low cost, easy-to-manufacture, high-structural-integrity, and simple replaceable structures. Similarly, with the use of PDMS connection mechanisms, SMoLBot turns to be soft and modular at the same time. Each module is made of a single acetate sheet with optimized fold-locks resulting in a highly resilient assembly, holding motors and electrical components. Each module consists of individually actuated and controlled DC motors, which allows various gait implementations and better locomotion. PDMS backbones make it possible to connect individual modules to each other while having the possibility of imposing different stiffness to the system. The main reason for designing a robot with individually actuated legs is not to claim that it is better or easier to control than miniature robots with coupled actuation but to enable gait modification during locomotion in a small scale. Next following sections will explain the design, manufacturing techniques, and evolution of SMoLBot.

2.2 SMoLBot Design

SMoLBot’s modules are folded using 100-micrometer-thick flexible A4 size cellulose acetate sheets. The main structural material, as well as the compliant flexure joint design approach, are very similar to other miniature foldable robots such as MinIAQ [12]. In order to increase the structural integrity of the body, certain folded structures such as T-folds and tab-and-fastener locking extensions are embedded into the original design. T-folds are out-of-plane extensions that have the capability of stiffening the body frame and acting as a beam between two vertical planes, as shown in Fig. 2.2. Tab-and-fastener extensions are U shaped fastener tabs, that keep the folded structures locked in place. A combination of rigid T-folds and tab-and-fastener mechanisms reduce the twist and buckling movement of the body. Enough space for two DC motors and a battery housing

is embedded between T-folds, and PDMS lock housings are embedded on the vertical stationary planes as shown in Fig. 2.2(b).

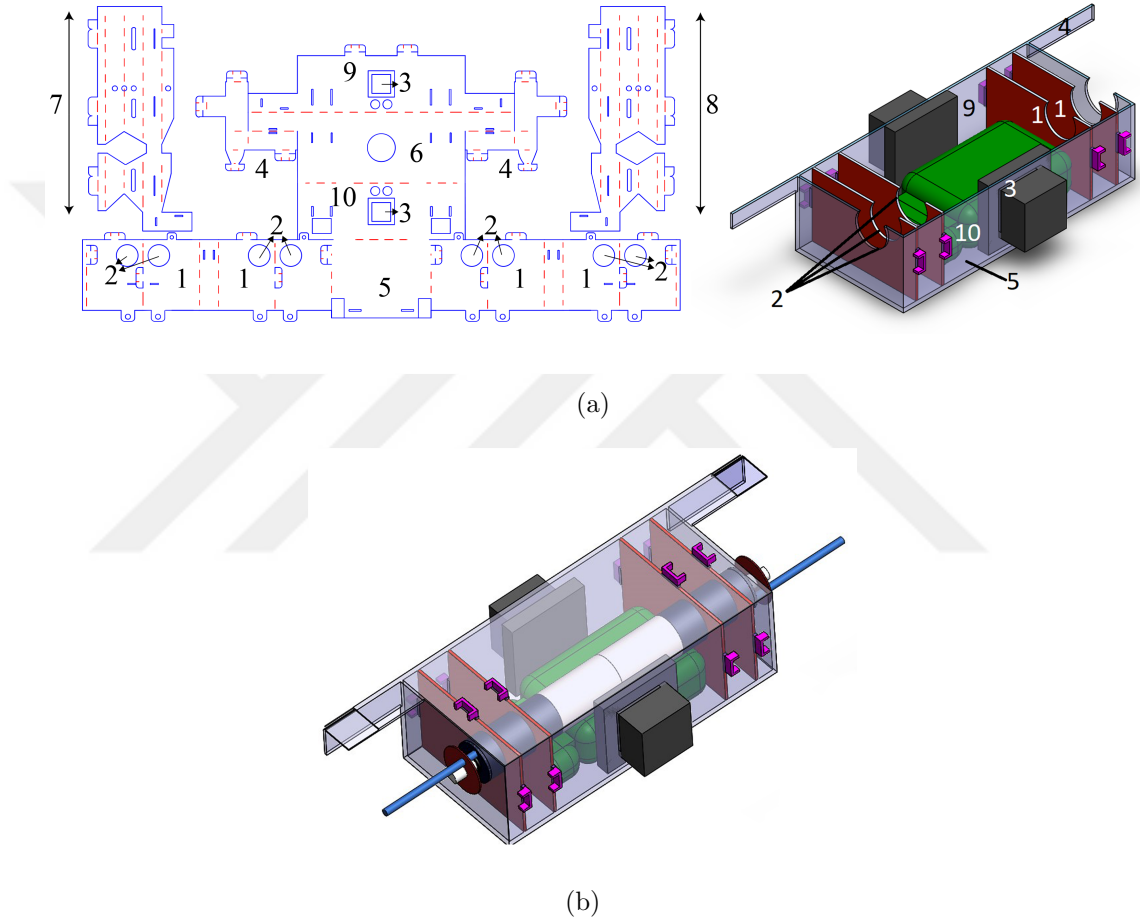


Figure 2.2: (a) AutoCad design and cut perspective of a folded robot. T-folds(1), motor housing (2), PDMS lock housing (3), leg locking patch (4), bottom patch and battery housing (5), top patch (6), left leg (7), right leg (8), rear patch (9), front patch (10), fastener and locks (purple), battery (green), PDMS locks (black), leg pin connections (blue), motors (black and grey). (b) Body design out-look.

Getting the smallest robot housing was aimed during the design process. A single frame of the module is approximately in the size of two DC motors (Pololu, Sub-Micro Plastic Planetary Gearmotor) and a single cell 3.7 Volt, 150mAh Li-Po battery. Two DC motors are placed back-to-back and parallel to each other inside two tight circular openings on the T-folds. Battery is placed just under the motor

housing with T-folds holding it in-place (two pairs of T-folds are placed inside the body). Battery is easily accessible through the rear hatch door for charging or removal.

2.2.1 Material Selection

The primary aim while designing the multi-legged modular SMoLBot’s modules was to make an embedded single-piece crease pattern for ease of manufacturing. To select a proper material in terms of compliance, rigidity, and joint life-time, 100, 250, and 500-micrometer thick cellulose acetate sheets were selected (Figure 2.3). During the manufacturing phase of SMoLBot, it has been observed that the thinner acetate sheets were easier to cut, fold and assemble. On the contrary, using thick films with higher structural rigidity makes the folding, and bending the sheet to form the corners difficult and time-consuming, particularly while scaling down to smaller-scale creases. Besides, the thicker sheets have lower joint performance; Flexure joints that are manufactured using thick acetate sheets would plastically deform, forming permanent fold-lines and break sooner than the joints that are made of thin-acetate sheets. Alternative materials can also be used such as Kapton® to achieve strengthened mechanical properties such as increased stiffness and higher joint cycle life.

2.2.2 Actuation Mechanism Design

Integrating a mechanism into a design, which has an elliptical trajectory and a simple unfolded form for locomotion is a challenge for foldable legged miniature robots. The flexure joints in foldable foot designs of the miniature robots have a limited degree of rotation, meaning that the joints deflection angle should be limited in a specific range to prevent shear at the joints. Leg actuation in SMoLBot is achieved by a four-bar mechanism that is cut and folded from the same sheet used for the body (Fig. 2.2(a)).

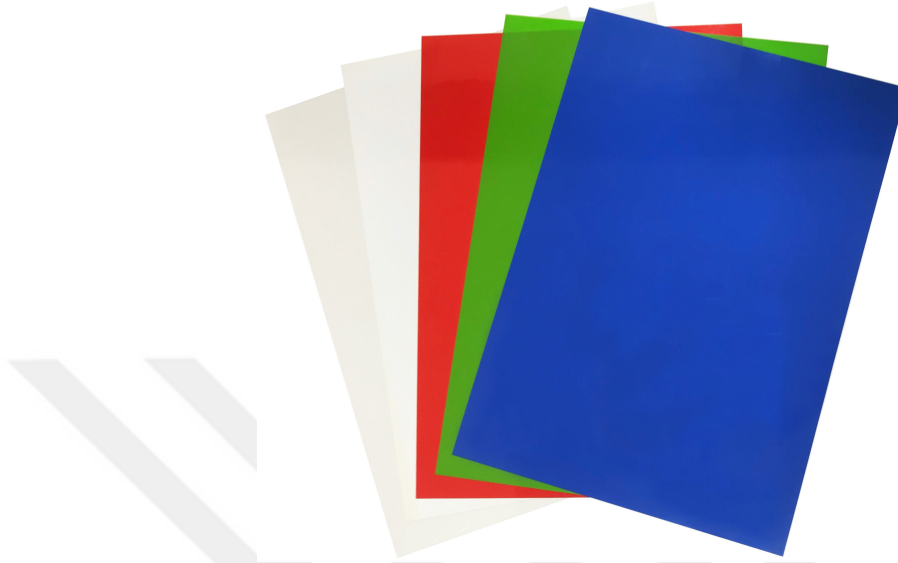


Figure 2.3: Various colors of 100 μm thick A4-sized cellulose acetate sheets used to manufacture module frames of SMoLBot.

Figure 2.4 shows the folding procedure of an actual leg and its generalized four-bar model. SMoLBot’s feet are modeled as a four-bar linkages, overall with a single degree of freedom (DOF). Each leg is connected to the main body through a one-DOF rotational 3D-printed cam-shaft and fold-locks. 3D-printed cam-shaft construct a tight-fit connection between the DC motor and the foot. Triangular beam shaped parts of the folded leg are the rigid links and single thin plate in the middle acts as the flexure joint. In this configuration, the beam’s rigidity is dependent on its length, width, thickness, and Young’s modulus of material used [36]. Joint width, length, thickness, and maximum deflection angle can be optimized to increase the fatigue life cycle of the flexure joints, by distributing the load more uniformly and reducing the stress at compliant joints. Furthermore, it is important to note that the robot’s locomotion is affected by small alterations in the dimensions of the flexure joint of the folded leg; i.e. changing the width or length of the thin plate changes the stiffness of the joint that result in a different locomotion pattern.

With an initial assumption of known planar coordinates of the feet attachment points to the body, motor locations, and cam-shaft length, kinematic analysis of the foot is conducted to determine the unknown parameters such as the positions

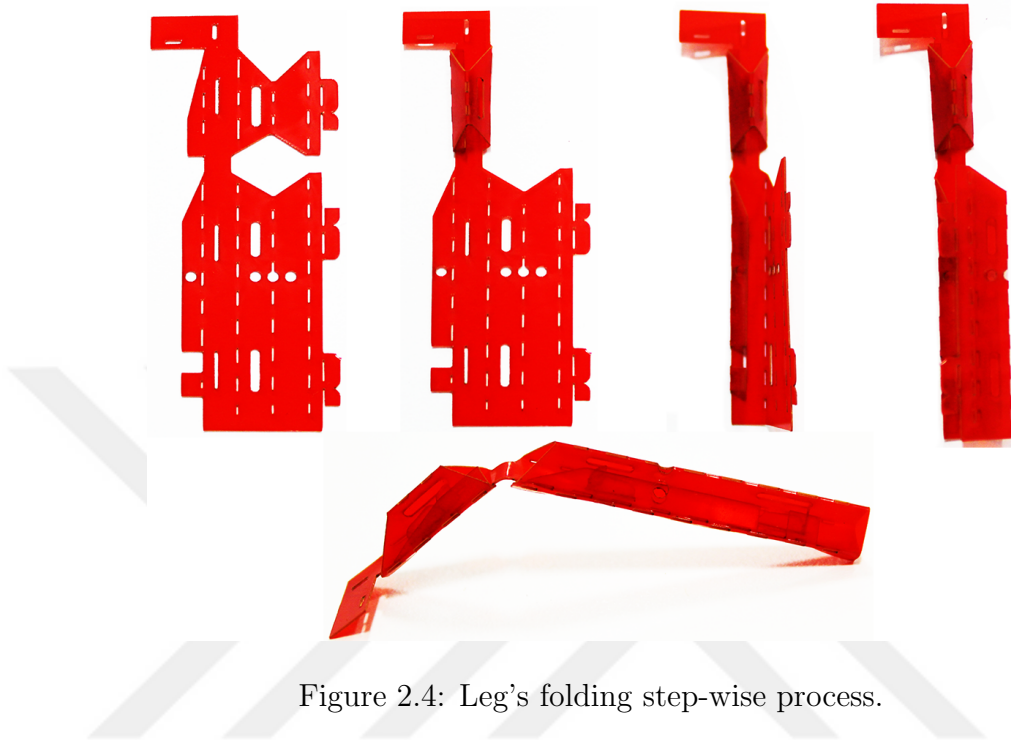


Figure 2.4: Leg’s folding step-wise process.

of the contact points, the deflection angles, and the velocities. For SMoLBot’s feet, a simple four-bar cam-driven mechanism was designed and synthesized by altering the dimensions of the foot, the position of the joints and radius of the cam (input crank link) in order to obtain an acceptable gait path to form a maximum contact to the ground with a relatively long stride length and acceptable foot lift, as shown in Fig. 2.5. The selected four-bar is not optimal performance-wise; However, its simplicity was favored over the complexity of the compound planner foldable assembly.

2.3 Backbone Design

Backbones can be categorized into three different types, namely: continuous, discrete, and hybrid [37]. Robotic systems with continuous backbones (referred as continuum robots) often only use elastic materials for the robot’s structural parts [38]. Robotic systems with discrete backbones use articulated linkages as connection mechanisms, and hybrid mechanisms similarly utilize a mixture

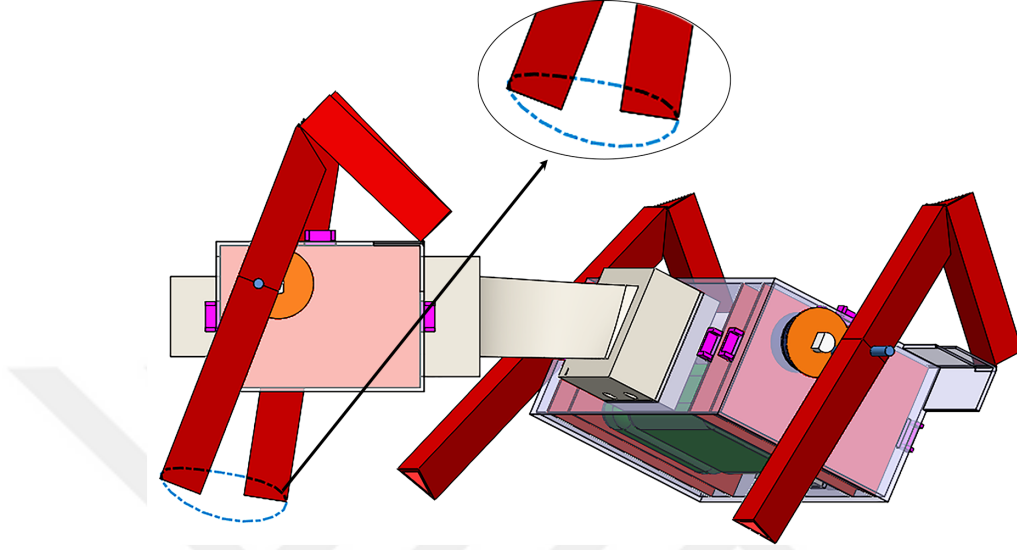


Figure 2.5: Gait trajectory of the cam-driven four-bar mechanism of SMoLBot.

of elastic elements and linkages to achieve a relative motion between the body modules neighboring the backbone.

We designed an easy-remove-easy-assemble connection mechanism that can be embedded to the foldable body, using puzzle shaped molds. 3D-printed molds with diverse shapes and sizes based on the backbone’s intended stiffness, have been used in the molding process, an example of such molds is shown in Fig. 2.6. Manufacturing backbones with different designs and stiffness values are possible with this fabrication method. Structural and geometrical factors have a great effect on the moment of inertia. The shape of the backbones have been modified as a means to achieve desired stiffness values. We designed and categorized SMoLBot’s backbones based on their overall geometric shapes. Connection assembly consists of two individual pieces, the backbone connecting two individual modules to each other, and the locking mechanism connecting each module to the backbone. PDMS is used for manufacturing both the backbone and the locking mechanism. PDMS locks are fixed inside the modules in order to avoid any undesired movements, and pins are used to fix the PDMS locks to the backbones. Slots for pin connections have been embedded on both the PDMS lock and the backbone molds during the molding process with circular cuts. This connection mechanism between the locks and the backbone makes the lock and backbone

mechanism feasible for easy-remove-easy-assemble operation purposes.

The need to eliminate module collisions sets a minimum for the length of the backbone and the desired stiffness values at different axes change the backbone cross-section shape and dimensions. The initial dimensions of the backbones have been derived using beam stiffness relations with intended stiffness and Young's modulus of the PDMS. PDMS Young's modulus is dependent on its mixing ratio and curing temperature [39,40]. In order to manufacture connection mechanisms, PDMS is mixed with 5:1 and 1:10 ratios, and is poured into the 3D-printed PLA molds, and baked in temperature of 65 °C for two hours [41].

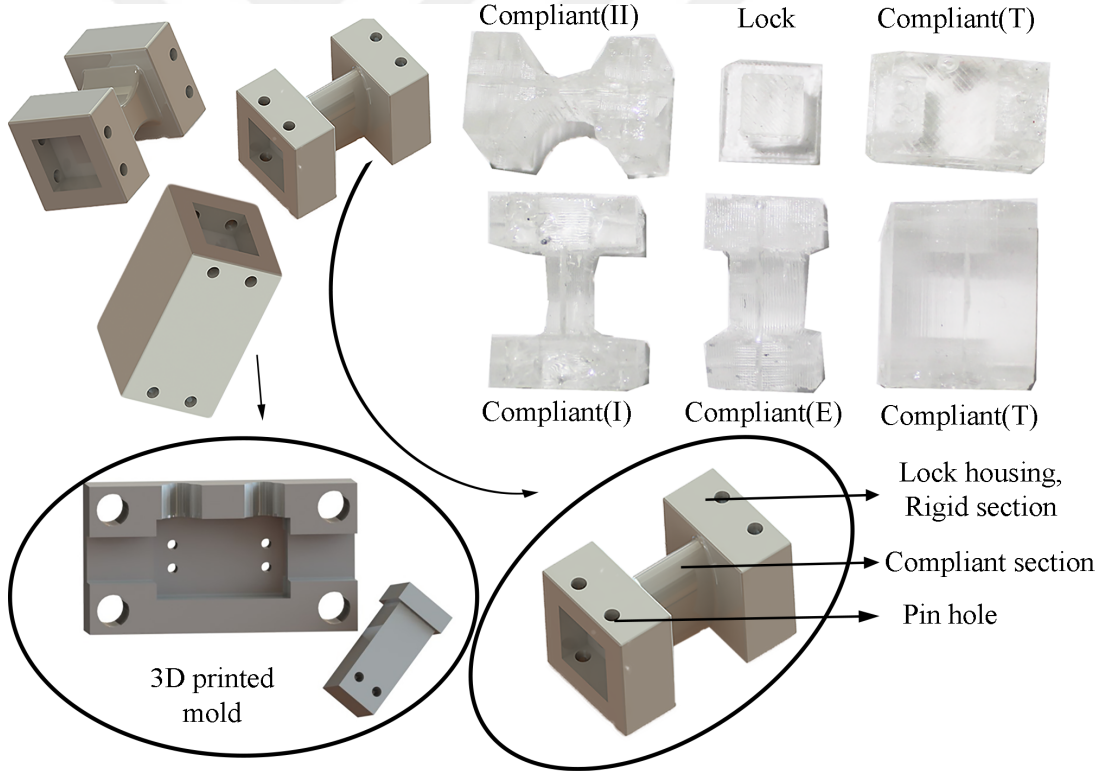


Figure 2.6: PDMS locks and PDMS backbones: only torsional, compliant I-beam and compliant with elliptical mid-cross-section.

SMoLBot's backbones are categorized into two main classes: rigid and compliant. Rigid backbones are a solid block of PDMS with metal pin insertions possessing the highest bending and torsional stiffness in all directions. Compliant backbones are grouped into four different types: backbones with only torsional deflection,

very soft backbones, medial-soft, and soft backbones. Backbones are constructed from three different sections, two of which acts as PDMS lock and one section that defines the overall stiffness of the backbone. Locks are rectangular-shaped holes embedded at the two ends of the PDMS backbone. PDMS locking mechanisms embedded inside each module are placed inside these holes and are mounted to the backbones using pins. Mid-section shapes of the backbones are chosen considering the intended overall stiffness of the backbone. Backbone's stiffness is controlled with geometric factors using the width, the length, and the height of the mid-section. Table 2.1 shows the bending and torsional stiffness of the backbones used in SMoLBot. Rigid backbone is fully stiff PDMS blocks with metallic insertions. Remaining backbones are manufactured using only PDMS molded in 3D-printed molds. Compliant backbone (I) and (II) are I-beam backbones with different rectangular cross-sections, compliant(E) is the I-beam backbone with an elliptical cross-section and compliant(T) is a rectangular solid block with only torsional deflection. Compliant(T) backbones have the highest bending stiffness compared to the compliant(I), (II), and (E) backbones; however, since the torsional stiffness values of the compliant(T) backbones are lower than the backbone's bending stiffnesses, modules still have limited rolling behavior, and that is the reason to call these rectangular prisms as only torsional backbones. Compliant(E) backbones with elliptical mid-cross-section possess higher torsional stiffness compared to the compliant (I) and (II) backbones. Two rectangular I-beam cross-sections with different width are used to manufacture compliant (I) and compliant (II) backbones. The compliant(II) backbones are rectangular I-beams that possess bigger length and width compared to the I-beam compliant(I) backbones.

Torsional stiffness of the compliant backbones are determined using (2.1) - (2.3), as follows:

$$k_t = c_2 G a b^3 / L, \quad (2.1)$$

$$k_t = G a_e^3 b_e^3 / L (a_e^2 b_e^2). \quad (2.2)$$

in which G is the shear modulus, a, b , and L are the width, the height, and

the length of the part, and c_2 is the correction coefficient as explained in [42]. Similarly, a_e and b_e are defined for the backbones with elliptical cross-sections and are the semi-minor and semi-major lengths of the ellipse. Overall torsional stiffness of the backbones with varying cross-section is given by:

$$k_{t_{total}}^{-1} = \sum_{n=1}^3 1/k_{tn} \quad (2.3)$$

in which k_{tn} is the torsional stiffness of each section on the backbone and $k_{t_{total}}$ is the overall torsional stiffness of the backbone. Equivalent bending stiffness for the backbones with varying cross sections can be found by integrating the beam bending equation over the length, as follows:

$$k_{b_i} = \int_0^L \frac{M(x)}{EI_i(x)} dx, \quad i = [1, 2] \quad (2.4)$$

in which E is the Young's modulus, I is the moment of inertia for corresponding section, M is the moment, and k_{b_i} is total directional bending stiffness. Subtitles $i = 1$ and $i = 2$ show the directions of the bending stiffness and moment of inertia along the width ($i = 1$) and height ($i = 2$) of the backbone.

Table 2.1: BACKBONE STIFFNESS

Backbone	k_t (Nm/Rad)	k_{b1} (Nm/Rad)	k_{b2} (Nm/Rad)
Rigid	∞	∞	∞
Compliant(T)	0.075	0.669	0.669
Compliant(I)	0.015	0.090	0.043
Compliant(II)	0.017	0.107	0.071
Compliant(E)	0.045	0.258	0.165

2.3.1 Electronics and PCB Design

With the intention of independent control and actuation of each module, each individual module has a printed circuit board (PCB), that has the same width

and length as a single module. Each module in SMoLBot has two lightweight DC motors that are individually controlled and each motor is driving a single leg. The PCB has an Atmega-328P as the main controller, along with one L293DD motor driver that is able to drive two DC motors. In order to control the speed and position of the DC motors, two position sensors, Bourns Potentiometer 3382 series, are placed on the PCB, and connected to the motor shafts with a 3D-printed cam-shaft. To run the robot, a single cell 3.7 V, 150 mAh LiPo battery is used for each module. Voltage is boosted up to 5 V with a step-up regulator, located on the top layer of the PCB, powering the micro-controller, the motor driver, the sensors, and the DC motors.

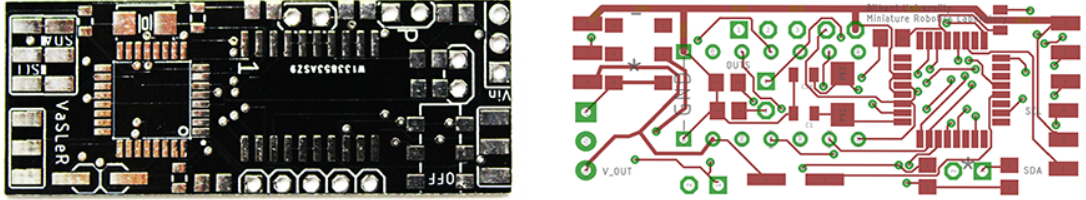


Figure 2.7: SMoLBot's real PCB and Eagle board schematics. Green colors show the pin hole insertions and red rectangular plates show the solder patches.

2.4 Fabrication and Assembly

After finalizing the PCB and soldering the electrical components, each module is fabricated and assembled. The fabrication process begins with the laser cutting of the crease pattern on the cellulose acetate sheets with a laser engraver (Universal Laser systems, VLS 3.60) and then folding. Body and locomotion mechanisms consist of consecutive foldings of T-folds and tab-and-fasteners, that transform the two-dimensional planar design to a three-dimensional complex shape. The first step in assembling SMoLBot is folding the T-shaped plates that are labeled as '1' in Fig. 2.8(a). Next, T-folds are fastened by using double-sided tab-and-slot fasteners (Fig. 2.8(a)-2). Then, the extension tabs, labeled as '3' in Fig. 2.8(a), are attached to the front and back of the main-frame. The top cover

(Fig. 2.8(a)-5) of the frame is folded next and locked on the T-folds by using the U-shaped fasteners existing on top of the T-folds (Fig. 2.8(a)-4).

The next step is placing electronics, DC motors, and PDMS locks inside the robot housing and closing and fastening the rear hatches (Fig. 2.8(a)-6). Then the leg mechanisms (Fig. 2.8(a)-7) are folded and fixed to the body with fasteners provided on the top surface (Fig. 2.8(a)-8), separately. Lastly, I^2C pins of the PCBs are connected using thin wires. The assembly time for each module is about 40 minutes, and the folded structure of each module is approximately 16 mm long, 44 mm wide, 15 mm high. Each module is about 18 g in total, 2 g of which is the structural part, 2.5 g DC motors, 5 g battery and 8.5 g that consist of the board and electrical components and pins.

2.5 C–SMoLBot Design

Primarily, C–SMoLBot and SMoLBot are designed to only differ in their foot designs so as to have robotic platforms to compare the performance of the robot with two different feet types. C-shaped legs provide the robot a high mobility, high maneuverability, and better climbing and rough terrain performance. Additionally, combining characteristics of the soft materials with C-shaped leg designs in robots with soft backbones would result in a system with higher maneuverable and operational capabilities. C–SMoLBot’s main body design, electronics, and control strategy are identical to that of SMoLBot’s but its legs are fabricated and assembled as separate parts and added to the mainframe of each module at the last step of the robot assembly.

C–SMoLBot main module frames are similar to SMoLBot and are cut and folded from cellulose acetate sheets. The two-dimensional unfolded technical drawing cut file of the mainframe of the C–SMoLBot can be seen in Fig 2.9. The only difference in the module design is the absence of the feet connection patches, since C–SMoLBot does not have compliant feet mechanisms, and the connection between the module frame and the feet are done using camshafts. 3D-printed

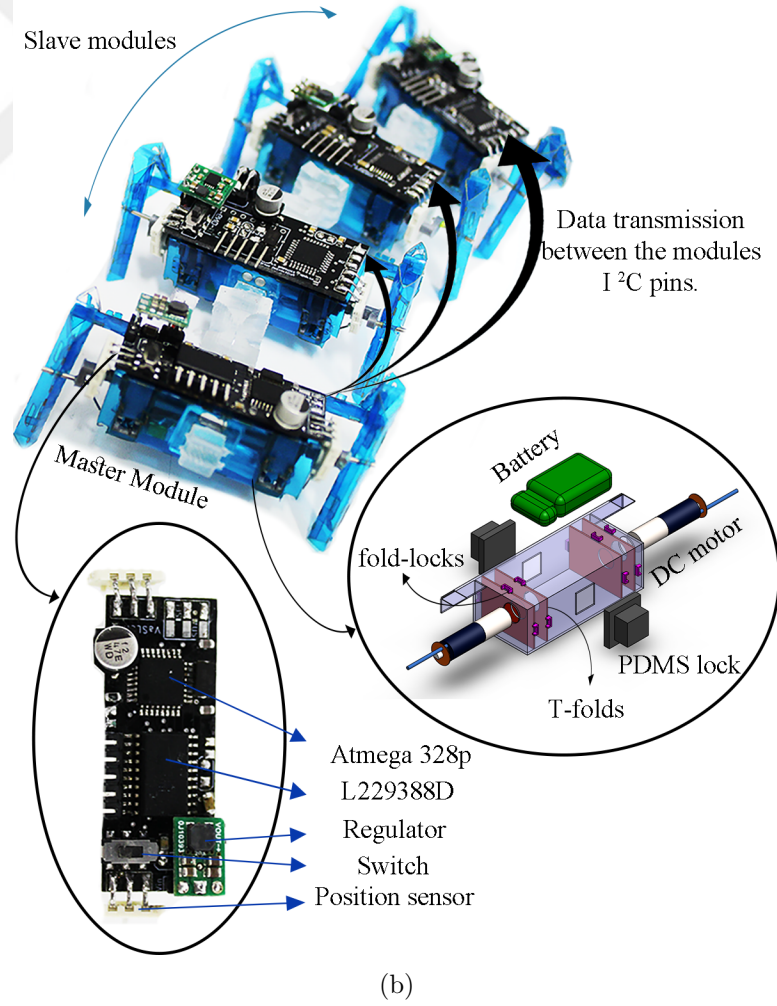
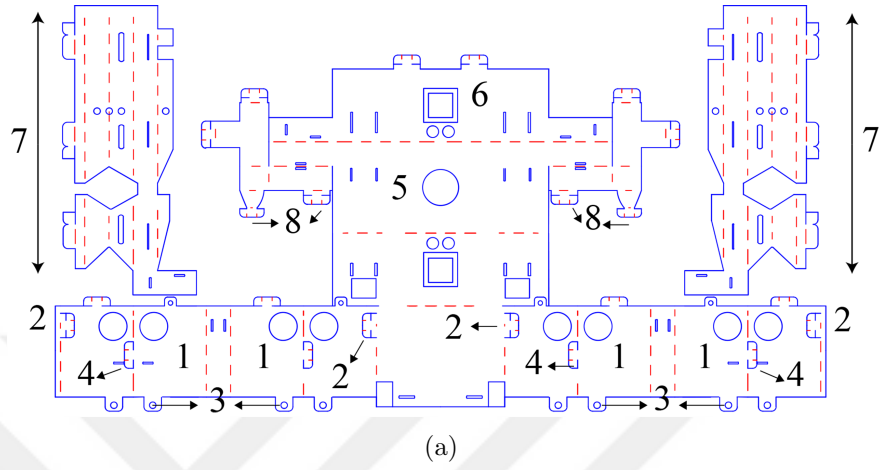


Figure 2.8: (a) SMoLBot's AutoCAD design (b) Eight-legged four-module SMoL-Bot and a single module's exploded view with electrical components.

cam-shafts are designed to build the connections between the module body and the C-shaped feet with a tight-fit insertions holding the position sensors as well.

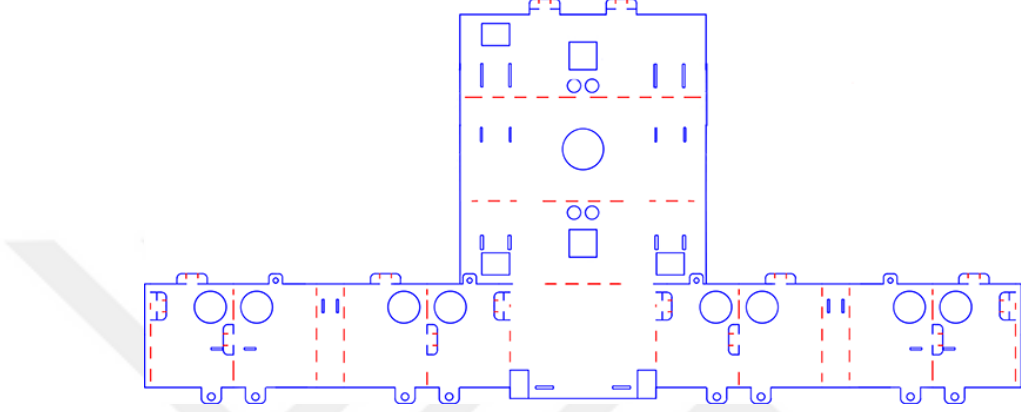


Figure 2.9: Schematics of the C-SMoLBot's AutoCAD module design.

