Faculty of Engineering and Materials Science
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# Design and Implementation of a Single Series Elastic Actuated (SEA) Kangaroo Robot Leg

A thesis submitted in partial fulfilment of the requirements for the degree of Bachelor of Science in Mechatronics Engineering

By

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This is to certify that:

(i) the thesis comprises only my original work toward the Bachelor Degree of Science (B.Sc.) at the German University in Cairo (GUC),

(ii) due acknowledgment has been made in the text to all other material used

Mostafa Ahmed Kashaf
August 16, 2022

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# Abstract

Single-legged hopping robots are currently and previously energetically linked and lack mobility. In this project, I will present a way to actuate a single legged robot using passive compliance. Series Elastic Actuator (SEA) has many benefits like high fidelity force control, low friction, low impedance, and high back-drivability. It is an actuator that uses an elastic element, usually a spring, that is fixed in series with the motor, transmission and the load. The spring is intentionally used to decrease the stiffness of the actuator. I chose to implement the UT-SEA type, because I found a decent amount of references to aid me in fabricating it. The purpose of this project is to try using the SEA on a different leg design, and test its durability. This research should be able to aid ongoing researches in choosing the most suitable leg design that can jump for a good distance on any terrain using SEA.

# Contents

# List of Abbreviations

| | |
|---|---|
| **SEA** | Series Elastic Actuation |
| **RFSEA** | Reaction Force-sensing Series Elastic Actuation |
| **FSEA** | Force-sensing Series Elastic Actuation |
| **TFSEA** | Transmitted Force-sensing Series Elastic Actuator |
| **CNC** | Computer Numerical Control |
| **UT-SEA** | University of Texas Series Elastic Actuator |
| **CDSEA** | Cable-Driven Series Elastic Actuator |
| **cRSEA** | compact Rotary Series Elastic Actuator |
| **BCDSEA** | Bowden Cable-Driven Series Elastic Actuator |
| **RSEA** | Rotary Series Elastic Actuator |
| **CAD** | Computer-Aided Design |

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# Chapter 1

# Introduction

## 1.1 Robotics

Robotics is a growing field that is concerned with the desire to synthesize aspects of human functions by using mechanisms, sensors, and actuators, and it has the potential to greatly impact engineering and education of all levels. Robotics is a world of created devices that imitate the humans, animals, or even insects. It can mimic the basic functions of any living creature using computers, by programming and controlling them. Robotics also contains other devices and systems that coordinate with robots to perform any desired function. Robotics is an important subject that can benefit from lots of majors such as: mechanical, electrical and electronic engineering, computer science, biology, etc. It is a place that puts any idea into testing which then can be put in action or mix its idea with other robot [17], [18]. Finally, Robotics has many advantages such as working in hazardous environment where humans cannot get near, they work continuously without becoming tired, precision is achieved repeatedly, and can perform multiple tasks simultaneously. Some of its disadvantages include: robotics can replace human workers, it can lack the capability to respond to emergencies in an effective way, and robots are costly [19].

## 1.2 Industrial Robots

In the 1980s, the industrial robots made their first rapid widespread. The first industrial robot was introduced in Sweden by 1967. These robots today have become increasingly notable in the manufacturing industry, since most, sometimes all, operations of the production of a certain product is automated. They make programmable and repetitive functions such as picking, placing, welding, cutting, and most importantly assembly, which made industrial robots to rapidly spread all over the world. Important requirements are taken into consideration with these robots such as reliability and durability which are very important, since the industrial robots should work all day and every day. Accuracy and precision is another important requirement for some applications such as assembly tasks or precise electronic test. It is always very desirable that the robots be able to be greatly configurable to allow for more or new sensors to be added anywhere. Readiness of programming is very important, since the technology is updated every now and then which can make the robotic applications might be developed quickly. Communication is also important in robotics industry because it can provide autonomy to the field of mobile industrial robots [20], [21].

Figure 1.1: Industrial Robots [1]

### 1.2.1 Components of Industrial Robots

Industrial robots consist of five main components, a controller, sensors, a robotic manipulator, an end-effector, and a drive.

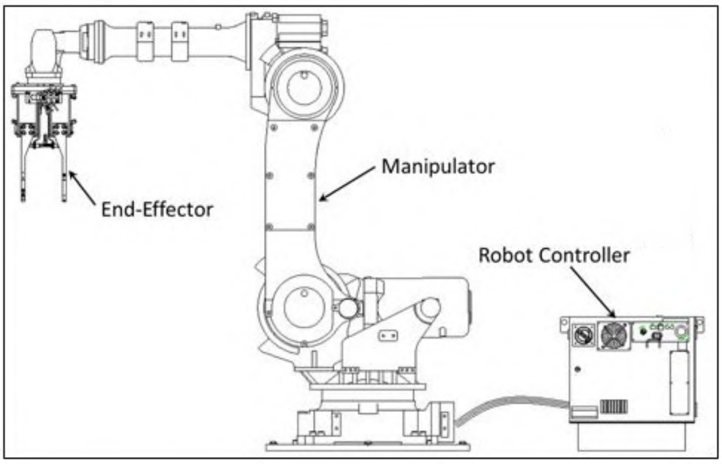



Figure 1.2: Components of an Industrial Robot [2]

