Title
An Application of The Flexostructure: Multifunctional Robot Using Flexostructured Appendages

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Publication Date
2022

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA SAN DIEGO

An Application of The Flexostructure: Multifunctional Robot Using Flexostructured Appendages

A thesis submitted in partial satisfaction of the
requirements for the degree Master of Science

in

Engineering Sciences (Mechanical Engineering)

by

Garam Kim

Committee in charge:

Professor Nicholas Gravish, Chair
Professor John Hwang
Professor Tania Morimoto

2022

The Thesis of Garam Kim is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

University of California San Diego

2022

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ACKNOWLEDGEMENTS

Firstly, I would like to sincerely thank my advisor Professor Nicholas G. Gravish, for giving me a great chance to learn about rigid, soft, and micro-robotics and for continuous support during my research as a master's student in his lab. He always motivated me to think more creatively to finish the project.

Furthermore, I appreciate the rest of my thesis committee members, Professor John Hwang and Professor Tania Morimoto, for attending my defense and their feedback.

I am also thankful to Mingsong Jason Jiang and Qifan Yu for giving me an experience of this project and to all the members of Gravish Lab. Without their constant feedback and creative suggestions, I could have lost in the middle of the project.

Lastly, I want to thank my family for giving me a chance to study abroad and supporting my stay at the University of California, San Diego.

ABSTRACT OF THE THESIS

An Application of The Flexostructure: Multifunctional Robot Using Flexostructured Appendages

by

Garam Kim

Master of Science in Engineering Sciences (Mechanical Engineering)

University of California San Diego, 2022

Professor Nicholas Gravish, Chair

This paper describes an application of tendon-actuated flexostructure appendages that can draw multi-movements, such as rolling and crawling, in a straightforward method. In the fabrication process, the appendage is made of PLA using a 3D printer, and PC film is attached to prevent its deformation and increase flexibility. This structure has many variables that can affect the performance of the appendage. If the mushroom structure's thickness, shape, and linear space change, the appendage's performance may vary. These variables can change the appendage's elastic energy, flexibility, and stiffness. In the application process, we make three versions of the robot which use flexostructured legs. Two flexostructure appendages are used for rolling motion

with a new rolling mechanism called 'Kick and Roll.' Two appendages use their elastic energy to kick the ground. Due to using flexostructure appendages, the robot can make not only rolling motions but also different motions such as crawling, gripping, and dragging. Further research might have a chance to have various types of motions. Ultimately, the robot using the advantages of flexostructure appendages can make a rolling motion with a different kind of mechanism and different motion.

Chapter 1

Introduction

1.1 Introduction

Nowadays, many different types of bio-inspired locomotive robots have been developed significantly. Locomotive robots perform their specific movement, such as rolling, crawling, and jumping. The first type of bio-inspired robot is a rigid locomotive robot. Due to its rigid property, a rigid robot has high stiffness performance and reconfigurable function [1]. The second robot type is a soft robot. Using a soft material makes robot size smaller [2]. Here, we introduce Flexostructure, which has both rigid and soft robot advantages to improve their performance.

Flexostructure is a structure that is not only flexible but also stiff. The structure is made of rigid material Polylactic Acid (PLA) using a specific structural design called Mushroom structure. Flexostructure uses the simplest actuation method, tendon-driven actuation. While the tendon is fully pulled, the structure makes a curved C-curl shape. The space of the mushroom array determines the angle of the C-curl shape. Moreover, since flexostructure has elastic properties, the base layer's thickness has to be relatively thinner than other rigid robots. A 3d printer has been used to fabricate flexostructure. Polycarbonate (PC) film is attached at the bottom of the flexostructure when printing to block the deformation of the structure and add more flexibility [3].

Animals, insects, and plants usually inspire bio-inspired robots. It can be anatomical [4], functional [5], or locomotive properties [6]. In recent high-end robot research, the robot only has one locomotion, which is not competitive. In this research, we are highly inspired by two insects, a grasshopper and a golden spider, both have multi-functionality. While the golden spider moves, it uses its eight legs to walk, crawl, and even dig the ground. However, in the case of downside slope terrain, the golden spider curves its legs inside the body. Eventually, the spider becomes a circular shape to roll down the slope. A grasshopper can walk on the grass and jump to the next grass. Both insects have the same locomotive advantage, multi-functionality. When Flexosturcutre is fully curved, it can curve inside like a golden spider to make a circular shape to roll. Furthermore, flexostructure can store elastic energy during a fully curved stance for the possibility of a jump.

In the process of design and fabricating, we make the prototype of a multi-functional robot called “Rollbot” as an application of flexostructure. Rollbot has gone through three versions of development. Rolling is the first locomotion of the robot. Rollbot is fully untethered with a wifi module to control the robot remotely. A new rolling mechanism has been used, which is called “Kick and Roll.” This rolling mechanism is faster than just using a wheel for rolling motion. Rollbot can even crawl and grab an object using flexostructured appendages. Rollbot has the possibility to jump by using flexostructure’s storing elastic energy property. Further research would allow Rollbot to develop its multi-functionality and performance.

This paper shows the process of fabricating the application of flexostructure. A comparison in the bio-inspired robotics field regarding the advantages and disadvantages of rigid and soft robots elicits the introduction of flexostructure. Experimental results of flexostructure’s performance are included. The process of fabricating Rollbot is listed in terms of the version of Rollbot. At last, the paper concludes the performance of Rollbot and discusses what kinds of further research can improve Rollbot for future work.

1.2 Purpose and Goals

This research is based on the purpose and goals. The first goal is to figure out the performance of flexostructure, which depends on its structural variables. The second goal is to make a bio-inspired multi-functional locomotive robot using flexostructure as an application. Due to these two goals, we fix some variables that hardly affect its performance and figure out what variables can highly affect the flexostructured appendage. The next goal is to use a new mechanism for a robot's rolling motion. Since the robot consists of different types of appendages to make a rolling motion, it is necessary to use a unique mechanism. The last goal is to make a robot as simple, small, and cheap as possible. The recent trend of locomotive multi-functional robotic research is trying to make a robot small and simple but still efficient. To be competitive research, we need to apply the same trend. Furthermore, Flexostructure has a hybrid property of both rigid and soft appendages. Thus, the application can explore various terrain that both rigid and soft locomotive robots can do. In addition, the robot has to be multi-functional because it is the distinct advantage of using appendages. The final goal is to make the most straightforward and cheapest robot, which can be mass-productive at a low cost because we only use the 3D printer to make the whole shape.

Chapter 2

Bio-Inspired Robots

2.1 Bio-Inspired Rigid Robots

Bioinspiration uses biological features, such as anatomical, structural, or locomotive, and mimics their property to have a better performance. Nature has every possible breakout, which is hard to understand, but we can still find a better way. Bioinspiration affects robotics a lot. The most popular and well-known bio-inspired robot is the Gecko lizard robot [7]. Gecko has its unique structure on its foot so it can crawl and stick to the wall. Researchers tried to mimic the Gecko foot's structure and finally make a robot with similar movement, for example, sticking to a vertical wall. Another example is an octopus-inspired robot arm [8]. Octopus structure is called Cephalopod, and its physical fluidity can manipulate objects to grasp or grip. Bio-inspired research can be applied in various fields, including chemical, and nanotechnology, for daily necessities because bio-inspired new technology might have better performance and biocompatibility, so it has been developed as a next-generation research topic.

In this paper, we focus on bio-inspired locomotive robots. Primarily, bio-inspired robot locomotions are based on the animal's locomotion, such as walking and running. In order to mimic animal movement, most robots were made of iron or plastic. Rigid robots use an electronic circuit to actuate the legs. The simplest way to control the legs is using DC motors or servo motors. However, in terms of multimodality, rigid robots require reconfigurable property, and to do it, rigid robots need to use many motors. Using many motors can make the most

Figure 2.1. Gecko lizard inspired adhesion robot

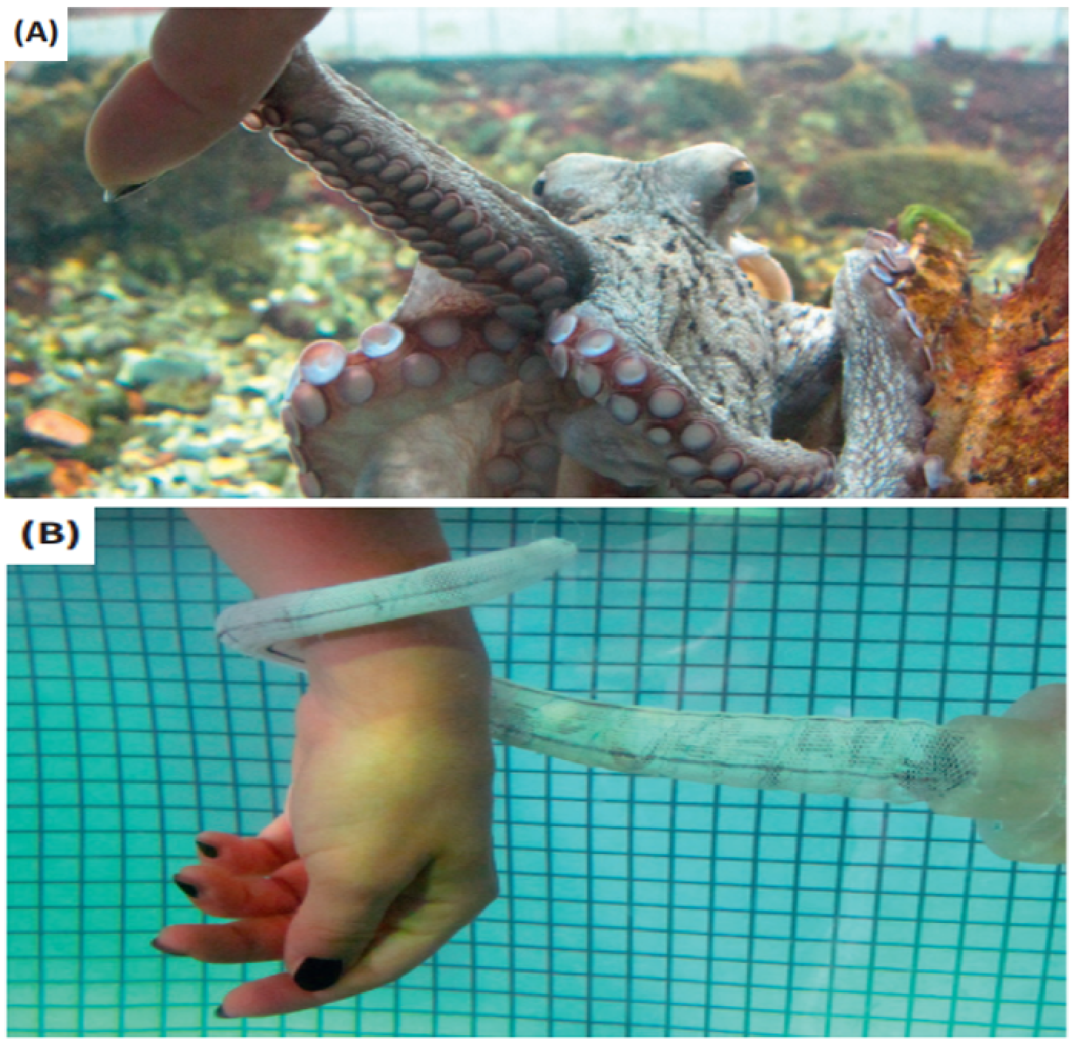


Figure 2.2. Octopus inspired soft robotic arm

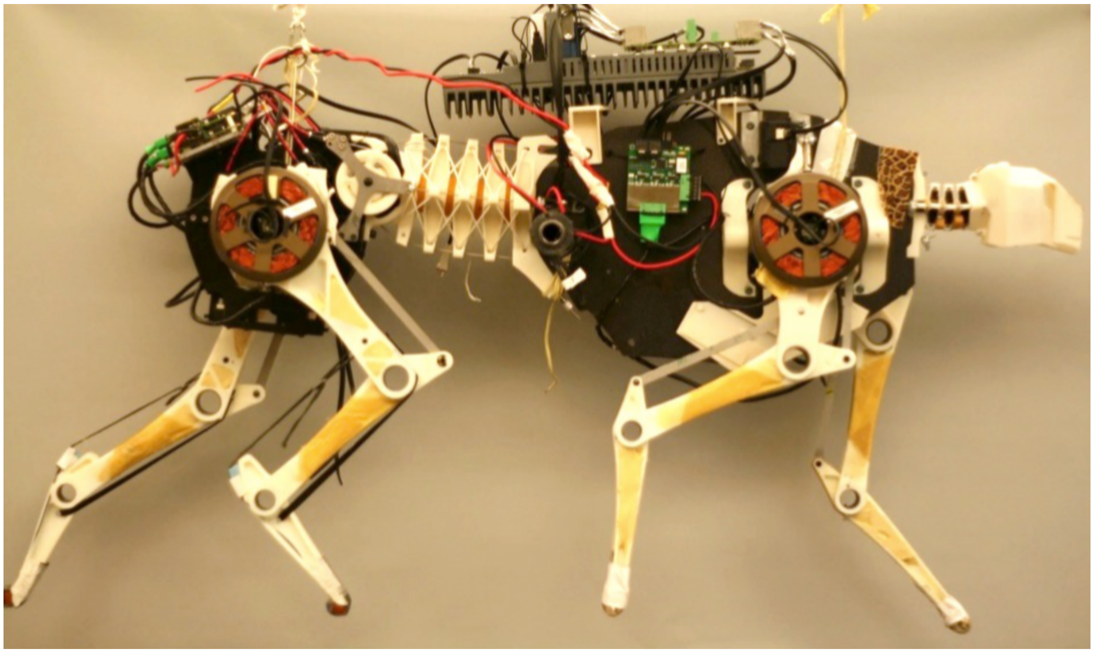


Figure 2.3. Rigid multifuntional robot example: MIT Cheetah

straightforward way of actuation complex and complicated. Furthermore, a big and heavy battery is necessary to control all motors. Rigid materials have a high young's modulus and stiffness. Hence, rigid appendages are able to sustain the relatively heavy body weight of the robot and generate high force to make locomotion like running or jumping. A representative example is MIT Cheetah [9]. MIT Cheetah uses stiff legs to hold the body weight and even walk and run. Nowadays, rigid robot research tries to minimize the size of the total robot and keeps the multimodality. Another example is the Scorpio robot that has a steering function while it is crawling and rolling motion, but it is small [10]. Both two examples are highly representative of the bio-inspired rigid locomotive robot. Cheetah and Scorpio have multimodality, and those rigid legs can generate high energy to move. Nevertheless, unfortunately, a rigid appendage has a disadvantage: the lack of flexibility. Since a rigid leg is not flexible enough, the degree of freedom has to be high for the rigid robot's flexible movement. So as to make various flexible movements, a reconfigurable method is usually chosen, but the method might need a more complicated control method. In the case of the Scorpio robot, it uses 16 servo motors to make various locomotion so that the simplest actuation method would be getting complicated.

Figure 2.4. Rigid multifuntional robot example: Scorpio

2.2 Bio-Inspired Soft Robots

Recent robotics research is highly interested in soft robotics. Rigid robots are limited in size and flexibility, so they would not be adaptable to exploring unique terrains. Soft robots are usually made of soft materials such as silicon for the whole body and appendage, and they can explore the narrow environment or conduct special missions even for the human race. In addition, many researchers use soft robotics in wearable devices for rehabilitation therapy.

Regarding soft locomotive robots, speed is relatively slower than rigid robots, but due to their flexibility, they can make a specific movement that rigid robots do not perform. In addition, there is a possibility that the size of the robot will become as small as possible. For example, the GoQbot is bio-inspired by a caterpillar's ballistic movement [11]. A caterpillar can crawl by its complicated muscle system and crouch down to roll. This locomotion could be a typical flexible soft robot movement that rigid robots cannot make.

However, due to their small scale, soft robots have a problem with an actuation method. These days, many up-to-date actuation methods have been developed. Soft robots can use dielectric elastomer actuation or shape memorial alloy method to stimulate little parts of soft appendages like some insect's complex muscle systems. Despite numerous up-to-date actuation methods, a soft robot's actuation is intricate mainly compared to a dc motor or servo motor, and hard to generate high force.