2.5.1 C-shaped Leg Design

Robust structure, fast running, better in-place turning, easier steering, and obstacle scaling capabilities make C-legged robots applications to have much higher levels of adaptability in different environments. C-shaped leg design would allow the body to adapt to the surface conditions without requiring much control effort, which was first introduced in Rhex [43]. Simple half-circle shaped design similar to the C-leg model in Rhex is used to manufacture the C-SMoLBot's feet. In order to investigate the effect of feet compliance in the miniature robot's locomotion and their climbing capabilities, two different types of soft and hard feet are used in the C-SMoLBot experiments. Hard feet are 3D-printed structures coated with PDMS and soft feet are manufactured using PDMS with a mixing ratio of 5:1. Avoiding any collision between two individual feet on consecutive modules and obtaining a range of stiffness that can carry the weight of the module are two main parameters that affect the dimensions of the foot. The need to eliminate module collisions sets a maximum radius length of the foot which is defined based on the length of the backbone and the module, and the intended stiffness range of the foot defines the thickness of the C-shaped leg. Two different feet types of the C-SMoLBot are shown in Fig. 2.10.



Figure 2.10: C-shaped 3D-printed and PDMS feet with 3D printed cam-shaft extensions.

Long half-cylindrical parts of the feet in Fig. 2.10 are the cam-shafts that make it feasible to connect the feet to the motors. 3D-printed cam-shafts are placed inside the 3D-printed molds before curing the PDMS feet to make a tight-fit connection between the PLA and the PDMS. A single foot in C-SMoLBot is 4 *mm*-thick half-circle with inner and outer radiuses of 5.5 *mm* and 12 *mm*, respectively.

2.5.2 Performance of C-SMoLBot

Headmost experiments of the multi-legged C-SMoLBot are done to measure the translational velocity of the robot and to observe the obstacle climbing performance of the C-SMoLBot (Fig. 2.11). Experimental results are inspected to compare the maneuver and climbing potentials of the legged and C-legged SMoL-Bots. Additionally, a study investigating the effect of soft C-shaped feet on the robot's locomotion is conducted as well, comparing the results in soft C-shaped with hard C-shaped feet.

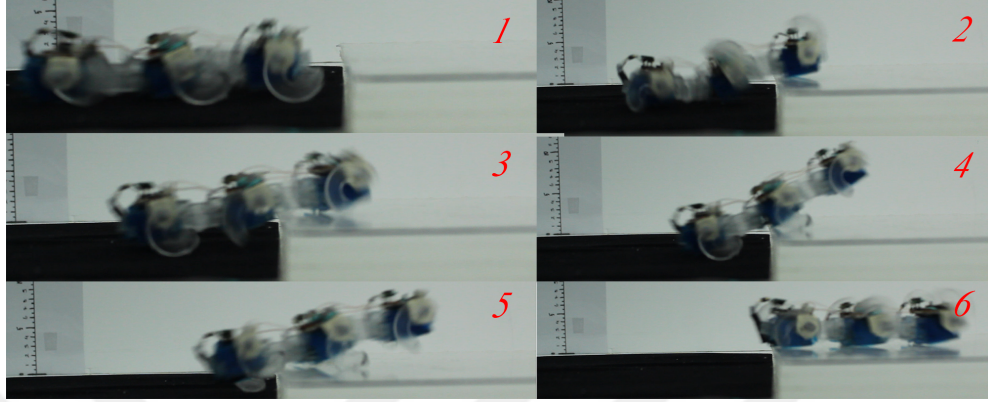


Figure 2.11: Six-legged three-module C-SMoLBot obstacle climbing experiment.

2.6 Evolution of SMoLBot

This section will demonstrate briefly the earlier versions of the robot and SMoLBot's design evolution.

2.6.1 Body and Leg Mechanisms

With the intention of obtaining the smallest possible module frame, different frame designs that each uses various positioning combinations of the components (DC motors and battery) were considered. In earlier versions of SMoLBot, the motors were placed parallel on top of each other and the battery was placed on top of the module inside a rectangular housing structure. One of the earliest versions of SMoLBot where the DC motors are placed on top of each other is shown in Fig. 2.12.

Using the design concept mentioned earlier, we were able to manufacture modules that are almost in the half size of the latest version of SMoLBot. However, the initial robot configuration requires designing two different four-bar leg mechanisms for the right and left legs due to the miss-alignments of the motors. Using four-bar leg design formulations and an optimization technique, it was possible to achieve two different leg designs that have similar trajectories, shown in Fig.

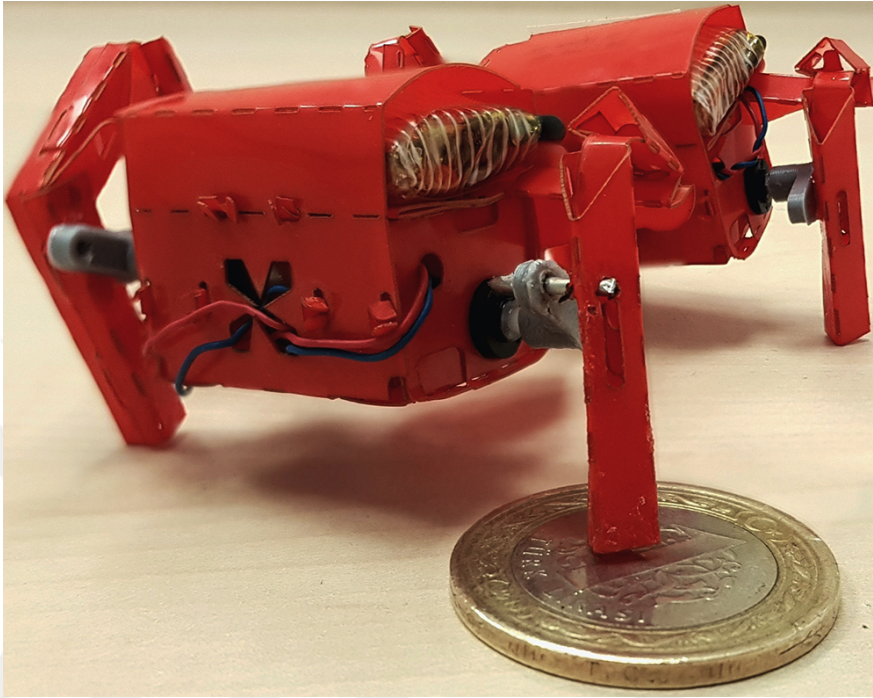


Figure 2.12: Old version SMoLBot with two different four-bar (right and left) feet designs.

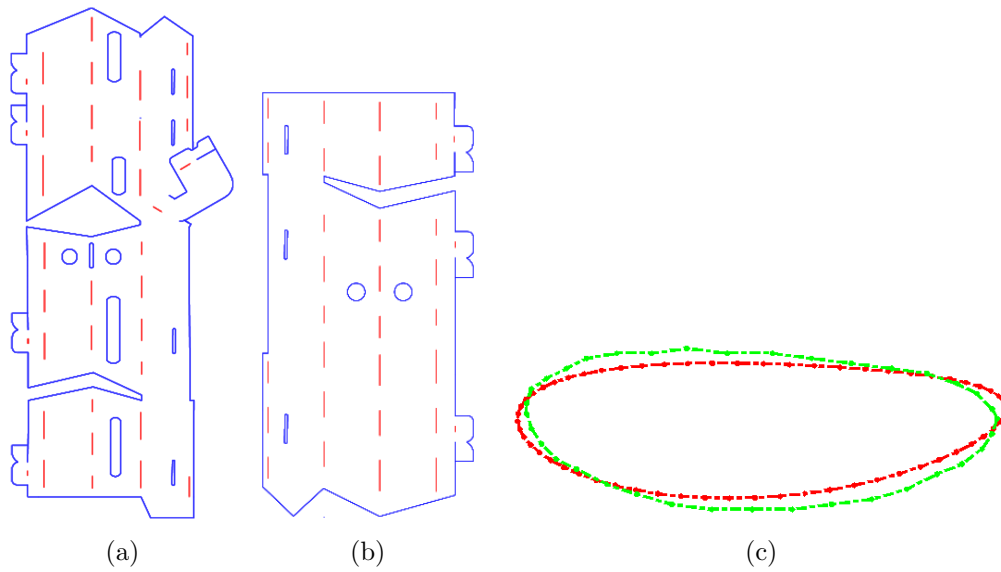


Figure 2.13: (a) Non-straight knee-shaped four-bar leg. (b) Straight four-bar leg. (c) Trajectory of the knee-shaped and the simple four-bar legs of the old version SMoLBot.

2.13(c). The first leg model is a simple straight leg design, shown in Fig. 2.13(a), and the other leg is a non-straight knee-shaped design with a fixed locking angle, shown in Fig. 2.13(b). The proposed design for the knee-shaped link consists of two regular triangular beams connected with a short flexure joint and an inclined fixed-angle tab-and-fastener. It should be noted that the angle between the inclined fastener and the leg on the unfolded structure is equal to the resulting desired fixed-angle lock between the folded beams. Even though it was possible to achieve feet trajectories that are similar to each other, straight walking/running locomotion was not achieved. This was the reason to design the latest version of SMoLBot with a slightly bigger module frame but similar left and right feet, that eliminates the revolving motion of the robot.

2.6.2 Backbones

The initial version of the backbones were cut and folded using the same acetate sheets that are used to manufacture the modules (Fig. 2.14). Backbone designs consist of consecutive folds that form three-dimensional mechanisms that integrate rigid structures to the soft plates in order to achieve an extra DOF in a specific direction. Acetate sheet backbones were categorized into three different types: stiff, 1-DOF, and 2-DOF (Fig. 2.15). Acetate sheet backbones are placed on the rear patches of the modules and are connected to the second module using fold-locks. Stiff backbones are square cylinder-shaped structures that possess the highest bending and torsional stiffness, and compliant acetate sheet backbones are a combination of folded prisms and thin plates. The number of the plates in different directions determines the DOF of the compliant acetate sheet backbone. 1-DOF backbone has only one compliant plate in only one direction and the 2-DOF backbone possesses two plates in two perpendicular directions.

Foldable compliant backbones have two major problems; First, minimizing the dimension of the backbones is not possible, i.e. scaling down the compliant patches increases the stiffness of the backbone and makes the folding process longer and

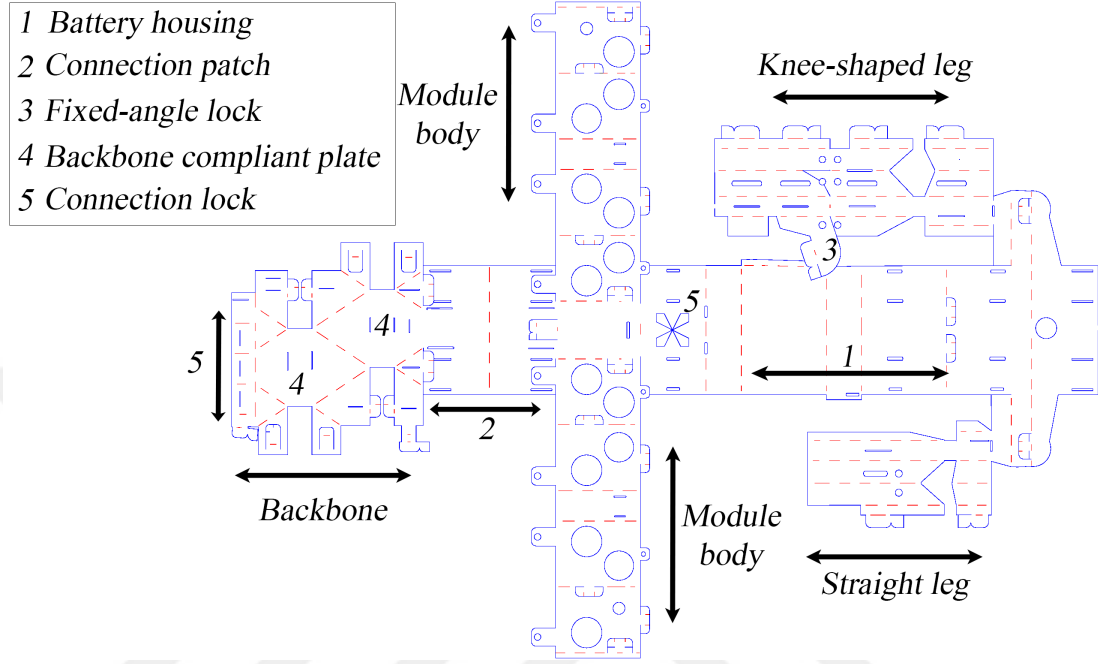


Figure 2.14: Old version SMoLBot's AutoCAD design with a 2-DOF acetate sheet backbone.

even sometimes impossible. The second problem is related to the nature of the manufacturing method of the foldable backbones, in which the fold lines play an important role in manufacturing an origami structure. Appearance of the permanent fold lines on the compliant patches due to the tension and compression forces, eliminates the elastic behavior of the foldable compliant backbone (Fig. 2.16) and results in the robot's failure. This problem was observed shortly in all foldable compliant backbones during the robot's operation due to the periodical compression-tension bending motions. Failure of the foldable backbones during the operation was the main reason to modify the backbone's design. Two main factors are considered while manufacturing the new backbones: the possibility of modeling the backbone and changing the stiffness values easily. The concept of manufacturing backbones using PDMS, enables imposing different stiffness values to the system by simply changing the backbone's geometrical dimensions, and makes it possible to model the backbone using the beam's theory and the PDMS properties.

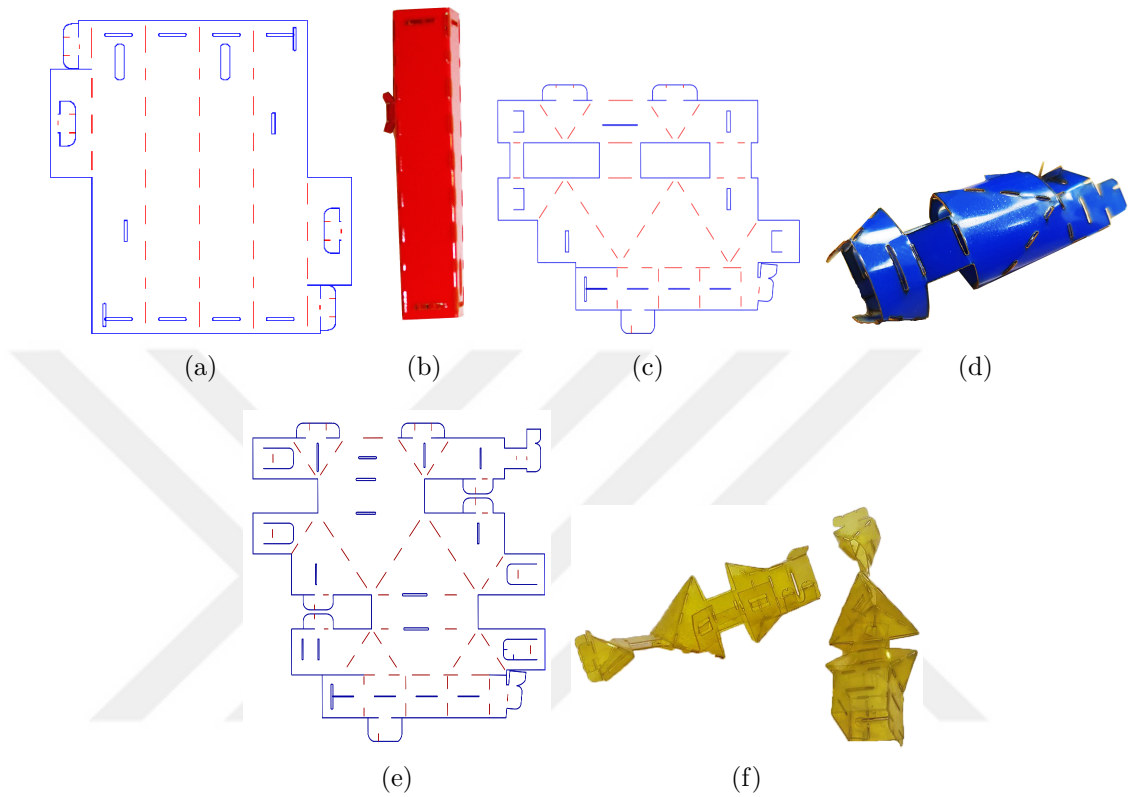


Figure 2.15: (a) Stiff acetate sheet backbone's AutoCAD design, and (b) real Stiff acetate sheet backbone. (c) Foldable 1-DOF acetate sheet backbone's AutoCAD design, and (d) real foldable 1-DOF acetate sheet backbone. (e) Foldable 2-DOF acetate sheet backbone's AutoCAD design, and (f) real foldable 2-DOF acetate sheet backbone.

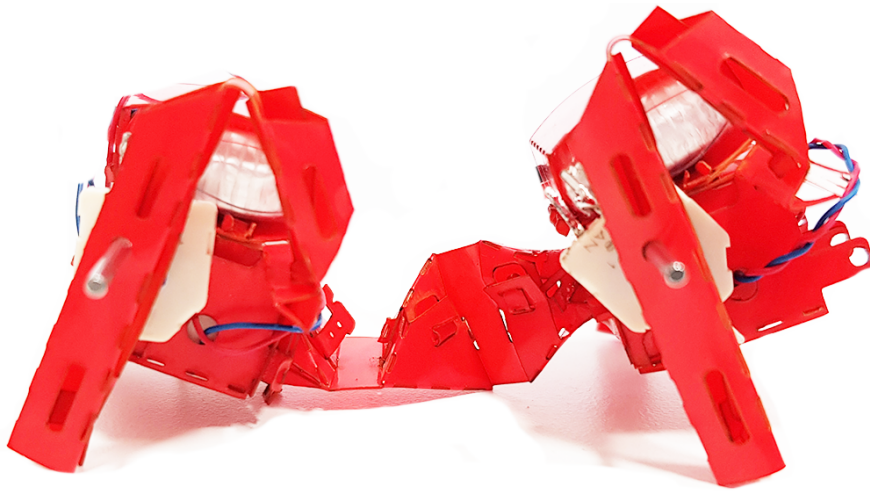


Figure 2.16: Operation failure of a four-legged two-module initial version SMoL-Bot with 2-DOF foldable compliant backbone.

Chapter 3

Operation and Control

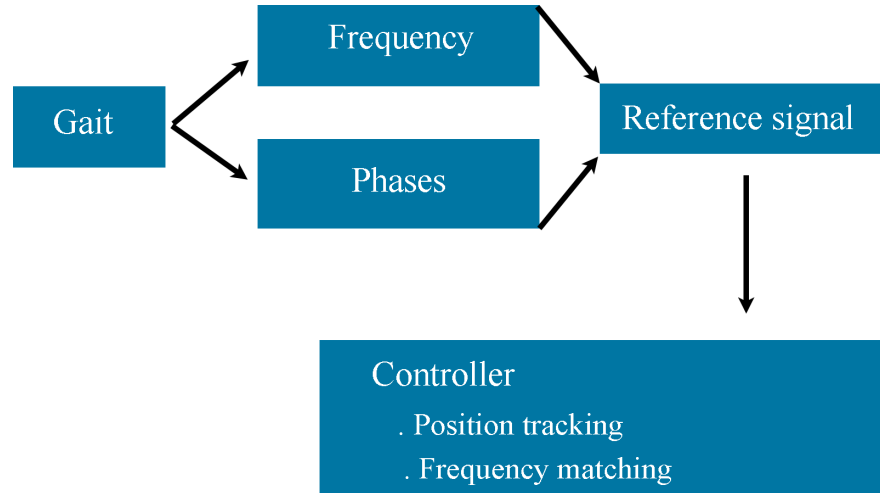
This chapter discusses the control strategy of SMoLBot and briefly demonstrates the dynamic locomotion parameters of the robot with different backbones and module numbers, on a terrain. The motors used in SMoLBot do not have any feedback sensors attached. Therefore, low-cost position sensors, Bourns Potentiometer 3382 series, are used for the position and the velocity control of each leg. To achieve gait synchronization with specific constant feet phases, legs are controlled using two parallel PD control loops: one controlling the position of the motor and one controlling the velocity.

3.1 Controller Design

With an aim to study the effect of the number of legs on miniature modular robot's locomotion and in order to investigate the motion behavior of the robot with various types of backbones while operating with distinct combinations of running/walking gaits, each leg is actuated and controlled individually. The signal from each sensor is used to estimate both the frequency and the phase of the motors with respect to the main reference signal. Since sensors used in SMoLBot are position sensors with 330° output range, motor speeds are calculated at each

controller loop only within the controllable range of the cycle to avoid system failure in 30° sensor dead range. The controller reference signals consist of two main parameters: the desired stepping frequency and the desired position. Both these parameters are chosen, based on the gait that is being studied and the desired translational velocity of the robot. The electrical connections between different modules are done by using I^2C pins of the micro-controllers. Instantaneous value of reference signal generated in the leader module is transferred to all remaining modules which are referred to as the follower modules. Step-wise process of the control stage can be summarized as follows:

1. Gait is defined by the operator.
2. Desired frequencies are imposed to the system by the operator.
3. Reference signal is generated in the leader module.
4. Desired phase differences and frequencies of the legs are transmitted to the follower modules.



5. Instantaneous value of the reference signal is transferred to the follower modules.
6. Motors are individually controlled with PWM signals, based on the reference signal with two parallel controller loops for the frequency and position.

Steps 1 - 4 are executed only once in the beginning and their outputs are stored in the main code, remaining steps are continuously executed in each loop for controlling purposes. A modified PD controller similar to [44] is used to control the motor positions, which uses two parallel PD control loops for the position of the motor and the estimation of the velocity as in (3.1). Reference tracking of two motors with 0 and 180° phases (trot gait) can be seen in Fig. 2.7. Trot gait is a quadruped gait where diagonal legs are in phase and two side-by-side pair legs are 180° apart in phase.

$$PWM^i = PWM^{i-1} + kp_{frq} \cdot E_{frq}^i + kd_{frq} \cdot (E_{frq}^i - E_{frq}^{i-1}) + \quad (3.1) \\ kp_{pos} \cdot E_{pos}^i + kd_{pos} \cdot (E_{pos}^i - E_{pos}^{i-1})$$

where, the superscripts i and $i - 1$ correspond to the current and previous step values, and the subscripts pos and frq denote position and frequency related parameters. E shows the error between the current value and the desired one. k_p and k_d are the proportional and derivative gain of the controller.

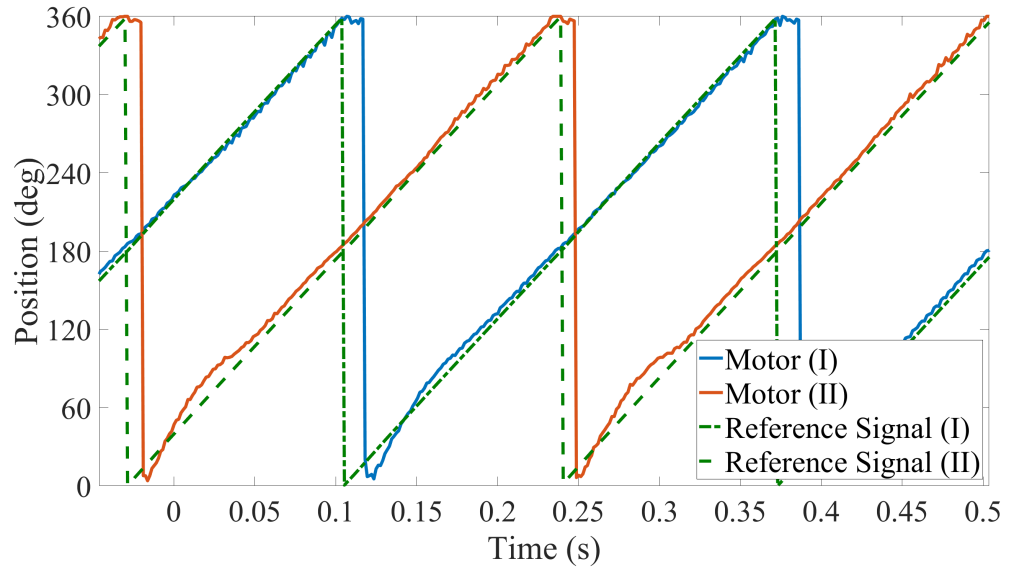


Figure 3.1: Controller output for two DC motors with π phase difference.

In Fig. 2.7 dash lines are reference signals with the phase difference equal to 180°. The results are obtained using serial communication between the Arduino

on the PCB and MATLAB, demonstrating the reference signals and the sensors' output showing the motors' real-time positions.

3.2 Performance of SMoLBot

3.2.1 Operation and Experiments

The first experiments on SMoLBot are designed to observe the effect of the backbone stiffness on the smoothness of the robot's locomotion. The experiments are run with two and three-module robots with rigid backbones and compliant backbones. The robots are run with trot gait at 2 Hz stepping frequency on smooth and rough surfaces and the roll and pitch angles of the robots, as well as their translational velocities, are compared. A picture of a four-legged two-module SMoLBot walking on rough terrain is shown in Fig. 3.2, in which the surface used is a 1 : 10M scaled version of the NASA Shuttle Radar Topographic Mission 90M elevation data for Oregon [45].

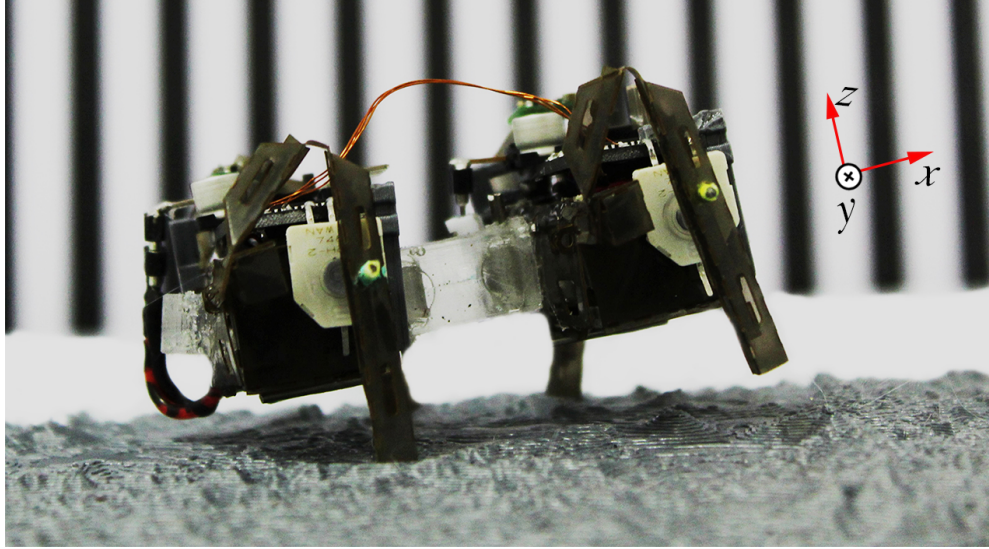
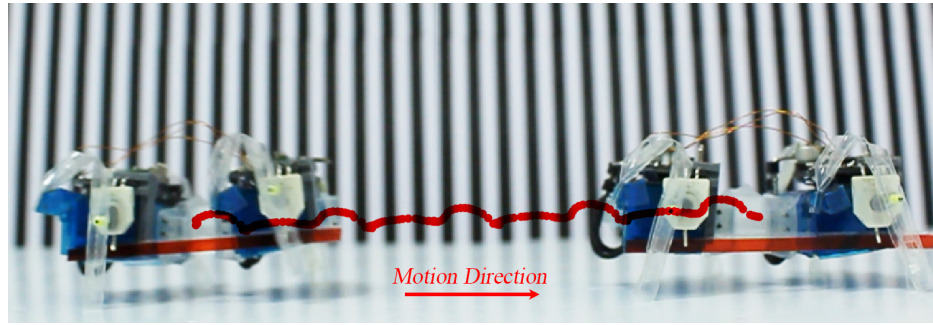
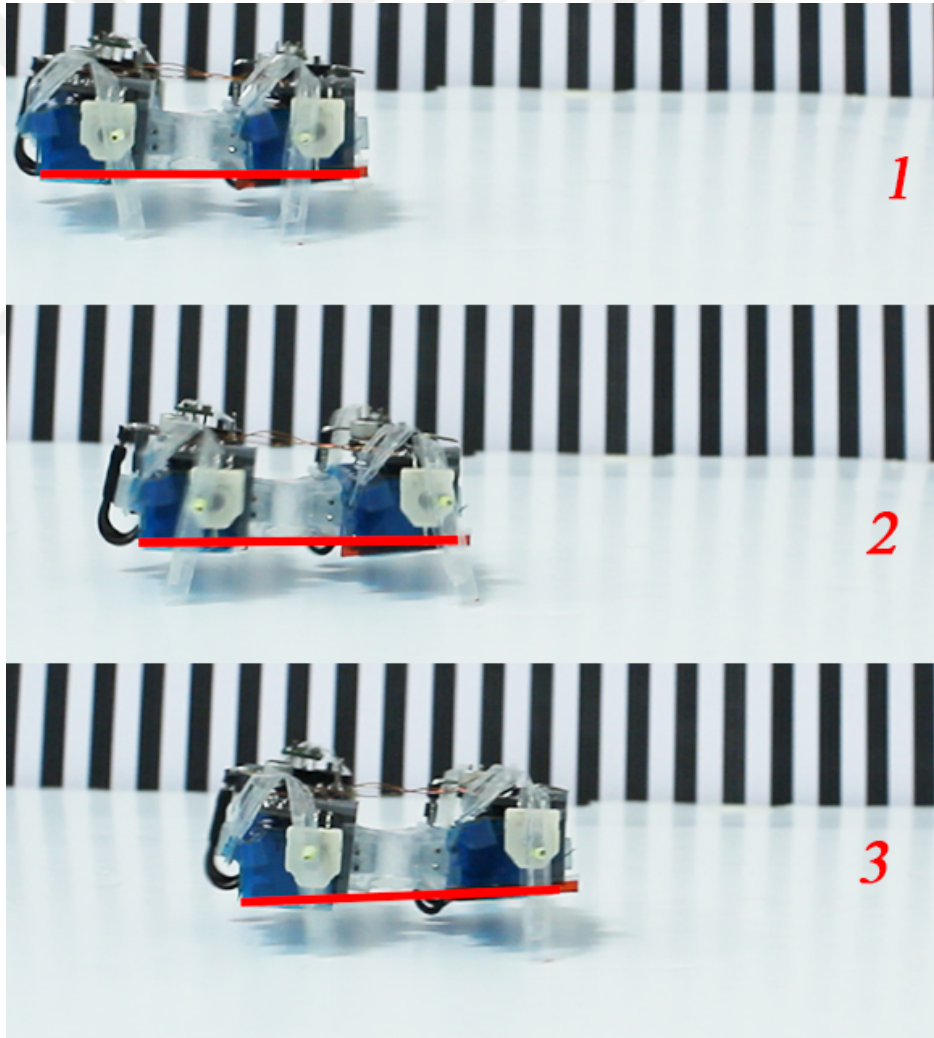


Figure 3.2: The rough terrain locomotion of four-legged two-module SMoLBot with rigid backbones.

Roll and pitch angles of SMoLBot are defined about the axis parallel to the length



(a)



(b)

Figure 3.3: (a) Center of gravity detection and pitch angle measurement of the four-legged two-module SMoLBot with compliant(E) backbone. (b) Crawling four-legged two-module SMoLBot with compliant(I) backbones and zero pitch angle.

(x) and width (y) of the robot; these axes are shown in Fig. 3.2. Orientation and velocity data are obtained using raw videos showing the robot from side, front, and top. Roll and pitch angles are measured using front and side view videos, respectively. Top-view videos are used to detect the robot’s center of gravity in the xy plane and to measure SMoLBot’s velocity.

The difference of pitch and roll angles of the four-legged two-module SMoLBots with compliant(E) and rigid backbones can be seen in Fig. 3.4 and 3.5, respectively. The four-legged two-module robot with compliant(E) backbone (SMoLBot₂(E)) has smoother walking behavior compared to the four-legged two-module robot with a rigid backbone (SMoLBot₂(R)) on smooth terrain. The results show that the roll angle variation during locomotion is reduced from 10° to 7° and the pitch angle variation decreased from 12° to 6° switching from the rigid backbone to the compliant one for SMoLBot₂. Four-legged two-module robots with compliant backbones conform to the surface better because of the body undulations and the torsion between the two modules, resulting in a smoother locomotion.