1. The robot controller is a computer that is connected to the robot and serves as its "brain." All industrial robots need a controller in order to be able to operate. For example, the Motoman MH50 is paired with a Motoman DX100 for its controller, while the FANUC Lr Mate 200ic works with a R-30ia controller. The controller is used to instruct the robot on how to operate through code, which is more commonly referred to as a program. Robotic programs are inputted into a controller through the use of a teach pendant. Once the program is in putted to the controller, it will send the program information to the robot's CPU (central processing unit). The CPU is a small chip located within the robot that allows the robot to process and run the program [22].

2. Robot sensors may consist of cameras or microphones. Sensors provide industrial robots with feedback about their workspace. The most common types of sensors include vision systems and microphones as these act as the eyes and ears of a robot. Sensors allow robots to dynamically adapt to their work environment by sending signals to the robot's CPU [22].

3. The robotic manipulator or robot arm as it is more commonly called, is responsible for moving and positioning the end-effector. Robot arms can vary in size and shape, but in general they are designed to mimic a human arm with shoulder, elbow, and wrist like parts. These parts are what allow robots to position end effectors correctly in order to perform an application. The parts of a robot arm each serve as an individual degree of freedom or axis. Most industrial robots have 6 axes for a range of motion that is similar to a human's [22].

4. End-effectors attach to the end of an industrial robot's arm and are the devices responsible for interacting directly with work pieces. There are many different types of end-effectors. The type of end-effector integrated with an industrial robot will depend upon the application being automated [22].

5. The drive of an industrial robot is the engine or motor which moves the different robot parts around. Robot drives are typically powered hydraulically, electrically, or pneumatically. Hydraulic drives can provide increased power and speed, while electric drives tend to be less powerful. Smaller robots typically utilize pneumatic drives [22].

## 1.3 Rigid Robots

Hard robots are rigid-linked, with actuators for every joint. These robots require precision control of rigid joints to grasp an object. They are made of hard materials with invariable properties. Smooth contact with its environment is facilitated by advanced feedback control strategies and sensors. Discrete topology with finite Degrees of Freedom (DoF) consist of rigid elements connected to each other with single DoF joints. Rigid robots are unsafe and intolerant with limited adaptability to operate in unknown environments, unless intricate control measures

Figure 1.3: Rigid Robot [3]

are applied. They are usually used in conventional electronics and power source. They have low level of behavioural diversity and bio-inspiration (which is the development of novel materials, devices, and structures inspired by solutions found in biological evolution and refinement which has occurred over millions of years [23]). Rigid robots have high accuracy, and they can be used in in high speed and force applications. Their main drawback is having high weight and cost [24], [25].

## 1.4 Compliant Robots

Compliant mechanisms, as opposed to rigid body motions in conventional mechanisms, are flexible structures that supply a desired motion by undergoing elastic deformation [26]. Because of the extremely nonlinear geometrical form of these deflections, analysis and design methodologies are frequently complicated, limiting the employment of compliant mechanisms to considerably simpler applications. Continuous development of analysis and design tools is, however, easily justified due to the inherent advantages associated with compliant systems [27]. By transferring input actuation (i.e. force, motion) through the deflection of elastic components, these systems provide similar benefits. The input might be conveyed through the entire mechanism's elasticity or at key locations. To generate specific output motions and/or force, compliant mechanisms are an alternative to typical rigid-linkage systems [26]. The interest towards compliant mechanisms and the investigation on their properties and design criteria have been increasingly growing in the past years, with significant applications in many fields, including MEMS (micro electro mechanical systems) and robotics [28]. The compliance properties of industrial robots are very important for many industrial applications, such as automatic robotic assembly and material removal processes (e.g., machining). Moreover, the compliance properties of robots appear very important in emerging fields such as flexible assembly systems [29], [30] and collaborative robotics [31]. Advantages of compliant legged robots: Improved energy efficiency, higher speed and obstacle avoidance, and shock absorption. Additional advantages of compliant mechanisms include reduced part count, assembly time, and manufacturing processes while increasing performance through minimizing wear, weight and maintenance demands [26]. Maintaining dimensional quality by preventing major deformations during handling operations is a critical challenge in production with compliant parts [32].