How about using both rigid and soft robot properties together? In the past research, a hybrid appendage called Flexostructure was developed, which is made of a rigid material, but due to its structural layout, the appendage can also have elastic properties as a soft appendage [3]. Since it is made of rigid material, flexostructure can have stiffness, and even when it is fully actuated, the structure can store elastic energy. Flexostrcuture depends on how the structure's design is. The complete design of the structure can change the flexostructure's properties so we can make more flexible or stiff appendages depending on the purpose. Thus, using flexostructure can have both rigid and soft appendages advantages. Moreover, flexostructure supplements soft

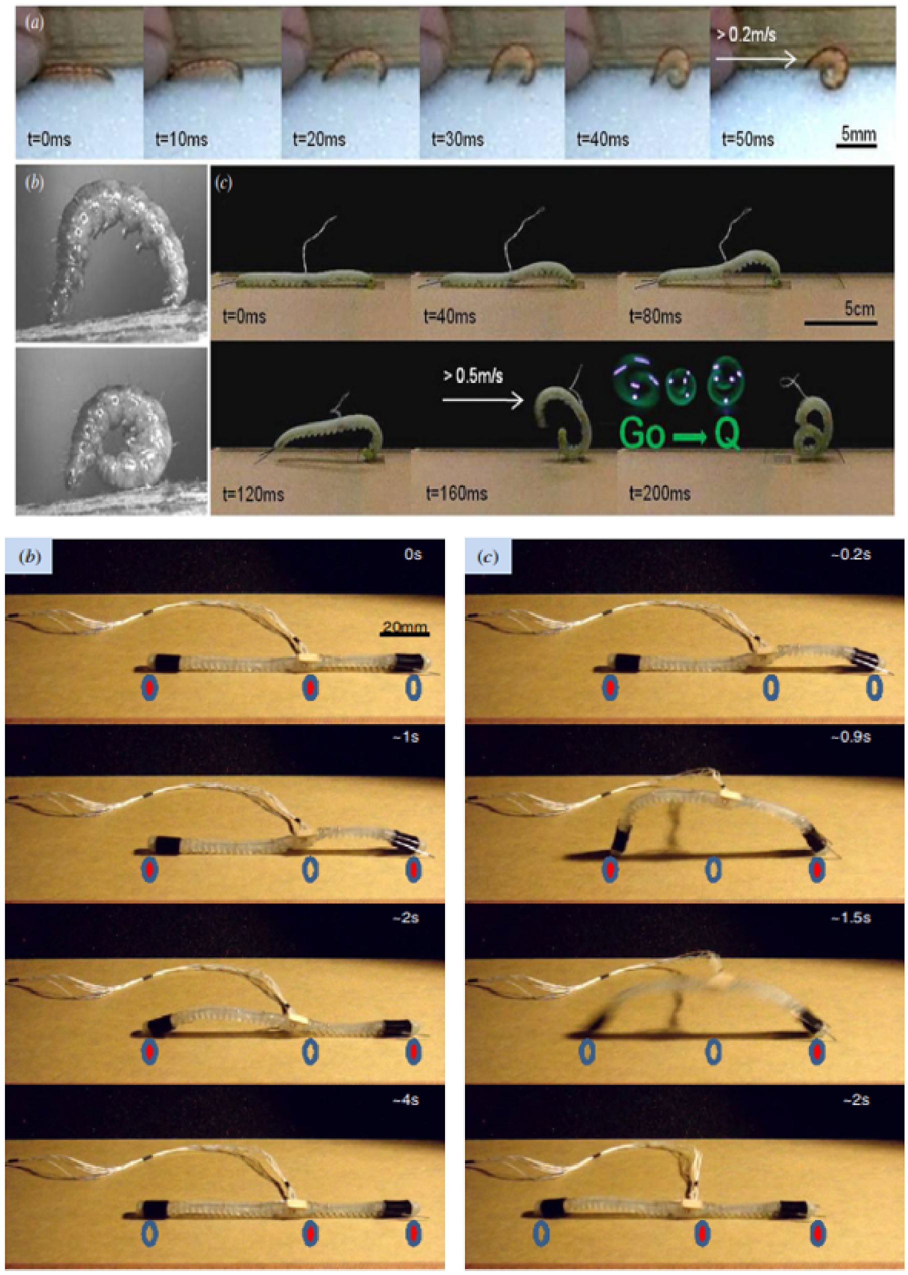


Figure 2.5. Caterpillar inspired GoQbot

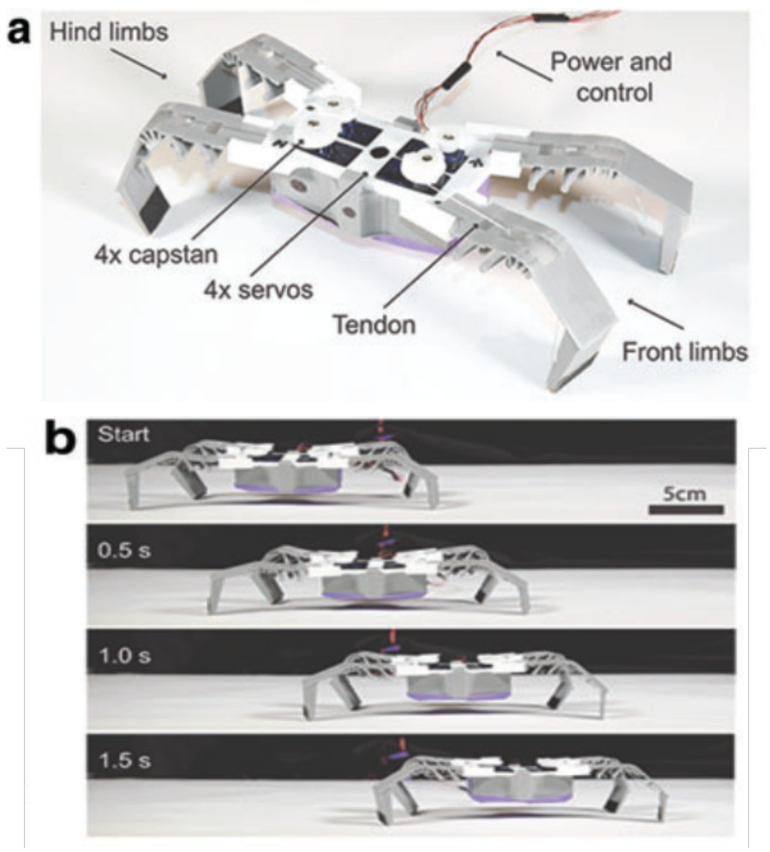


Figure 2.6. Origin of the flexoskeletonized appendage robot

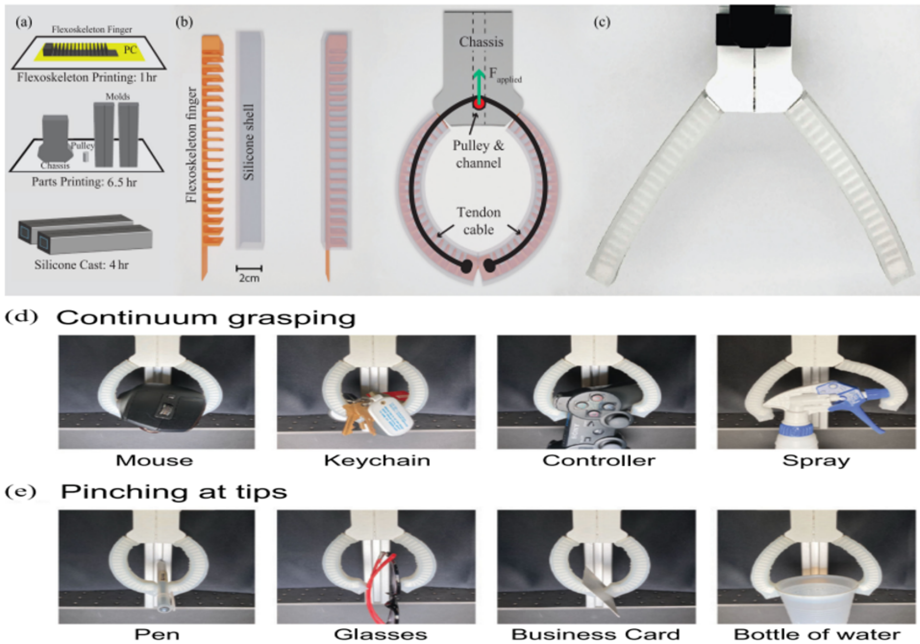


Figure 2.7. Soft gripper using the flexostructured fingers

and complex rigid appendages complicated control method because it can perform various and flexible movements due to a tendon-driven actuation with a small number of DC motors. There is a gripper using flexostructure [12]. In the next chapter, the relationship between flexostructure's variables and its performance is figured out, and we use the result to make a specific flexostructure leg for making a multi-functional robot.

Chapter 3

Flexostructure

3.1 What is Flexostructure

Using different and new appendages can give various advantages and motions in robotics. Rigid-legged robots, including the quadrupedal robot [13], the small insect robot [14], and the MSU jumper [15], use their design appendages to make a different motion. In the case of

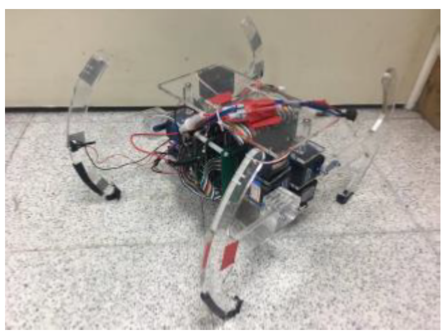


Figure 3.1. Rigid legged robot example: Quadrupedal robot

soft-legged robots such as the untethered soft robot [16], and a starfish inspired robot [17] use soft appendages to make a different motion for its purpose of the robot. Rigid appendages can perform better than soft appendages in terms of durability and stiffness. However, if rigid appendages need to make a high degree of freedom movement, the usage of many motors and complicated control methods might be required [10]. Soft appendages can have more flexibility and advantages in size than rigid appendages, but soft appendages have comparably less power than rigid appendages.

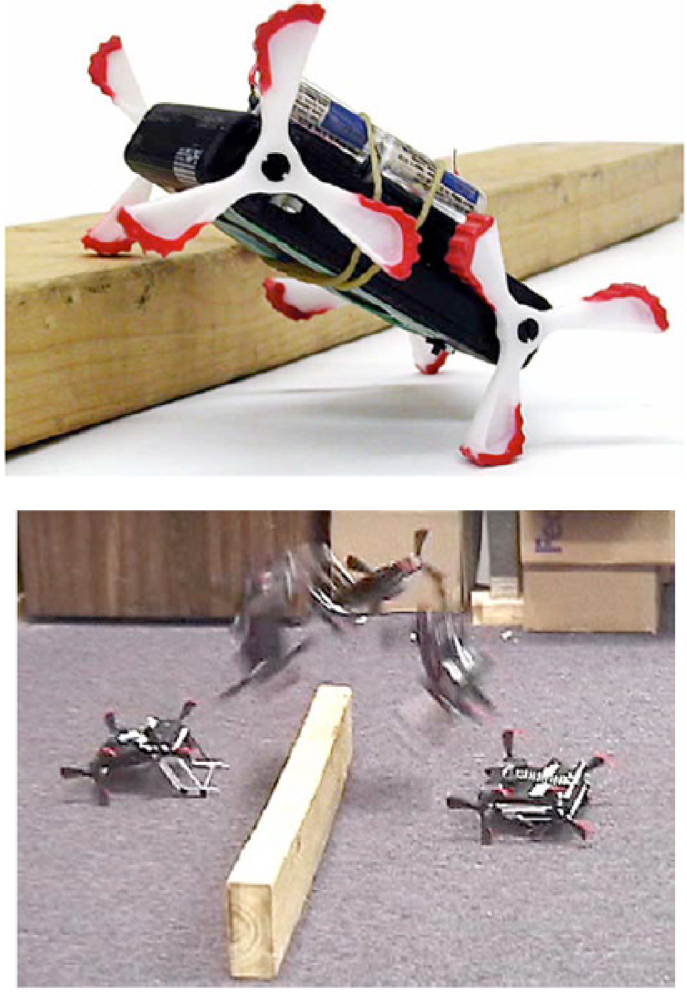
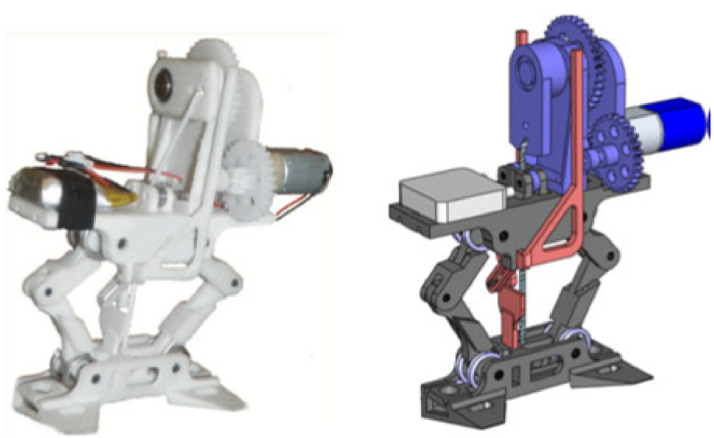


Figure 3.2. Rigid legged robot example: MiniWheg



(a) (b)