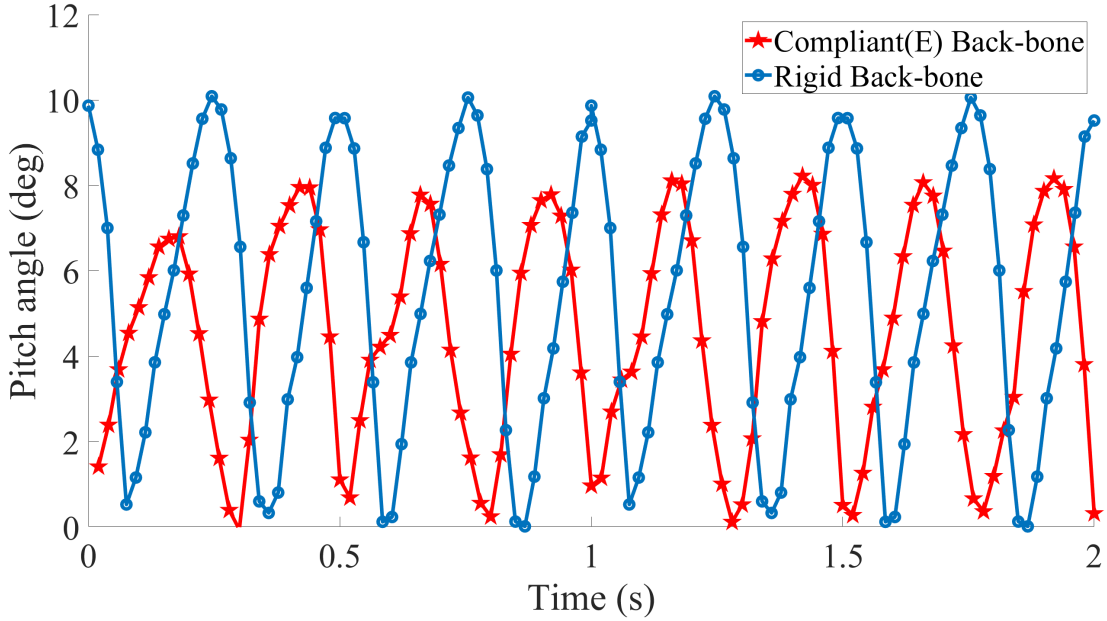


Figure 3.4: The pitch angle of four-legged two-module SMoLBot with rigid and compliant backbones on smooth terrain that are operating with a trot gait.

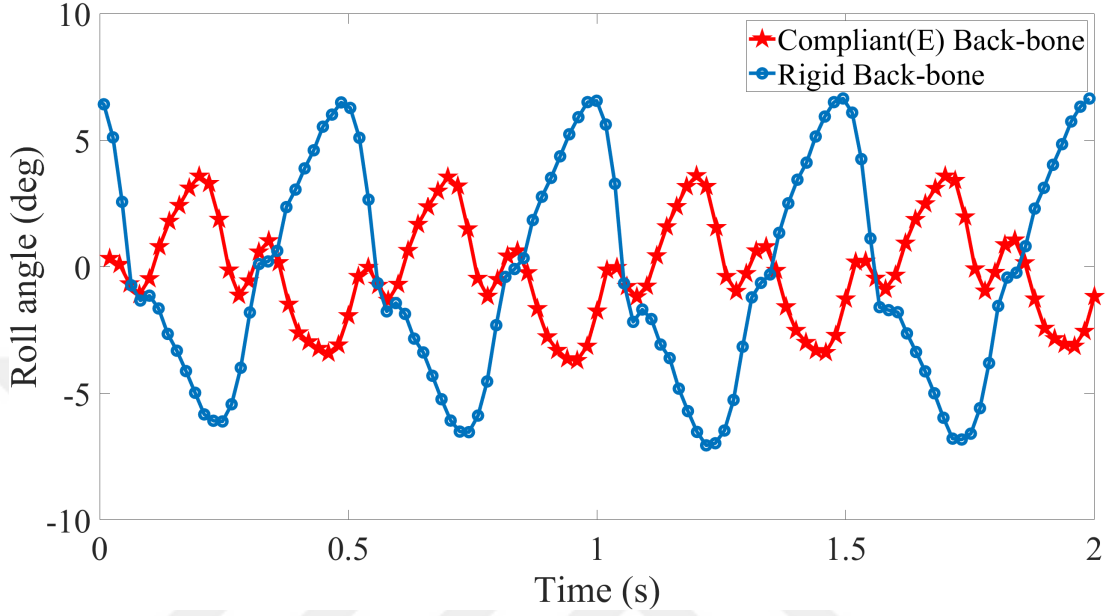


Figure 3.5: The roll angle of four-legged two-module SMoLBot with rigid and compliant backbones on smooth terrain that are operating with a trot gait.

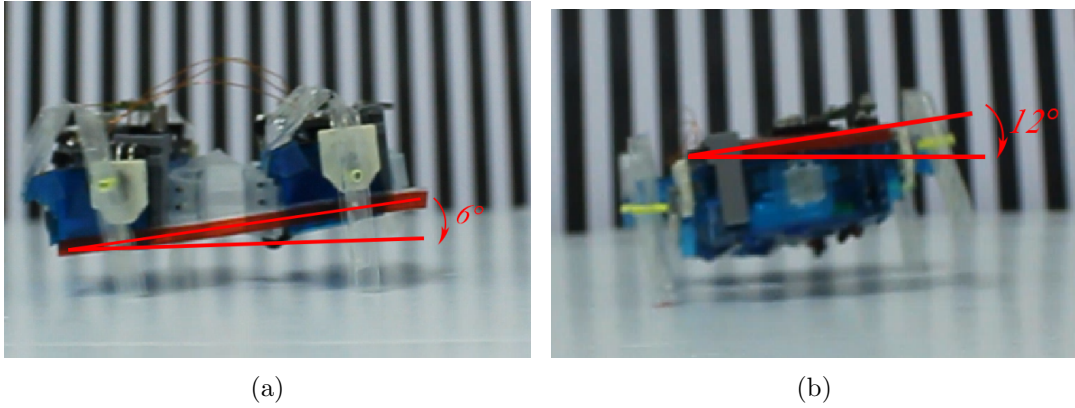


Figure 3.6: (a) Pitch angle measurement experiment of SMoLBot with compliant(E) backbones. (b) Roll angle measurement experiment of SMoLBot with rigid backbones.

Table 3.1: TRASNLATIONAL VELOCITIES OF THE FOUR-LEGGED TWO-MODULE AND SIX-LEGGED THREE-MODULE SMoLBotS

Robot	SMoLBot ₂ (R)	SMoLBot ₂ (E)	SMoLBot ₃ (R)	SMoLBot ₃ (E)
$v(\frac{\text{mm}}{\text{s}})$	46.10	52.40	64.26	61.36

The smoother locomotion achieved due to the compliance of the backbone, shows its effects on the locomotion speed, as well. Table 3.1 shows the linear velocities of four-legged two-module and six-legged three-module SMoLBots with compliant and rigid backbones on smooth terrain. Two-module robots with rigid backbones roll and pitch more compared to the compliant robots. These body rotations result in a difference between the commanded trot gait and the actual gait achieved by the robot because of the lack of touch feedback in the robot's feet. The compliant backbones allow the robot to conform to the surface better and increase the contact duration of the feet in the stride period, resulting in a higher velocity in four-legged two-module compliant robots compared to the four-legged two-module rigid robots.

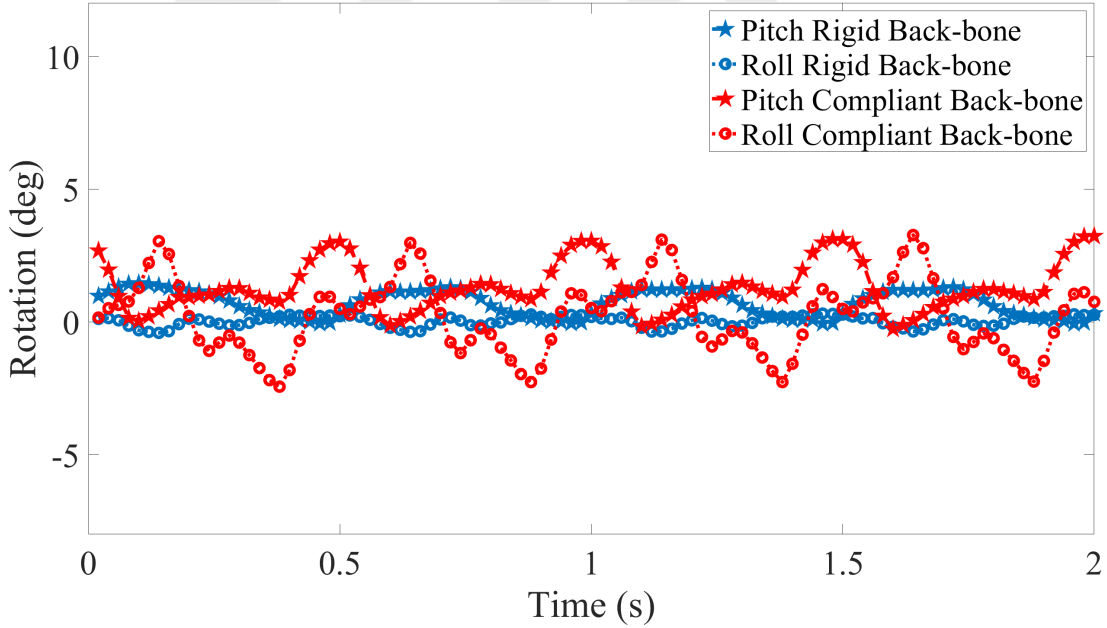


Figure 3.7: The pitch and roll angles of SMoLBot₃(R) and SMoLBot₃(E) with alternating-tripod gait at 2 Hz stepping frequency on smooth terrain.

Experimental results show that such speed difference between the compliant and the rigid versions does not exist for three module SMoLBots. This speed indifference also supports the hypothesis that the four-legged two-module robots with compliant backbones have faster locomotion because of the difference between the intended gait and the achieved gait, because the gait difference is minimal in three-module robots that are operating with alternating-tripod gait. Three

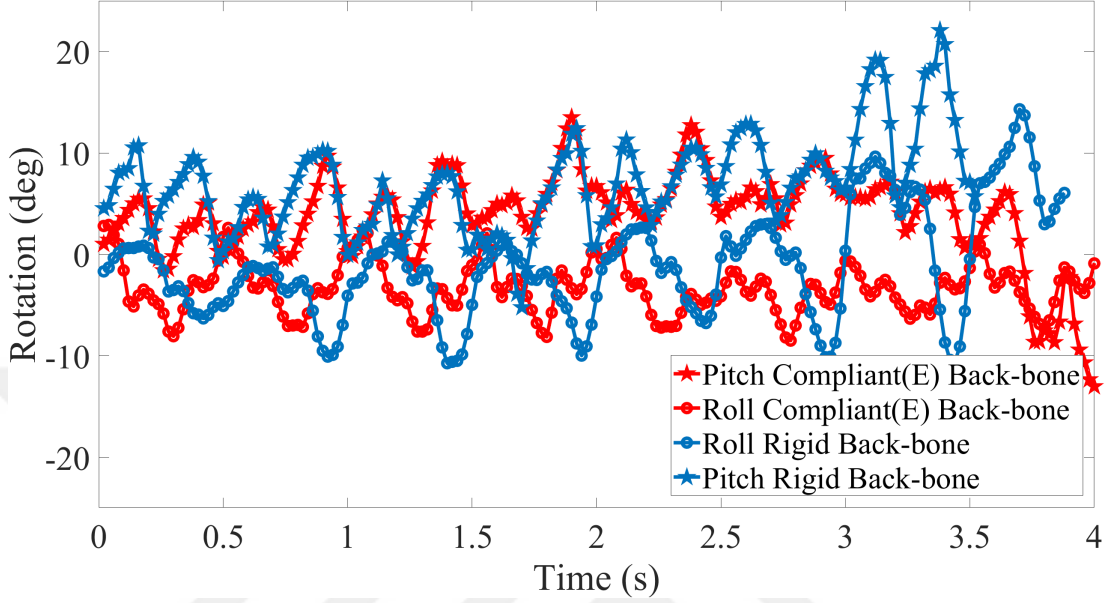


Figure 3.8: Experimental roll and pitch angles of SMoLBot₂ with trot gait on rough terrain.

module SMoLBots operate with an alternating-tripod gait, as a result, three legs are always in contact with the ground during walking. The tripod configuration results in very small pitch and roll angles, as shown in Fig. 3.7. Therefore the robot's gait is almost the same as the intended gait. It can also be observed that a smoother locomotion can be achieved with six legs rather than four legs. This is rather an expected result, since, in a trot gait, a quadruped should be on two feet, but often falls on a third leg forming a tripod, whereas, with six legs, the trot gait turn into a statically stable alternating tripod gait. Roll and pitch angles for the six-legged three-module robots are reduced compared to the four-legged two-module robots. The maximum roll angle is reduced almost from 10° to 1° and pitch angle decreased from 12° to 2° . Similarly, the maximum pitch angle of SMoLBot with the compliant(E) backbone is reduced from 7° to 3° . On the contrary, the roll angles for SMoLBot₃ and SMoLBot₂ are almost equal to each other. This is due to the fact that roll angles for the robots with compliant backbones are mainly dependent on the torsional stiffness of the backbone rather than the number of legs. Torsional stiffness between the modules for SMoLBot₃ and SMoLBot₂ are equal to each other and constant, which explains the roll angle's

behavior for SMoLBot₃ and SMoLBot₂ with compliant backbones.

SMoLBot's experimental results on rough terrain have shown that SMoLBots with a compliant backbone shows a slightly smoother locomotion on rough terrain compared to the rigid one. This can be concluded by observing the y -range of the red curves and comparing them to the range of blue curves shown in Fig. 3.8. On the other hand, a secondary observation is made during the rough terrain experiments. Legs on SMoLBot with compliant backbones face no fatigue issues during the experiments, conversely, legs in rigid backbone experiments faced failure and were changed several times during the experiments. This is due to the sharp changes in the contact force while the legs are hitting the ground and random physical behavior of the rough terrain. The flexible behavior of the soft backbone serves as an impact damper, reducing the effect of sudden and sharp contact forces on SMoLBot's legs.

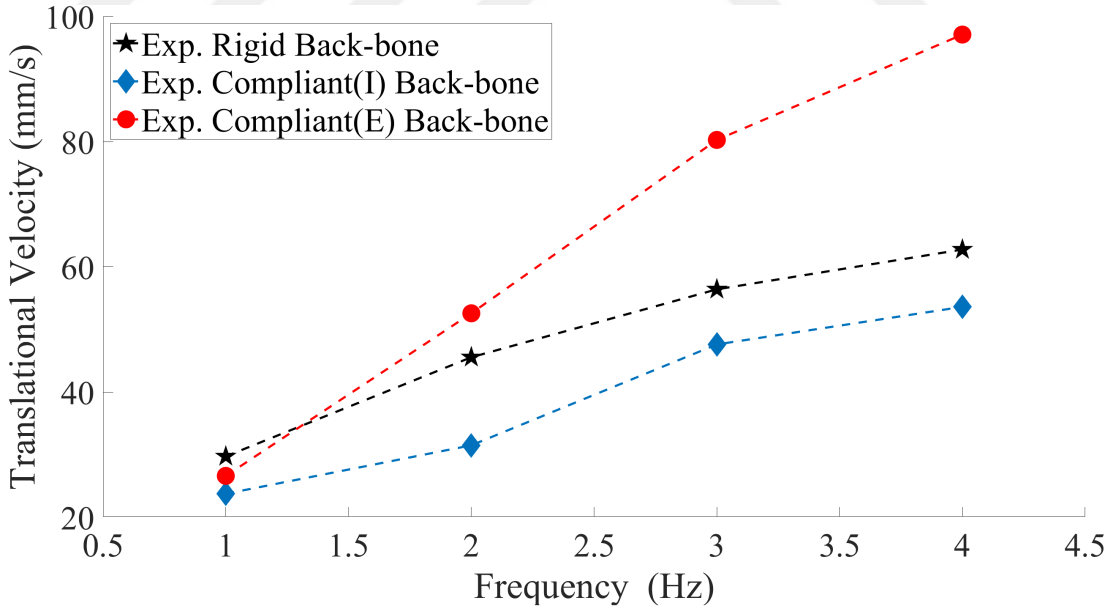


Figure 3.9: Experimental velocity results for SMoLBot₂ with trot gait over the frequency range of 0 - 5 Hz on smooth terrain.

In order to investigate the effect of backbone stiffness on miniature modular legged robot's locomotion, experiment results for SMoLBot with four legs and two modules are compared as shown in Fig. 3.9. Velocity results indicate the

existence of an optimum stiffness value that would make the robot walk with a higher translational velocity within the frequency range of 0 - 5 Hz. As Fig. 3.9 shows, the compliance of the backbone is increasing the linear velocity to some extent; SMoLBot with compliant(E) backbone has higher translational velocity than SMoLBot with rigid backbone. Four-legged two-module SMoLBot(I)'s feet have zero lift and the robot tends to crawl on the ground rather than following a lift and stride trajectory. This crawling motion introduces noticeable opposing friction forces to the system that decreases the overall translational velocity of the robot.

Chapter 4

Dynamic Modeling

SMoLBot, is an under-actuated multi-legged robot with soft module connections providing varying multiple degrees of freedom in spatial space. The DOF of the robot depends on the module number and the backbone type embedded into the robot. Each leg in SMoLBot is actuated by a single actuator that is driving a closed-chain 1-DOF four-bar mechanism with passive joints, and SMoLBot's backbones are modeled as compliant three-dimensional spring-damper joints that connect individual modules. A kinematic model of the robot or two-dimensional dynamic models are insufficient to predict the motion of SMoLBot in the space, due to the out-of-plane motions of a single module and relative three-dimensional motions of the modules with respect to each other, that result in a complex non-uniform locomotion. Thus, to study the multi-legged miniature robot's locomotion and the efficient running/walking gaits of the robot, and to investigate the importance of the individual design parameters on the miniature robot's performance, a three-dimensional full-body dynamic model of the robot is indeed required.

4.1 Robotic Modeling Literature

Since many biological systems utilize soft and hard materials in unison, studying and modeling complex soft-hybrid structures would help us for better understanding and exploiting the natural locomotion concepts [46]. By the means of understanding biological locomotion dynamics, many researchers are investigating the underlying dynamics of insects and their locomotion trends [47], [48], [49]. On the other hand, robotics are exploiting the biological locomotion dynamics to design walking [50], [51], [9], [44], crawling [52], [53], [54], [32] and swimming [55], [56] miniature robots. Most of these works are templates to predict the dynamic motion of miniature robots using experimental trials [57], or for the sake of simplicity, the works consider only planar locomotion or a two degree of freedom (2-DOF) system model and avoid three-dimensional real and complex dynamics [58], [59]. Even though the simplified 2-DOF planar model for modular robots with crawling motion would seem satisfying [60], [61], a 2-DOF model would not be a high fidelity approach for the legged miniature robots that possess out-of-plane motions and significant angular orientations in all directions. With the intention of analyzing miniature modular legged robots walking patterns and to study the effects of soft connections on the locomotion of the miniature legged robots, a comprehensive three-dimensional model of the body rotations and out-of-plane dynamics should be used. Full body dynamics of the robot would provide a better insight into the miniature modular legged robots' locomotion trends with varying ranges of compliance between the modules.

Conventionally, mechanical systems are considered to have sets of rigid bodies and links connected to each other with joints, spring, and/or dampers. Commonly in legged robots, one body is considered to be a floating-base and the remaining bodies and links are modularized using that particular object. Modeling feet of the robot with 180° rotating linkages that drive the robot would be the foremost step of the legged robot models. One of the most common leg model is the Spring-Loaded Inverted Pendulum (SLIP) leg template [62], which has been used in numbers of robotic platforms with several DOF [63], [64]. The SLIP leg template would be a nice candidate while modeling robots that have active joints or if the

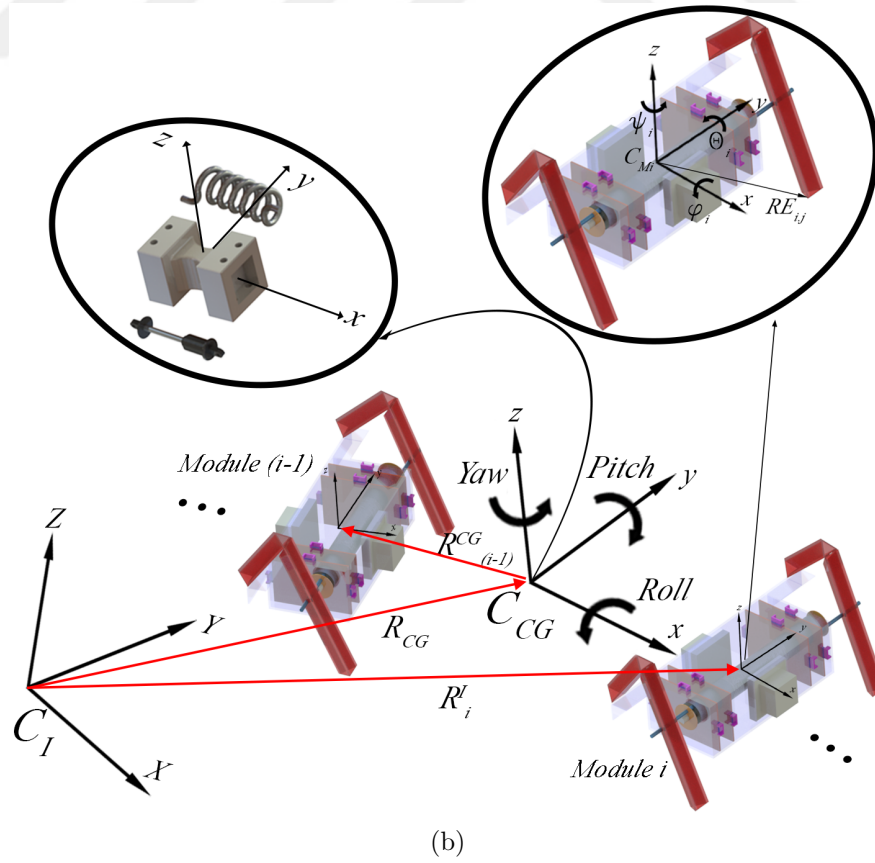
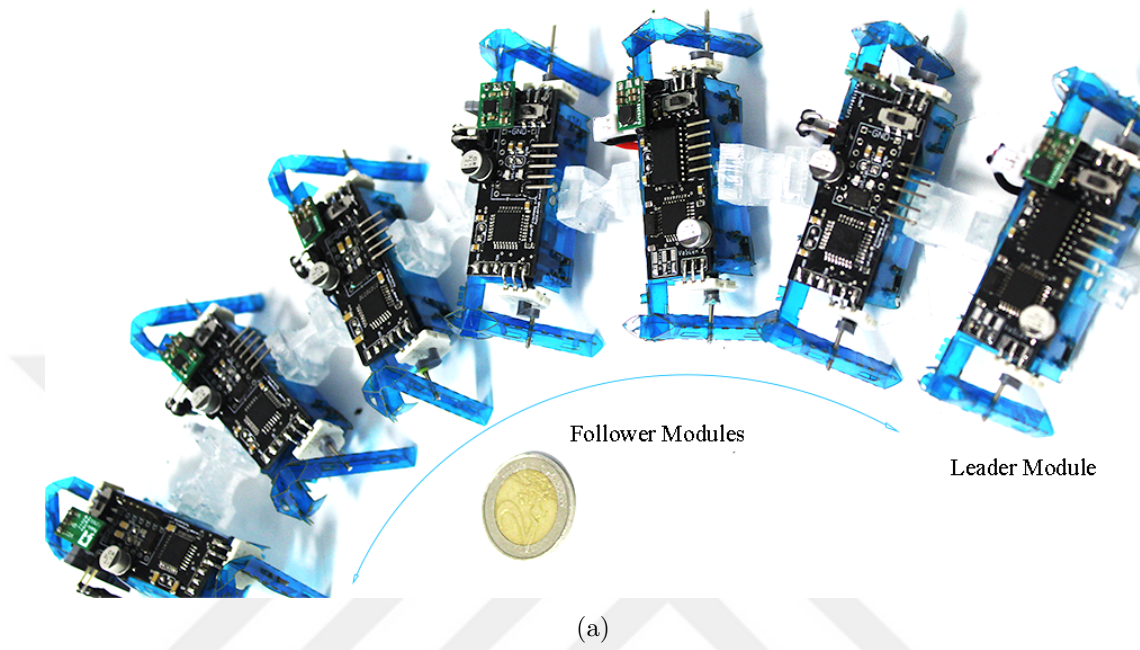


Figure 4.1: (a) Fourteen-legged seven-module SMoLBot's leader-follower definition. (b) Simulation schematic of the modules and coordinate systems used in SMoLBot's simulations.

feet is actuated using a single-link direct drive systems such as the ones used in the RHex [43], Sprawl hexapods [65], and BigDog [66]. However, for the one-DOF four-bar leg mechanism that uses passive joints to obtain a 180° rotation, which are excessively used in miniature robots, the SLIP leg template would be hard to implement. The SLIP model uses the kinematic and dynamic parameters of the soft joints to describe the overall motion, and obtaining the parameters for the flexure joints of the feet, requires solving nonlinear large deflection beam theories. Also, the unknown and uncontrolled torques of the small-scaled DC motors used to actuate the feet of the miniature robot and the absence of possible sensors in miniature scale to measure the generated torques, make the implementation of the SLIP model almost impossible. One possible approach to model the feet would be closed-chain kinematic analysis. The kinematic analysis method seems to be a better technique for miniature legged robots with passive joints and simple four-bar leg mechanisms, since the model uses the angular position of the motors rather than the generated torque to determine the unknown motion parameters of the leg.

The dynamic model of SMoLBot is developed using the Newton-Euler formulation and closed-chain leg kinematics similar to [67]. Closed-chain kinematic analysis of the feet is used to model SMoLBot's feet, which determines the position and the velocity of the feet at the instance. The dynamic model of the multi-legged robot is dependent on the physical properties of the contact and constant backbone parameters. Backbones are modeled as rotational spring-dampers systems, that connect two individual modules. The dynamic model determines the locomotion parameters such as: the position and the orientations of the modules' COG and their rate change, and the locomotion parameters defining the n-legged robot's COG. Different sets of coordinate systems are used in the simulation that are shown in Fig. 4.1. Coordinate system C_I corresponds to the inertial coordinate system fixed on the ground, C_{Mi} , where $i = [1, 2, \dots, N]$, correspond to the coordinate systems attached on the center of geometry of each module's body frame and N is the number of modules. Reference frame C_{CG} is the frame attached to the robot's center of gravity (COG) at each instant.

4.2 Assumptions

The following assumptions are made for the formulation of this model:

1. A folded leg of SMoLBot is a flexure based compliant mechanism. Determining the kinematic parameters of the flexure joints is done by solving the complex nonlinear large deflection beam theories that are computationally heavy. Thus, legs in the simulation of SMoLBot are modeled as simple four-bar linkages with rigid links and pin joints. Additionally, the legs are considered to remain always parallel to the body and do not deform while the feet are in contact with the ground. Finally, the motion parameters of the feet are derived using a kinematic analysis of the four-bar linkages while assuming the soft foldable patches of the foot as revolute joints.
2. A single point contact is assumed to occur between the feet and the ground. Also, a single contact point of the feet results in a zero contact radius, which eliminates the need to model torsional friction at the feet while it hits the ground. This is a valid assumption considering the thickness of a 0.1 mm-thick cellulose acetate sheets that are used to manufacture the feet of SMoLBot.
3. Legs are considered to be mass-less and the entire mass of the robot is uniformly distributed within the frames of SMoLBot's modules. This can also be verified considering the fact that a single module with electrical components and two PDMS locks almost weighs 19 g, and a single leg is about 0.15 g which is less than one percent of the total weight. Besides, the majority of the mass is concentrated in the main body which comprises the actuators, the sensors, the PCBs, the battery, and the PDMS locks, which is making up to more than 95 percent of the weight.
4. The stepping frequencies of the motors are assumed to be constant, which keeps the relative phase offset between the feet persistence according to the desired operating gait of the robot.

Additional minor assumptions are pointed out throughout the text.

4.3 Kinematic Analysis of a Leg

Leg model consists of 5 links connected to each other overall with a single DOF. Each leg is actuated using a DC motor, which is attached to the body and is connected to the leg with an external cam-shaft (Fig. 2.4). With the assumption of legs being parallel to the module frame, a set of three-dimensional local position vectors, and linear and rotational velocity vectors are defined for each leg, with respect to the module's body attached frame C_{Mi} . The kinematic parameters such as the length, the attachment point of the legs to the body, and the attachment point to the motors are known from the primary design. The leg is designed using the optimization techniques to obtain a trajectory path with a relatively long stride length and large foot lift. Table 4.1 shows the constant dimensions of a single leg of SMoLBot.

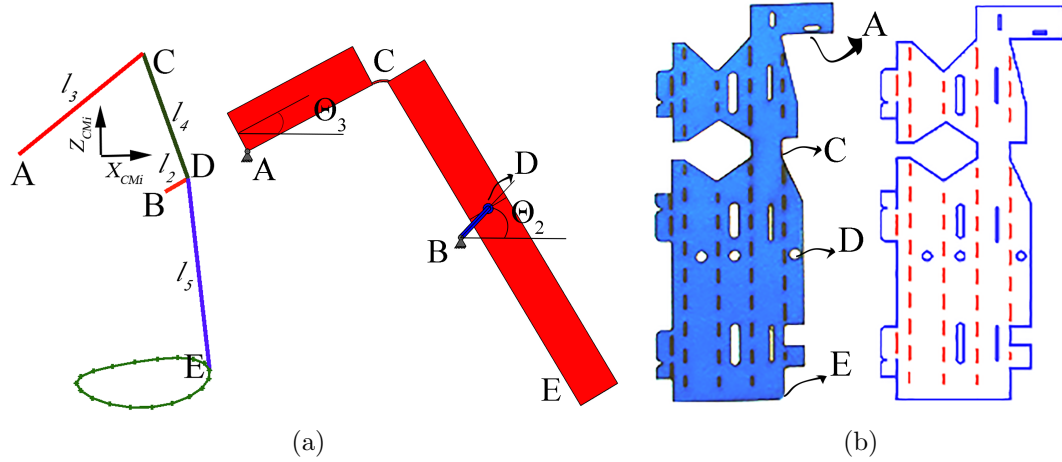


Figure 4.2: (a) A representation of a folded leg and a schematic diagram of a four-bar mechanism of SMoLBot. (b) Actual unfolded leg and its AutoCAD design with cut lines in blue and fold lines in red.