### 1.4.1 Active Compliance

The primary idea behind active compliance is to guide an end effector's motion in such a way that steady-state force errors are proportional to displacement errors. In this context, active denotes that the compliant nature is generated by a control system rather than a basic spring [33]. By adjusting the parameters of the virtual springs, such as stiffness and damping coefficient, an active compliance scheme can dramatically affect the dynamic behaviour of a system without changing the physical properties of the robot (such as changing physical springs in robot legs). This allows for the evaluation of a large range of movements with various parametrizations, which simplifies the control in each leg [34]. The capability for active compliant motion allows a robot the flexibility to deal with a much broader range of tasks where compliance is required [35]. The main advantages of active compliance are that it is mainly software achievable, easy to regulate and compute, and it can often observe instability. Active compliance is relatively expensive for some applications, and it has a limited response rate [36].

Figure 1.4: Active Compliant Robot [4]

### 1.4.2 Passive Compliance

Passive compliance means mechanical compliance of members of robot arm or some special joint mechanisms. This compliance works well in all frequency ranges (both fast and slow responses), but it has limited programmability. Because there are numerous humans in the surroundings of humanoid robots, passive compliance is critical in terms of safety [37]. Passive compliance is the intrinsic mechanical structural compliance due to the finite stiffness of the robot base, links, joints, and drive mechanism [36]. The inclusion of passive compliance in robotic joints improves both their manual manipulation capabilities and the efficiency and stability of their dynamical movements [38]. Most passive compliance based devices use linear springs as I will be using in my project, since it is the main component to achieve elasticity. One disadvantage of using a linear spring is that positional accuracy is unachievable because the spring always operates even for minor external forces that do not require shock absorption, and the spring's elastic characteristic frequently creates undesired oscillations [39]. Advantages of passive compliance are that overall stability is guaranteed, fast response rate (naturally), passive compliance can be set with very high stiffness, and it's relatively cheap (for most applications). Another drawback of passive compliance is that it is hard to regulate, compute, and is usually dedicated to particular applications. Researches were conducted to enhance its programmability [36].

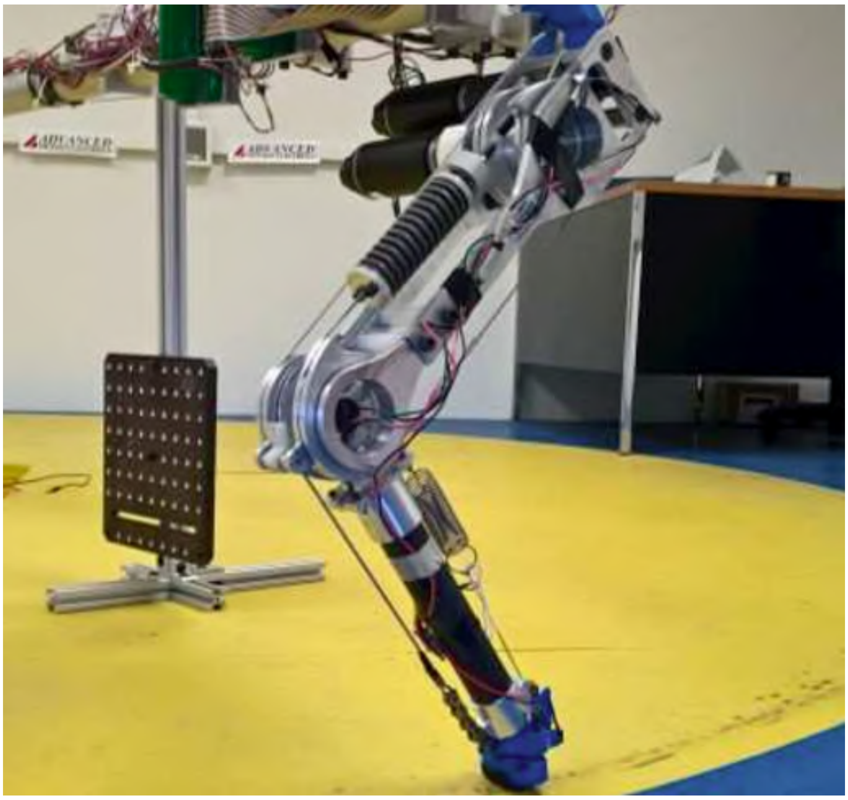


Figure 1.5: Passive Compliant Robot [5]

# Chapter 2

# Literature Review

## 2.1 What is SEA?

Series Elastic Actuator (SEA) is a type of actuator that uses an elastic element (usually spring), which is instrumented with strain gauges, together with an electric motor to be able to implement a high performance torque control [7]. SEA has low friction and impedance which can make it achieve high quality force control [6]. The spring is usually placed between the motor and the load. The actuator exhibits high back-drivability and low impedance, because the friction is nearly invisible at the output. Other advantage for SEA is that the springs absorb the shocks making the actuator mostly shock proof. The springs can also store and release energy which improves the efficiency in harmonic applications [7]. However, some disadvantages are that the gears increase the reflected inertia of the motor and great shocks that may cause the gear teeth to break, the gear reduction system can also reduce back-drivability, the mechanical properties of the spring can limit the maximum force that the actuator can output, force control bandwidth reduction due to low pass nature of the spring, and complexity and bulking of the mechanical design [40].