Figure 3.3. Rigid legged robot example: MSU jumper

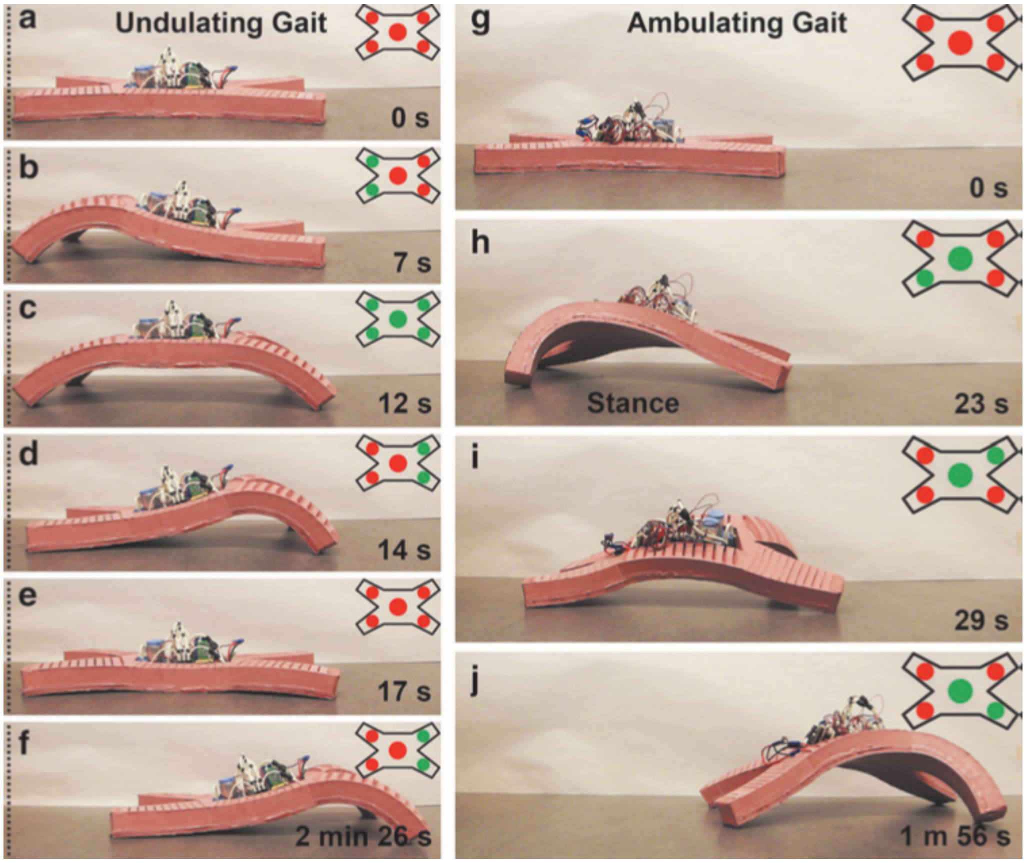


Figure 3.4. Soft legged robot example: A resilient and untethered soft robot

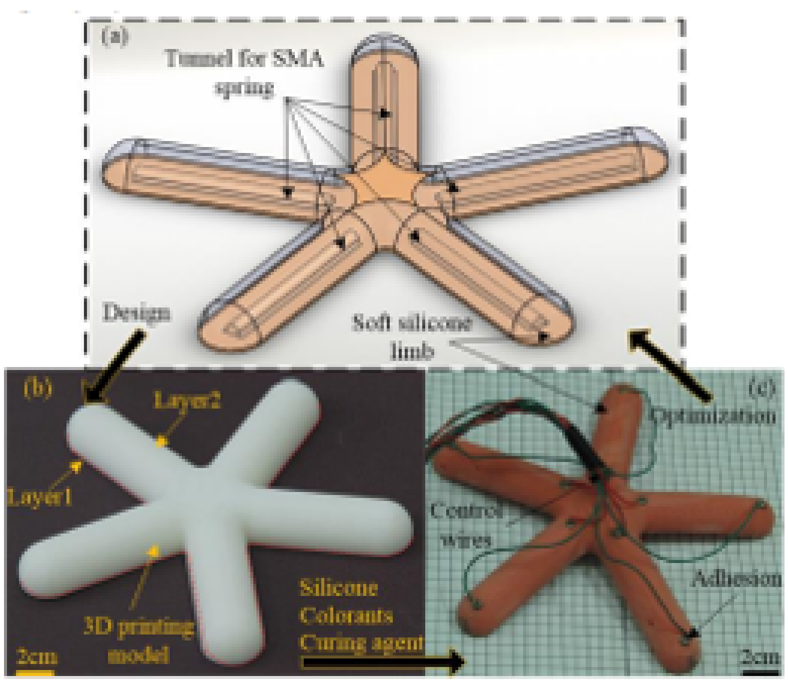


Figure 3.5. Soft legged robot example: Starfish inspired multi-limb soft robot

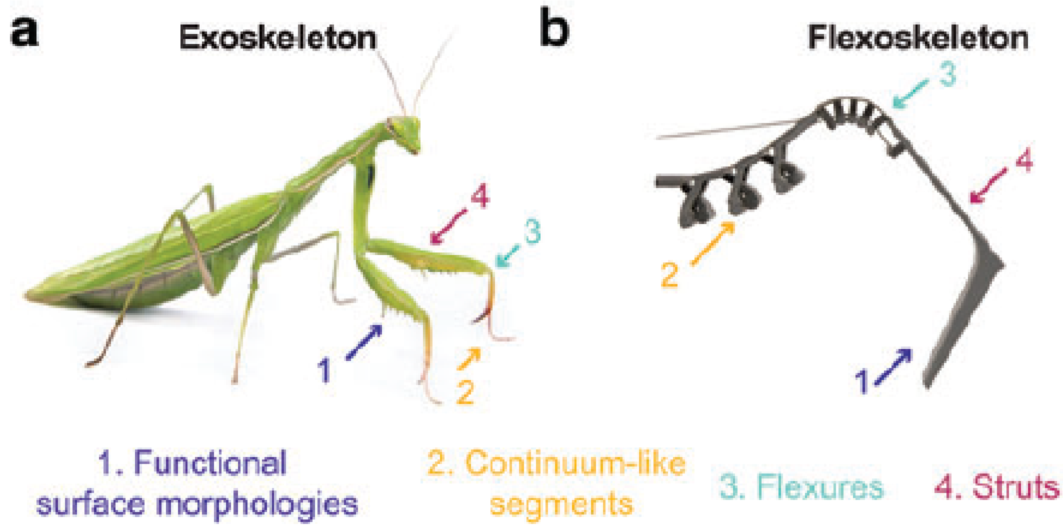


Figure 3.6. Exoskeleton-inspired design of the first flexostructure

In the previous research by Mingsong Jiang, he used a bio-inspired design of a new leg [3]. He is inspired by an insect's exoskeleton, such as a mantis's front legs, and makes a new exoskeleton-inspired robot. Flexostructure uses both rigid and soft appendages advantages at the same time. Flexostructure is made of plastic using a 3d printer which is a rigid material. However, a thin thickness of the base layer allows this 3d printed rigid material to have flexibility. Furthermore, the 'Mushroom structure' layout can make a different curved shape. When the mushroom structure is linearly spaced, flexostructure can be curved in, but the curve angle depends on the space. There are many different shapes and variables for the flexostructure. Thus, in this research, we fix some variables to perform what we want for an application, 'Rollbot.' A particular combination of variables can make a specific performance, and this performance would show us a new mechanism of various motions.

3.2 Fabrication of Flexostructure

The basic process of fabrication is shown in previous research by Mingsong Jiang [3]. As we know, by using a 3D printer, we can easily make various designs. SolidWorks 2021 is

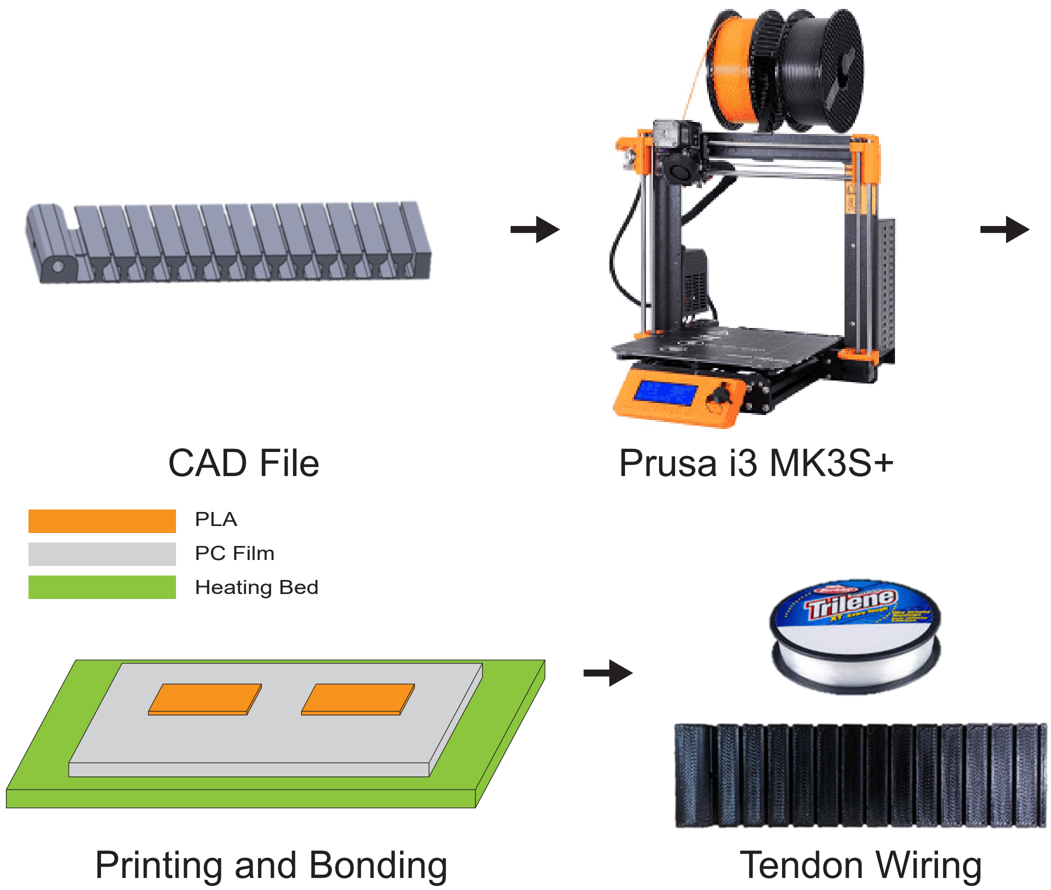


Figure 3.7. Fabrication process of flexostructure

used in this research to make the most of the robot, especially flexostructure appendages. After having a 3D CAD file, the 'Prusa slicer' program helps to make a 3D CAD file into a 'G-code' to print. Prusa i3 MK3S+' is used for the 3D printer. Due to using Polylactic acid (PLA), the nozzle temperature of the printer has to be set to 215'C, and the bed temperature needs to be over 60'C. In the case of printing one appendage, the average printing time is about 1.5 hours.

Firstly, 0.05mm PC film is attached to the 3D printer bed using a glue stick. There are some reasons why we attach PC film to the heating bed. Since flexostructure has a comparably thin first layer thickness, less than 1mm, if we print this thickness on the printing bed directly, the bonding between the first layer and the bed is too weak, so the whole printing result might be broken. On the other hand, heated PC film can bond with 3D printing filament strongly

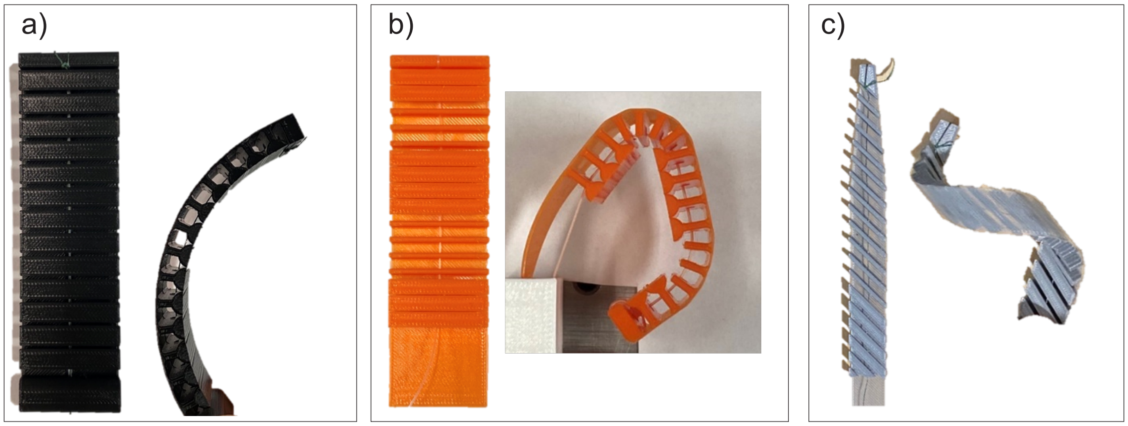


Figure 3.8. Examples of the flexostructured Appendages. a) One-joint basic curved shape. b) Two-joint curve shape. c) Tilted mushroom array makes helical curved shape

and stabilize the first layer printing. In addition, PC film attachment helps flexible motion of flexostructure and blocks the deformation. After printing, we detached PC film from the bed and cut unnecessary parts of PC film using scissors. The last step of the fabrication process is connecting the flexostructure with a tendon. For the tendon, Berkley's 'Trilene super strong XT extra tough' fishing wire is used, which is cheap, hardly deformable, and easily found around us.

3.3 Variables of Flexostructure

3.3.1 Basic Setup

Designing the flexostructure is highly easy and flexible. Solidworks 2021 is used for making 3D CAD files for the flexostructure. Many different types of design can be made without difficulty. For example, in figure 3.3, we can make different joint legs or tilted flexostructure. The degree of freedom of the design of flexostructure is very high. Hence, we need to fix some variables for the purpose of the robot.

In the previous flexostructure research, design variables, including mushroom feature height and width of the legs, have been studied. In the case of this paper, one of the goals is to try to make a small-sized robot. Thus, the width, mushroom structure's height, and basic shape of the design are fixed factor

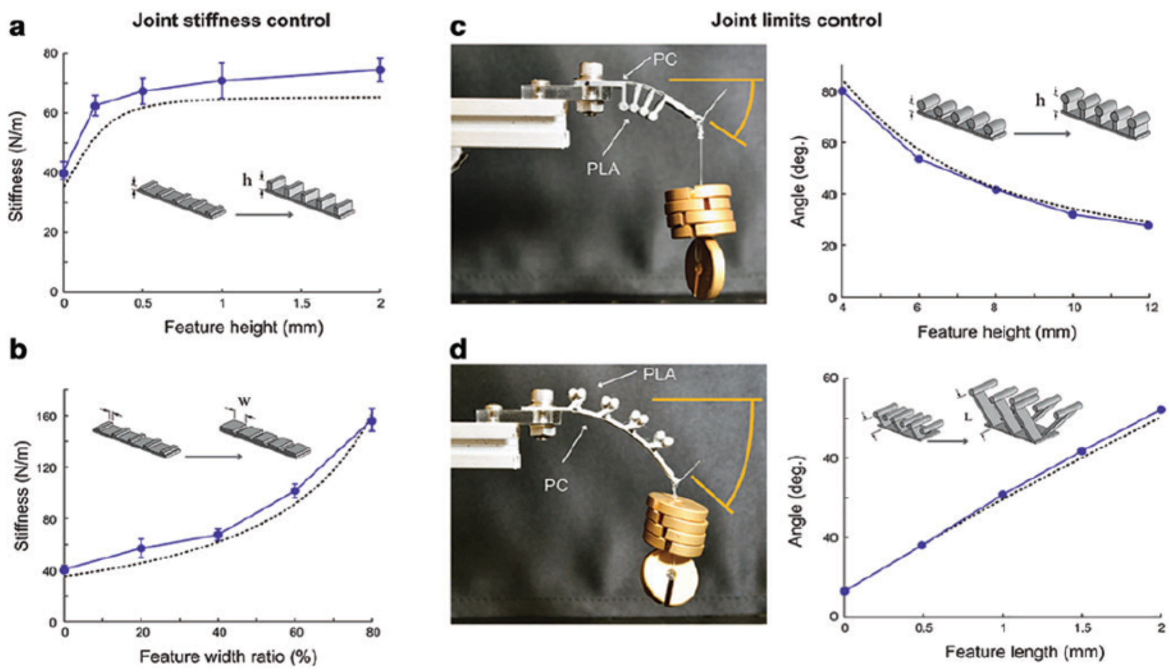


Figure 3.9. Previous research of the joint stiffness test using mushroom structure's height and width ratio, and angle difference test using mushroom structure's height and length