Legs' crank angles $\theta_2^{i,j}$, where $i = [1, \dots, N]$ and $j = [1, 2]$, are defined as functions of time. Parameter i is the module number, and j showing the right ($j = 1$) and left ($j = 2$) leg. The constant angular velocity of the cranks attached to the legs

are defined as $w_2^{i,j}$. Using four bar leg kinematics, leg dimensions and the crank angles, leg's contact point with the ground in C_{Mi} is represented by,

$$(x_C - x_A)^2 + (y_C - y_A)^2 = l_3^2 \quad (4.1)$$

$$(x_C - x_D)^2 + (y_C - y_D)^2 = l_4^2 \quad (4.2)$$

$$(x_A \pm \sqrt{l_4^2 - (z_C - z_A)^2 - x_D^2} + (z_C - z_D)^2 - l_3^2 = 0 \quad (4.3)$$

$$x_A + \sqrt{l_4^2 - (z_C - z_A)^2} = x_C \quad (4.4)$$

$$\theta_3 = \text{atan2}(z_D - z_C, x_D - x_C) \quad (4.5)$$

$$x_E = x_D + l_5 \cos(\theta_5) \quad (4.6)$$

$$y_E = x_D + l_5 \sin(\theta_5) \quad (4.7)$$

Considering a constant rotational frequency $f_{i,j}$ for the motors that are driving the feet, crank's angular velocity can be defined as $w_2^{i,j} = [0 ; 2\pi f_{i,j} ; 0]$. Defining the link's position vectors as $r_{k_{i,j}}$, where $k = \{A, B, C, D, E\}$ (shown in Fig. 2.4), and a kinematic velocity analysis of a four-bar mechanism in the body attached reference frame (C_{Mi}), the velocity vectors of the points D and C are determined as follow:

$$v_{D_{i,j}} = v_B + w_2^{i,j} \times r_{BD_{i,j}} \quad (4.8)$$

$$v_{C_{i,j}} = v_A + w_4^{i,j} \times r_{AC_{i,j}} \quad (4.9)$$

$$v_{C_{i,j}} = v_{D_{i,j}} + w_3^{i,j} \times r_{DC_{i,j}} \quad (4.10)$$

in which $r_{kl_{i,j}} = r_{l_{i,j}} - r_{k_{i,j}}$, where $l = \{A, B, C, D, E\}$. Equations (4.8) - (4.10) can be solved to find the rotational velocities $w_3^{i,j}$ and $w_4^{i,j}$. Finally, the velocity vector of the point E can be determined by,

$$v_{E_{i,j}} = v_D + w_5^{i,j} \times r_{DE_{i,j}} \quad (4.11)$$

Detailed version and derivation of the kinematic equations can be found in [67]. Defining the length parameter as L_x , the width parameter as L_y and the height parameter as L_z for each module, the leg's attachment point to the body and the motor positions inside each module in C_{Mi} are as $r_{A_{i,j}} = [-L_x/2 ; (-1)^{j+1}L_y/2 + 10.5 ; L_z/2]$ and $r_{B_{i,j}} = [-L_x/2 - 4.21 ; (-1)^{j+1}L_y/2 + 10.5 ; L_z/2 - 4.20]$, respectively.

Table 4.1: CONSTANT LEG DIMENSIONS OF SMoLBot

Dimension	Value (mm)
BD	03.00
CD	16.18
AC	16.83
DE	21.86

4.4 Dynamic Analysis

4.4.1 Dynamical Modeling

The set of dynamic equations defining the three-dimensional locomotion of a robot with N number of modules and soft connections are composed of multiple numbers of non-linear and complex ordinary differential equations (ODEs). For robotic systems, in a three-dimensional Cartesian space, there are two main methodologies used for dynamic modeling: Lagrange [68] and Newton-Euler [69] methods. To derive SMoLBot's dynamic model in Cartesian space, the classical Newton-Euler method including the inertial and the Coriolis forces are utilized. The main purpose of the Newton-Euler method is to find the accelerations associated with the DOF of the legged modular robot for a given set of initial positions and velocities. These accelerations can be integrated to find the corresponding position and the velocity vectors at each time step.

Two sets of parameters with respect to an inertial reference (C_I) and body attached reference frames (C_{Mi}) are used to derive the corresponding dynamic equations. The formulation representing the dynamic parameters, roll, pitch, and yaw angles, and the Euler angle transformation matrices (Eq. (4.17)) are in accordance with [70]. Two separate sets of ODEs are used to define the position, the orientation, and the translational and rotational rates. Initially, the first set of ODEs define the position, the orientation, and their first derivatives for the COG of the robot with 12 ODEs. This initial set of ODEs only concerns the external forces and the moments acting on the whole robot. The second set of equations has a varying number of ODEs with respect to the number of modules in SMoLBot. Adding a module to the robot adds 6 more degrees of freedom to the system, which means 6 more equations are added to the system of ODEs. This set of equations defines the orientation and the rotational velocity of each module in response to the external forces and external moments due to the contact interaction and the moments due to the soft backbones. First set of ODEs considers the robot as a single body and defines the system parameters for COG of the robot, the second set of ODEs considers each module as a separate system and determines the dynamic parameters in body attached reference frame (C_{Mi}).

4.4.2 Body Dynamics

Using Newton-Euler formulation, the translational and rotational equations of motion in the inertial reference frame can be derived using Newton's second law. The forces and the moments acting on the COG of the robot are three-dimensional orthogonal vectors F and M due to the external contact forces, expressed in alternate frames. F_{CG} and M_{CG} are the net external forces and the moments acting on the COG of the robot, expressed in the C_{CG} , are given by:

$$F_{CG} = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \quad M_{CG} = \begin{bmatrix} \chi_x \\ \chi_y \\ \chi_z \end{bmatrix} \quad (4.12)$$

Six equations of motions are developed using F_{CG} and M_{CG} , while considering the Coriolis terms to determine the absolute time rate of change of a moving vector using Newton's second law in the COG attached reference frame (C_{CG}) [71]. The net external force formula can be defined as follow:

$$F_{CG} = \frac{d(m_t V_{CG})}{dt} + \Omega_{CG} \times (m_t V_{CG}) \quad (4.13)$$

in which, V_{CG} and Ω_{CG} are SMoLBot's translational and rotational velocities, represented in C_{CG} reference frame, respectively. m_t is the constant mass of the robot. V_{CG} and Ω_{CG} define the six degrees of freedom corresponding to the translation velocity along the C_{CG} axes and the rotational velocities, rate change of roll, pitch, and yaw angles, about the C_{CG} axes, where:

$$V_{CG} = \begin{bmatrix} u \\ v \\ w \end{bmatrix} \quad \Omega_{CG} = \begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (4.14)$$

Net external moment on robot's COG, expressed in the COG attached reference frame (C_{CG}), can be determined as:

$$M_{CG} = \frac{d(I_G \Omega_{CG})}{dt} + \Omega_{CG} \times (I_G \Omega_{CG}) \quad (4.15)$$

in which, I_G is the mass moment of inertia tensor that is calculated with respect to the C_{CG} axes.

Equation (4.15) requires the use of the parallel axis theorem and rotational transformation of moment on inertia using the Euler angles. This is due to the dispersed constant mass over each module on SMoLBot and the rate of change of the body orientation parameters. Modules' positions and orientations in terms of Euler angles in inertial reference frame are denoted by $R_i^I = [X \ Y \ Z]^T$ and $\Theta_i^I = [\phi_i \ \theta_i \ \psi_i]^T$, where $i = [1, \dots, N]$ and N is the number of modules. Similarly,

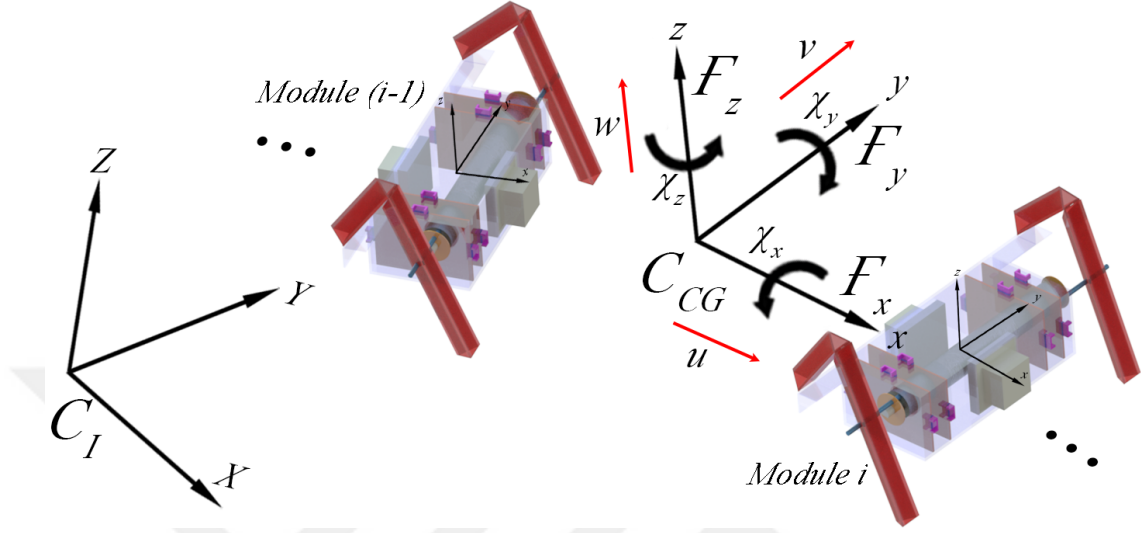


Figure 4.3: SMoLBot's COG dynamic parameters used in the model.

R_{CG} and Θ_{CG}^I define the position of the COG of the robot and its orientation in the inertial reference frame. Using the module's position and orientation vectors, parallel axes theorem, and mass moment of inertia rotation theorem, I_G can be found [72] by:

$$I_G = \sum_{i=1}^n H_I^{CG} (H_i^I I_{Mi}^p H_i^I) H_{CG}^I \quad (4.16)$$

where, I_{Mi}^p is the moment of inertia of the module i with respect to the frame that is parallel to the C_{Mi} , and is placed on the center of gravity of the robot. Each module is considered as a rectangular prism with a constant weight. Same procedure introduced using the parallel axes theorem and (4.16) is used to determine the I_{Mi} if the COG of the module and the center of geometry of the prisms are not identical. H_l^k are rotation matrices that are expressed in the terms of yaw-pitch-roll ($Z - Y - X$) rotation angle sequence, where l and k identify two different reference frames. Any vector defined in l reference frame can be expressed in the k reference frame by multiplying it with the rotation matrix H_l^k . Rotation matrices between the reference frames attached on COG of the modules and the inertial reference frame, are as follows:

$$H_I^i = \mathfrak{R}_{\phi_i} \mathfrak{R}_{\theta_i} \mathfrak{R}_{\psi_i} \quad (4.17)$$

$$\mathfrak{R}_{\phi_i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\phi_i & -s\phi_i \\ 0 & s\phi_i & c\phi_i \end{bmatrix}, \mathfrak{R}_{\theta_i} = \begin{bmatrix} c\theta_i & 0 & s\theta_i \\ 0 & 1 & 0 \\ -s\theta_i & 0 & c\theta_i \end{bmatrix}, \mathfrak{R}_{\psi_i} = \begin{bmatrix} c\psi_i & -s\psi_i & 0 \\ s\psi_i & c\psi_i & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$H_I^i = \begin{bmatrix} c\theta_i c\psi & c\theta_i s\psi_i & -s\theta_i \\ s\theta_i s\phi_i c\psi_i - c\phi_i s\psi_i & s\phi_i s\theta_i s\psi_i + c\phi_i c\psi_i & s\phi_i c\theta_i \\ c\phi_i s\theta_i c\phi_i + s\phi_i s\psi_i & c\phi_i s\theta_i s\psi_i - s\phi_i c\psi_i & c\phi_i c\theta_i \end{bmatrix} \quad (4.18)$$

in which, s and c are in short the $\sin()$ and the $\cos()$ functions. ϕ , θ , and ψ are the Euler angles defined about the x , y and z axes, respectively. The reverse procedure of transforming a vector on the C_{M_i} to the inertial reference frame is done using H_I^I , which is equal to inverse of H_I^i . $(H_I^i)^{-1} = (H_I^i)^T$, since H_I^i is an orthogonal matrix, therefore, its inverse and transpose are equal to each other. Position vector R_{CG} , orientation vector Θ_{CG} , and their derivatives can be related to their counterparts defined in the C_{CG} using transformation matrices. Six more ODEs that define the dynamic parameters for robot's COG in the inertial reference frame using transformation matrices, as follows:

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} = H_i^I \begin{bmatrix} u \\ v \\ w \end{bmatrix} \quad (4.19)$$

$$\begin{bmatrix} \dot{\phi}_{CG} \\ \dot{\theta}_{CG} \\ \dot{\psi}_{CG} \end{bmatrix} = L_i^I \begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (4.20)$$

in which, L_i^I represents a separate transformation of the rates of the three Euler

angles by the rotation matrix defined as follows:

$$L_i^I = \begin{bmatrix} 1 & s\phi_i t\theta_i & c\phi_i t\theta_i \\ 0 & c\phi_i & -s\phi_i \\ 0 & s\phi_i/c\theta_i & c\phi_i/c\theta_i \end{bmatrix}.$$

12 ODEs in (4.13), (4.15), (4.19), and (4.20) define the translational velocity, rotational velocity, position, and the orientation of the robot's COG. These parameters are prerequisites in determining the dynamic locomotion parameters of each module, described in the next step.

4.4.2.1 Modular Dynamics

In order to represent the dynamics of an N -module robot, $6 \times (N - 1)$ ODEs are added to the system of equations. This new set of equations defines the orientation and the rotational velocity vectors for each module in C_{Mi} , where $i = [2, 3, \dots, N]$. Module $i = 1$ is assumed to have the same orientation and rotational velocity vector as the COG of the robot. Ω_{CG}^i is the rotational velocity vector of the module i in C_{Mi} defined as:

$$\Omega_{CG}^i = \begin{bmatrix} p_i \\ q_i \\ r_i \end{bmatrix} \quad (4.21)$$

where, p_i , q_i , and r_i are the rate changes of the roll, pitch, and yaw angles of the module i about C_{Mi} axes. Equation (4.22) defines the rotational velocity parameters for each module in C_{Mi} reference frame.

$$M_{CG}^i = \frac{d(I_{Mi}\Omega_{CG}^i)}{dt} - \kappa^{i-1}.\delta\varphi_F^i + \beta^{i-1}.\delta\varpi_F^i - \kappa^i.\delta\varphi_B^i + \beta^i.\delta\varpi_B^i - \quad (4.22)$$

$$I_{Mi}.\alpha_{CG}^{Mi} + \Omega^i \times (I_{Mi}\Omega^i)$$

$$\dot{\Theta}_i^I = L_i^I \begin{bmatrix} p_i \\ q_i \\ r_i \end{bmatrix} \quad (4.23)$$

where, $i = [2, 3, \dots, N]$. M_{CG}^i and I_{MG}^i are the moments on the COG of the module i (COG^i) and the moment of inertia of the module i . κ^i and β^i are the rotational stiffness and the rotational damping coefficient of the backbone, that connects the module i to the module $i - 1$ (Fig. 4.4). $\delta\varphi_F^i$ and $\delta\varpi_F^i$ are the relative angular orientation and the relative angular velocities of the module $i - 1$ and i in C_{Mi} . α_{CG}^{Mi} is the time rate of change of the angular velocity of the robot's COG expressed in C_{Mi} . Ω^i is the vector sum obtained using the Ω_{CG}^i and Ω_{CG} , expressed in C_{Mi} .

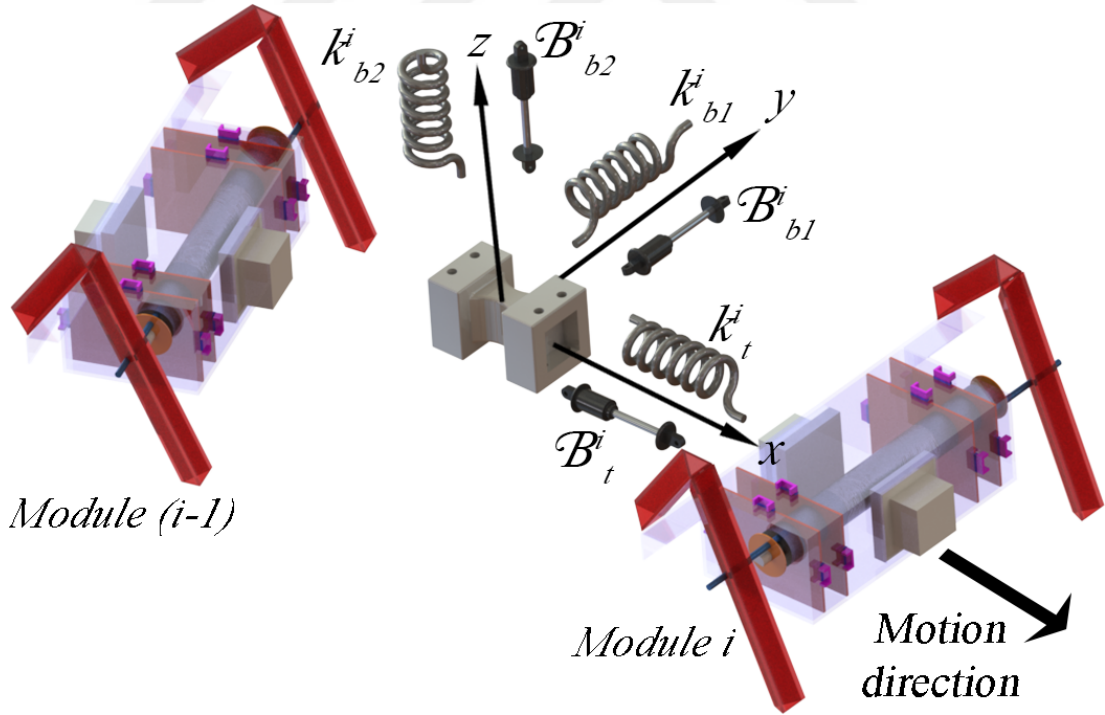


Figure 4.4: Connection between two modules, modeled as a spring-damper system.

$12 + 6 \times (N - 1)$ number of ODEs describe the position, the orientation, translation and rotational velocities of the COG of the robot along the C_{CG} axes, and the

orientation and rotational velocities of each module's COG^i along the C_{Mi} . Final formulation of the dynamic equations are summarized bellow:

$$\begin{aligned}
\dot{V}_{CG} &= \frac{F_{CG}}{m} - \Omega_{CG} \times (m_t V_{CG}) \\
\dot{\Omega}_{CG} &= I_G^{-1} (M_{CG} - \Omega_{CG} \times (I_G \Omega_{CG}) - \dot{I}_G \Omega_{CG}) \\
\dot{R}_{CG}^I &= H_i^I \begin{bmatrix} u \\ v \\ w \end{bmatrix} \\
\dot{\Theta}_{CG}^I &= L_i^I \begin{bmatrix} p \\ q \\ r \end{bmatrix} \\
\dot{\Omega}_{CG}^i &= (I_{Mi})^{-1} (M_{CG}^i + \kappa^{i-1} \cdot \delta \varphi_F^i - \beta^{i-1} \cdot \delta \varpi_F^i + \kappa^i \cdot \delta \varphi_B^i - \beta^i \cdot \delta \varpi_B^i + \\
&\quad I_{Mi} \cdot \alpha_{CG}^{Mi} - \Omega^i \times (I_{Mi} \Omega^i)) \\
\dot{\Theta}_i^I &= L_i^I \begin{bmatrix} p_i \\ q_i \\ r_i \end{bmatrix}
\end{aligned}$$

4.4.2.2 Modular Body Kinematics

Contact and friction forces of the legs are dependent on the position of the COG^i . Equations (4.24) and (4.25), determine the center of mass and the transformation matrices connecting the module $i-1$ to the module i . These equations determine R_i^I , using the position of COG of the robot and the Euler angles.

$$R_{CG}^I = \frac{\sum_{i=1}^n m_i R_i^I}{\sum_{i=1}^n m_i} \quad (4.24)$$

$$R_i^I = R_{i-1}^I + \hbar_i^I \quad (4.25)$$

where, $i = [2, 3, \dots, N]$. $\hbar_i^I$ are the set of vectors and transformation matrices

connecting the module $i - 1$ to the module i , expressed in C_I . $\hbar_i^I$ are dependent on the lengths of the backbones and the modules in different directions. For a single backbone, lengths are in the form of $LB = [l_{b1}, l_{b2}, l_{b3}, l_{b4}, l_{b5}]$, where l_{bk} represent the lengths of the backbone, $\hbar_{i-1}^I$ as:

$$\begin{aligned} \hbar_i^I = H_{i-1}^I \begin{bmatrix} \frac{-Lx}{2} - l_{b1} \\ 0 \\ 0 \end{bmatrix} + \Re_{\psi_i} H_I^i H_{i-1}^I \begin{bmatrix} -l_{b2} \\ 0 \\ 0 \end{bmatrix} + \Re_{\phi_i} H_I^i H_{i-1}^I \begin{bmatrix} -l_{b3} \\ 0 \\ 0 \end{bmatrix} \\ + \Re_{\theta_i} H_I^i H_{i-1}^I \begin{bmatrix} -l_{b4} \\ 0 \\ 0 \end{bmatrix} - H_i^I \begin{bmatrix} \frac{+Lx}{2} + l_{b5} \\ 0 \\ 0 \end{bmatrix} \end{aligned} \quad (4.26)$$

Using (4.25) and (4.26) the positions of the COG^i ($i = [2, 3, \dots, N]$) can be written in a way, that are only dependent on the position of module $i = 1$ and the Euler angles. This formulation and (4.24) determine the position of module $i = 1$ as the only unknown parameter and then it can be used to calculate R_i^I for $i \geq 2$.

4.5 Estimation of Ground Reaction Forces

4.5.1 Impact Force Model

Input parameters for the ordinary ODEs are the external forces and moments acting on the robot and the internal moments. Internal moments are due to the backbone's torsional and bending deformations, which are used in calculating the dynamic parameters of the individual module's COG, and the external forces and moments are due to the contact forces between the legs and the ground, which is used in calculating the dynamic parameters of the robot's COG. However, to define the ground reaction forces generated due to contact of the feet and the ground, analysis within the fixed inertial reference frame is required. Different models present different approaches to determine the contact forces such as the Hertzian contact model that studies the elastic contact of two different curved

surfaces without considering the energy loss [73]. On the other hand, many researchers developed linear and nonlinear contact modeling methods to account for the energy dissipation. One of the initial models concerning the energy dissipation of the contact is the Kelvin-Voigt's model, which assumes a linear spring-damper system [74, 75]. Kelvin-Voigt's model is able to determine an approximation of the viscoelastic nature of the contact, however, it is proven that the model's linear behavior has failed to determine the contact parameters while facing a relatively high impact velocity [76].

In this work, we use the contact force model presented by Hunt and Crossley [77]. The calculation of the ground reaction forces of the contact, while the feet are touching the ground, is done within the inertial reference frame C_I . The represented model considers the ground as a nonlinear viscous-elastic spring-damper system, and defines the normal contact force, as follows:

$$F_c = K\epsilon^n + D\dot{\epsilon} \quad (4.27)$$

In this model F_c is the normal contact force, K represents the contact stiffness, n is the nonlinear exponent, D donates the damping coefficient, and ϵ^n and $\dot{\epsilon}$ are the penetration depth and rate of the feet, respectively. ϵ^n and $\dot{\epsilon}$ for the legged robots are determined using the leg's position and relative velocity vectors with respect to the ground in the inertial reference frame. The velocity of the legs along the C_I axes are estimated using kinematic analyses and are dependent on the velocity of the modules. More detailed information about the ground interaction kinematic formulation will be provided in the section 4.5.3.

For a foot that is in contact with the ground, a normal force part of the impact force is generated as a function of a nonlinear spring stiffness (K_c) and displacement-based damping (D_{ϵ_z}), described as,

$$F_c = \begin{cases} 0 & \epsilon_z \geq 0 \\ K_c(\epsilon_z)^e - D_{\epsilon_z}\dot{\epsilon}_z & \epsilon_z < 0 \end{cases} \quad (4.28)$$

where, $D_{\epsilon_z} = S(\epsilon_z, 0, 0, d, c_{max})$. ϵ_z is the penetration depth of the leg, and $\dot{\epsilon}_z$ is the absolute foot penetration rate along the Z axes of the C_I . K_c is the contact stiffness between the leg and the ground, e is the nonlinear force exponent, c_{max} is the maximum damping coefficient, and d is the maximum penetration depth at which the maximum damping is applied to the leg in contact. The $S(x, x_1, y_1, x_2, y_2)$ function is a smooth cubic approximation to an input variable x , rising at (x_1, y_1) and dropping at (x_2, y_2) .

4.5.2 Pseudo-Coulomb Friction Model

The friction force of the the contact is represented in terms of a Pseudo-Coulomb dry friction model given by [78]. Pseudo-Coulomb friction model assumes that pure stiction does not occur, and two bodies have a continuous relative movement with respect to each other. Friction force direction is determined using relative planar velocities between the feet and the ground along X and Y axes of inertial reference frame C_I . The Pseudo-Coulomb friction coefficient denoted by μ is given by;

$$\begin{aligned} \mu = & S(V_{rel}, -V_d, \mu_d, -V_s, \mu_s) + \\ & S(V_{rel}, -V_s, \mu_s, V_s, -\mu_s) + , \\ & S(V_{rel}, V_s, -\mu_s, V_d, -\mu_d) \end{aligned} \quad (4.29)$$

where, V_{rel} is the relative velocity between the leg and the ground, μ_s and μ_d are the static and dynamic coefficients of friction that are $\in [0, 1]$, and V_s and V_d are static and dynamic transition velocities, respectively. Typically it is proven that $\mu_s > \mu_d$, and $V_s < V_d$. Finally, the magnitude of the friction force (F_{fr}) is determined using (4.30).

$$F_{fr} = F_c \mu \quad (4.30)$$

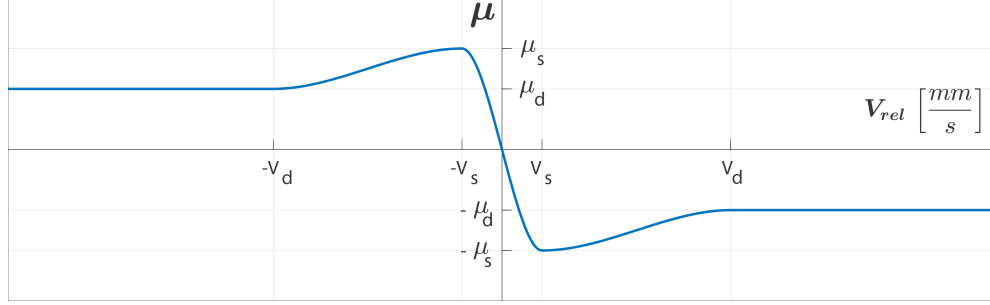


Figure 4.5: Pseudo-Coulomb dry friction model.

4.5.3 Foot Contact Determination

Impact and friction forces depend on the position and the velocity of the leg, that are expressed in inertial reference frame C_I . Position and velocity of the contact point with the ground are denoted as $r_{E_{i,j}}^I$ and $v_{E_{i,j}}^I$, respectively, and are given by:

$$r_{E_{i,j}}^I = R_i^I + H_i^I r_{E_{i,j}} \quad (4.31)$$

$$v_{E_{i,j}}^I = H_i^I (v_{E_{i,j}} + V_i + (\Omega_{CG}^i \times r_{E_{i,j}})) \quad (4.32)$$

where, $i = [1, 2, \dots, N]$ showing the module number and $j = [1, 2]$ representing the right or left leg on the module. V_i is the translational velocity of the module i that is expressed in C_{Mi} , $r_{E_{i,j}}^I = [\epsilon_x \ \epsilon_y \ \epsilon_z]^T$ and $v_{E_{i,j}}^I = [\dot{\epsilon}_x \ \dot{\epsilon}_y \ \dot{\epsilon}_z]^T$. Relative sliding velocity of the foot and the ground for the friction force model is defined as $V_{rel} = \sqrt{\dot{\epsilon}_x^2 + \dot{\epsilon}_y^2}$, and total velocity of the foot is defined as $V_E = \sqrt{\dot{\epsilon}_x^2 + \dot{\epsilon}_y^2 + \dot{\epsilon}_z^2}$.

4.5.4 Net Force and Moment Calculation

Equations (4.28) and (4.30) are used to determine the magnitude of the normal contact and friction forces in inertial reference frame. Total contact force ($F_{E_{i,j}}^I$) for each leg can be written in the vector form, as:

$$F_{i,j}^I = F_{c_{i,j}} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} + F_{fr_{i,j}} \begin{bmatrix} \frac{\dot{e}_{xi,j}}{V_{E_{i,j}}} \\ \frac{\dot{e}_{yi,j}}{V_{E_{i,j}}} \\ 0 \end{bmatrix} \quad (4.33)$$

Net external force on COG of the robot (F_{CG}) in the equation (4.13) is given by:

$$F_{CG} = \sum_{i=1}^N (H_I^{CG} W_i^I + H_I^{CG} H_i^I \sum_{j=1}^2 F_{i,j}^I) \quad (4.34)$$

where, $W_i^I = [0 \ 0 \ -m_i g]^T$ is the weight of each module in the inertial reference frame, m_i is the mass of the module, g is the gravitational acceleration and N is the number of modules. Similarly net external moment (M_{CG}) is given by:

$$M_{CG} = \sum_{i=1}^N H_I^{CG} [(\Delta R_{CG(i)}^I \times W_i^I) + \sum_{j=1}^2 H_i^I (\Delta r_{CG(i,j)}^I \times F_{i,j}^I)] \quad (4.35)$$

where $\Delta R_{CG(i)}^I = R_i^I - R_{CG}$ and $\Delta r_{CG(i,j)}^I = r_{E_{i,j}}^I - R_{CG}$.

Similar approach is used in defining the moments acting on the COG^i (M_{CG}^i), which is used in Eq. (4.22), as:

$$M_{CG}^i = \sum_{j=1}^2 H_I^i H_i^I (\Delta r_{mi,j}^I \times F_{i,j}^I) \quad (4.36)$$

where, $\Delta r_{mi,j}^I = r_{E_{i,j}}^I - R_i$ and $i = [2, \dots, N]$.

4.6 Solving the System of Stiff ODEs

Dynamic model of a legged modular miniature robot with soft backbones is given by $12 + 6 \times (N - 1)$ highly non-linear ODEs, describing the position (Eq. 4.13), orientation (Eq. 4.15), translation velocity (Eq. 4.19) and angular rotation rates (Eq. 4.20) of the COG of the robot, and the orientation (Eq. 4.23) and angular rotation rates (Eq. 4.22) of the individual modules. 12 states defining the dynamic parameters of the robot's COG and $6 \times (N - 1)$ states defining the orientations and the angular rates of the modules, are given by:

$$\chi = [R_{CG}^I, V_{CG}, \Theta_{CG}^I, \Omega_{CG}, \Theta_2^I, \Omega_{CG}^2, \dots, \Theta_n^I, \Omega_{CG}^N]^T \quad (4.37)$$

For any given initial conditions, $12+6 \times (N-1)$ non-linear ODEs, describing $\dot{\chi}$ can be obtained using the equations (4.13), (4.15), (4.19), (4.20), (4.22) and (4.23). Due to the sharp changes in the contact force at the instance that the leg touches the ground, standard numerical nonlinear ODE solution methods such as Euler or Runge-Kutta exhibit instability in the solutions. Hence, MATLAB's build-in numerical ODE stiff solver *ode15s* is used to solve the system, which has shown an increase in stability and a significant decrease in the simulation time. The ODE formulations presented above facilitate the frame work of a dynamic model for a modular robot with soft connections; however, the contact interaction parameters like friction coefficient between the acetate sheets (material used to manufacture the legs and the body) and the ground, contact interaction stiffness, as well as the damping coefficients of the PDMS backbones are unknown and cannot easily be measured. Contact parameters and damping coefficients are obtained using sets of optimization functions, comparing the experimental results in soft and rigid backbones and the results obtained using the dynamic model. Table 4.2 shows the contact parameters used in the simulation.

For plastics such as cellulose acetate sheets, material used to manufacture the feet of SMoLBot, it is suggested to use a force exponent as $e > 1.5$ and it is proven that using $e < 1$, will lead to discontinuity while calculating the force of the

Table 4.2: FORCE MODEL PARAMETERS USED IN THE SIMULATIONS

$K_c(\text{N/mm}^e)$	$c_{max}(\text{N s/mm})$	μ_s	μ_d	$V_s(\text{mm/s})$	$V_d(\text{mm/s})$	$d(\text{mm})$
638.6	0.825	0.59	0.39	11.47	1.10	0.07

contact during the initiation of the contact between the leg and the ground [79]. Therefore, $e = 2$ is chosen to model SMoLBot’s dynamics. Table 4.3 shows the damping coefficients for PDMS backbones obtained using optimization functions.

Table 4.3: BACKBONE DAMPING COEFFICIENTS

backbone	$\beta_t(\frac{\text{N.mm}}{\text{Rad.s}^{-1}})$	$\beta_{b1}(\frac{\text{N.mm}}{\text{Rad.s}^{-1}})$	$\beta_{b2}(\frac{\text{N.mm}}{\text{Rad.s}^{-1}})$
Rigid	∞	∞	∞
Compliant(T)	6.85×10^{-4}	$9.39 \times 10^{+1}$	$9.39 \times 10^{+1}$
Compliant(I)	1.30×10^{-4}	$3.87 \times 10^{+1}$	9.68
Compliant(II)	6.62×10^{-3}	$4.10 \times 10^{+1}$	$5.07 \times 10^{+1}$
Compliant(E)	27.60×10^{-4}	$5.84 \times 10^{+1}$	$1.71 \times 10^{+1}$

Chapter 5

Model Verification

5.1 Verification of Trot Gait Locomotion

Various sets of SMoLBot’s walking/crawling experiments with different types of backbones and different module numbers are used to validate the dynamic model presented in this manuscript. Simulation and experiment results such as roll and pitch angles (that are defined about the axes parallel to the length (x) and width (y) of the robot) and the velocities of the robots with different number of modules are compared, the axes are shown in Fig. 5.1.