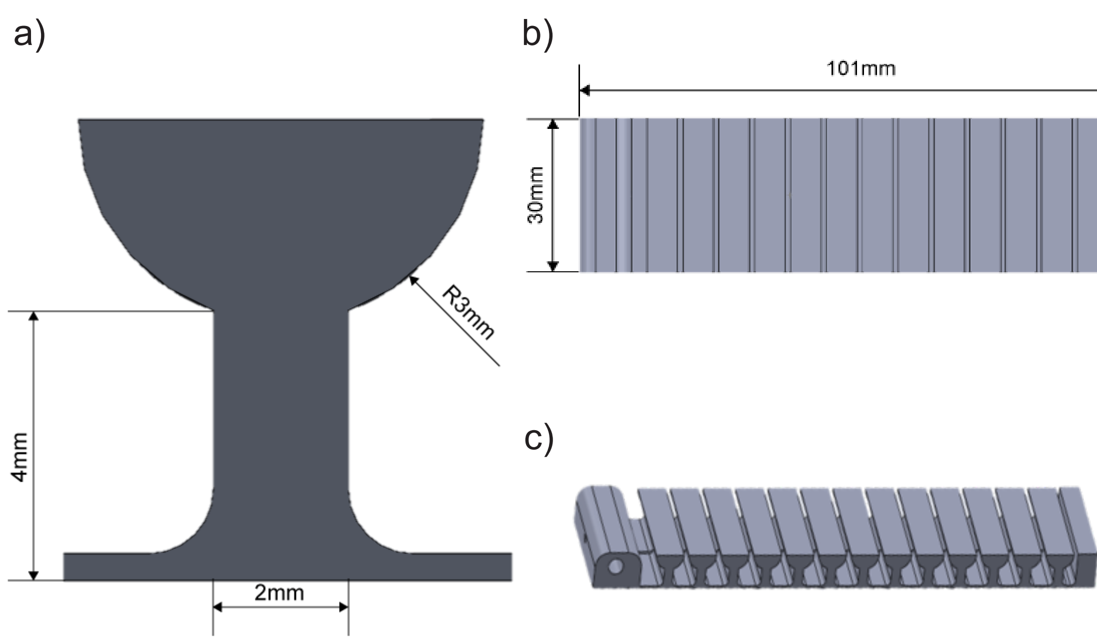


Figure 3.10. Fixed Variables

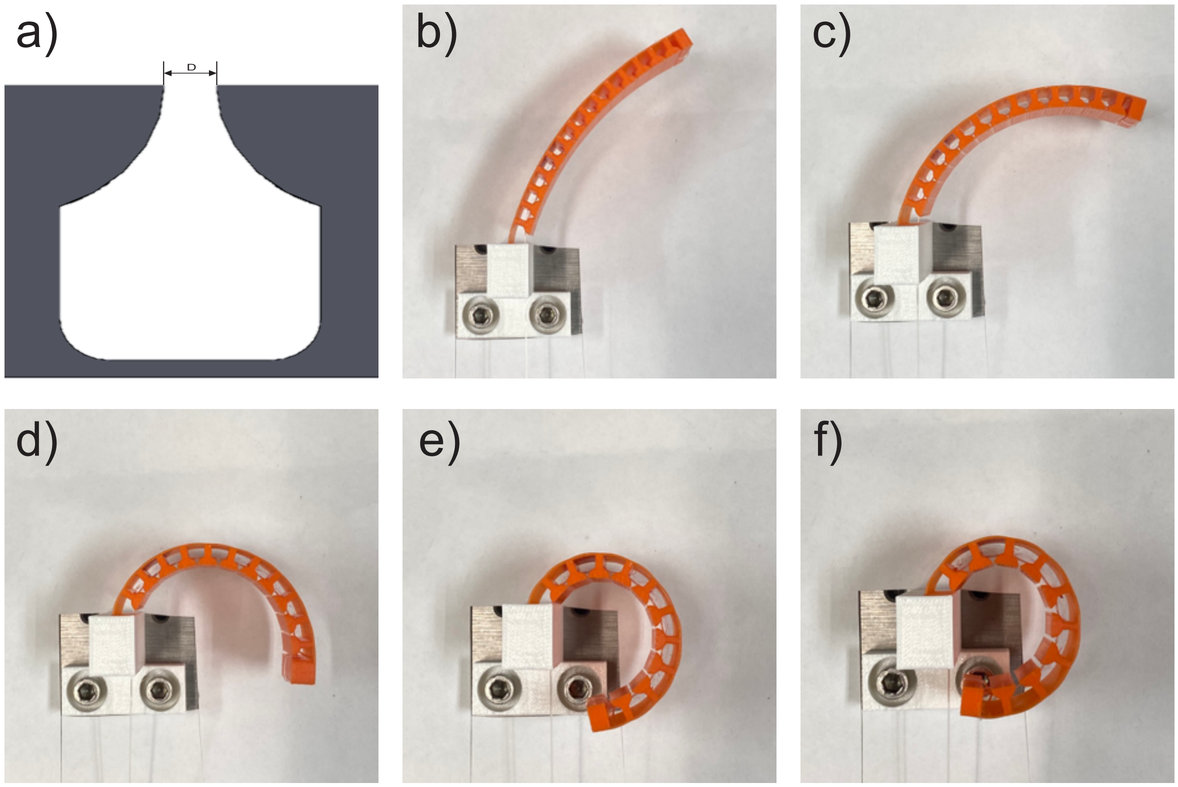


Figure 3.11. Different mushroom's linear space of the fully curved flexostructured appendage. a) 'd' value of the mushroom's linear space. b) d is 0.5mm. c) d is 1.0mm. d) d is 2.0mm. e) d is 3.0mm. f) is 3.0mm

3.3.2 Spacing of Mushroom Structure

The first variable is the linear space difference. According to 3.3.1, we nail down the width, mushroom structure's height, and general design. At this point, the estimated size of the robot's shape has been brainstormed, so the leg length is also fixed. In terms of the prototype design, the appendage needs to make a specific angle when curved inside. Eventually, spacing the layout of the mushroom structure is the factor in making a specific leg angle.

Intuitively, we realize that the more linear space of the mushroom structure, the more angle displacement would be. However, the appendage has to make a perfect circular shape when fully curved. Thus, the relationship between angular displacement and linear space of the mushroom space needs to be measured. In this test, 'd' represents the linear spacing value. The smallest value of the linear space is 0.5mm. In effect of the fixed factors, if the linear space is less than 0.5mm, the mushroom structure would be no more flexostructure but just a beam. The largest linear space is 4.0mm because more than 4.0mm is unnecessary for our application purpose. The measured angle is between the extension line of the leg's start point and the leg's tip. The relationship between linear space and angle is quite linearly proportional. However, in the case of 4.0mm, it is not fully following the linear proportion because the leg mount blocks the curved leg, so the whole leg cannot be fully curved.

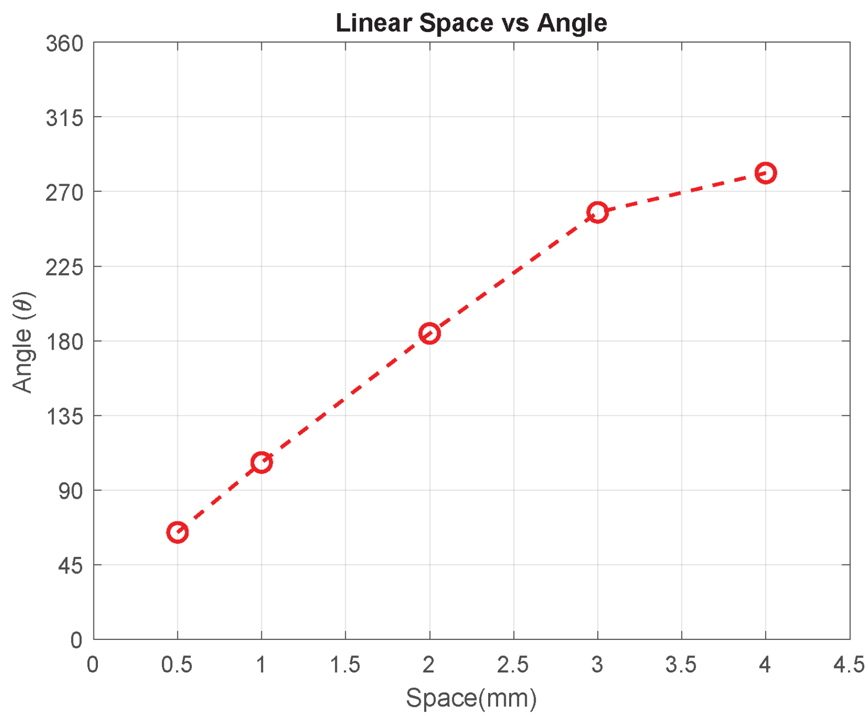


Figure 3.12. Linear space versus angle plot

From the linear spacing test, we realize the space between the mushroom structure can make different curving shapes. For example, if the space is not linear, the legs would have different results and shapes.

3.3.3 Thickness

Although, in the previous research, mushroom structure's height and width can affect the stiffness of the flexostructure, in this research, we use a specific the mushroom structure's height, width, and design are fixed based on the previous study. The advantage of the flexostructure is the flexibility of the rigid material and the thickness of the flexostructure is the most influential variable.

Prusa 3d printer has a limitation of first-layer thickness and it has to be more than 0.2mm, so we start printing 0.2mm. 0.2mm thickness appendage has high performance in flexibility but it is too thin, so the PLA can not be a dominant factor of the structure. We figure out that if the flexostructure has a specific thickness which is not too thin or too thick, the appendage can store an elastic energy while it is curved. Thus, the relationship between force and displacement is also measured. In this test, 5kg load cell using load cell amplifier (HX711) are connected to Arduino uno to measure the curving force. 3D printed appendage mount is installed at Thor Lab working bench, and the appendage's tendon is tied to the load cell which is mounted on the linear stage with 3D printed load cell mount.

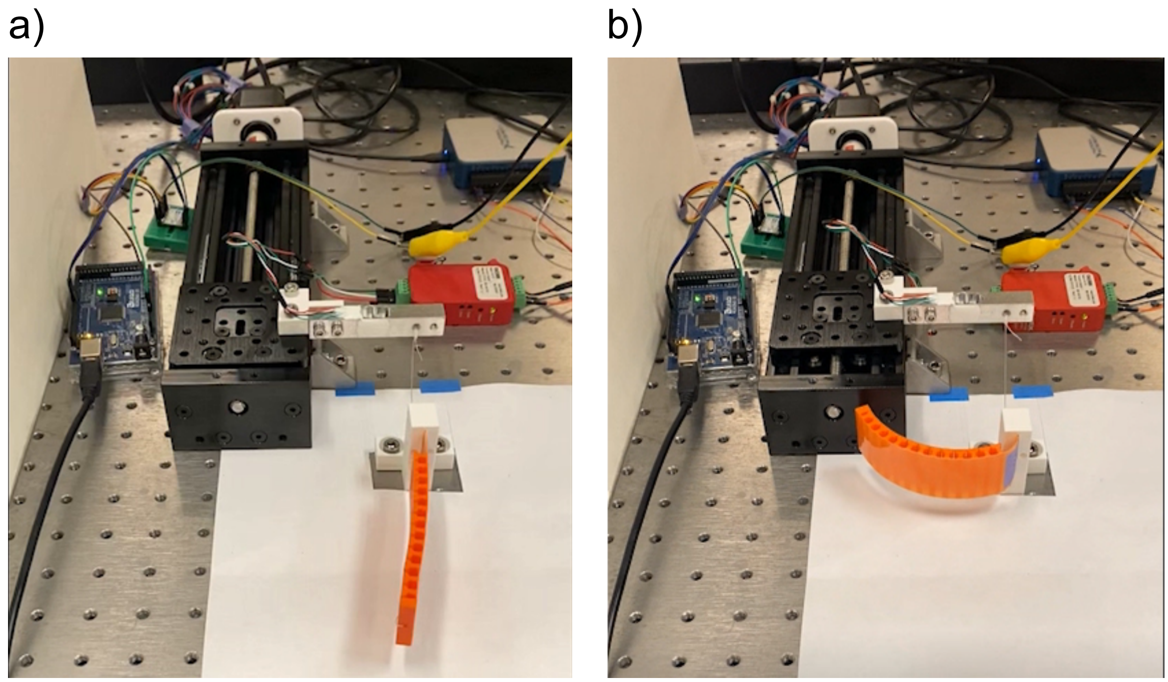


Figure 3.13. Force and displacement test environment using linear stage

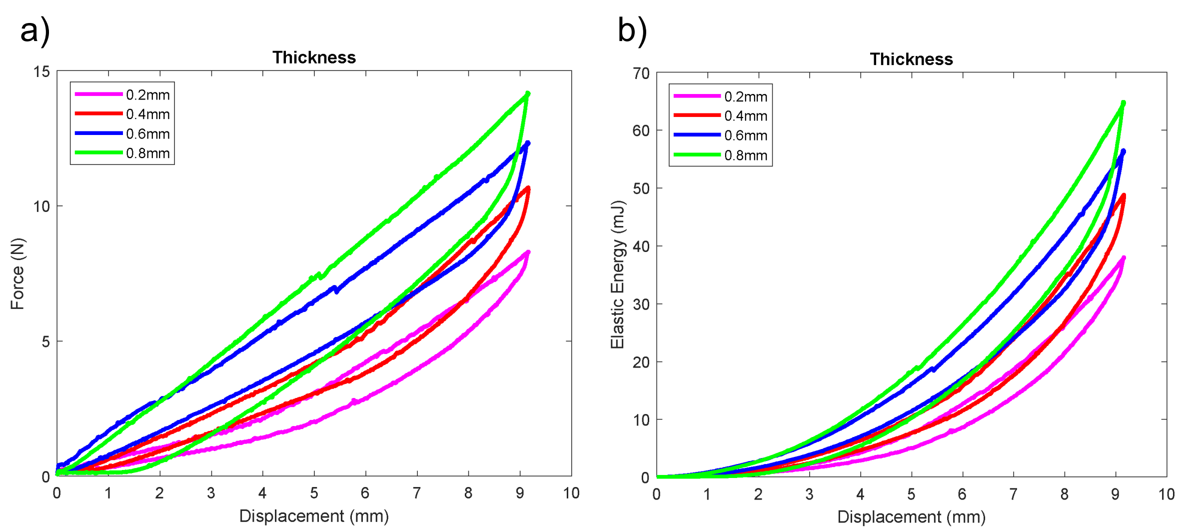


Figure 3.14. a) Required force versus displacement. b) Stored elastic energy versus displacement

Chapter 4

Application of Flexostructure: Rollbot

4.1 Rollbot V1

4.1.1 Design and Mechanism

First, we focus on the insects that can make various motions. For example, Grasshopper uses its legs to make a simple walking motion. Moreover, Grasshopper uses two back legs to store the energy and makes a jump motion. The stored elastic energy test in chapter 3 shows that the tendon-driven flexostructure can store the elastic energy. Hence, we think the jumping motion might be similar to the Grasshopper. We also find a spider called the 'Golden spider' that can crawl and curve its legs to make a circular body shape to make a rolling motion when the spider needs to run away from the predator in the downside slope circumstance. This golden spider's rolling motion is very efficient because the only thing that the spider do is curve its legs. The disadvantage of this rolling motion is that the motion can be made in a specific environment. We immediately think the flexostructured appendage can make multi-motions such as crawling, rolling, and jumping.

Basically, in this research, we are inspired by these two insects leg's multifunctionality. The first motion we concentrate on is a rolling motion. We designed the whole body shape perfectly circle based on the golden spider's rolling motion. In this research, our goal is to make a robot as small as possible, so using micro-high power DC motor is necessary. For the first leg design of Rollbot V1, we chose a 1.0mm linear space of the mushroom structure because

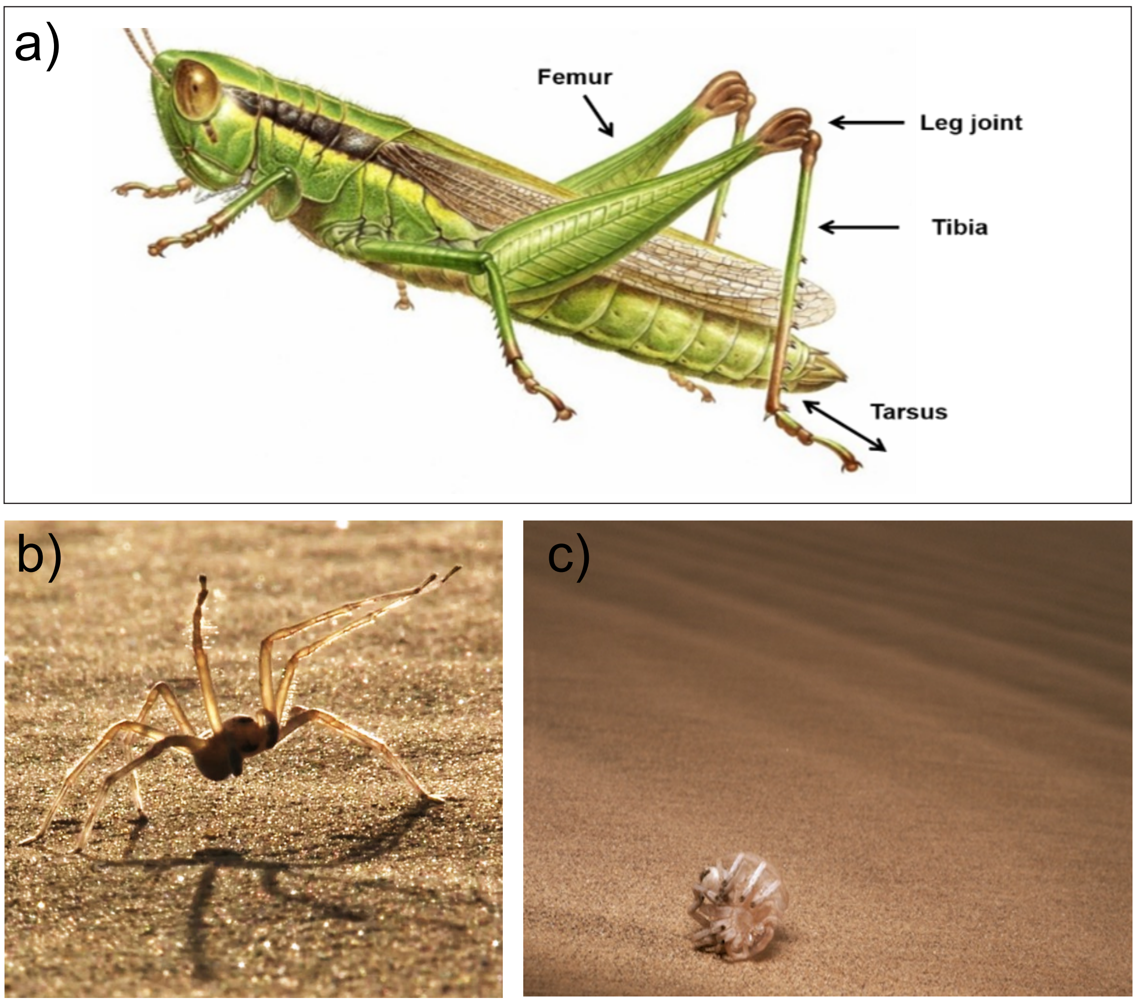


Figure 4.1. Grasshopper's leg morphology and the golden spider's multi-motions

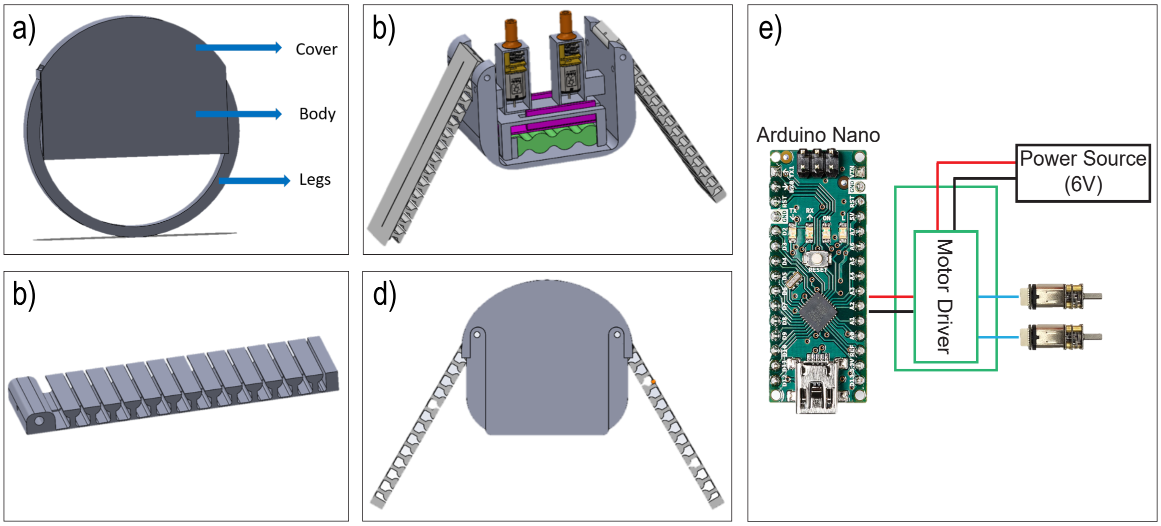


Figure 4.2. The schematic of Rollbot V1. a) Circular shape of whole robot. b) Rollbot V1 leg CAD design. c) Overall Assembly with no cover d) Front view of overall assembly with cover. e) Electronic circuit

when the robot leg is curved inside, the whole body has to be circular. Secondly, the base layer thickness is 0.2mm because the curving force must not be too big for a micro dc motor. We can use a high gear ratio of the DC motor for more torque, but the wind speed of the motor is also an essential part of the robot's overall speed. Finally, we design the robot's minimum total size for installing all electronic parts in the body and the purpose of this project. The body and legs part make up 70 percent of the circular shape, and the cover part covers the rest of the circular shape. In control parts, we use 'Arduino Nano' as a board, two 'Pololu 6V 380:1 Micro Metal Gearmotors with encoders, and a DRV8833 dual motor driver. Closed loop dc motors position control is used due to the precise winding and unwinding process.

4.1.2 Tethered Test

All of the parts are made of PLA using the 3d printing method. Firstly, we test the possibility of rolling motion without installing every inner part, and the circular shape can make the rolling motion. After installing all the parts inside, we do the tethered test first. In this research, a new rolling mechanism is used, called 'Kick and Roll.' First, both leg is fully curved

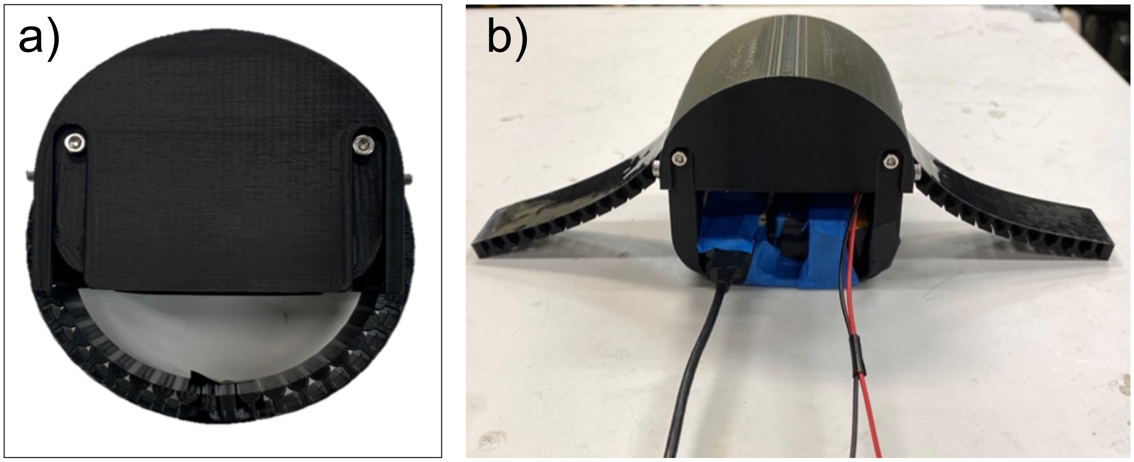


Figure 4.3. The prototype of Rollbot V1. a) Fully curved leg status. b) Tethered Rollbot V1 with fully stretched legs

inside by winding tendons, and this motion makes the robot fully circular shape. In the case of rolling from the left to the right direction, Rollbot V1 stretches the left leg outside first by unwinding the tendon so that V1 starts the rolling motion. After the robot starts rolling, V1 stretches the right leg immediately to kick the ground with the left leg and push the ground. Then, when both stretch legs are heading toward the sky, both legs are curved inside again to be a circular shape, and the robot finally makes one revolution of rolling.

4.1.3 Problems

Unfortunately, Rollbot V1's rolling motion using the new rolling mechanism is not working. In figures 4.4 c) and d), Rollbot V1 can start rolling motion, but power source lines hold and hinder the rolling motion. Moreover, In figure 4.3 a), the total shape of Rollbot V1 with fully curved legs is not a perfect circle. The bolt positions connecting the cover and body parts right next to the legs make a dimple. The dimple also interrupts rolling motion. Lastly, the leg's kicking force is not enough to roll. However, due to Rollbot V1's first tethered test, we find the possibility that a new rolling mechanism using flexostructured appendages can work.

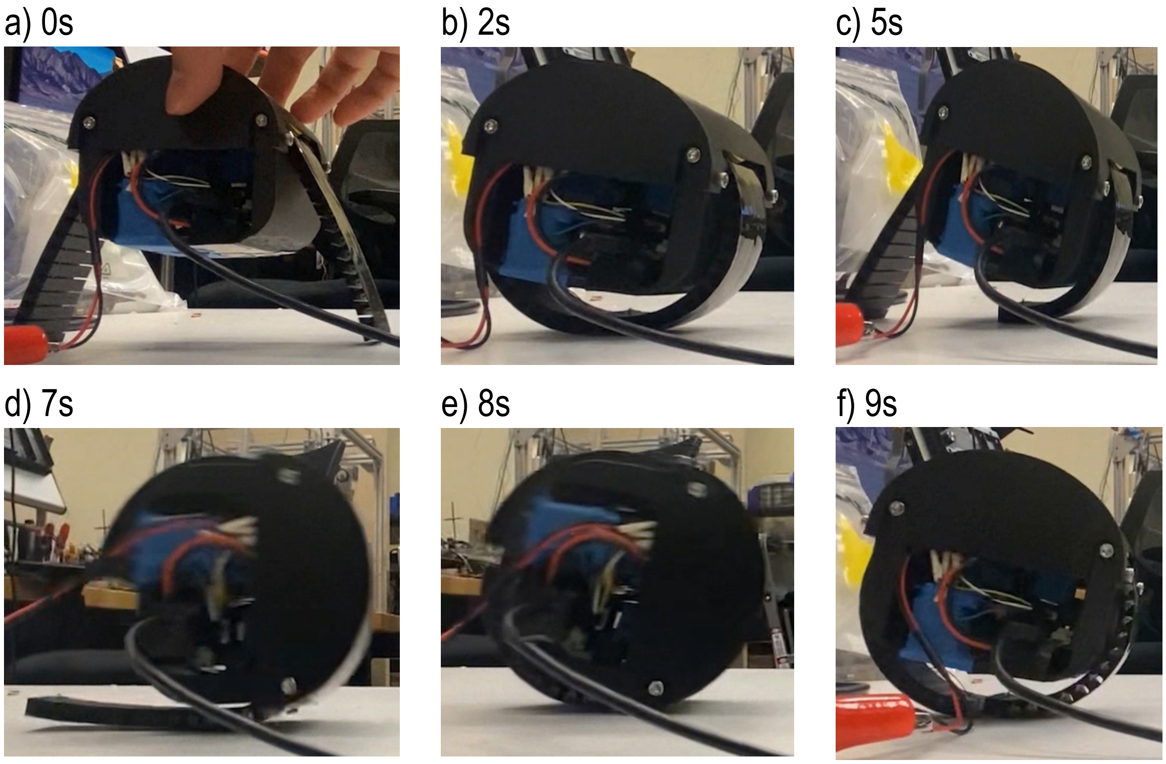


Figure 4.4. Process of Rollbot V1's rolling motion

4.2 Rollbot V2

4.2.1 Design

We decide to make a new version of the robot 'Rollbot V2'. First thing to change is to make a robot untethered. Even though, Rollbot V1 is the first prototype, so tethering test is necessary experiment, to watch a real rolling motion, untethering the wires is required. Moreover, design has to be changed because the kicking force is not enough to make a smooth rolling motion due the robot's total weight.

The first change is a cover. To make a perfect circular shape without dimples on both sides, we use 'The Glowforge Basic' Laser cutter to cut an acrylic auxiliary circular cover. 3D printing the cover shape takes more than 5 hours, but the laser cutting method only takes 3 minutes. For untethering problem, we change the board because an untethered control board is required. We choose the 'Arduino MKR 1010 Wifi' board, which is small and has a wifi module.

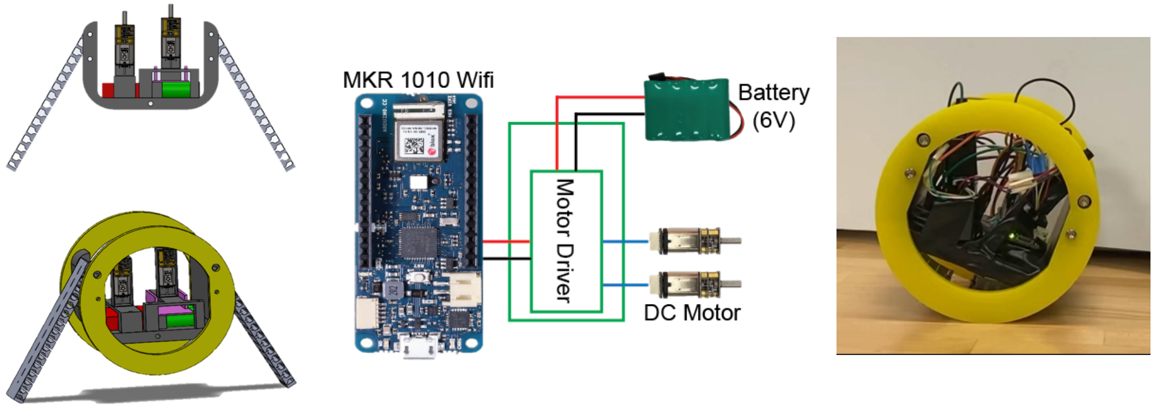


Figure 4.5. Schematic of the first prototype of Rollbot V2

In addition, we installed a 6V NiMH rechargeable battery inside Rollbot V2. Hence Rollbot V2 is perfectly untethered. Closed loop DC motor position control is used the same as Rollbot V1. Despite changing the design and untethered test, the rolling motion is the same as Rollbot V1. The reason is that while changing the design, the center of mass position changes because of the battery position. Of all parts inside the body, the battery is the heaviest part and is on the right side of the whole body. Also, the kicking force is not enough to overcome this center of the mass problem.

In order to solve problems, the cover design is changed. We make holes in the auxiliary circular cover and put some weights on it using bolts and nuts. We find the perfect spot of the weights against the battery position. Putting bolts and nuts helps to change the center of mass position while the robot is rolling.

4.2.2 Untethered Test

After changing the cover design, new wifi buttons are made to control codes. In figure 4.7, the untethered test of Rollbot V2 is successful. Since the bolts and nuts keep changing the center of the mass, the new mechanism with flexostructured appendage works, and finally, Rollbot V2 starts rolling. After both legs are stretched and point to the sky, the center of mass position changes so V2 can roll more than before. If both legs are curved at the right time, V2

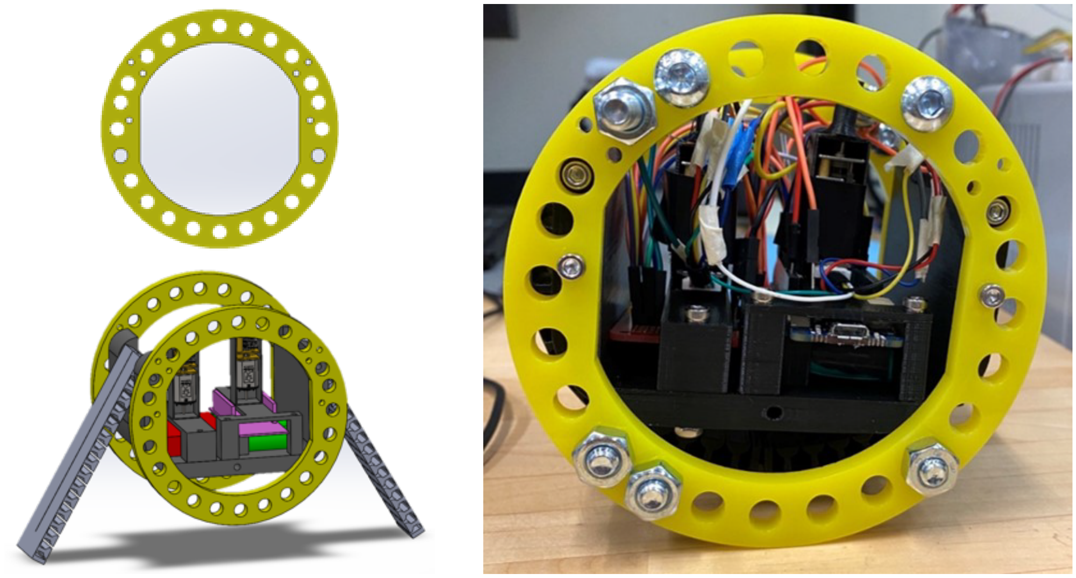


Figure 4.6. Schematic of the second prototype of Rollbot V2

finishes one revolution of rolling. In figure 4.7, we try the two revolutions of rolling motion. In this rolling motion, we use time-dependent control codes. When the wifi button is pressed, Rollbot V2 starts rolling, and the amount of revolution is controllable.

4.2.3 Problems

Rollbot V2 is working as expected using a new rolling mechanism. The untethered test of Rollbot V2 proves the possibility of the new rolling mechanism using flexostructrued legs. However, in this case, we have more problems to solve.