Due to the lack of position and orientation sensing devices on the robot, experimental state variables such as roll and pitch angles are estimated using raw videos and by attaching color bands on the robots during the experiments. Roll and pitch angles are estimated by detecting and measuring the angular orientations of the color bands. Orientation data in the straight walking locomotion experiments are taken from the side and front views for the pitch and roll angles, simultaneously. Similarly, the videos for the experimental speed data are shot from the top view, detecting the position of the COG of the robot in the xy plane.

Symmetric physical appearance of the modules, and identical legs on both right and left sides, imply a symmetrical periodic trend of the locomotion parameters, which can be seen both in the simulation and the experimental results (Fig. 5.2(a))- 5.3). Roll and pitch angles for the four-legged two-module SMoLBot (SMoLBot₂) with rigid, compliant(T), and compliant(I) backbones, running with a trot gait at 2 Hz stepping frequency, are shown in Fig. 5.2 and 5.3, respectively. A comparison of the results for different types of backbones have shown a smoother locomotion pattern, indicated by the lower roll and pitch angle magnitudes, while decreasing the bending and torsional stiffness of the backbones (Fig. 5.2 - 5.3). Two-module SMoLBots with compliant backbones conform to the surface better because of the body undulations and the torsion between the two modules, resulting in a smoother locomotion.

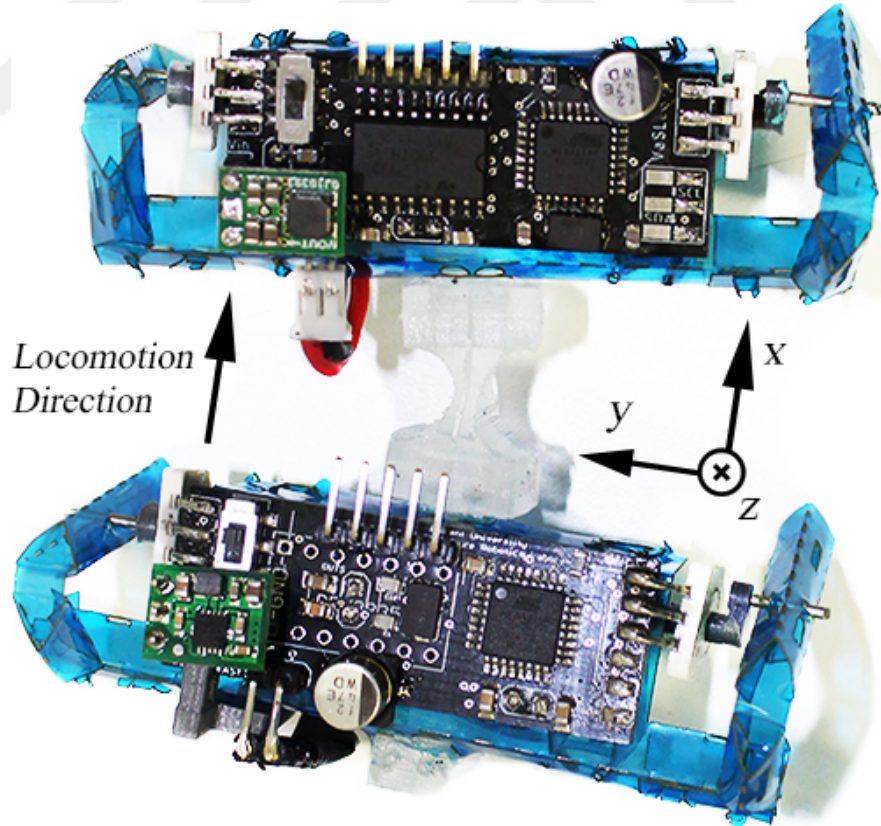


Figure 5.1: Four-legged two-module SMoLBot with a compliant(I) backbone.

Experimental and simulation results for SMoLBot with three modules (SMoLBot₃) walking with alternating-tripod gait at 2 Hz stepping frequency are

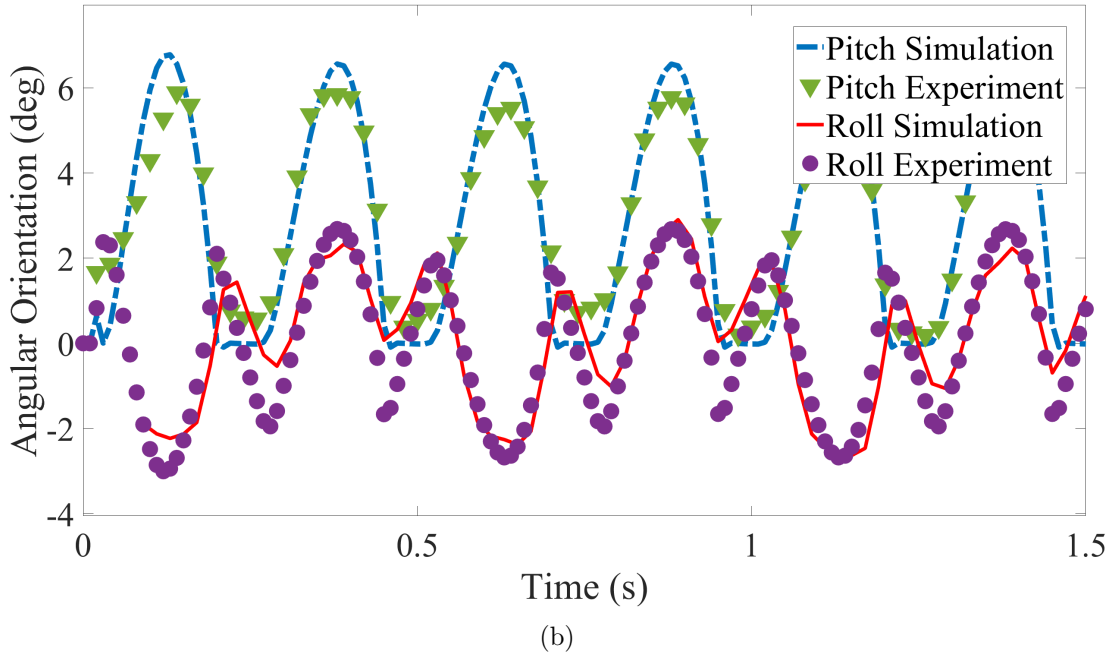
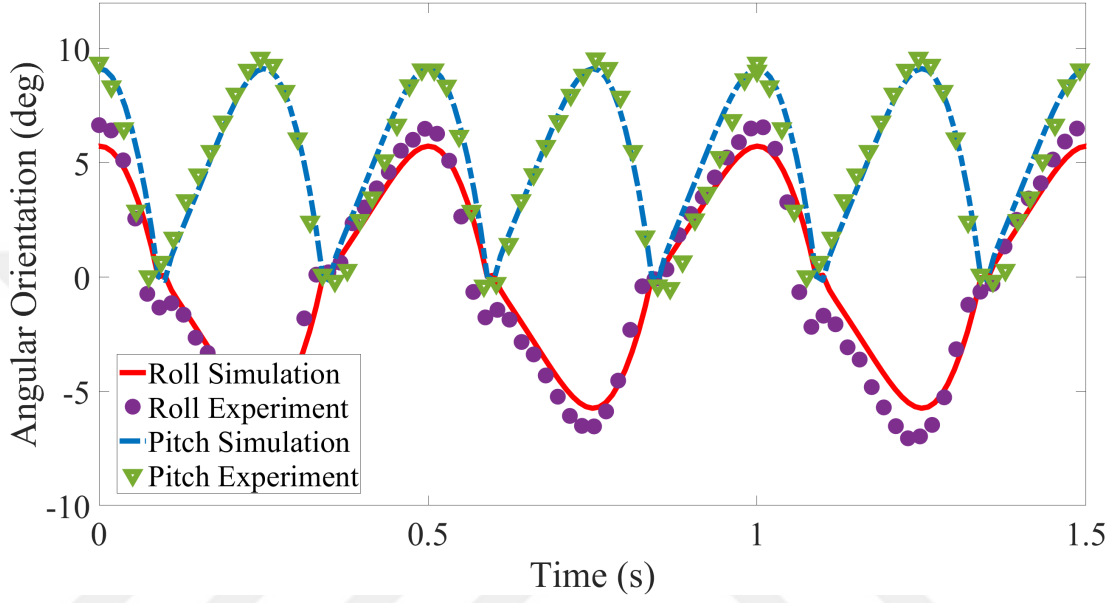


Figure 5.2: Trot gait 2 Hz roll and pitch angles for four-legged two-module SMoLBot with (a) rigid, (b) compliant(T) backbones

shown in Fig. 5.5 and 5.4. Six-legged three-module SMoLBots operate with an alternating-tripod gait, therefore, three legs are always in contact with the ground during walking, which results in very small pitch and roll angles for SMoLBot₃ with rigid backbones (Fig. 5.4(a)). The difference between the experimental and the simulation results for this case is because of the possible errors in the manufacturing and the assembly of the robot and the video processing toolbox, in consequence of not detecting all the pixels on the color bands attached to SMoLBots.

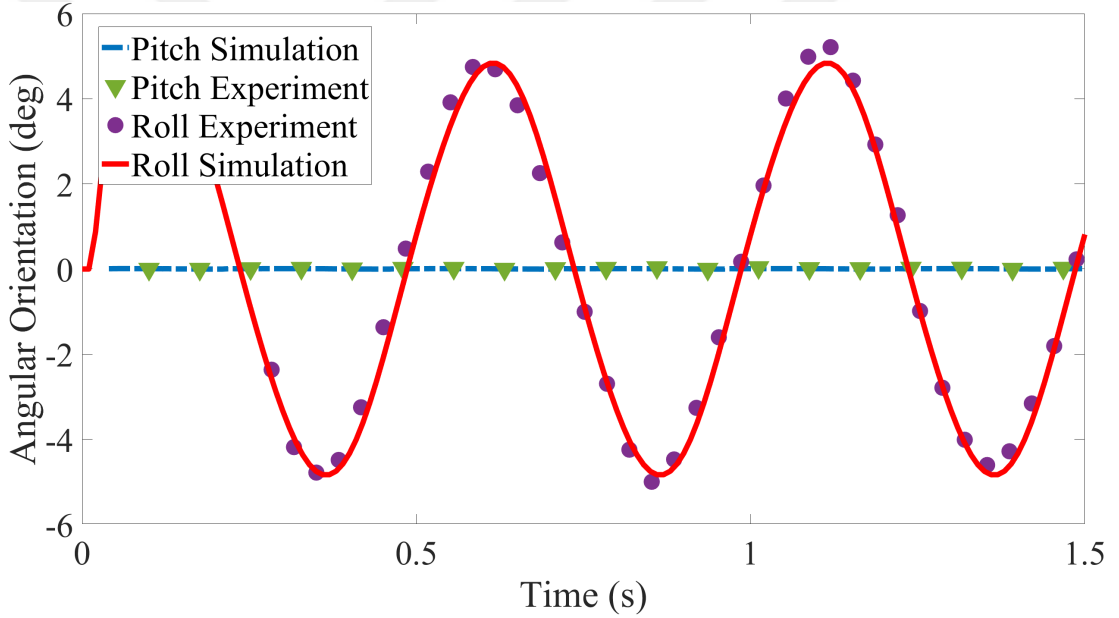


Figure 5.3: Trot gait 2 Hz roll and pitch angles for four-legged two-module SMoLBot with compliant(I) backbones.

Similar to SMoLBot₂, the legs' symmetrical adjustment of SMoLBots would result in a symmetrical pattern for the roll and pitch angles. Angular orientation results for SMoLBot₃ with compliant (I) backbones are shown in Fig. 5.4(b). A similar explanation about the angular orientations for SMoLBot₃ with rigid backbones, are valid here too, except the trend in the roll angle. SMoLBot₂ and SMoLBot₃ with compliant backbones have similar roll angles, this is due to the fact that the roll angle is more dependent on the torsional stiffness of the backbone rather than the number of legs, and torsional stiffness of the backbone in both four-legged two-module and six-legged three-module SMoLBots are equal to each other.

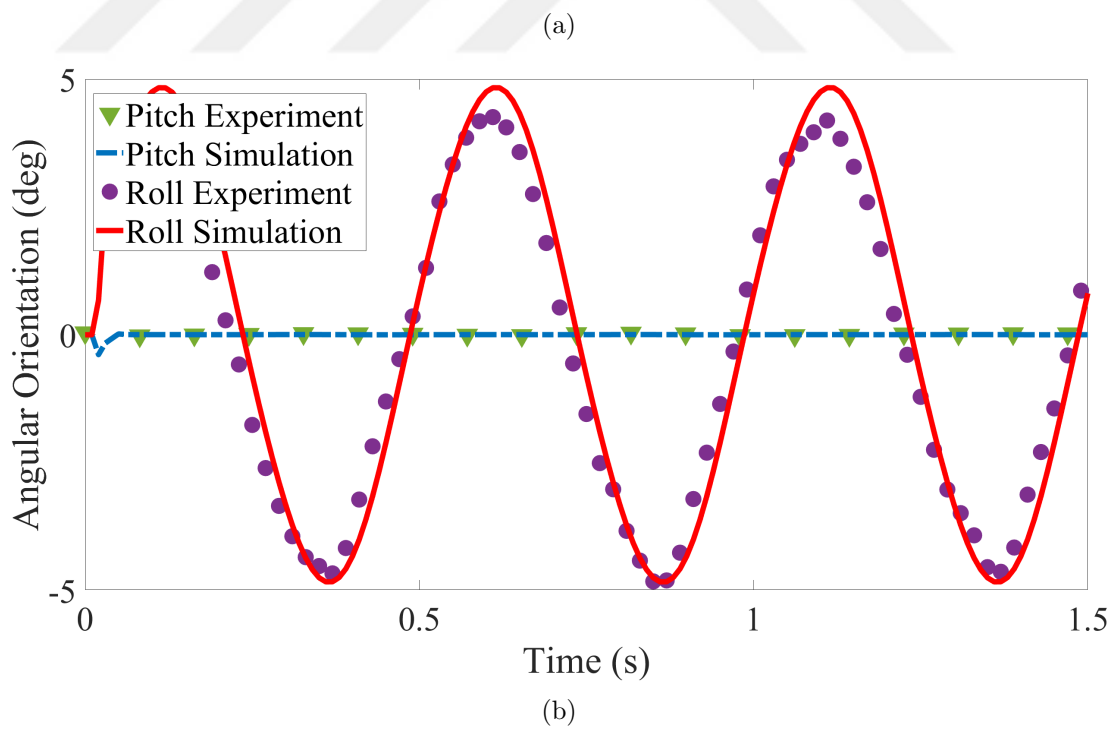
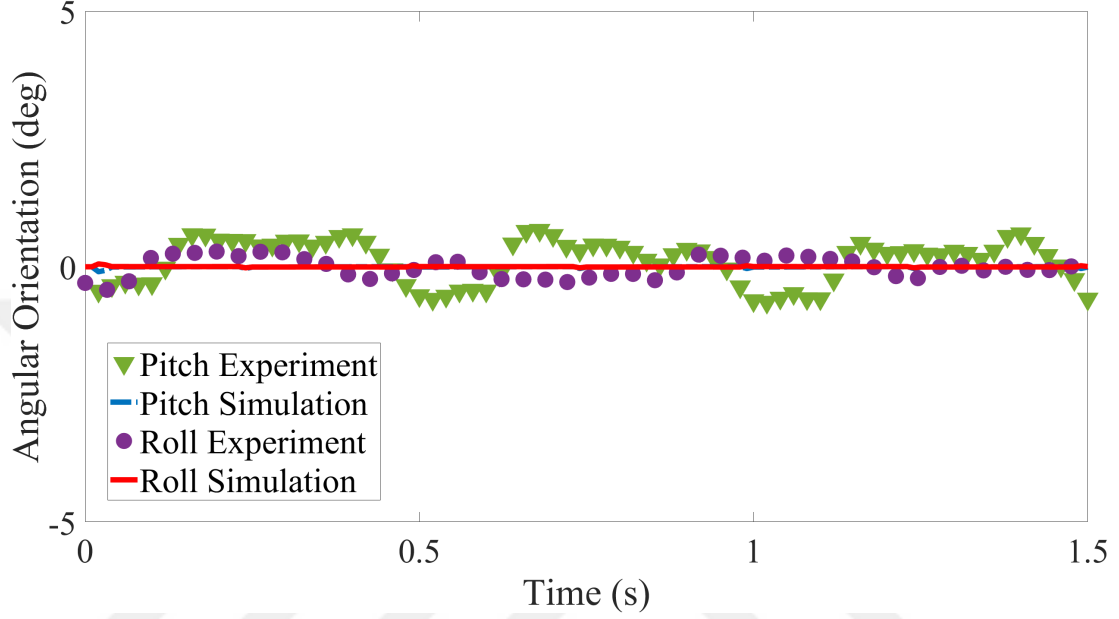


Figure 5.4: (a) Continuous-trot gait 2 Hz roll and pitch angles of the six-legged three-module SMoLBot with rigid backbones. (b) Continuous-trot gait 2 Hz roll and pitch angles of the six-legged three-module SMoLBot with compliant(I) backbones.

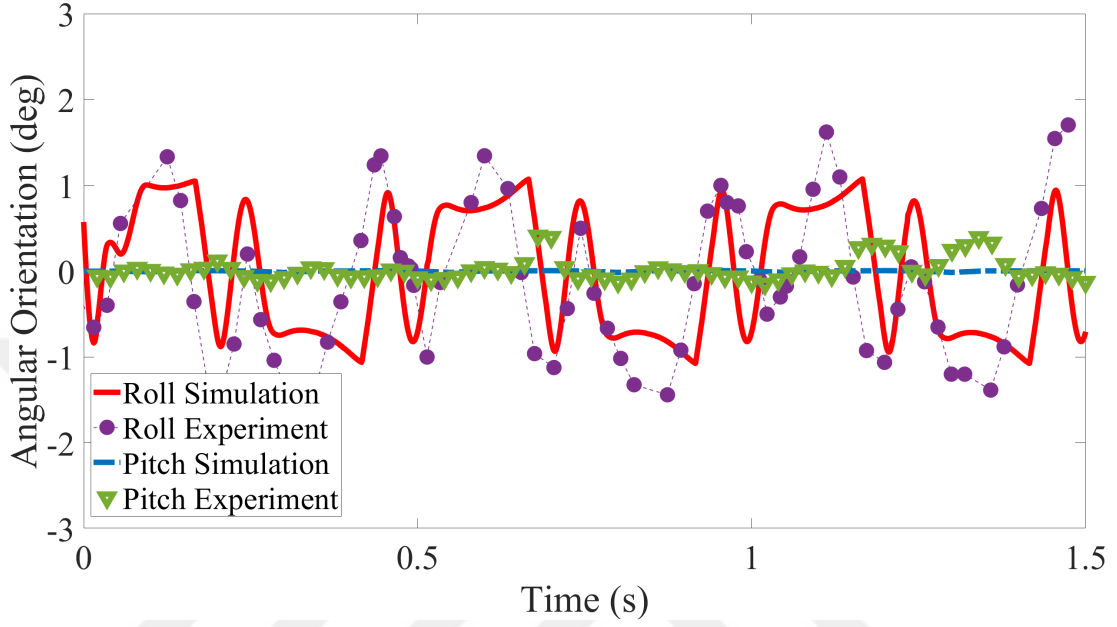


Figure 5.5: Continuous-trot gait 2 Hz roll and pitch angles of the six-legged three-module SMoLBot with compliant(T) backbones.

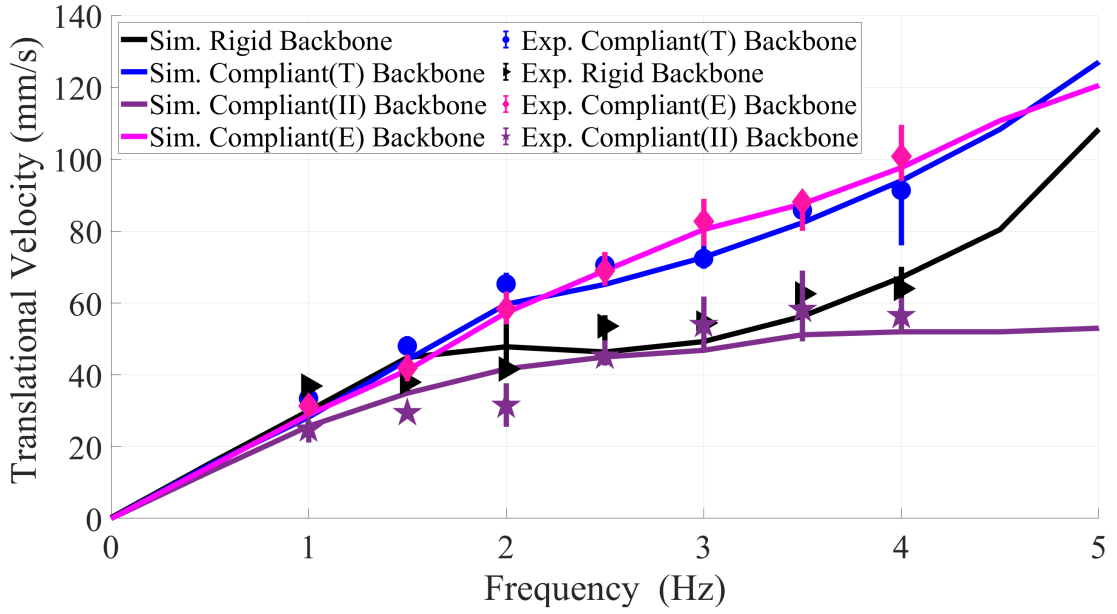
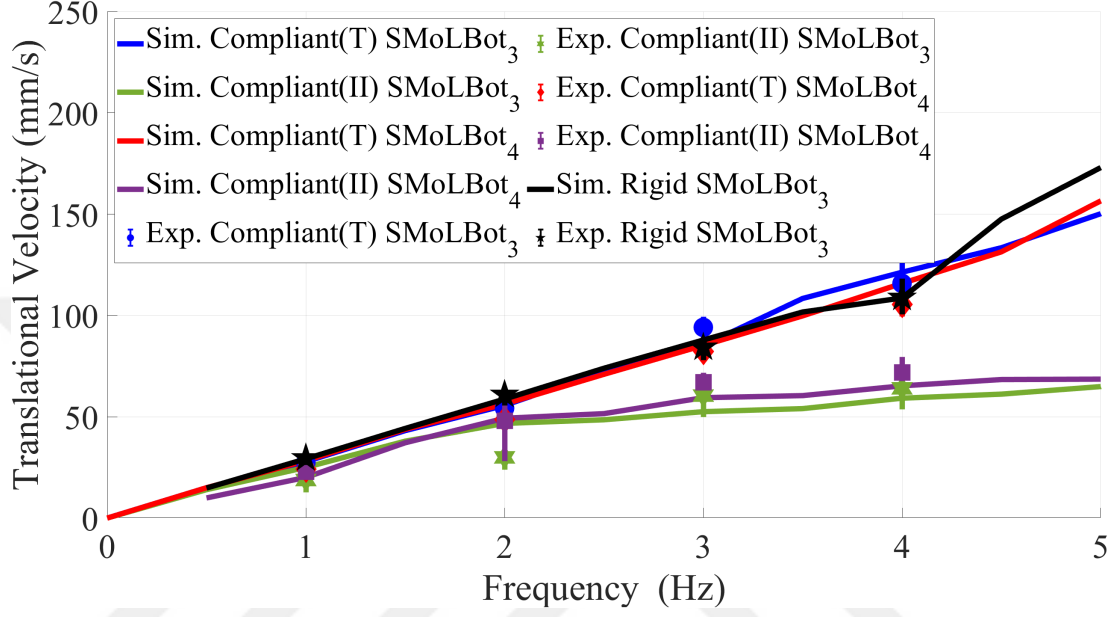
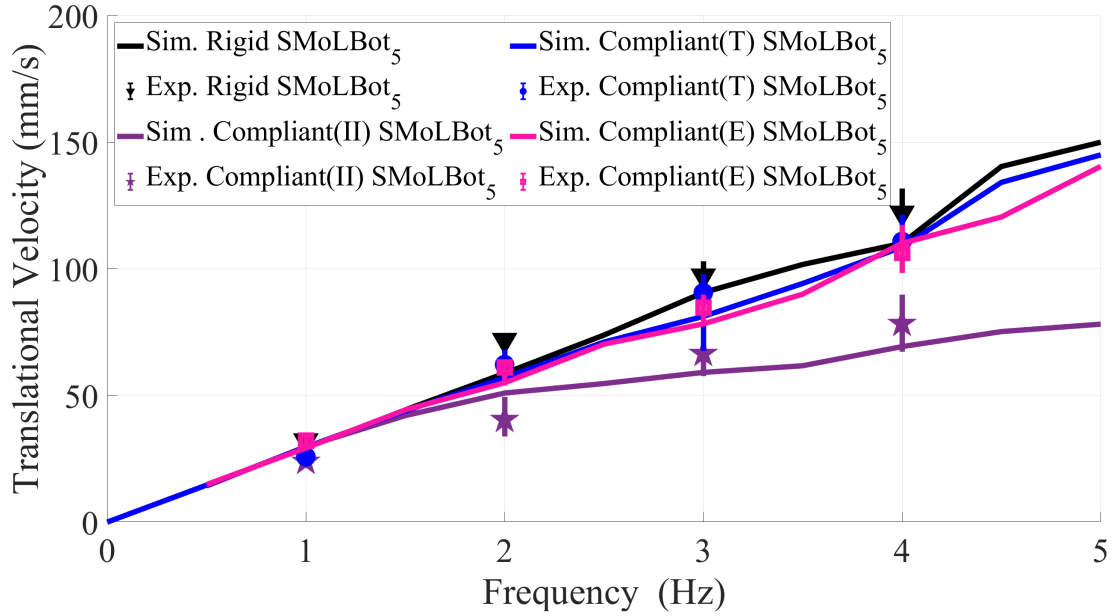


Figure 5.6: Trot gait, translational velocity of SMoLBot₂ with rigid and compliant backbones.

Insufficient torque generated by the small motors used in SMoLBot for the frequencies higher than 5 Hz, limits SMoLBot’s experiments to be only in the range of 0 - 5 Hz. Fig. 5.6 shows the experimental and simulation translational velocity results of SMoLBot₂ over the frequency range of 0 – 5 Hz. Simulation velocity results are obtained by analyzing the SMoLBot’s locomotion with 0.5 Hz stepping frequency intervals, and the error bars for the experimental results in Fig. 5.6 are determined using the range of the velocity in four trials at each individual stepping frequency (i.e. the error bars indicate the maximum and minimum velocity and not the standard deviation). Results show the existence of break points dependent on the stiffness of the backbones, resulting in higher velocity for two-module robots. Similarly, translational velocity results for SMoLBot₃, SMoLBot₄, and SMoLBot₅ with rigid and compliant backbones, are shown in Fig. 5.7.



(a)



(b)

Figure 5.7: (a) Translational velocity of SMoLBot₃ and SMoLBot₄ with rigid and compliant backbones operating at continuous-trot gait. (b) Translational velocity of SMoLBot₅ with rigid and compliant backbones operating at continuous-trot gait.

Chapter 6

Locomotion Analysis

In this chapter, the locomotion behavior of a multi-legged SMoLBot with different types of backbones and module numbers is studied. The presented dynamic model and SMoLBot's experimental data are used to investigate the effect of soft backbones on the actual gaits of the robot and to investigate the optimum gaits resulting in the maximum translational velocity. Furthermore, a velocity comparison study concerning the torsional stiffness of the backbone is conducted, which shows the effect of the backbone torsional stiffness on the robot's velocity while all remaining design parameters of the robot are kept constant. Next, in this chapter, a failure locomotion study is presented, that investigates the effect of multiple different feet failure cases on the robot's locomotion trends, while the operating gait is not altered.

6.1 The Gait Coordination Problem

Flexibility and higher degrees of freedom are features of soft-hybrid modular robots, which open up new classes of dynamic motion that were previously unavailable with rigid mechanisms. High maneuverability, ability to walk with variable gaits, low weight, and improved resistance to impacts make these soft-hybrid

modular robots notable candidates for inspection and exploration tasks. On the other hand, most of the advantages listed above require a dynamically controlled feet movement cycle; yet, generating a dynamically stable feet cycle pattern for a miniature robot to deal with different environments is still a challenge. Studying the biological locomotion of the legged small-scale insects has led to the realization that these animals select their gaits, according to the velocity and terrain characteristics. It is a certain fact that there is no common locomotion pattern that can be employed for all different terrains with various desired locomotion speeds as an efficient run or walk gait. A comprehensive definition of the gait is defined by "the time and the location of the placing and lifting of each foot, coordinated with the motion of the body in its six degrees of freedom, to move the body from one place to another" [80]. This means that for a given gait, the feet landing point are dependent on the robot's orientation such as roll and pitch angles, and how the body is interacting with the ground. For large robots, the feet movement cycle is controlled using contact sensors, however, for miniature robots, these sensors are not feasible, due to the limitation on the size, payload capacity, and power. Therefore, it is not known whether the implemented gait for a miniature robot is an optimum of the desired motion or works as envisioned during the design phase. As a result, the requirements to control the robot's gait for improved locomotion mostly reduce down to controlling the orientation of the robot, which is a function of the geometry, the compliance between the modules, and the number of legs. Hence, determining the optimum stiffness within a specific stepping frequency range that the legged miniature robot operates, and obtaining the optimum module number for a given specific compliance range between the modules are two main factors that results in maximum translational velocity for the legged soft-hybrid modular miniature robots with enhanced maneuverability.

6.2 Stiffness Analysis And Gait Comparison

Module number, stepping frequency, gait, and stiffness range are four major parameters of a legged modular miniature robot that define the overall locomotion

behavior of the system. Considering a specific optimization goal such as: high maneuverable capabilities, or a maximum locomotion velocity would result in a specific set of design parameters that would not be a suitable candidate for another optimization study. On the other hand, optimizing all parameters mentioned above at the same time is mostly impossible. This is due to the limitations on the capacity and the manufacturing techniques of the soft materials controlling the stiffness range, insufficient operating stepping frequencies provided by the motors used in the robot, lack of actuation on the system with limited DOF, and restrictions on the size of the robot to be capable of operating in a tight-small environment. These restrictions limit the number of legs, frame dimensions, stepping frequency, and the stiffness range of the robot, which makes it impossible to redesign a miniature robot while applying all the optimum parameters, simultaneously. The study in this manuscript shows how the presented dynamic model can be used to obtain an optimized design parameter to satisfy a specific optimization goal while all or some of the remaining design parameters are kept constant. This design method in conjunction with the locomotion analysis of the multi-legged modular miniature robot presented in this research makes it feasible to manufacture a miniature robot to achieve its maximum operational capabilities with selectively desired optimum parameters at a real-world environment.

In order to investigate the effect of the backbone stiffness on the locomotion of the legged miniature modular robots, stiffness analysis over a range of stepping frequencies are studied. Varying backbone stiffness values over a range of stepping frequencies are used to study the resulting dynamic behavior of the robot and to compare the locomotion trends of each particular case with a different module number and backbone type. Experimental and simulation results show a very small change on the velocity of SMoLBot with respect to the variations in the bending stiffness of the backbones when the torsional stiffness is kept constant. On the contrary, a key factor resulting in a larger change in velocity is the torsional stiffness of the backbone. Changes in the torsional stiffness of the backbone result in different locomotion characteristics for the modular robots with compliant backbones. Investigation in this study uses the definition of slip and stride length and lift height in order to analyze the robot's behavior on a terrain while operating

with different stepping frequencies, schematics of these parameters for a single-foot trajectory are shown in Fig. 6.1.

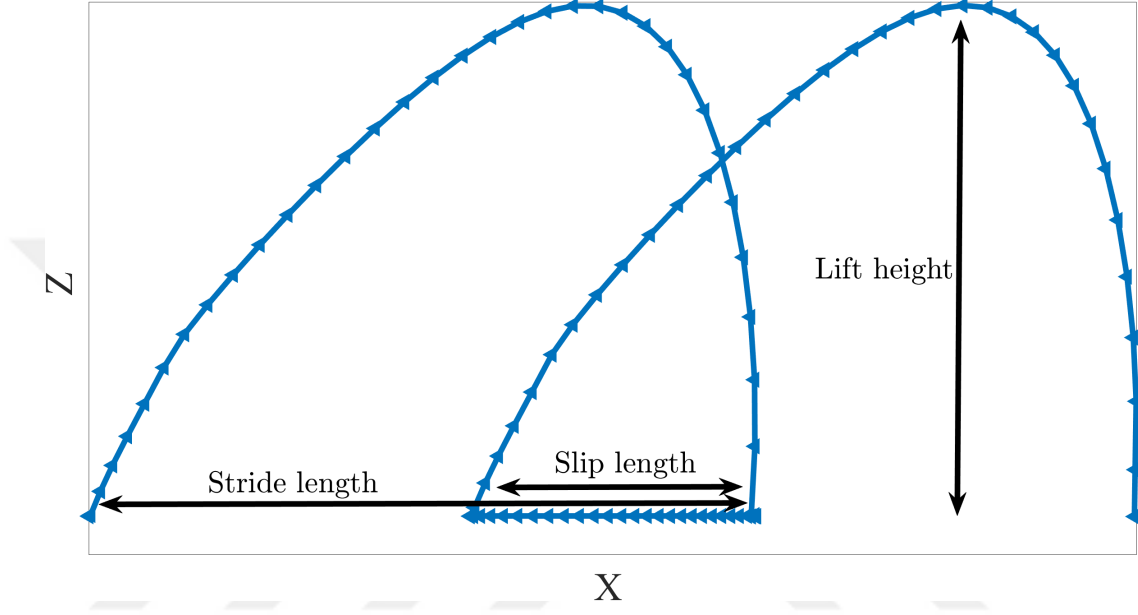
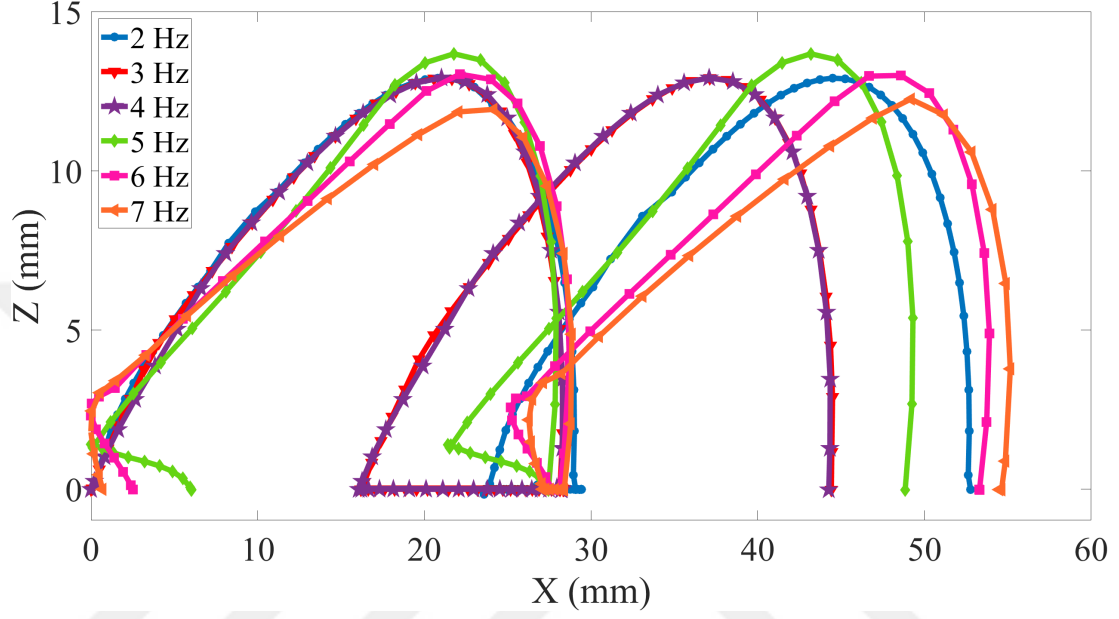


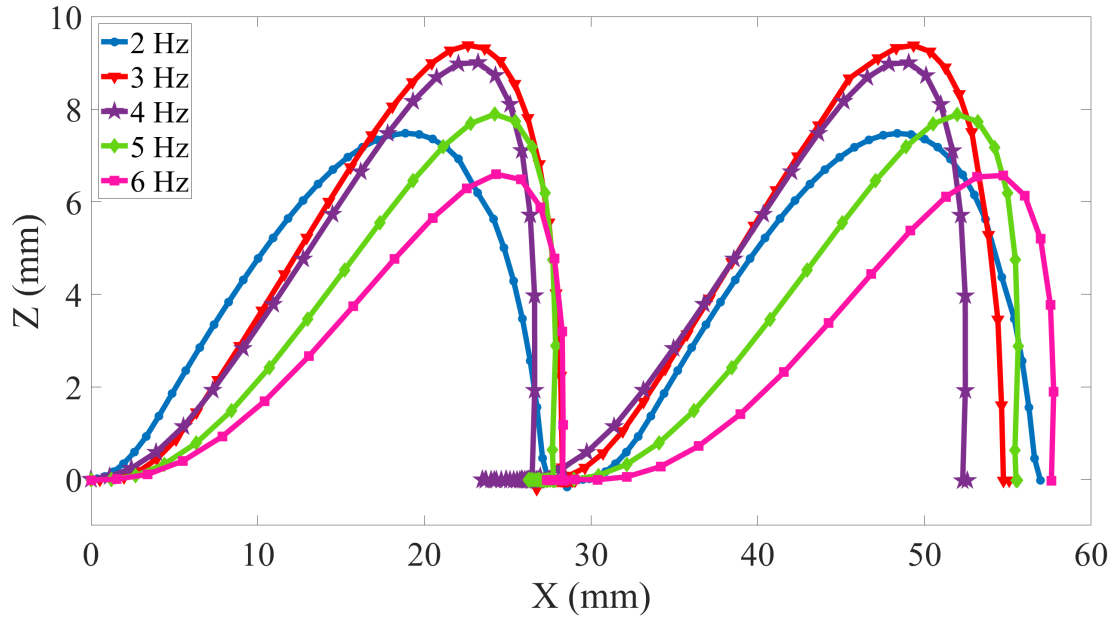
Figure 6.1: Stride and slip length and lift height definition.

Figures 6.2 - 6.4 demonstrate the effect of the soft and rigid backbones on the stride and slip lengths of the feet. Falling and rising behavior of the velocity of SMoLBot₂ with the rigid backbone in the frequency range of 2 – 5 Hz (black colored line in Fig. 5.6, velocity values between 1.5 to 5 Hz) can be explained, by the trajectory of the module's feet shown in Fig. 6.2(a). Increasing the stepping frequency to the values higher than 4 Hz results in a bouncing four-legged two-module rigid robot, that lifts the feet from the ground during the slipping cycle. Lifting the feet while it is on the slip period eliminates the undesired contact between the feet and the ground, which increases the velocity of SMoLBot.

Similarly, increasing the stepping frequency for SMoLBot₂ with compliant (T) backbones decreases the slip length (Fig. 6.2(b)), resulting in a higher velocity. On the contrary, the slip length for SMoLBot with compliant(E) backbones while increasing the stepping frequency is almost constant (Fig. 6.3(a)), and is lower than the slip length of SMoLBot with compliant(T) backbones (Fig. 6.3(b)). Lower slip length values of SMoLBot with compliant(E) backbones, explains the



(a)



(b)

Figure 6.2: (a) Leg trajectories over 2–7 Hz frequency range for SMoLBot₂ with rigid backbone. (b) Leg trajectories over 2–6 Hz frequency range for SMoLBot₂ with compliant(T) backbone.

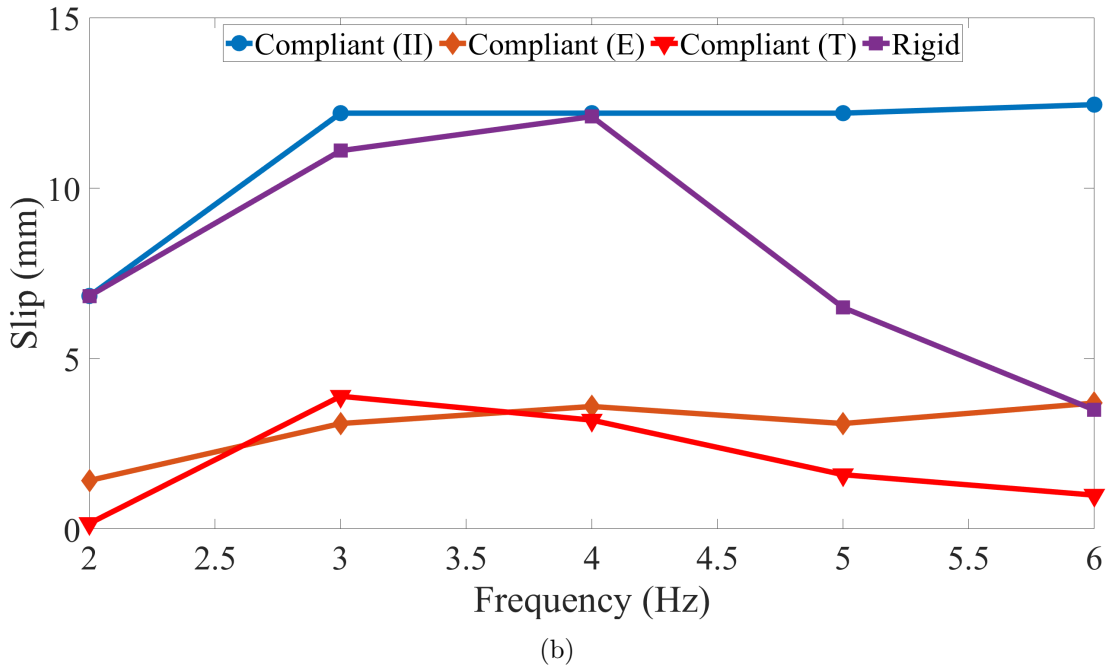
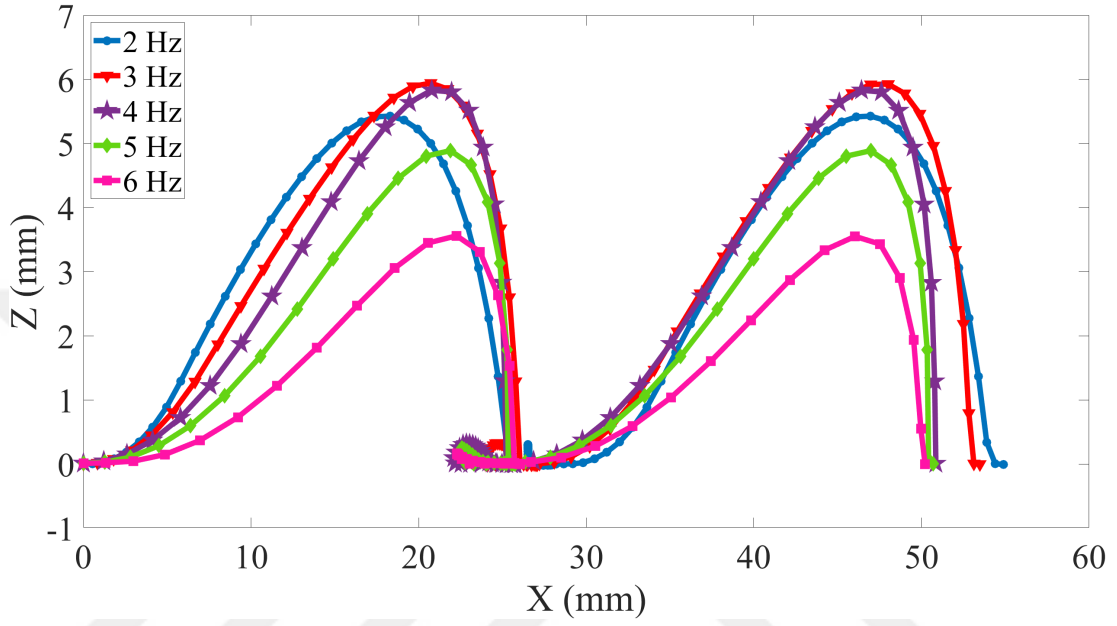


Figure 6.3: (a) Leg trajectories over 2–6 Hz frequency range for SMoLBot₂ with compliant(E) backbone. (b) Slip length of the leg in a full cycle for SMoLBot₂ with rigid and compliant backbones operating with a trot gait.

increasing trend of SMoLBot's velocity between 2.5 to 5 Hz (Fig. 5.6-lines colored in pink and blue). The slip length values for the four-legged two-module SMoLBots with rigid, and compliant backbones over the frequency range of 2 – 5 Hz are shown in Fig. 6.3(b).

Slip to stride ratios of SMoLBots with different backbone types at 2 and 5 Hz while the number of feet is increasing are shown in Fig. 6.4(b), that shows the effect of module number on the robot's slip length. Six-legged three-module SMoLBots running with an alternating-tripod gait possess smaller slip length due to the statically stable behavior of the gait compared to the four-legged two-module robots. Similarly, adding extra modules to the multi-legged robot decreases the slip-stride ratio, due to the statically stable behavior of the continuous-trot gaits. Additionally, increment in the slip to stride ratios while the stepping frequency is increasing from 2 to 5 Hz for SMoLBots with compliant and rigid backbones, proves the existence of an optimum module number with respect to the backbone type in a specific stepping frequency, that should be considered while designing a legged modular miniature robot.

Figures 6.6 and 6.7 show the effect of the stiffness of the backbone on SMoLBots' actual gait, where the results are obtained considering the contact sequence of the feet from the dynamic simulation. Two-module robots tend to drag the rear module as they walk on the ground. Low feet lift of the rear module (leg 3 and 4) decreases the stride length and increases the dragging of the feet, which is the case for both SMoLBot₂ with the rigid and compliant (E) backbones (Fig. 6.6(a), 6.6(c)). Actual feet contact sequence of the four-legged two-module SMoLBot with compliant(I) backbone is shown in Fig. 6.6(b). Despite the lift and stride motion behavior of SMoLBots with rigid and compliant(E) backbones, SMoLBot with compliant(I) backbone has a crawling motion, that results in a zero pitch angle. Very low torsional stiffness of the backbone in SMoLBots with compliant(I) and compliant(II) backbones eliminates the lift of the feet, which decreases the stride length of the robot and SMoLBot's velocity. SMoLBot with compliant(I) and compliant(II) backbones tend to crawl on the ground rather than following a stride and lift trajectory.

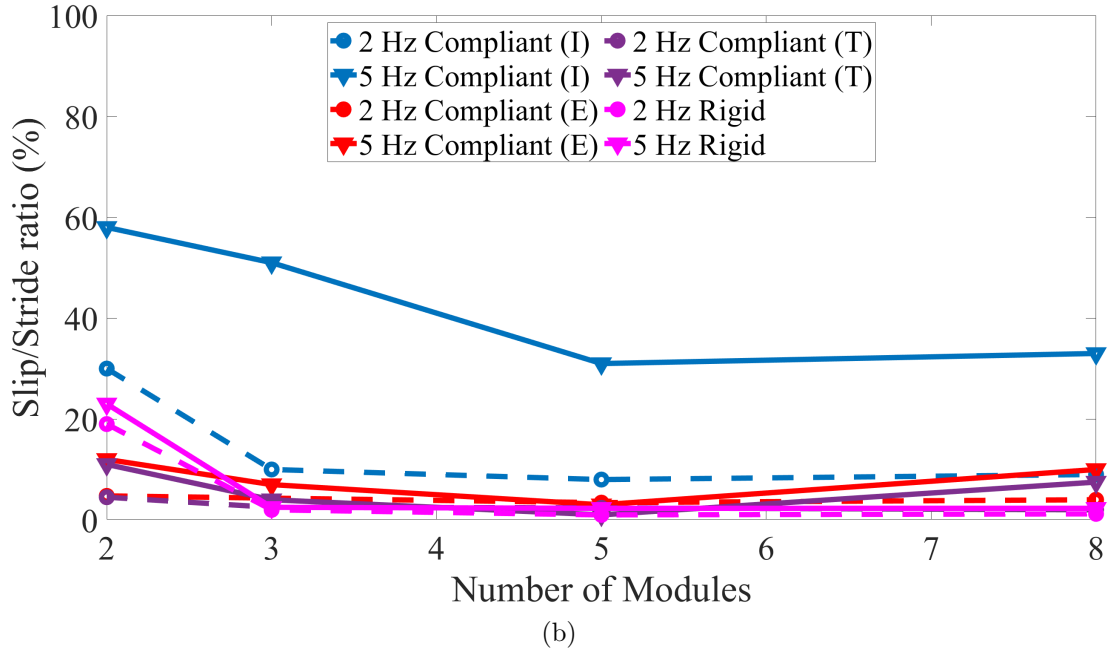
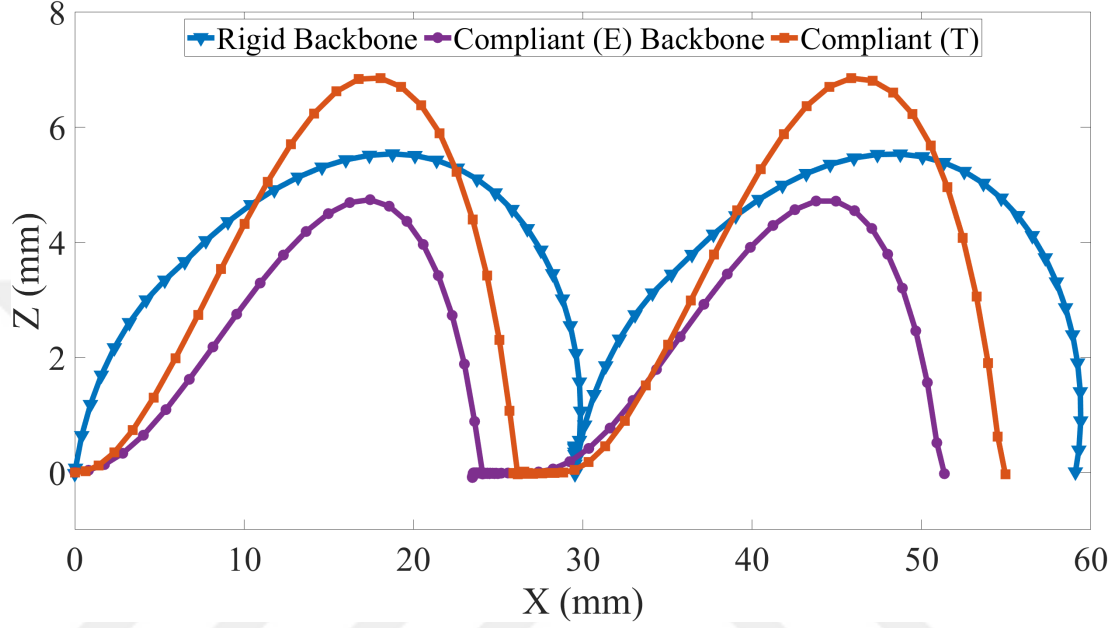


Figure 6.4: (a) Leg trajectories with 3 Hz stepping frequency for the six-legged three-module SMoLBots. (b) Slip to stride ratio for the N module SMoLBots running at 2 and 5 Hz stepping frequencies.

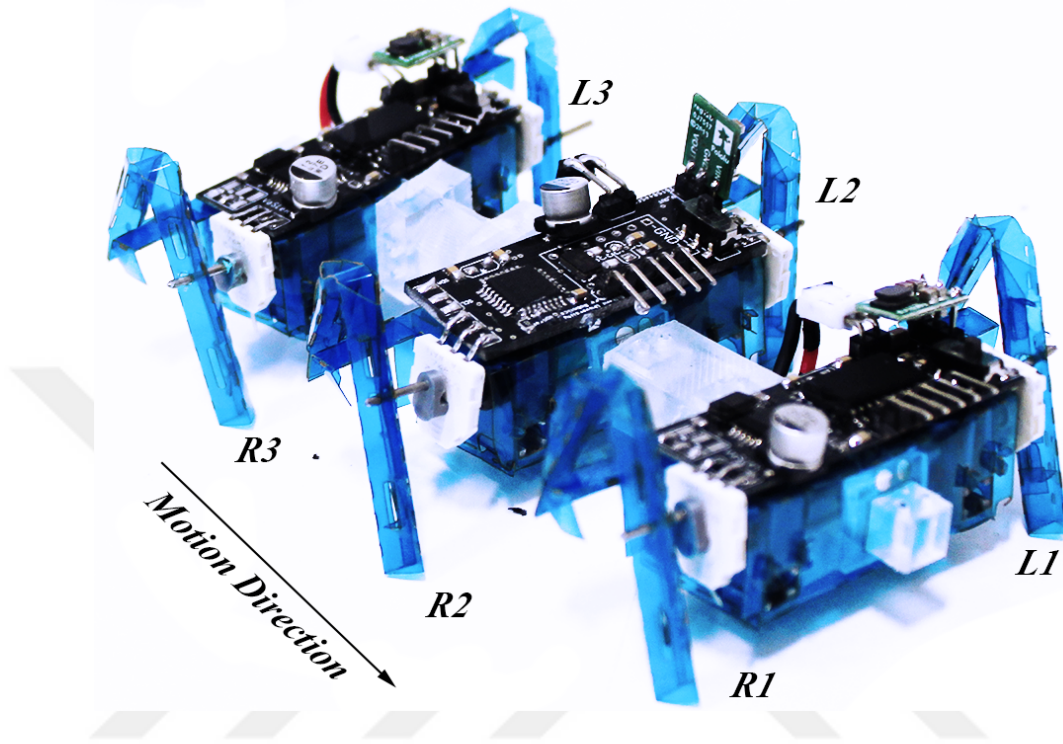
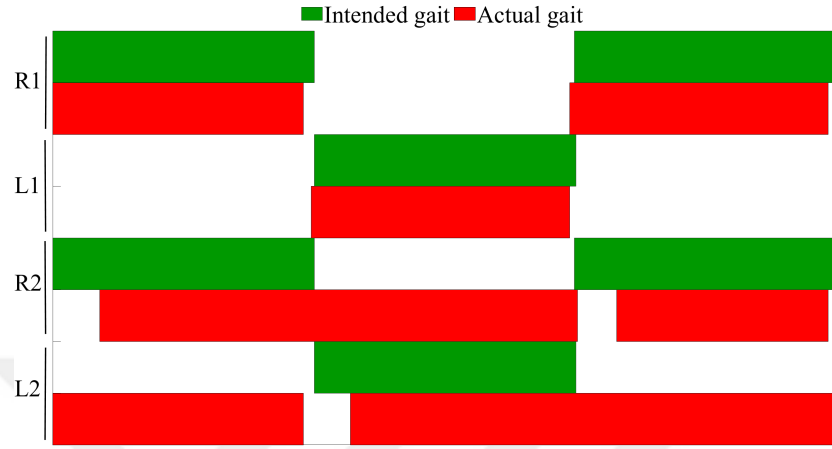


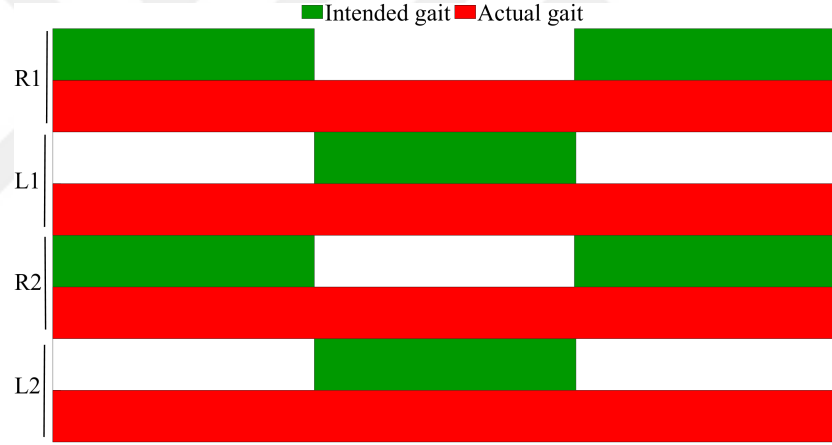
Figure 6.5: Feet naming pattern of SMoLBot.

As mentioned earlier, longer stride length of the legs on the first module of the robot with the compliant (E) backbone and smaller slip length, decrease the effect of the unfavorable forces of the rear legs during the slip cycle, resulting in a higher speed. However, three-module SMoLBot with the rigid backbones operating with statically stable alternating-tripod gait has relatively the lowest roll and pitch angles, which eliminates the troubles with rear legs being dragged on the ground (Fig. 6.7(a)). Elimination of the legs' dragging problem, explains the decrease in the slip length for SMoLBots with more than two modules and rigid backbones. SMoLBot₃ with compliant (E) backbones, similar to SMoLBot₂, suffers from the unfavorable effect of the rear legs being dragged on the ground, however long stride length of the front legs compensates the opposing forces generated during the slip cycle (Fig. 6.7(b)) that results in a higher translational velocity. Velocity results for SMoLBots with rigid, compliant (II), and compliant (E) at 3 Hz stepping frequency are summarized in Table 6.1, and legs' naming pattern for SMoLBot used in this study is shown in Fig. 6.5.

In order to investigate the effect of the backbone stiffness on the locomotion of



(a)



(b)



(c)

Figure 6.6: Trot gait diagram for: (a) SMoLBot₂ with a rigid backbone. (b) SMoLBot₂ with a compliant(I) backbone. (c) SMoLBot₂ with a compliant(E) backbone.

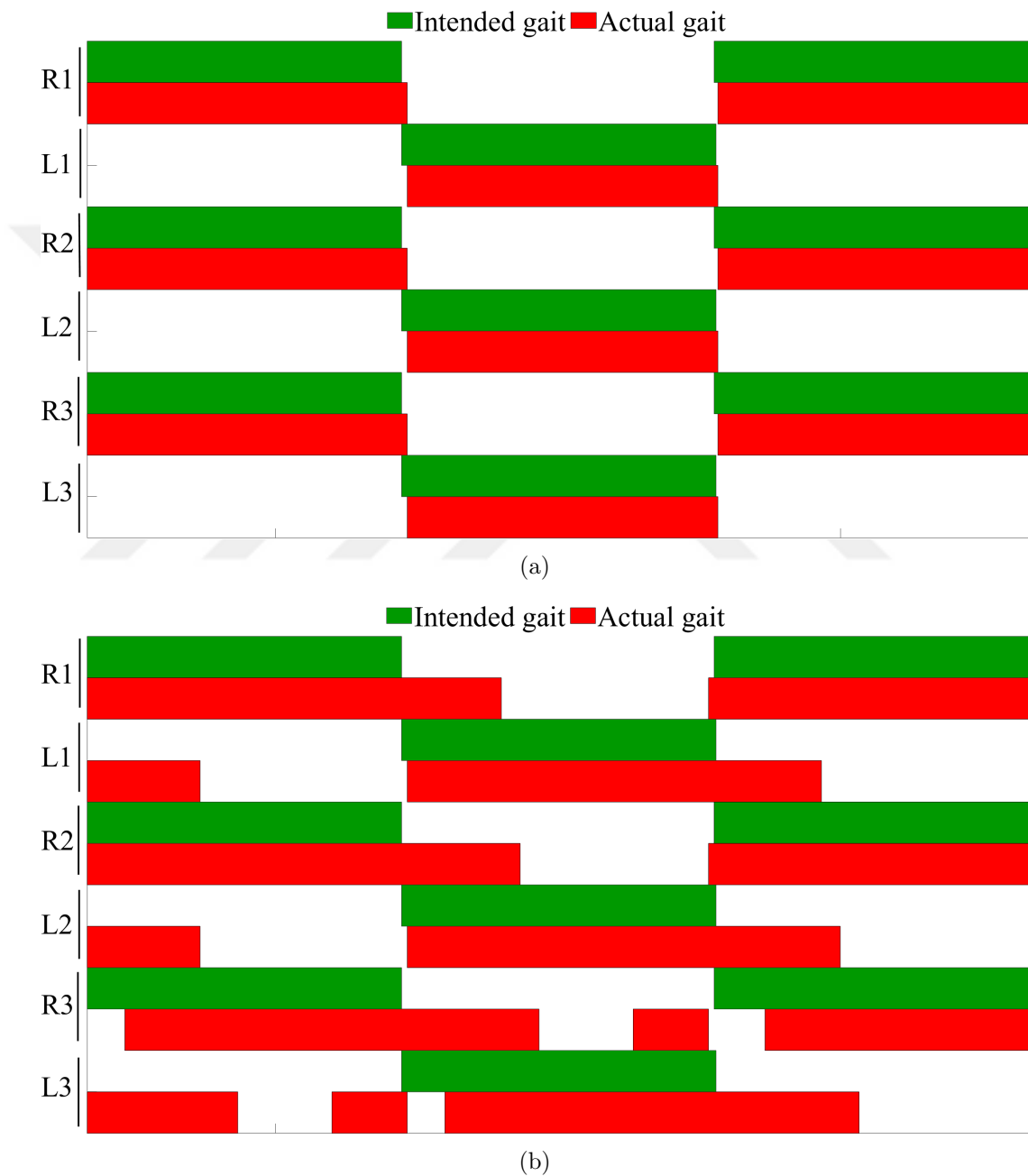


Figure 6.7: Alternating-tripod gait diagram for: (a) SMoLBot₃ with rigid backbones. (b) SMoLBot₃ with compliant(E) backbones.

Table 6.1: SMOLBOT VELOCITIES

Robot	Velocity (mm/s)
SMoLBot ₂ with a rigid backbone	56.0
SMoLBot ₂ with a compliant(II) backbone	48.0
SMoLBot ₂ with a compliant(E) backbone	80.0
SMoLBot ₃ with compliant(E) backbones	83.0
SMoLBot ₃ with rigid backbones	87.0

the four-legged miniature robots, stiffness optimization studies that consider wide ranges of backbone's stiffness, ranging from soft backbones to completely rigid ones, are conducted. Fig. 6.8 shows the optimum torsional stiffness over the range of 2 to 14 Hz for SMoLBot₂ that maximizes the translational velocity. Results show that there is an optimum torsional stiffness that maximizes the linear speed of a miniature robot for a given number of modules and stepping frequency, e.g. for a two-module SMoLBot, the optimum torsional stiffness is approximately 4 N.m/Rad for a stepping frequency of 10 Hz.

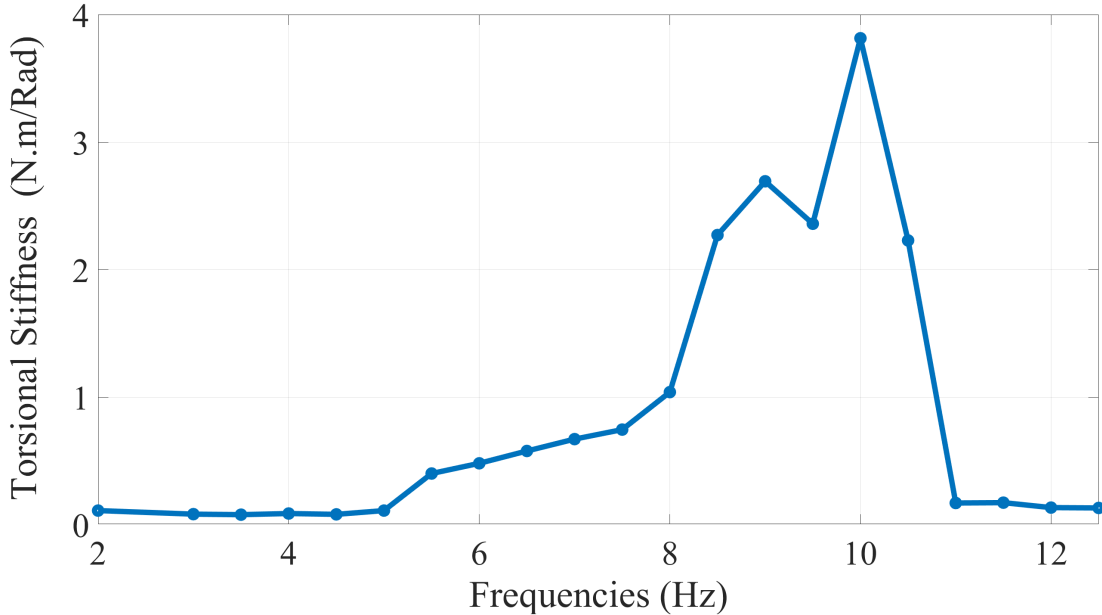


Figure 6.8: Optimum torsional stiffness values of SMoLBot₂ resulting in maximum translational velocities at varying stepping frequencies in trot gait.