The first problem is the control method. We can make the V2 roll, but we must push the button at the right time. If the robot is too far from the wifi-connected device, the signal arrives too late to move at the right time. Since the bolts and nuts position changes the center of mass of Rollbot V2, it naturally starts rolling when we release the robot from our hands. In this situation, the whole rolling motion would not work if the signal arrived late. Moreover, the leg design is too weak to move the robot itself. After putting the weight, V2 can roll, but it is not because of the flexostructured leg. Actually, flexostructured legs kick the ground using their stored elastic

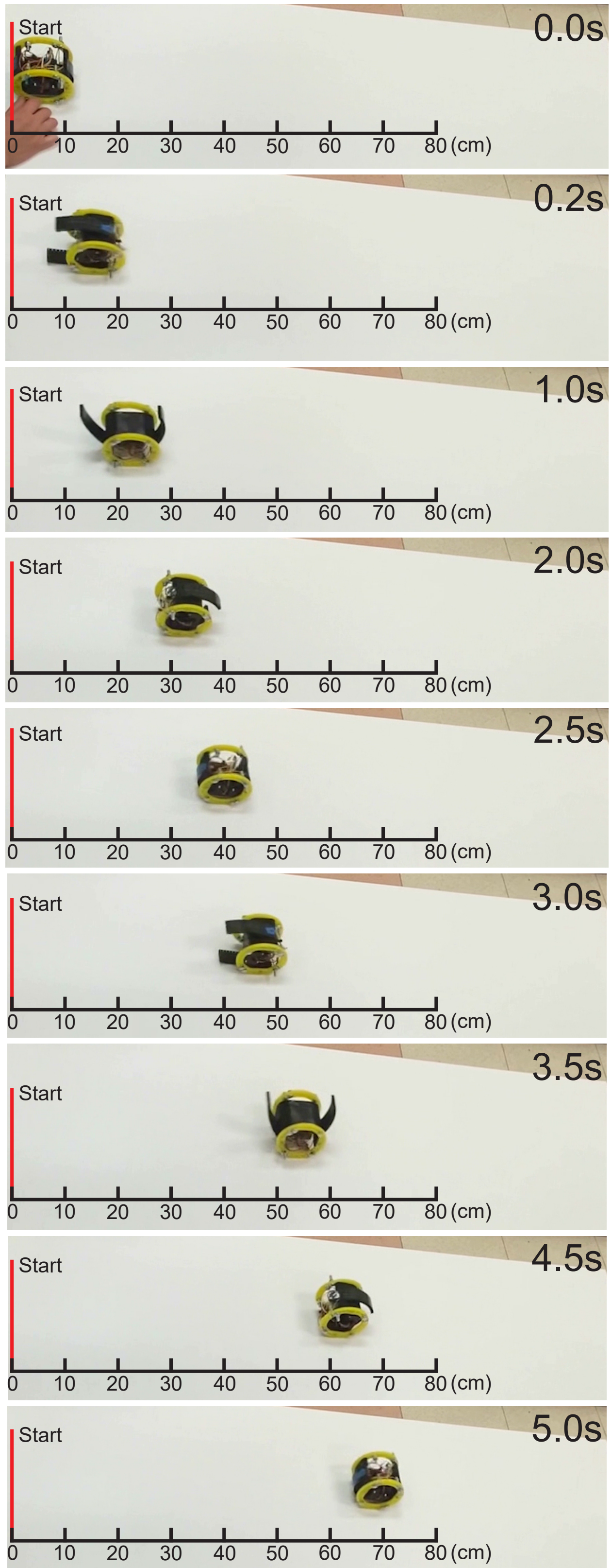


Figure 4.7. Rollbot V2's two revolution rolling process

energy, so the new mechanism is working, but the kicking force is still not enough. Thus, the main factor of the rolling is just the center of mass transition. The leg is also not stiff enough to make a standing position itself. Therefore, in every untethered rolling trial, someone has to hold the robot not to start the rolling motion before pressing the button.

4.3 Rollbot V3

4.3.1 Final Design

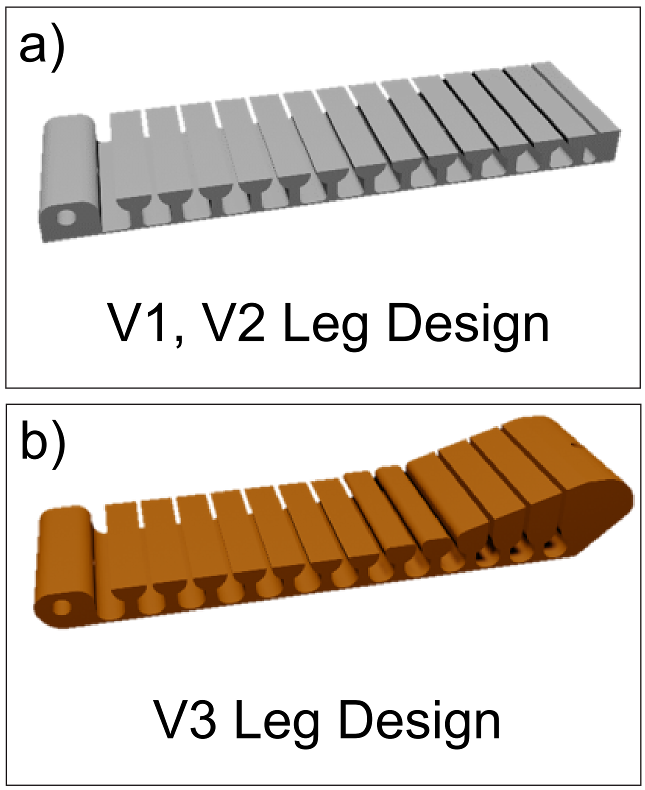


Figure 4.8. Difference between V1,V2 leg design and V3 leg design

The significant problem of Rollbot V1 and V2 was the lack of elastic energy and stiffness of the flexostructured leg. To increase these factors, we need to change the design of the leg. First, the mushroom height increases from the fifth mushroom to the first. Increasing mushroom height gives more stiffness to stand V3 itself. In addition, this new toe part leg design makes more elastic energy than V1 and V2's leg design. In figure 4.9 a), the V3 leg's torque requirement for winding is about twice bigger than the V1 and V2 leg, but Pololu 6V 380:1 micro dc motor can make enough torque to handle it. Due to its linear relationship between force requirement and stored elastic energy, the V3 leg can store twice more elastic energy than the V1 and V2 legs.

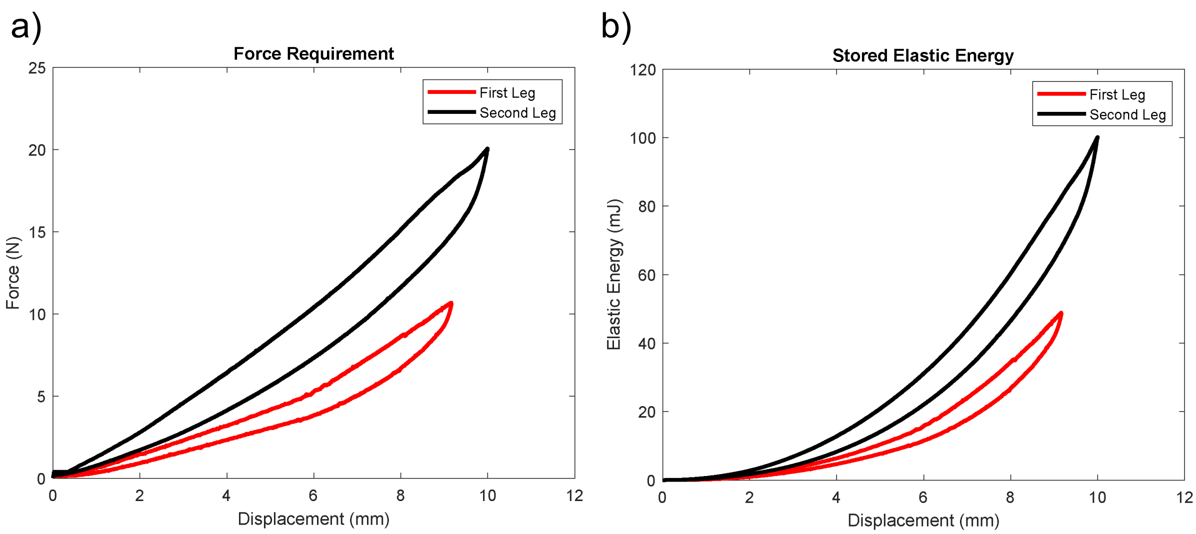


Figure 4.9. V1,V2 leg and V3 leg design force, elastic stored energy plots

The next problem was the control method. Time-dependently pressing the rolling button is not a suitable control method. After changing the leg, Rollbot V3 can stand itself. Thus, we can only focus on the controlling method. Making a repeatable control method, we add the Inertial Measurement Unit (IMU). We use Pololu's 'Minimu-9 v5 (LSM6DS33 and LIS3MDL Carrier).' Using the specific accelerometer value at the specific position allows an automatic rolling motion control in both directions.

The first step of the rolling motion is the standing position. When rolling left to the right direction, when the rolling button is pressed, the right leg is curved first, then the left leg is curved with no time delay so that Rollbot V3 can be circular. Due to the gravitational force of bolts and nuts position, the robot roll one revolution. After one revolution, the IMU module reads the robot's position and stretches both legs. Since the leg's stored elastic energy is enough to kick the ground and make another rolling motion, the robot keeps rolling. After that, the IMU reads the robot position, which will be the half-rolling status. In that position, the IMU value

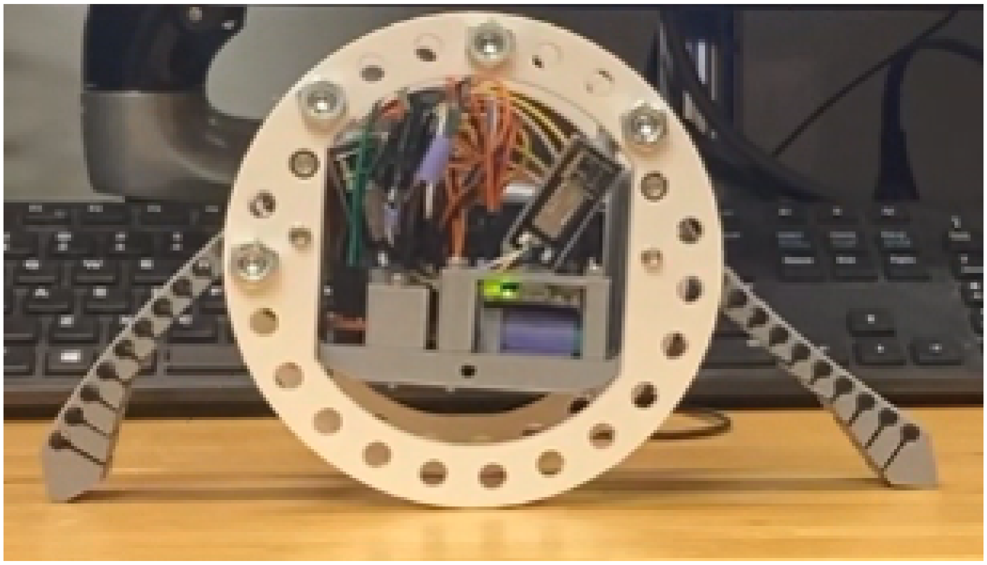


Figure 4.10. Prototype of Rollbot V3 using New leg design

makes both legs curve inside. These two IMU values controlling methods allow keeping rolling automatically. If the robot needs to stop, the only thing to do is to stretch the right leg. This rolling mechanism works when V3 needs to change its direction while rolling. After finishing the rolling motion in one direction, the ’change direction’ button, which consists of the IMU control method, changes the direction from right to left.

In figure 4.11, Rollbot V3’s new rolling motion is more smooth and faster than V2’s rolling motion. Changing the leg design gives us significant differences in the rolling speed and stiffness. This New leg design allows Rollbot V3 to stand and hold the whole body by its legs. Using this stored elastic energy of the V3 leg design increases the rolling speed of Rollbot V3 twice more than Rollbot V2’s rolling speed. The average rolling speed of Rollbot V2 is 11.9cm/s, and Rollbot V3 is 25.13cm/s.

4.3.2 Multifunctionality

The new V3 leg design with toe part is not only able to have more elastic energy for ’kick and roll’ rolling mechanism, but also make the robot stand itself due to its stiffness. However, some people might think that using a servo motor and install the wheel might be a better choice.

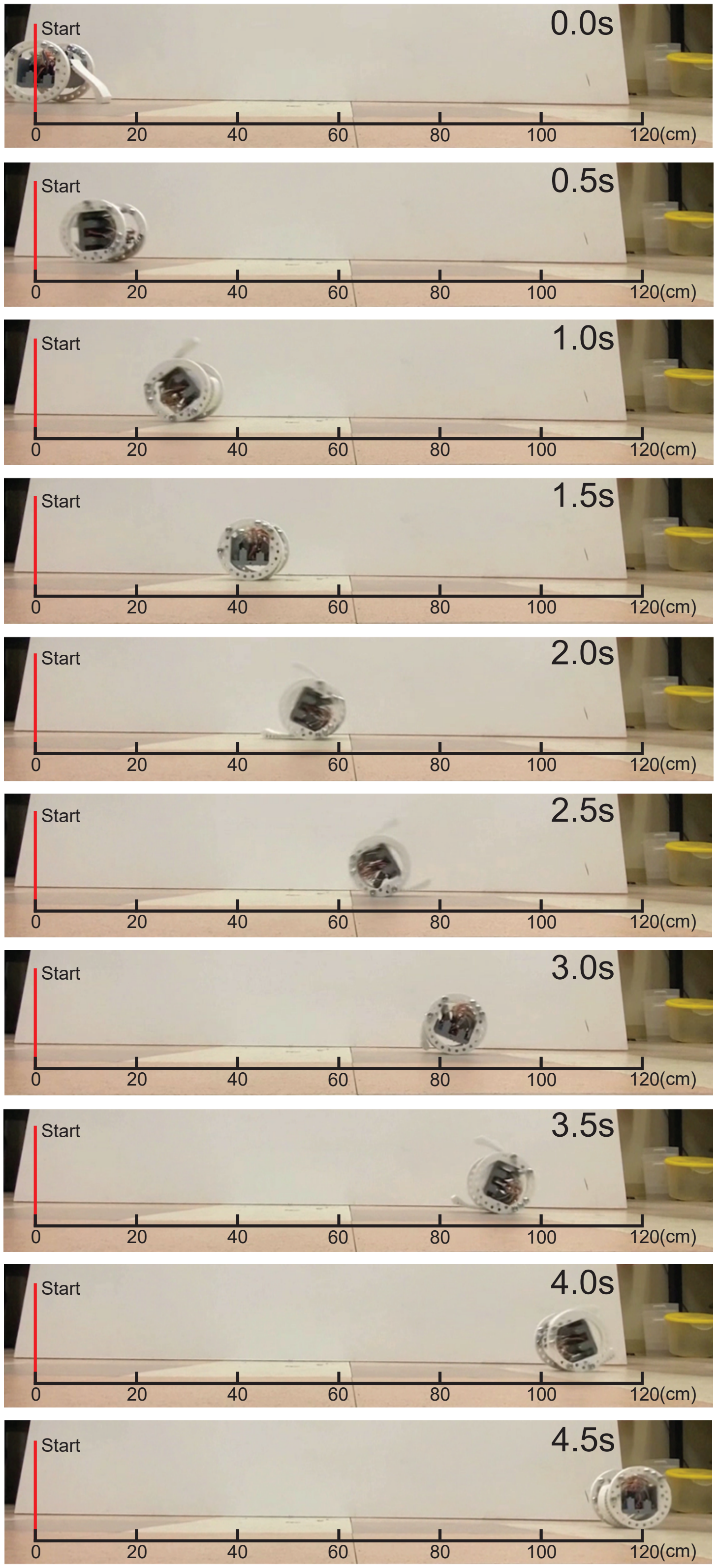


Figure 4.11. Rollbot V3's 3 revolutions rolling motion process

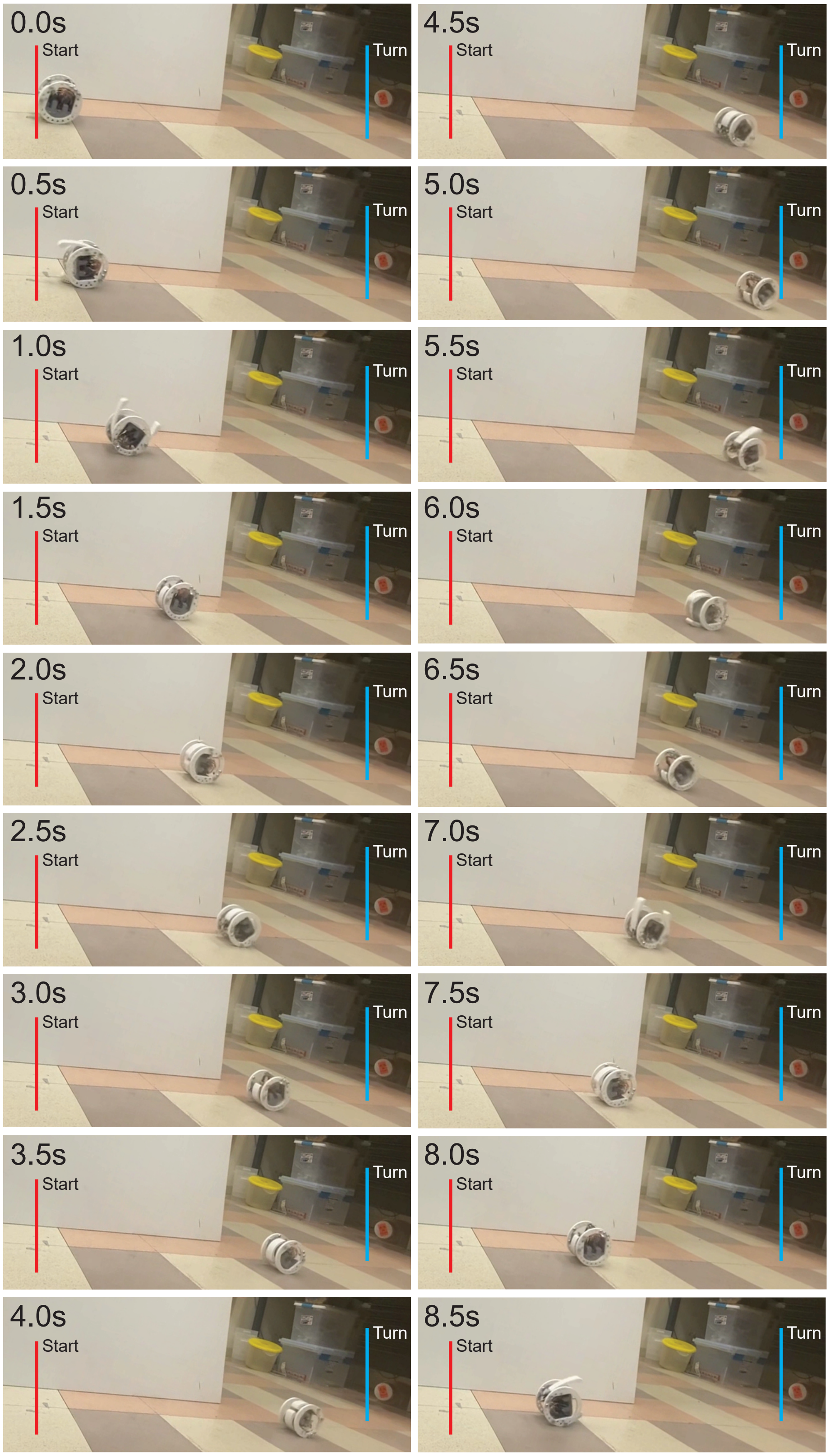


Figure 4.12. Rollbot V3's change direction motion process

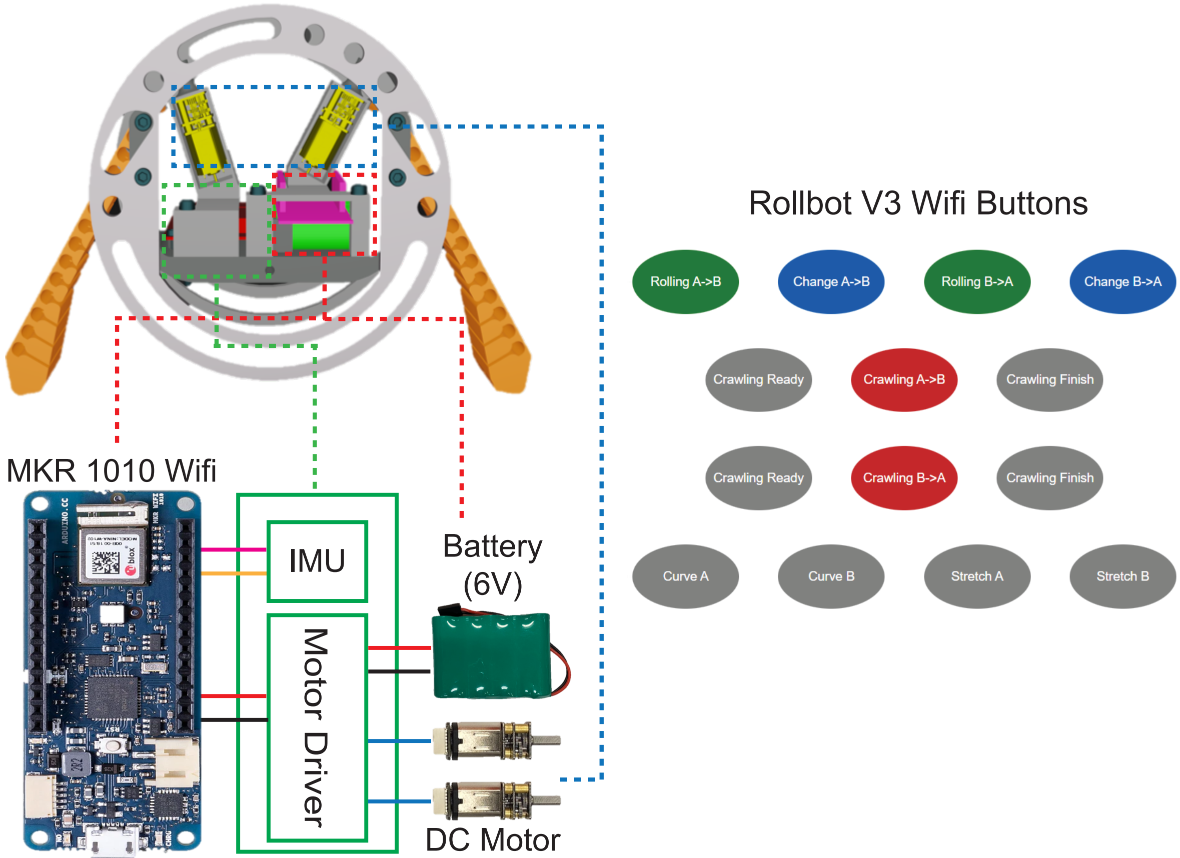


Figure 4.13. Final schematic of Rollbot V3

Intuitively, the opinion makes sense, but the main reason of using flexostructured appendage is the multifunctionality. For some reason, such as broke leg and cover issues, we determine the final design of Rollbot V3. Most the parts are made of 3D printed PLA and get rid of unnecessary parts as possible as we can to decrease the total weight. Finally, the total weight including bolts and nuts is about 330g.

In terms of rolling motion, Rollbot V3 somehow depends on the gravitational force at the beginning of the 'kick and roll' motion. In some cases, winding the DC motor to curve both legs would not be the best method to start rolling. We try the trial: What if the first rolling motion cannot make one revolution? The entire process of the failure of the first revolution is shown in figure 4.15. Although the first revolution fails, since Rollbot V3 is still using the IMU module to read a specific value at the proper position of the Rollbot V3, releasing stored elastic energy of

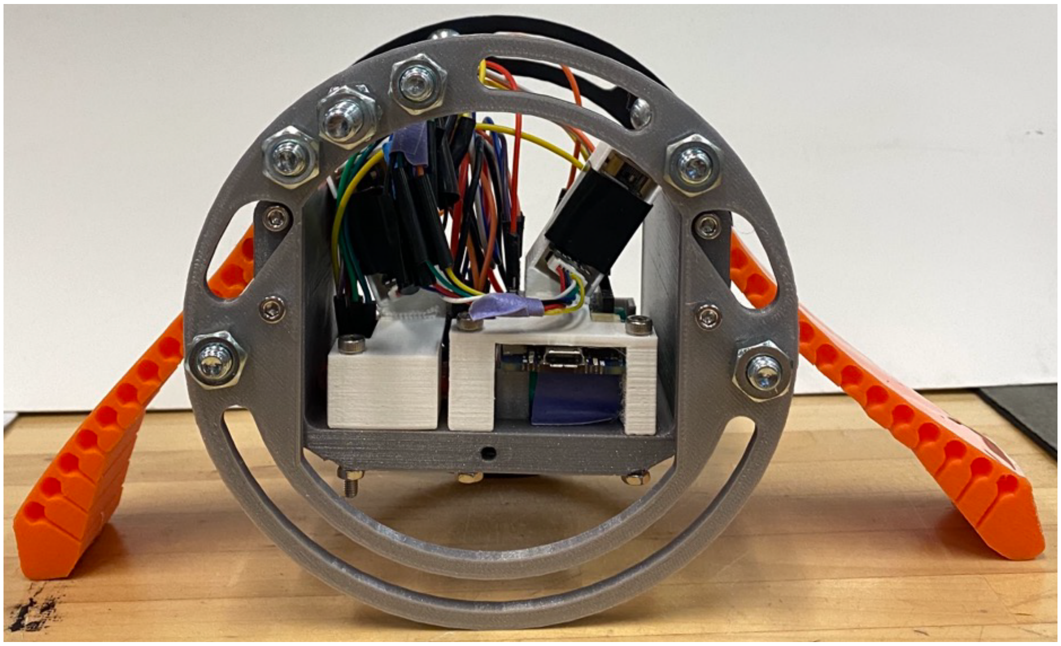


Figure 4.14. Final Rollbot V3

the leg allows for rolling again. The new results from this test are that the kicking mechanism keeps adding more energy for rolling, and the rolling speed is proportionally faster than the last revolution. The IMU cannot read the value at the proper position when the speed is too fast. This means the Rollbot V3 has a limited speed for using the kick and roll mechanism. However, when the rolling speed is lower than the highest speed that the IMU cannot read, the IMU re-reads the value and keeps using the kick and roll mechanism for rolling motion. The new automatic kick and roll mechanism can be an efficient method for rolling motion.

In the beginning of flexostructure appendage research, we realized that this appendage could definitely make multimotion. The actual first motion that we planned was the crawling motion. V2 leg design can make Rollbot V2 rolling, but in terms of multifunctionality, V2 leg is too weak to stand itself. Some auxiliary device or someone need to hold the V2's body because legs is stretched outside too much due to the total weight of V2, so the kick and roll motion is not working. On the other hand, V3 leg design has enough stiffness to withstand the whole V3 body weight. On account of V3 design's both stiff and flexible hybrid advantages, Rollbot V3 can have possibility of making different type of motion. Rollbot's second motion is crawling.