Velocity results in Fig. 5.6 and 5.7 show minimal change with respect to the

variations in the torsional stiffness of the backbones in the range of 0 to 2 Hz; However, the velocity optimization study shown in Fig. 6.8 proves the existence of break-points at 2, 5, and 10 Hz that appear as peaks in the velocity values. Furthermore, we believe that, the rapid velocity change in the frequency range of 8 to 11 Hz is due to the natural frequency of the robot. To prove that this is the case, simulation of a robot possessing a higher constant mass shows a shift in the frequency range of the peak, supporting the hypothesis of effect of natural frequency on robots velocity. The existence of an optimum torsional stiffness means that the design of the robot should be iteratively improved after the modeling phase, and the stepping frequency should be selected according to the torsional stiffness of the backbones in order to maximize the speed.

Fig. 6.9 shows SMoLBots' velocity at 3 Hz stepping frequency with varying number of modules. The gait used for the robots with $N > 2$ modules is a continuous form of the trot gait, where the legs on the modules with odd numbers are in the same phase as the legs on the module $N = 1$ and the legs on the modules with even numbers are in phase as the legs on the module $N = 2$. Statically-stable characteristics of the continuous-trot gaits for the robots with $N > 2$ modules form a maximum contacting stride length, resulting in a noticeable increase in the velocity values for the robots with rigid backbones. This explains the increasing trend for SMoLBots' velocity while the module number is higher than two, as explained before. However, a relatively long totally-rigid robot will lack maneuverability capabilities in rough terrain locomotion, such as doing turns in tight spaces, which is required for exploring small and complex environments. The constant behavior of the velocities of SMoLBots with compliant (I) and compliant (II) backbones with N number of modules where $N > 5$, can be explained considering the slip to stride ratio shown in 6.4(b). Similarly, increasing behavior of the slip to stride ratio explains the decreasing velocity behavior of SMoLBots with compliant (T) and compliant (E) backbones.

Fig. 6.10(a) - 6.10(d) show the velocity of SMoLBot with varying number of modules while the stepping frequency is increasing from 3 to 7 Hz. Increasing the stepping frequency to a value higher than 5 Hz changes the velocity trend of SMoLBots with different backbone types; i.e. Our previous studies have shown

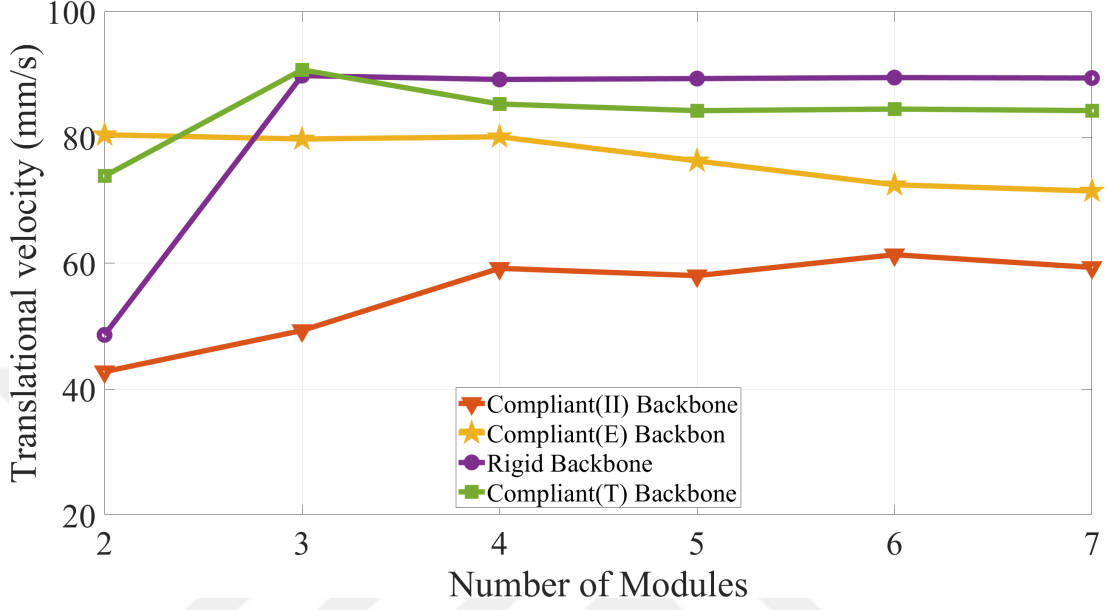


Figure 6.9: SMoLBot’s translational velocity for N number of modules at 3 Hz stepping frequency.

that a modular legged robot with rigid backbones that has zero roll and pitch angles and a module number higher than 2, possess the highest translational velocity compared to SMoLBots with compliant backbones. However, increasing the stepping frequency to a value higher than 5 Hz, increases the velocity of SMoLBot with compliant(E) and compliant(T) backbones up to the values higher than the velocity of SMoLBot with rigid backbones (Fig. 6.10(a) and 6.10(c)). Similar to the compliance analysis, the existence of an optimum number of modules and stepping frequency means that the design of the robot should be iteratively improved after the modeling phase to maximize the velocity or to satisfy any different specific optimization goal that is considered during the design procedure of the robot.

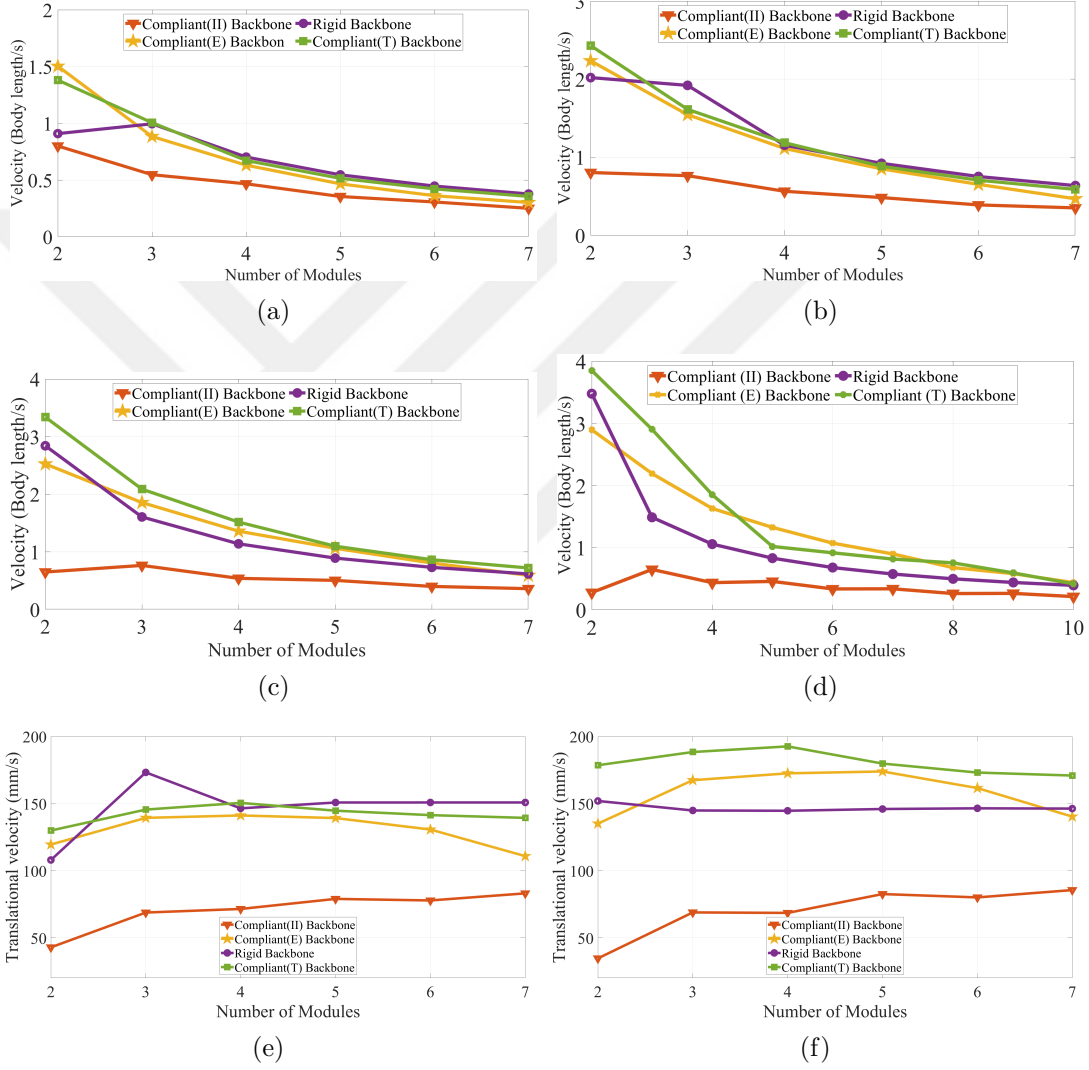


Figure 6.10: (a) SMoLBot's body per length velocity for N number of modules at 3 Hz stepping frequency. (b) SMoLBot's body per length velocity for N number of modules at 5 Hz stepping frequency. (c) SMoLBot's body per length velocity for N number of modules at 6 Hz stepping frequency. (d) SMoLBot's body per length velocity for N number of modules at 7 Hz stepping frequency. (e) SMoLBot's velocity for N number of modules at 5 Hz stepping frequency. (f) SMoLBot's velocity for N number of modules at 6 Hz stepping frequency.

6.3 Gait Analysis

Multi-legged modular miniature robots show significant advantages compared to the four-legged robots on rough and smooth terrains with their high maneuverable capabilities and ability to perform a variety of statically stable gaits [81], [35]. Low weight, robustness in the case of feet failure, versatility, and mobility make the multi-legged miniature robots a suitable candidate for accomplishing tasks such as inspection, surveillance, and environment exploration [82]. However, such applications require gait modification concerning the robot's stepping frequency and terrain characteristics [83]. There are at least two approaches to overcome the legged robots' locomotion adaptability problems; One approach is to build a reactive system similar to the robot's biological inspirations to move stochastically encountering a new environment. Second approach would be using different pre-planned individually optimized feet motions compatible with the new environment, while ensuring the stability of the robot. The pre-planned optimized motion pattern approach seems a practical strategy to overcome the problem due to the lack of feasible sensors in the miniature scale and lower computational power needed on-board. Besides, this approach will eventually provide a certain statically and dynamically stable overall motion, considering the robot's limitations.

Achieving all-terrain mobility, and adapting to terrain variations outside of the protected laboratory environment is still a huge challenge for the legged robots. However, it is feasible to overcome this problem using robots that can modify their gait suitable with their design and terrain characteristics. Currently, different approaches exist for gait coordination in the multi-legged robots; While large-scaled robots rely on reactive algorithms to sense and react to the environment [84], [85], miniature scaled robots favor the use of commonly known gaits of their biological inspirations (like reptiles, insects, and mammals) such as: Walk, Trot, Pronk, etc. [9], [10], [43]. This different approach to overcome the locomotion adaptation problems of the miniature robots is due to the limitations on the payload capacity, power, and lack of feasible sensors and computational power available for the small-scaled robots. However, for a legged miniature robot

with independent leg actuation, optimized gait pattern which considers geometry factors, compliance between different parts, and stable dynamic behavior of the robot would be a better approach to adapt the leg motion pattern to the terrain variations. This optimized motion pattern will satisfy the use of statically stable gaits in the multi-legged robots during the operation and is a feasible approach for the legged miniature robots considering their manufacturing limitations.

6.4 Optimization Algorithm

Gaits are motions of the legs that define the position of each leg in a periodical sequence. In this study, $(n - 1)$ unique phases where n shows the number of legs, are selected to define the gait; i.e since the gait is a periodical motion, the origin of the absolute phase is arbitrary and is considered to be the phase of the leg R_1 (right foot of the module $N = 1$). Feet naming pattern used in this section is similar to the one introduced in Fig. 6.5.

The angle of the joint BD in the leg j of the module i , is derived from the relationship between the joint's constant stepping frequency and its phase as follows;

$$\theta_2^{i,j} = \omega_2^{i,j} t + \Theta^{i,j} \quad (6.1)$$

where, $\Theta^{i,j}$ shows the foot phase based on the origin of the absolute phase and t is the time. To study the optimum gait pattern of an n -legged robot with constant feet stepping frequencies and different types of backbones, the performance index R is defined as:

$$P_m = \sqrt{(x_{m+1} - x_m)^2 + (y_{m+1} - y_m)^2} \quad (6.2)$$

$$R = \frac{V_{max}}{\frac{\sum_{m=1}^{ST-1} P_m \cdot \text{sign}(u^m)}{t_{end} - t_1}} \quad (6.3)$$

where, ST is the number of time steps of the simulation starting from $t = t_1$ to $t = t_{end}$. t_1 shows the time where transition motion is passed and the robot has a stable periodical motion. x and y show the COG position in C_I , and P_m is the position vector at each time step. $sign(u^m)$ shows the movement direction at instant, where $sign(u^m) = +1$ is used for striding and $sign(u^m) = -1$ for the sliding movement of the robot. Eventually, walking/running pattern optimization study of the miniature robot with a specific range of compliance between modules and constant feet stepping frequency f_2 , is implemented using Genetic Algorithm (GA) optimization by minimizing the R value. In the meantime, in order to obtain all possible gaits that maximize the velocity of the robot and by the means of avoiding a set of feet phases that results in a turning robot in an undesired direction, a secondary correction algorithm is integrated within the Genetic Algorithm optimization code. Secondary correction algorithm considers a correction parameter index C that is defined as (6.6).

$$u_1^I = H_{CG}^I u_1, \quad at \quad t = t_1 \quad (6.4)$$

$$u_2^I = H_{CG}^I u_2, \quad at \quad t = t_2 \quad (6.5)$$

$$C = \sin^{-1}\left(\frac{u_1^I \times u_2^I}{|u_1^I||u_2^I|}\right) \quad (6.6)$$

where, $t_2 - t_1 = 1s$. u_1 and u_2 show the robot's velocity at $t = t_1$ and $t = t_2$, respectively. u_1^I and u_2^I show the robot's velocity along its length represented in C_I reference frame, and C defines the angle between u_1^I and u_2^I vectors, that indicates the amount of deviation angle.

Genetic Algorithm optimization, in conjunction with the secondary correction algorithm, investigate all possible optimum gaits that maximize the robot's translational velocity on a terrain while the stepping frequencies of the feet are equal and constant, as follows;

- A set of initial population is defined for the GA.
- A set of optimization parameters (OP) is selected.

- Locomotion of SMoLBot with selected OP is analyzed.
- Performance index R is determined.
- Performance index C is determined.
- if $C \geq 10^\circ$ then $R = \infty$.
- if $R \leq 1$ then

$$V_{max} = \frac{\sum_{m=1}^{ST-1} P_m \cdot \text{sign}(u^m)}{t_{end} - t_1}$$

- V_{max} and OP_{best} are updated.
- Iteration continues until the maximum iteration or the maximum time is achieved.

The algorithm mentioned above provides a global optimum gait and all possible local optimum results that are tested. Investigation study on the locomotion of the robot operating with the global optimum gait and local optimum gaits gives a better insight on the multi-legged robot's locomotion while operating with an unfamiliar and asymmetrical gait, discussion on the locomotion behavior of the robot while operating with an optimum gait are presented in next sections. Additionally, the optimization study in this research is done iteratively with different initial populations while starting the GA algorithm. The initial population of each trial is chosen using the local optimum results found in the previous trial. This iterative method would finally result in a single global optimum parameter that maximize the robot's velocity, and local optimum feet phases.

6.5 Numerical and Experimental Results

Using the optimization procedure, a numerical study on achievable optimum gaits of SMoLBot with rigid, compliant(T), and compliant(I) backbones at 3 Hz stepping frequency is implemented. Furthermore, the locomotion of SMoLBots with

various types of backbones and module numbers that are operating with different gaits are studied. Gaits are classified as walks or runs. The distinction is generally made based on the duty cycles of the feet. As an example, the walk gait for quadrupeds is defined where the duty cycles of the feet are higher than 0.5, which means that there is a stage where three legs are in-contact with the ground at the same time. Gaits are also classified as symmetrical and asymmetrical [86]. A symmetrical gait is a type of motion pattern in which the adjacent right and left legs have an equal duty cycle and usually equal to 0.5, such as the common gait for the hexapods known as alternating-tripod gait. This gait uses the same foot phase identification like the biologically inspired trot gait, where each foot has a 0.5 duty cycle, and the adjacent rear-front and right-left feet are 180° apart in phase. Similarly, for our robots with more number of feet, we use the same symmetrical gait generation method to determine the feet phases. For an n -legged robot, the feet phases of the odd-numbered modules are similar to the first module (leader) and feet phases of the even-numbered modules are as same as the second module of the robot. This gait generation method produces a symmetrical gait, where individual right and left feet have 180° phase difference.

Results show the existence of different but unique optimum locomotion patterns for each n -legged robot with a different type of backbone and module number. Investigation to find an optimum gait resulting in a maximum velocity is verified with SMoLBot running at 3 and 2 Hz stepping frequencies and simulation results of the desired optimum gait are shown in the range of 0.5 – 5 Hz to inspect the miniature robot’s locomotion behavior in a wider stepping frequency range. Fig. 6.11 shows the velocity results of the six-legged three-module SMoLBots operating with an alternating-tripod gait and the optimum gait. The optimization study on the six-legged robot shows a noticeable increase in the velocity values of SMoLBot with compliant(I) backbones. Table 6.2 shows the optimum feet phases of the six-legged three-module robots, where the compliance between the modules ranges from rigid to soft. SMoLBot(R), SMoLBot(T), and SMoLBot(I) used in the text are the short form of SMoLBot with rigid, compliant(T) and compliant(I) backbones, respectively.

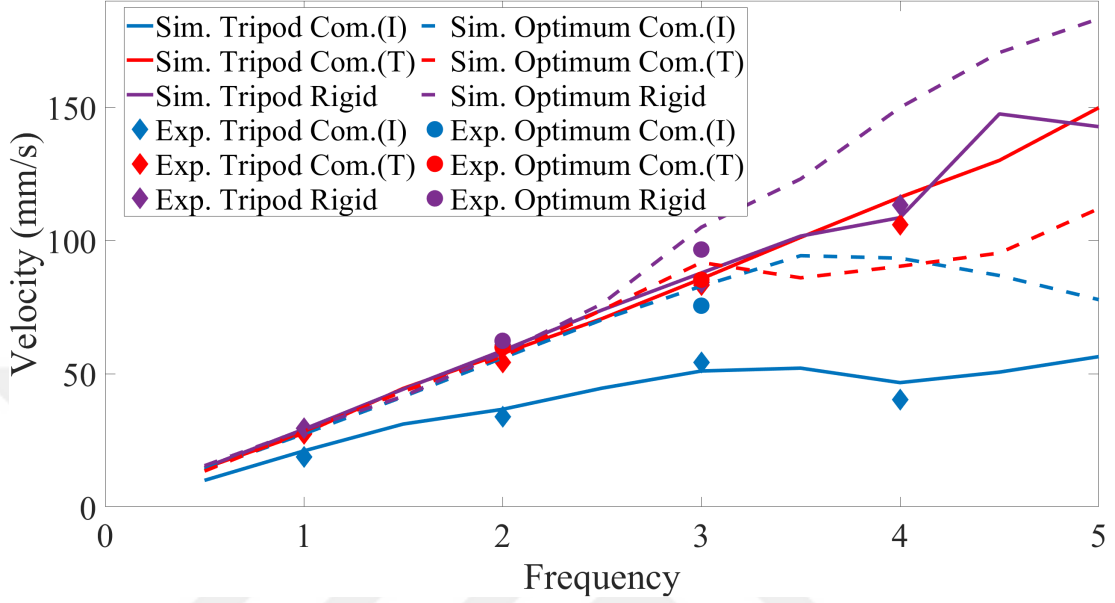


Figure 6.11: Simulation and experimental velocity results of the six-legged three-module SMoLBots with rigid, compliant(T), and compliant(I) backbones.

Figures 6.12 and 6.13 illustrates SMoLBot's locomotion behavior with compliant(I), compliant(T), and rigid backbones' in a single gait cycle. Fig. 6.12(a) and 6.12(c) show the feet contact sequence of SMoLBot(I) operating with the optimum gait and the alternating-tripod gait, respectively. Legs on SMoLBot(I) operating with continuous-symmetrical form of the trot gait (alternating-tripod gait) have zero lift and the robot tends to crawl on the ground (Fig. 6.12(c)). However, SMoLBot(I) operating with the optimum gait tends to bounce rather than crawl, where each module is lifted in a periodical sequence. A six-legged SMoLBot with compliant(I) backbones operating with the optimum gait has a jump and fall locomotion pattern where the rear legs are almost always on the ground to form a support for the robot to jump. Roll and pitch angles of the six-legged three-module SMoLBot with alternating-tripod gait and the optimum gait are shown in Fig. 6.12(d). As discussed earlier, six-legged SMoLBot with compliant(I) backbones uses the rear module legs as the support for jumping, the mid-module to lift and stride, and the front module to stride. This motion behavior can be seen in the pitch angle of the six-legged three-module SMoLBot operating with the optimum gait, too. The increasing pitch of SMoLBot is the

lift part of the motion and decreasing pitch is the stride period of the motion. Since feet phase differences of the side-by-side feet in the optimum gait is lower compared to the alternating-tripod gait (where side-by-side legs are 180° apart in-phase), SMoLBot(I) operating with the optimum gait has lower roll angle compared to SMoLBot(I) operating with the alternating-tripod gait.

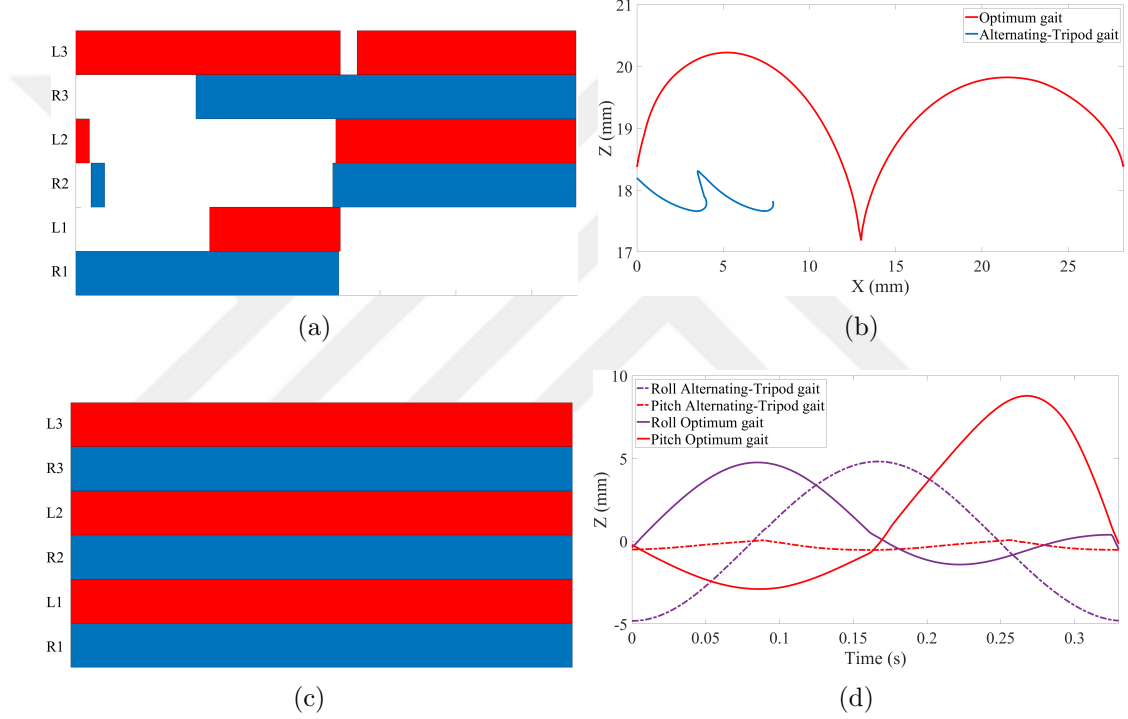


Figure 6.12: (a) Optimum gait of the six-legged three-module SMoLBot with compliant(I) backbones. (b) Three-module SMoLBot's COG in a single gait cycle. (c) Feet contact sequence of the six-legged three-module SMoLBot with compliant(I) backbones that is operating with the alternating-tripod gait. (d) Roll and pitch angles of the six-legged three-module SMoLBot with compliant(I) backbones operating with alternating-tripod and the optimum gait.

Figures 6.13(a) and 6.13(c) show the optimum gait of the six-legged three-module robot with compliant(T) and rigid backbones, respectively. Similar to SMoLBot(I), a six-legged three-module SMoLBot(T) operating with the optimum gait has a bouncy movement behavior with a lift and drop motion pattern. However, the six-legged SMoLBot with rigid backbones tends to use a different contact sequence pattern such that, during the operation, only two legs are in contact with the ground which follows with a fall on the third leg. Fig. 6.13(b) and

Table 6.2: OPTIMUM FEET PHASES OF THE SIX-LEGGED THREE-MODULE SMOLBOTS

	SMoLBot(R)	SMoLBot(T)	SMoLBot(I)
$R_1 - L_1$ (<i>deg</i>)	0-170	0-26	0-155
$R_2 - L_2$ (<i>deg</i>)	67-180	170-174	5-18
$R_3 - L_3$ (<i>deg</i>)	180-17	10-10	155-167

6.13(d) show the roll and pitch angles of SMoLBot(T) and SMoLBot(R) operating with the alternating-tripod and the optimum gait, respectively. Gait and locomotion behavior of the robot with only torsional backbones are almost similar to SMoLBot with compliant(I) backbones while they are operating with an optimum gait; However SMoLBot(T) rolls less than SMoLBot(I). This is due to the higher torsional stiffness of the only torsional backbones compared to the compliant(I) backbones. Six-legged three-module SMoLBot with rigid backbones that is operating with the alternating-tripod gait has almost zero roll and pitch angles. This is due to the statically stable behavior of the alternating-tripod gait where three diagonal legs are always in contact with the ground during the operation.

Figure 6.14 shows the velocity results of the eight-legged four-module SMoLBots operating with the optimum gait and the continuous-symmetrical form of the trot gait. Feet trajectory paths of SMoLBot(R), SMoLBot(T), and SMoLBot(I) shown in Fig. 6.15 briefly demonstrate the locomotion behavior of the robot in a single gait cycle, where $Z = 0$ indicates the contact between the foot and the ground. Fig. 6.15(a) shows the feet trajectory and the feet contact sequence of SMoLBot with compliant(I) backbones that is operating with the optimum gait. Eight-legged four-module SMoLBot(I) that is operating with the optimum gait follows a contact sequence pattern such that, in a large portion of the gait cycle only four periodically-changing legs are in contact with the ground. This locomotion pattern eliminates the effect of the undesired leg slip, which is the main reason of not achieving full running capacity and a maximum velocity. Contact sequence (*CS*) that shows the step-wise feet contact sequence in a single gait cycle for SMoLBot with compliant(I) backbones operating with the optimum

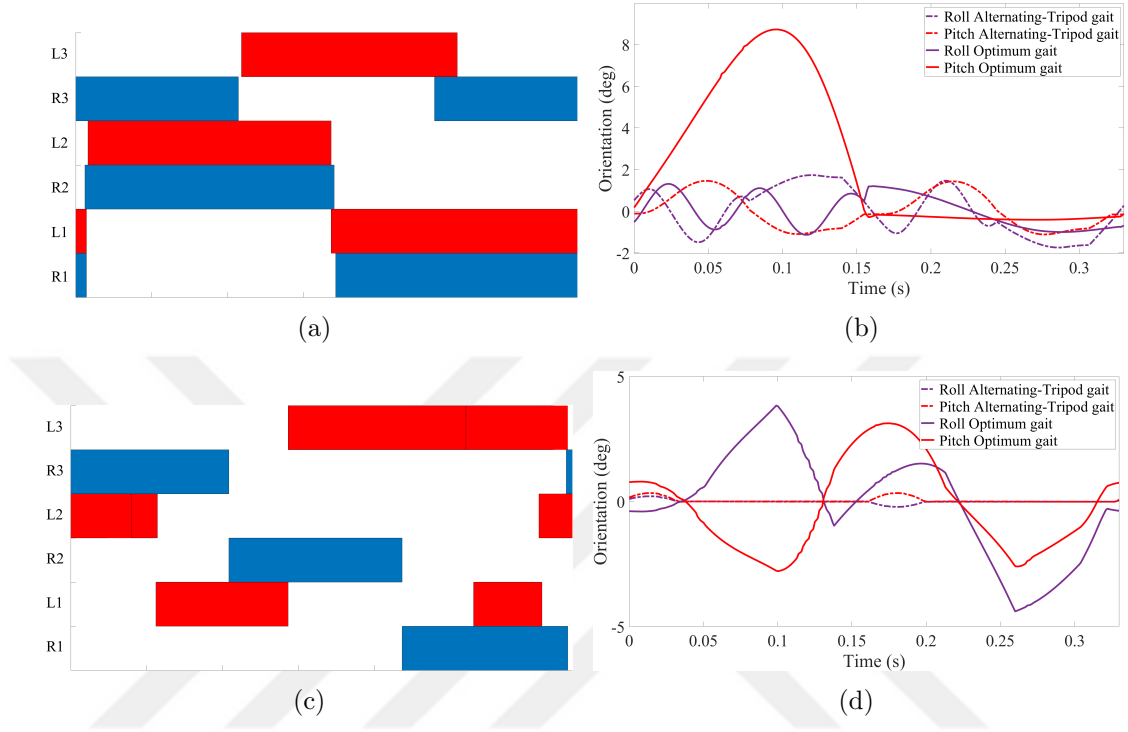


Figure 6.13: (a) Optimum gait of six-legged three-module SMoLBot with compliant(T) backbones. (b) Roll and pitch angles of SMoLBot(T) that is operating with alternating tripod and the optimum gait. (c) Optimum gait of six-legged three-module SMoLBot with rigid backbones. (d) Roll and pitch angles of SMoLBot(R) running with alternating tripod and the optimum gait.

gait, is as follows:

$$CS = \begin{pmatrix} R_3 & R_1 & R_2 & R_2 & R_1 \\ L_3 & L_1 & L_2 & L_2 & L_1 \\ & R_3 & R_3 & R_4 & R_4 \\ & L_3 & L_3 & L_4 & L_4 \end{pmatrix}$$

where, the first column is $t = 0$ and the last column is $t = t_{end}$ and individual columns show the in-contact feet of the robot. Table 6.3 shows the optimum feet phases of the eight-legged four-module SMoLBots with compliant(I), compliant(T), and rigid backbones.

Figure 6.15(b) shows the feet contact sequence of the eight-legged four-module

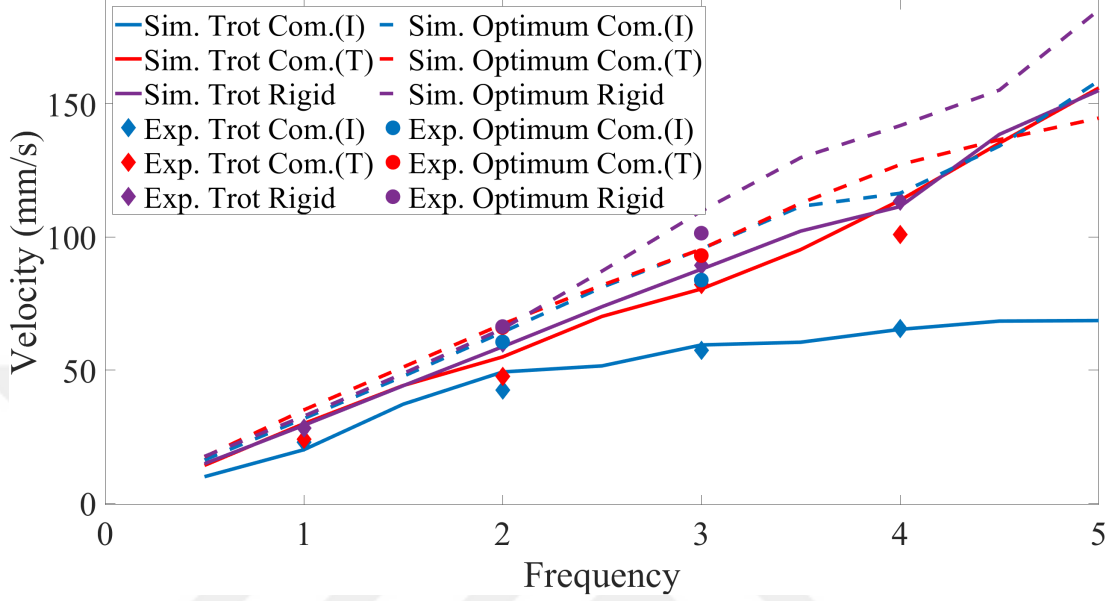


Figure 6.14: Simulation and experimental velocity results of the eight-legged four-module SMoLBots with rigid, compliant(I), and compliant(T) backbones operating with an optimum and continuous-trot gaits.