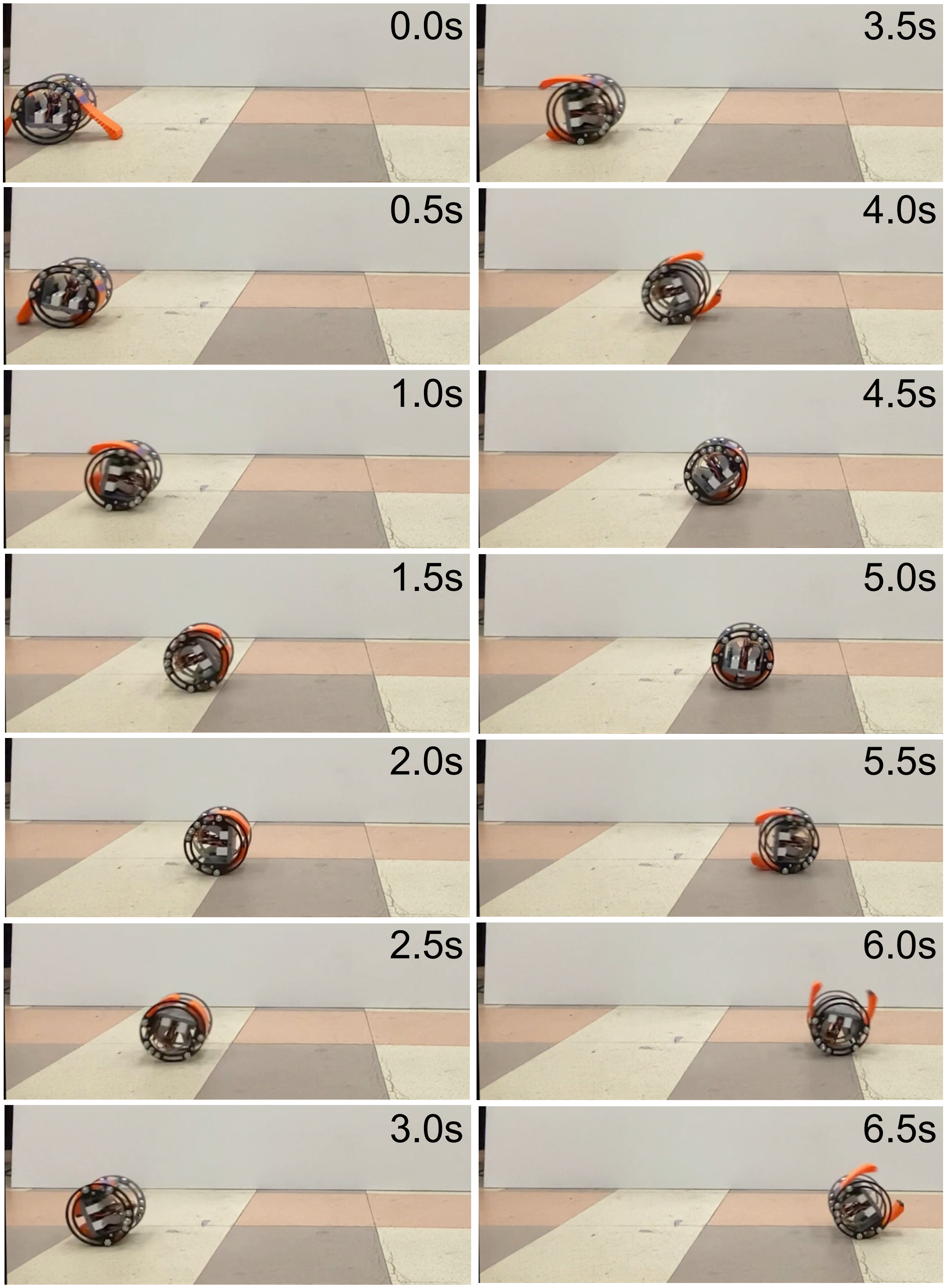


Figure 4.15. Rolling failure process

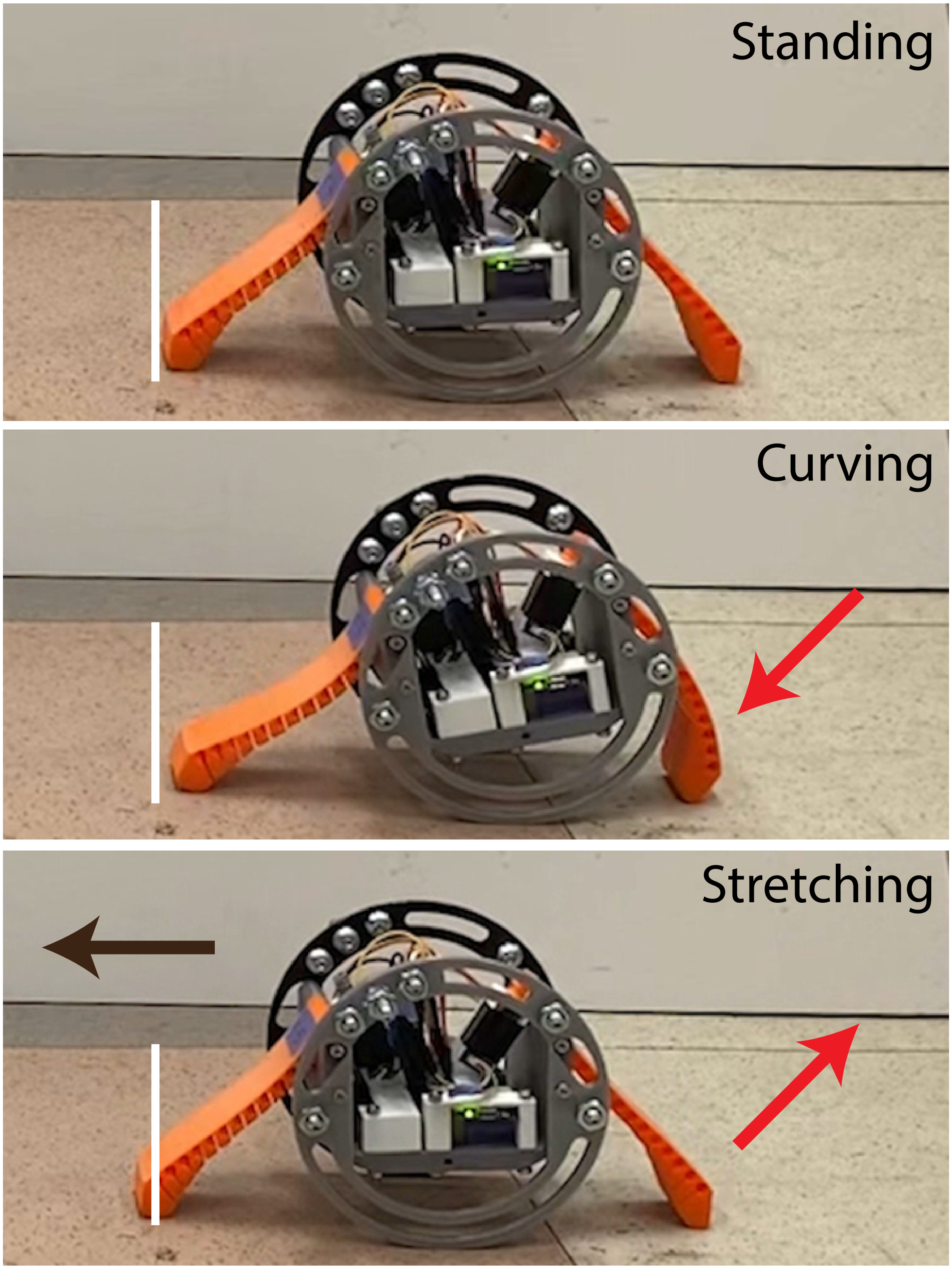


Figure 4.16. Rollbot V3 Crawling process

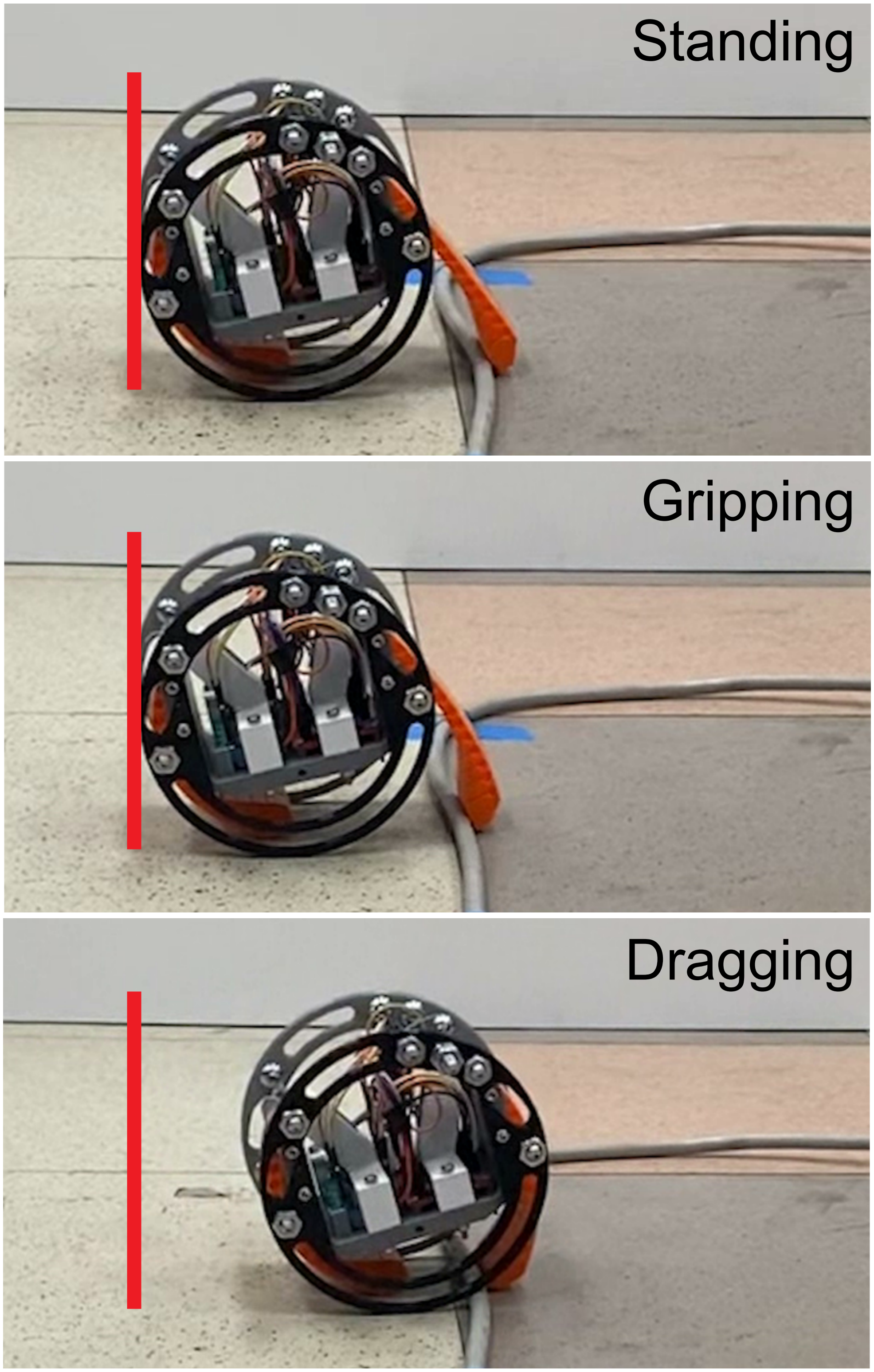


Figure 4.17. Rollbot V3 Gripping and Dragging Process

Crawling mechanism is quite simple. Firstly, both legs are fully stretched. In terms of moving right to left direction, Rollbot V3 curves the right leg just a specific amount right before the leg is curved by V3's body weight. During this period, curved right leg is storing a lot of elastic energy. Finally, a process of stretching the right leg pushes the ground and the Rollbot can crawl right to left. The average speed is about 2.22cm/s.

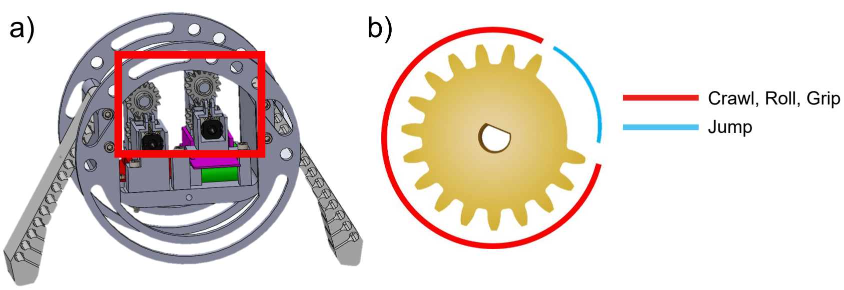
The third motion that V3 can make is grabbing an object. In the past research on flexostructure, researchers made a gripper. We use a similar design of the mushroom structure, so it is possible to implement the gripping motion. If the object is fixed, then the flexostructured leg drags the whole body to the object. The dragging motion has a possibility of overcoming the obstacle if the 'Kick and Roll' mechanism starts right after the dragging motion.

4.3.3 Possibility of Different Motions

At the beginning of chapter four, Rollbot is inspired by two insect locomotions, the 'Golden Spider' and 'Grasshopper.' The first thing that we concentrated on was to make a rolling motion like Golden Spider. The flexostructured leg mimics the Golden spider's circular shaping motion to roll. In the last subsection, Rollbot V3 performs different motions, such as crawling and gripping. Consequently, Rollbot V3's locomotion is highly similar to the Golden Spider. The last thing to maintain the concept of Rollbot is to make a jump.

We calculated the vertical jumping height using the V3 leg's stored elastic energy plot at the beginning of this chapter. Theoretically, Rollbot V3 can jump about 6.17cm vertically if both legs' stored elastic energy explodes. In order to test this theory, the V3 needs a system to release stored elastic energy. We finally use the 'Slip-Gear' mechanism. The slip gear mechanism consists of two different gears. The first gear has no slip part and is directly connected to the DC motor. The other gear has a slip part and is connected to each leg's tendons. A gear ratio of the slip gear is 1:1 to keep the DC motor position control. Before the slip, the gear still makes rolling, crawling, and gripping motions. If the non-slip gear meets the slip part, stored elastic energy is released in a short time to push the ground to jump. However, in the trial, when the non-slip gear is at the position right before the slip part, the leg is fully curved inside, then Rollbot V3 finishes the standing position and starts rolling. We block both directions of Rollbot V3 and do the test again, but the legs cannot push the ground as expected. Even after the legs are curved inside, they cannot be stretched out no more.

There are two reasons for the failure of the jumping trial. The first reason is the whole body weight. Rollbot V3 needs weights for overcoming and changing the center of mass position while rolling. The bolts and nuts total weight that Rollbot V3 has is almost a third of the whole body weight. Although the V3 leg design increases the stiffness to stand, it is still not enough to overcome the weight when fully curved inside. The second reason is that when the slip gear makes both legs release their stored elastic energy, the energy does not ideally push the ground vertically. Although the tendon is connected at the tip of the flexostructured leg's toe part, released elastic energy is distributed to all the leg parts. Thus, to achieve the ideal jumping height, Rollbot V3 needs to change its parts design or composition differently.



c)

ROLLBOT MASS

Body	54.2
Legs	34.2
Covers	21.6
Motorboxes and Gears	34.7
Electronic Parts	88.7
Bolts and Nuts	91
Total Mass(g)	**330.4**

Figure 4.18. Slip-gear mechanism. a) New gear design. b) Slip-gear schematic. c) The total mass of Rollbot V3

Chapter 5

Conclusion

5.1 Conclusion

From the flexostructure variable test, mushroom linear space distance can change the fully curved angle, and the relationship between the angle and the distance is linearly proportional. In addition, the total stiffness depends on the first layer thickness. The stiffness increases when the thickness increases, but there is some limitation because when the thickness is bigger than 1.0mm, the flexostructure loses flexibility. In the process of changing Rollbot V3's leg design, We also figured out that the mushroom's height can affect the flexostructured appendage's total stiffness. Moreover, Flexostructure has a possibility for further research. The total performance will be different if the flexostructure is made of high-performance rigid material. In addition, from the rolling trial of Rollbot V3, we find that the new rolling mechanism, 'Kick and Roll,' works perfectly for the flexostructured appendage. Rollbot V3 also shows multi-functionality. It can roll and crawl like the Golden spider and also has a possibility of jumping like the Grasshopper. Ultimately, Rollbot V3 can be mass-productive because most parts are made by a 3D printer. The estimated total price for the fabrication would be less than 100 dollars, and the total size of the robot could be smaller if we choose a better design.

Bibliography

[1] M. Rubenstein, K. Payne, P. Will, and W.-M. Shen, "Docking among independent and autonomous conro self-reconfigurable robots," in *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA'04. 2004*, vol. 3. IEEE, 2004, pp. 2877–2882.

[2] C. Huang, J.-a. Lv, X. Tian, Y. Wang, Y. Yu, and J. Liu, "Miniaturized swimming soft robot with complex movement actuated and controlled by remote light signals," *Scientific reports*, vol. 5, no. 1, pp. 1–8, 2015.

[3] M. Jiang, Z. Zhou, and N. Gravish, "Flexoskeleton printing enables versatile fabrication of hybrid soft and rigid robots," *Soft robotics*, vol. 7, no. 6, pp. 770–778, 2020.

[4] L. Dufour, K. Owen, S. Mintchev, and D. Floreano, "A drone with insect-inspired folding wings," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Ieee, 2016, pp. 1576–1581.

[5] K. Liu and L. Jiang, "Bio-inspired design of multiscale structures for function integration," *Nano Today*, vol. 6, no. 2, pp. 155–175, 2011.

[6] Y. Chen, H. Wang, E. F. Helbling, N. T. Jafferis, R. Zufferey, A. Ong, K. Ma, N. Gravish, P. Chirarattananon, M. Kovac *et al.*, "A biologically inspired, flapping-wing, hybrid aerial-aquatic microrobot," *Science robotics*, vol. 2, no. 11, p. eaao5619, 2017.

[7] S. Kim, M. Spenko, S. Trujillo, B. Heyneman, V. Mattoli, and M. R. Cutkosky, "Whole body adhesion: hierarchical, directional and distributed control of adhesive forces for a climbing robot," in *Proceedings 2007 IEEE International Conference on Robotics and Automation*. IEEE, 2007, pp. 1268–1273.

[8] S. Kim, C. Laschi, and B. Trimmer, "Soft robotics: a bioinspired evolution in robotics," *Trends in biotechnology*, vol. 31, no. 5, pp. 287–294, 2013.

[9] S. Seok, A. Wang, M. Y. Chuah, D. Otten, J. Lang, and S. Kim, "Design principles for highly efficient quadrupeds and implementation on the mit cheetah robot," in *2013 IEEE International Conference on Robotics and Automation*. IEEE, 2013, pp. 3307–3312.

[10] N. Tan, R. E. Mohan, and K. Elangovan, "Scorpio: A biomimetic reconfigurable rolling–crawling robot," *International Journal of Advanced Robotic Systems*, vol. 13, no. 5, p. 1729881416658180, 2016.

[11] H.-T. Lin, G. G. Leisk, and B. Trimmer, "Goqbot: a caterpillar-inspired soft-bodied rolling robot," *Bioinspiration & biomimetics*, vol. 6, no. 2, p. 026007, 2011.

[12] Q. Yu, M. Jiang, and N. Gravish, "Flexoskeleton fingers: 3d printed reconfigurable ridges enabling multi-functional and low-cost underactuated grasping," *IEEE Robotics and Automation Letters*, vol. 6, no. 2, pp. 3971–3978, 2021.

[13] Y.-C. Chen, S.-T. Ma, L.-Y. Hsu, Y.-C. Lin, and P.-C. Lin, "Design and implementation of a quadrupedal crawling-rolling robot," in *2017 International Conference on Advanced Robotics and Intelligent Systems (ARIS)*. IEEE, 2017, pp. 6–6.

[14] B. G. Lambrecht, A. D. Horchler, and R. D. Quinn, "A small, insect-inspired robot that runs and jumps," in *Proceedings of the 2005 IEEE international conference on robotics and automation*. IEEE, 2005, pp. 1240–1245.

[15] J. Zhao, J. Xu, B. Gao, N. Xi, F. J. Cintron, M. W. Mutka, and L. Xiao, "Msu jumper: A single-motor-actuated miniature steerable jumping robot," *IEEE Transactions on Robotics*, vol. 29, no. 3, pp. 602–614, 2013.

[16] T. TolleyMichael, F. ShepherdRobert, C. GallowayKevin, J. WoodRobert, M. Whitesides-George *et al.*, "A resilient, untethered soft robot," *Soft robotics*, 2014.

[17] S. Mao, E. Dong, H. Jin, M. Xu, and K. Low, "Locomotion and gait analysis of multi-limb soft robots driven by smart actuators," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2016, pp. 2438–2443.