SMoLBot(T) operating with the optimum gait. Our previous studies shows that SMoLBots with compliant(T) backbones suffer from rear module's feet being dragged on the ground while the front module's feet are striding. This dragging motion introduces an undesired friction force to the system that decreases the robot's translational velocity. The optimum gait of SMoLBot with compliant(T) backbones, has a unique feet contact sequence where it lifts the rear module legs (R_3 , L_3 , R_4 , and L_4) during the slip cycle. This lifting motion eliminates the undesired opposing motion of the feet and removes the undesired friction forces. *CS* for the eight-legged four-module SMoLBot with compliant(T) backbones operating with the optimum gait, is as follows;

$$CS = \begin{pmatrix} R_3 & L_1 & L_1 & R_1 \\ L_3 & R_2 & R_2 & L_2 \\ & R_3 & R_4 & R_4 \\ & L_3 & L_4 & L_4 \end{pmatrix}$$

Figure 6.15(c) shows the feet trajectory of the eight-legged four-module SMoLBot with rigid backbones that is operating with the optimum gait. Eight-legged four-module SMoLBot(R) running with the optimum gait follows a similar movement pattern to the six-legged SMoLBot(R) such that, motion starts with striding on two legs and then falling on the third leg. Contact sequence of the eight-legged four-module SMoLBot with rigid backbones and operating with the optimum gait, is described as;

$$CS = \begin{pmatrix} R_3 & R_1 & R_1 & R_2 & R_3 \\ L_3 & L_1 & L_2 & L_4 & L_3 \\ & L_2 & R_4 & & \end{pmatrix}$$

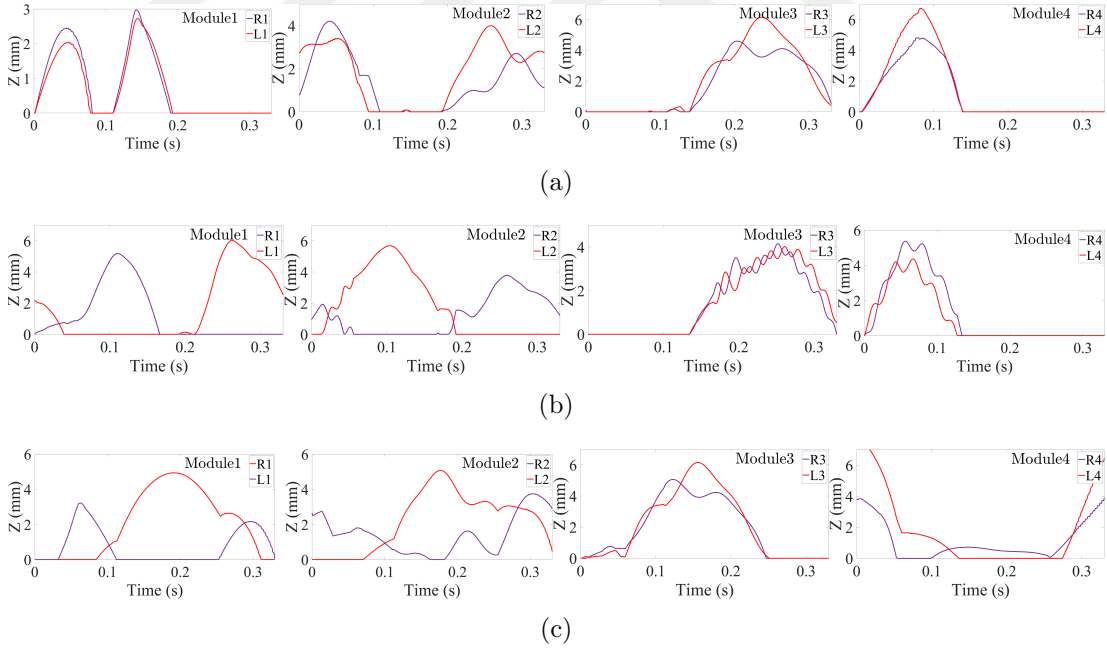


Figure 6.15: Feet trajectories of the eight-legged four-module SMoLBot in a single optimum gait cycle with (a) compliant(I) backbones, (b) compliant(T) backbones, and (c) rigid backbones.

Figure 6.16 shows the velocity results for the ten-legged five-module SMoLBots running with the continuous-trot gait and the optimum gait. Similar to the eight-legged and the six-legged SMoLBots, the ten-legged SMoLBot(I) have the highest

Table 6.3: OPTIMUM FEET PHASES OF THE EIGHT-LEGGED FOUR-MODULE SMOLBOTS

	SMoLBot(R)	SMoLBot(T)	SMoLBot(I)
$R_1 - L_1$ (<i>deg</i>)	0-132	0-172	0-0
$R_2 - L_2$ (<i>deg</i>)	32-118	155-0	62-90
$R_3 - L_3$ (<i>deg</i>)	180-180	180-180	162-173
$R_4 - L_4$ (<i>deg</i>)	100-15	80-108	77-50

increase in the velocity values while operating with the optimum gait. Our previous locomotion studies using the multi-legged SMoLBots that are operating with a symmetrical gait revealed that, the robots with the highest bending and torsional stiffness have the highest translational velocity; However, velocity comparison study in this manuscript indicates that, robots can run with a velocity in a similar range disregarding the compliance between the modules if an appropriate set of optimum gaits is used. Multi-legged SMoLBots with different range of compliance between the modules have a translational velocity in a similar range while operating with different gaits that are compatible with their operational-limitations and compliance range. Table 6.4 shows the optimum feet phases of the ten-legged five-module SMoLBots with rigid, compliant(T) and compliant(I) backbones. Fig. 6.17(a) shows the locomotion pattern of a ten-legged five-module SMoLBot(I) operating with the optimum gait in a single gait cycle with the time step of $\delta t = 0.1$. Blue arrows in Fig. 6.17(a) represent the nominal contact force and the tangential friction forces of the feet.

Figure 6.17(b) shows the optimum gait of the ten-legged five-module SMoLBot with compliant(I) backbones. Ten-legged five-module SMoLBot(I) operating with the optimum gait uses only five periodically changing legs to stride. All modules except the last module in the ten-legged SMoLBot(I) have a lift and drop motion, where at some point both feet of the module will lose contact with the ground. This lift reduces the slip length and increases the velocity. Contact sequence (*CS*) for the ten-legged five-module SMoLBot with compliant(I) backbones that is operating with the optimum gait, is described as;

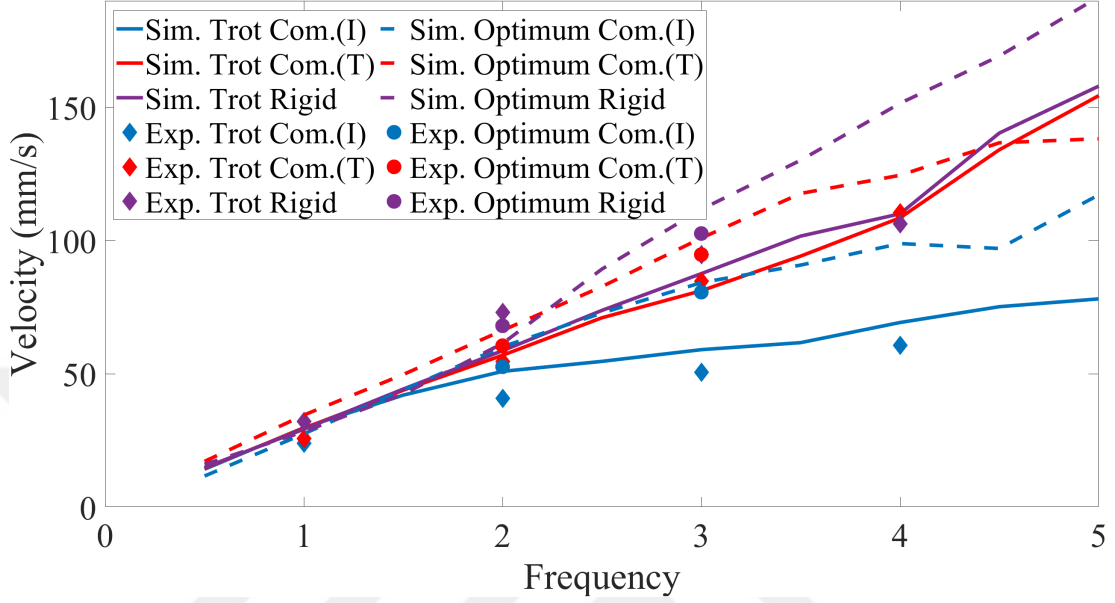


Figure 6.16: Simulation and experimental velocity results of the ten-legged five-module SMoLBots with rigid, compliant(T), and compliant(I) backbones operating with an optimum and continuous-trot gaits.

$$CS = \begin{pmatrix} R_1 & R_3 & R_3 & R_2 & R_1 & R_1 & R_1 \\ L_1 & L_3 & L_3 & L_2 & L_1 & L_1 & L_1 \\ R_4 & L_4 & R_5 & R_4 & R_4 & R_5 & R_4 \\ L_4 & R_5 & L_5 & R_5 & R_5 & L_5 & L_4 \\ R_5 & L_5 & & L_5 & L_5 & & R_5 \end{pmatrix}$$

Figure 6.17(c) shows the optimum gait of the ten-legged SMoLBot with compliant(T) backbones. Ten-legged five-module SMoLBot(T) has a feet contact sequence where at instance only two pairs of right and left feet are in contact with the ground. This generates a statically stable locomotion with maximum contact during the stride period. CS for the ten-legged five-module SMoLBot with compliant(T) backbones that is operating with the optimum gait, is described as:

$$CS = \begin{pmatrix} L_2 & R_1 & R_1 & R_2 & R_2 & R_2 \\ R_2 & L_2 & L_1 & R_3 & L_2 & L_2 \\ L_4 & R_4 & R_4 & R_5 & R_5 & R_5 \\ & L_4 & L_4 & L_5 & R_5 & L_5 \\ & & & & & R_1 \end{pmatrix}$$

Figure 6.17(d) shows the optimum gait of the ten-legged SMoLBot with rigid backbones. Ten-legged five-module SMoLBot(R) running with the optimum gait strides with only two legs while falling on a third leg. The periodical motion of the ten-legged SMoLBot(R) starts with lifting two front modules (positive pitch angle), following with zero pitch where front modules are dropped, and finally end by lifting the rear modules (negative pitch). CS for the ten-legged five-module SMoLBot with rigid backbones operating with the optimum gait, is described as:

$$CS = \begin{pmatrix} R_3 & L_1 & L_1 & R_2 & L_2 & L_2 & R_1 & R_1 & R_1 & R_1 \\ L_4 & L_3 & R_2 & L_4 & R_3 & R_3 & L_5 & L_2 & L_3 & L_3 \\ & R_4 & R_5 & & L_4 & L_5 & & L_5 & & R_4 \end{pmatrix}$$

Table 6.4: OPTIMUM FEET PHASES OF THE TEN-LEGGED FIVE-MODULE SMOLBOTS

	SMoLBot(R)	SMoLBot(T)	SMoLBot(I)
$R_1 - L_1$ (deg)	0-137	0-126	0-5
$R_2 - L_2$ (deg)	92-63	16-0	112-170
$R_3 - L_3$ (deg)	60-180	77-93	177-175
$R_4 - L_4$ (deg)	180-107	175-175	78-5
$R_5 - L_5$ (deg)	130-38	77-162	38-137

Compliance between the modules and feet motion patterns are two main properties of the miniature robots that can be exploited to maximize the robot's velocity. Robots with different backbone types (different range of compliance between the modules) show different locomotion behavior while operating with a similar gait. Results indicate that within a specific range of compliance there exists a unique set of feet phases that maximizes the robot's velocity. Furthermore, comparing

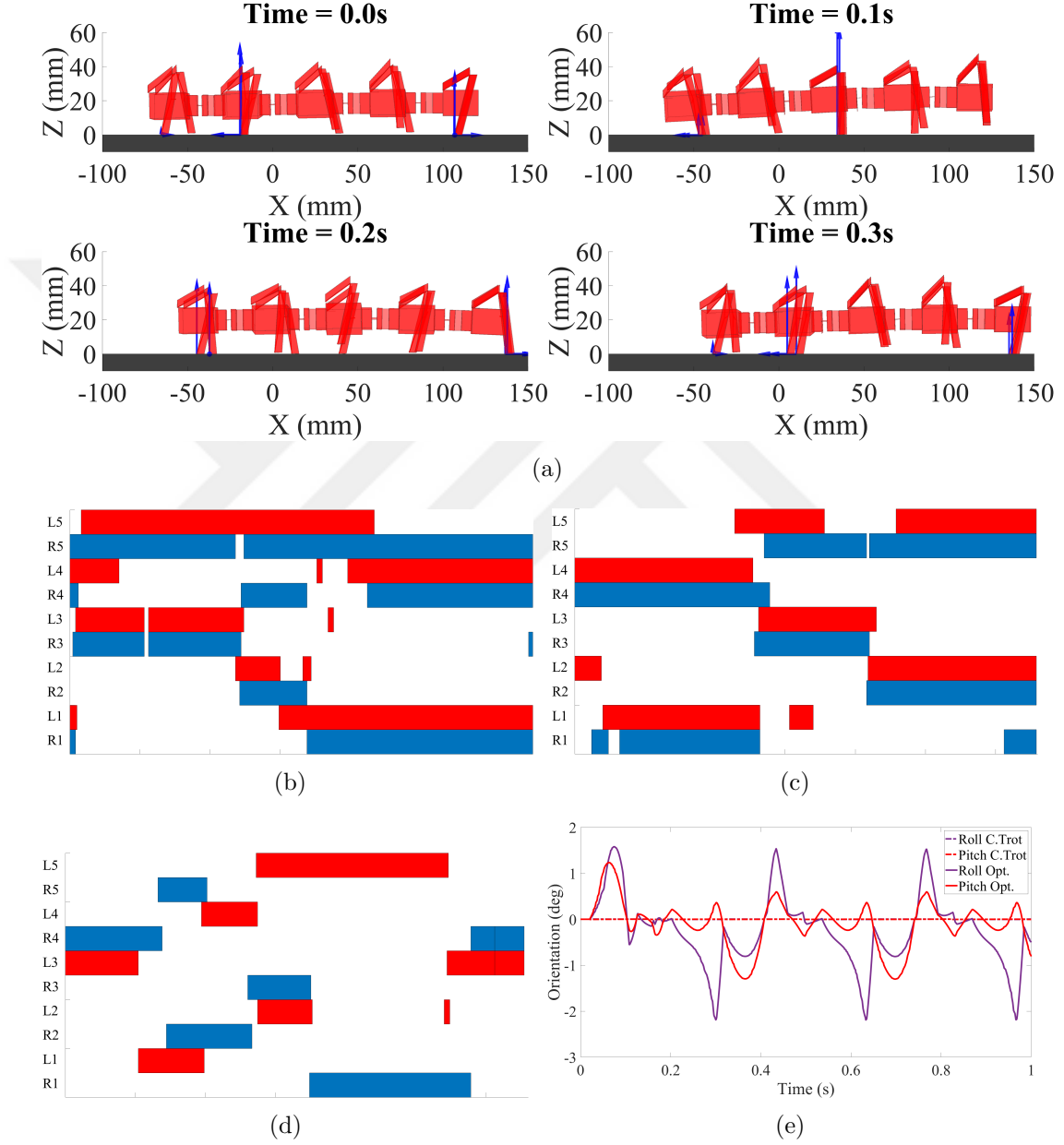


Figure 6.17: Ten legged five-module SMoLBot's locomotion pattern in a single gait cycle with the $\delta t = 0.1$ time step with compliant(I) backbones. (b) Optimum gait for the ten-legged five-module SMoLBot(I). (c) Optimum gait for the ten-legged five-module SMoLBot(T). (d) Optimum gait for the ten-legged five-module SMoLBot(R). (e) Roll and pitch angles of the five-module SMoLBot(R) operating with the continuous-trot (C.trot) and the optimum gait.

the results of the multi-legged robots, operating with different gaits, show a similar locomotion behavior, i.e, robots with different backbone types have different optimum gaits, however, they have a similar motion pattern to maximize the velocity. SMoLBots with compliant backbones tend to have a bouncy motion (lift, jump, and fall) with a considerable pitch. This bouncy motion eliminates the slip and any undesired motion of the legs in an unfavorable direction. On the other hand, SMoLBots with rigid backbones show a different type of locomotion behavior where they use a minimum number of rear or front feet to stride. This locomotion behavior results in a periodically switching motion of positive-negative pitch.

It is necessary to note that, gait analyses in this study are done at $3Hz$ stepping frequency, and experimental results are presented at 2 and $3Hz$ to validate the numerical study. Additionally, SMoLBot's locomotion behavior is studied in the range of 1 to $4Hz$, which is the achievable and controllable frequency range of the DC motors used in SMoLBot.

A common phenomenon that can happen in any legged miniature robot is the feet failure during the operation. Non-functioning feet can be the outcome of the damaged actuators, the fractured leg joints, or the controller failure. In order to investigate the effect of the feet fault on the locomotion of the legged miniature robots, two studies are conducted; First study investigates the robot's locomotion behavior with a specific number of inoperative feet with a random positioning, and the second locomotion study considers only the effect of two non-functioning feet of each module on the robot's locomotion. First study deals with multiple different cases, in which each individual case considers a different ratio of fractured feet to the total number of feet, as follows;

- Case(1) - 70% of the total number of the feet are fractured,
Velocity threshold $\geq 0.3 \times V_f$.
- Case(2) - 50% of the total number of the feet are fractured,
Velocity threshold $\geq 0.5 \times V_f$.
- Case(3) - 30% of the total number of the feet are fractured,

Velocity threshold $\geq 0.7 \times V_f$.

In this locomotion study, the effect of the feet faults are studied in a ten-legged five-module and a six-legged three-module SMoLBot with compliant(I) and rigid backbones. All locomotion studies consider two different symmetrical and asymmetrical gaits discussed in previous section, continuous-trot gait and the optimum gait, and the velocity thresholds are used to compare the velocity of the robot with non-functioning feet to the velocity of the robot with fully functioning feet. The velocity threshold for each case is defined as the percentage ratio of V_f , where V_f is the velocity of the fully-functioning like robot with a similar gait and the same number of feet. Locomotion study of the six-legged three-module and the ten-legged five-module SMoLBots with non-functioning feet can be seen in Table 6.5 and 6.6, respectively. 'X' and '✓' in these tables show that if the velocity of the robot with non-functioning feet is lower or higher than the defined threshold velocity for that specific case. Results indicate that the robots running with symmetrical gaits, such as the continuous-trot gait, are more sensitive to any disturbance due to the feet failure.

Table 6.5: SIX-LEGGED THREE-MODULE SMOLBOT FEET FAULT RESULTS

	Case(1)	Case(2)	Case(3)
SMoLBot(R) C.Trot gait	X	✓	✓
SMoLBot(I) C.Trot gait	X	X	X
SMoLBot(R) Optimum gait	✓	✓	X
SMoLBot(I) Optimum gait	X	X	✓

Table 6.6: TEN-LEGGED FIVE-MODULE SMOLBOT FEET FAULT RESULTS

	Case(1)	Case(2)	Case(3)
SMoLBot(R) C.Trot gait	X	X	✓
SMoLBot(I) C.Trot gait	X	X	✓
SMoLBot(R) Optimum gait	✓	✓	✓
SMoLBot(I) Optimum gait	X	X	✓

We observed different locomotion behavior comparing the motion patterns of

SMoLBot with different backbone types while similar combinations of the non-functioning feet were tested. Locomotion analysis of SMoLBot(R) with different sets of feet fault shows that SMoLBot(R) operating with the optimum gait possesses a velocity higher than the defined velocity threshold. In contrast, locomotion analyze of SMoLBots with compliant backbones indicates that the locomotion of the robot is considerably affected by any disturbance due to the feet failures, and the robot faces a total failure while considerable number of feet are not operating. This can be related to SMoLBot's locomotion characteristics with rigid or compliant backbones; i.e. removing d number of legs from an n -legged robot with rigid backbones results in an $(n-d)$ -legged robot that $(n-d)$ legs drive the robot in their stride period without slipping (even though falling on one side can happen based on the non-functioning feet positions). However, SMoLBots with compliant backbones crawling/running on the ground, where each module is pushing and pulling the rear and front modules, removing d number of the legs affect significantly the pulling/pushing motion, which result in a notable decrease in the velocity. It is important to note that comparing the results in different non-functioning feet combinations while the number of the non-functioning feet is kept constant, different locomotion behavior is observed from SMoLBots. This indicates that lacking a specific set of feet affect the multi-legged robot's locomotion capabilities more than the others when the gait is not altered, which shows the case sensitivity of the robot's locomotion on a specific set of robot's feet. Figures 6.18 and 6.19 show the effect of missing module _{i} 's feet on the locomotion of six-legged three-module and ten-legged five-module SMoLBots while the gait and frequency are not altered.

In these figures module₀ represents the case where all legs are fully functioning. It should be pointed out that for the six-legged three-module robot even removing a single leg will result in a statically unstable motion, no legs can be removed from a six-legged robot without compromising static stability. However, this is not the case for the robots with $n > 6$ legs, even though there is are cases resulting in a statically unstable system but statically unstable condition can be avoided if the appropriated combinations have appeared. It is clear that non-functioning feet effect is dependent on the feet contact sequence pattern; however, R_2 and L_2

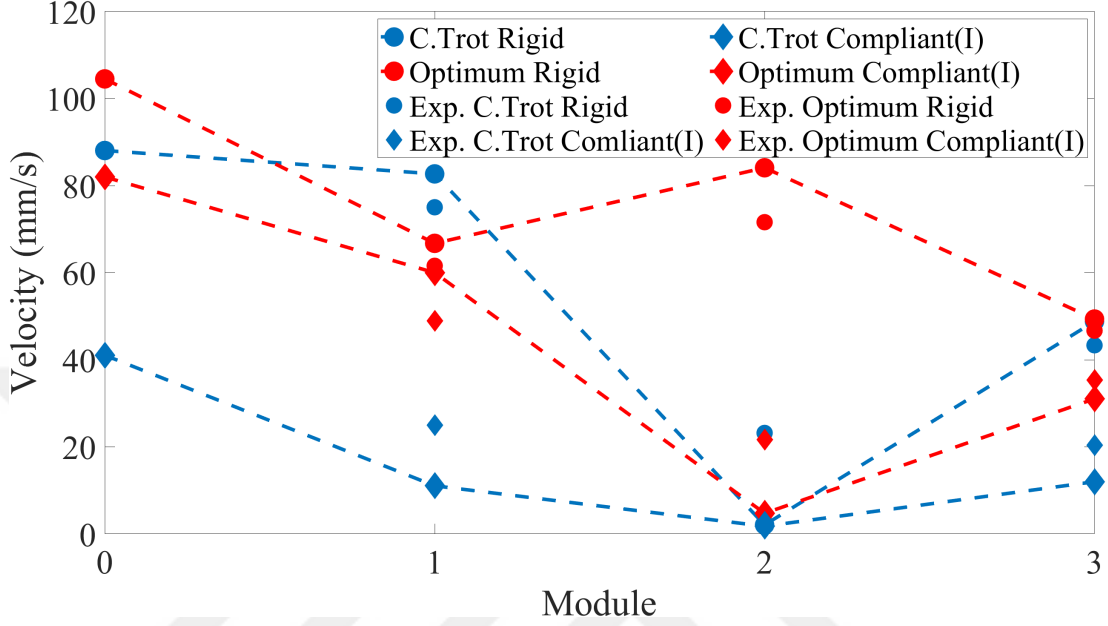


Figure 6.18: Six-legged three-module SMoLBot's velocity while both feet of a module_{*i*} are not functioning.

legs of the six-legged three-module SMoLBots have the most important effect on robot's locomotion, where the robot's velocity almost drops down to zero when the both feet on the second module are not functioning. Six-legged three-module SMoLBot with rigid backbones that is operating with the optimum gait uses rear module legs to lift and front module legs (R_1 , L_1) to stride. This lifting motion of the mid-module decreases the effect of the second module's feet fault on the robots overall motion. This explains the distinguishing behavior of SMoLBot with rigid backbones operating with the optimum gait. Additionally, locomotion analysis of the six-legged three-module SMoLBot(R) operating with alternating-tripod gait has shown that removing both feet of the second module results in an in-place crawling motion, however, removing both legs of the first or third module results in a walking four-legged robot.

Velocity comparison study indicates that SMoLBots with $N > 3$ modules and rigid backbones that are missing a pair of feet on a single module results in a statically stable robot where the velocity is not alternated, but for SMoLBots(I) that is operating with a symmetrical continuous-trot gait, missing mid-modules

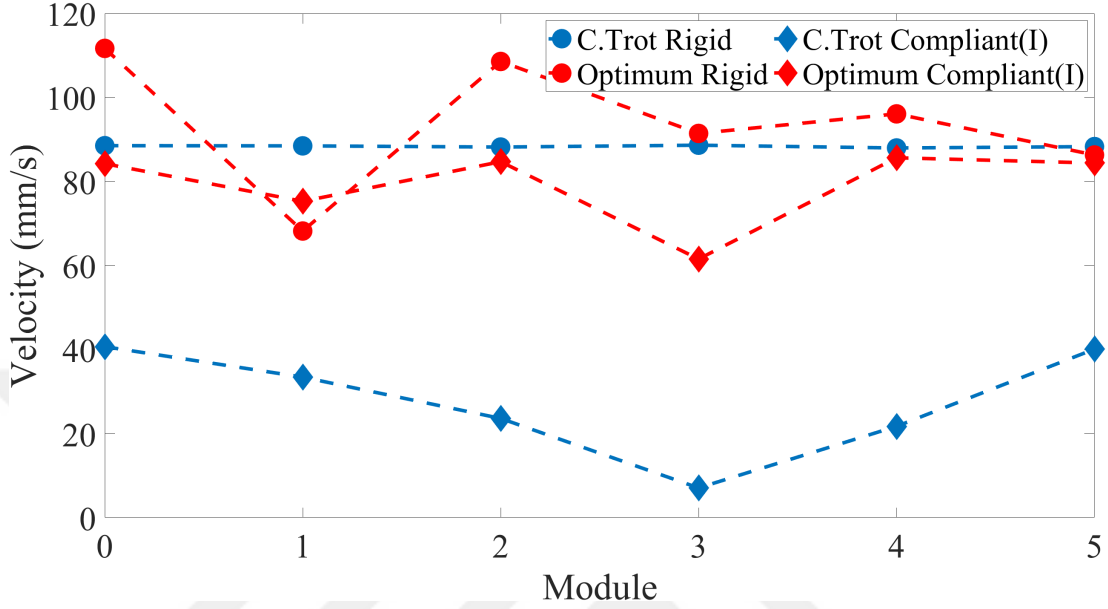


Figure 6.19: Ten-legged five-module SMoLBot's velocity while both feet of a module_{*i*} are not functioning.

feet can result in a significant velocity lost. Additionally, results indicate that using an asymmetric gait such as the optimum gait will decrease the effect of single module feet failure on the robots locomotion which can be seen in Fig. 6.19. Furthermore, it is a predictable observation that increasing the total number of feet will decrease the effect of a single module on the robot's locomotion disregarding the backbone type.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

This thesis is an overall study of designing, controlling, dynamic modeling, analyzing gaits, and investigating the locomotion patterns in a multi-legged miniature robot with soft backbones. Initially, in this thesis, we are introducing a new soft-hybrid modular miniature robot, SMoLBot, that utilizes the advantages of origami-inspired and soft robots at the same time. SMoLBot uses lightweight thin cellulose acetate sheets for body and locomotion mechanisms and PDMS as the base material for the module connection and locking mechanisms. A combination of soft backbones with resilient structures as the robot's body, in a modular concept, results in a robotic system with a smoother walking pattern and better maneuverability. Independent leg control and actuation in SMoLBot enables gait performing and locomotion analysis of the multi-legged robots while various ranges of compliance can be imposed on the system. More importantly, since robots with high degrees of freedom do not exist much in miniature scale, SMoLBot can be used as a platform to properly study and examine locomotion behavior at a small scales, as well.

Next, this thesis presents a general framework for the dynamic modeling and

locomotion analysis of the legged modular miniature robots with soft connections. The position of the contact point for each leg is estimated using the closed-chain leg kinematic model, and the ground interaction forces for the model are obtained assuming a spring-damper model. Newton-Euler formulation is utilized in order to obtain a general dynamic formulation of an n -legged robot with soft/rigid backbones. Backbones as connection mechanisms in SMoLBot are modeled as torsional spring-damper systems that connect two individual modules to each other. The model is verified with experimental results obtained using SMoLBot with different types of soft/rigid backbones and different numbers of modules. The dynamic model of the legged miniature robots is crucial to study the dynamic locomotion behavior at a small-scale, in which the robots do not have any feet touch or force sensors. Additionally, since the robot's actual gait differs from the intended gait, due to the body rotations, the dynamic model can present a gait study framework for the modular miniature robots.

An investigation on the effects of the backbone stiffness on the locomotion of SMoLBot with different numbers of modules is conducted. Results indicate the existence of optimum stiffness values in different ranges of stepping frequencies for SMoLBots, which maximize the translational velocity of the robot. Furthermore, SMoLBots locomotion studies show that for a given type of backbone and a range of compliance between modules, there is an optimum module number that maximizes the translational velocity. The results offer a better understanding of the legged miniature robots' locomotion with soft backbones and guidelines for the design and control of the running/crawling legged miniature robots, in the absence of the contact sensors on the feet.

Additionally, In this thesis, the locomotion behavior of the running/walking multi-legged miniature robots with various range of compliance between the modules has been studied from a different point of view. An alternate approach to indicate possible achievable optimum gaits considering the dynamics of the robot with soft module connections is studied. Using the locomotion analysis of the robots running with numerically derived feet sequence patterns, we found that miniature robots with soft backbones tend to show a bouncing motion with a lift-jump-drop periodical sequence, where only a limited number of legs are in

contact with the ground. Furthermore, we have shown that there exists a unique but different gait for each individual multi-legged robot with a different backbone type; Yet, we have observed that the robots' locomotion behavior follows a common principle; SMoLBots with different backbone types that are operating with the optimum gait, follow a feet contact pattern sequence that minimizes the feet slip. Legged robots with different range of compliance between the modules use different locomotion patterns to remove the unfavorable slip forces, while multi-legged robots with compliant backbones favor the use of lift and drop motions, robots with rigid backbones take the advantage of using the statically stable gaits with a minimum in-contact feet number, to eliminate the feet slipping problems. Similar observations have been seen in SMoLBot's experiments while operating with an optimum gait. Additionally, investigation on the effect of the feet failure on the robot's locomotion is conducted. Results indicate that asymmetrical gaits such as the ones presented in the optimum gait study tend to be less affected than symmetrical gaits due to the disturbances caused by the feet faults. Furthermore, locomotion study results have proved that a specific set of non-functioning feet have significant effect on the robot's locomotion and can result in a zero velocity. Our analyses provide useful information including the locomotion trends of the multi-legged miniature robots with soft/rigid connections between the modules, that can be used by the researches while manufacturing and working with the miniature robots.

7.2 Future Work

While there are many ways to extend the work presented herein, primer future work would be active control and actuation of the backbones during the operation for better gait implementation. Similarly, active control on the backbones makes it possible to improve the obstacle climbing capabilities of the robot and can provide a mechanism for faster locomotion on a rough terrain. One possible approach, in order to control the actuation of the backbones, would be the utilization of strain gauges and SMAs. A combination of these two devices makes

it feasible to detect the deflection angles and to control the soft backbones angular orientations. Other means of extending the work, could be developing of autonomous locking and unlocking mechanisms. Integrating position sensors and IMUs to the PCB, in-conjunction with autonomous locking mechanisms, makes it possible to use SMoLBot as an autonomous re-configurable robot with swarm applications. Additional investigations can be done to predict the motion of the robot on rough terrains, that can be easily done using the model. On the other hand, different design techniques and manufacturing methods, such as C-shaped feet, can be used to examine the robots motion behavior on different terrains and to exploit soft maneuverable capabilities of SMoLBot for better performance, while modifying the robot's design.

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