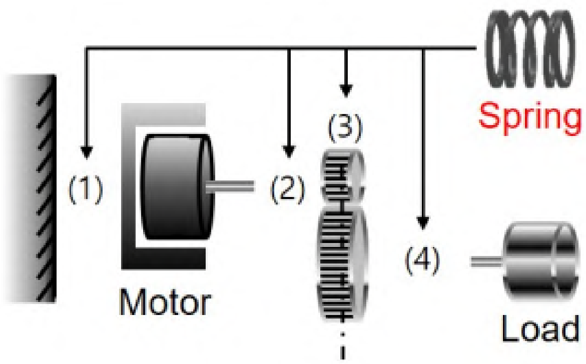



Figure 2.1: SEA composition [6]

### 2.1.1 Types of SEA

There are different types of SEA based on the design, which are categorized based on their type of movement (linear or rotary), linear consists of SEA (gear transmission) and Cable-Driven Series Elastic Actuator (CDSEA) (wire transmission) and rotary consists of compact Rotary Series Elastic Actuator (cRSEA) (gear transmission) and Bowden Cable-Driven Series Elastic Actuator (BCDSEA) (wire transmission).

| | | Output movement type | |
|---|---|---|---|
| | | Linear | Rotary |
| Transmission type | Gear | (a) SEA of MIT<br>(b) UT-SEA | (c) cRSEA<br>(d) cPEA |
| | wire | (e) RSEA<br>(f) CDSEA | (g) BCDSEA<br>(h) MARIONET |

Figure 2.2: Types of SEA [6]

The general design of the SEA has a linear movement and gear transmission. In CDSEA, the position of the elastic element is placed first, then the brushless DC motor with its reducer, then a pulley winded with a steel cable, then finally the load [41]. The CDSEA allows the detachment of the actuation motor from the robot frame, power transmission can be enabled from a far place, and it brings flexibilities into the system construction and control for physical human interaction applications [42]. A disadvantage for this type is that there is a noticeable linear cable-conduit friction with the force feedback control [43]. For rotary movement, there is cRSEA, the torque is generated by an electric motor which is amplified using spur and worm gears. The impedance of the system is minimized because the worm gear self-locks when rotated from the load side, this function makes it easy to achieve the desired control performance during the operation. The system impedance is also controlled by the position of the motor. The disadvantage of cRSEA is that there are disturbances that occur due to human interactions which impacts its performance [44]. Finally, the BCDSEA is used to control the generated drive torque following the concept of SEA in exoskeleton-type robots, since the Bowden cable is flexible [45]. It is also used to reduce the weight of the robotic arm or leg. A disadvantage for BCDSEA is that the bandwidth of the actuator might become negatively influenced as complex friction is introduced by the Bowden cables [46].

### 2.1.2 Types of SEA (based on spring location)

The placement of the spring can vary (anywhere between the power source, transmission, and load), resulting in a variety of SEA configurations. Figure 2.3 depicts the probable spring locations (1), (2), (3), and (4) in the SEA. Ever since the SEA structure was proposed by

[40], many types of SEA have embraced the configuration where the spring is located at (4). However, new SEAs have recently been proposed that have varied configurations by putting springs at different positions from (1) to (3) [6]. The SEA configurations have been categorized to three types based on spring locations by [6].

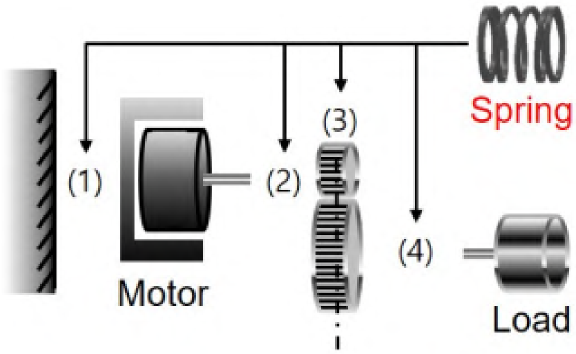



Figure 2.3: Different possible spring locations of UT-SEA [6]

### FSEA

In FSEA, the spring is located in position (4) (Figure 2.3). FSEA is a type of SEA that includes a motor, a gear reduction, a spring, and a load in that order, for the spring to measure the force directly from the load. Many SEA designs have adopted this layout, which was proposed as the structure of the first SEA. In Figure 2.4, the FSEA structure is illustrated, where the motor stator is fixed to the ground to be able to provide the maximum force coming from the load to the transmission. The spring deformation is driven by the amplified force to generate spring force/torque. Meaning, the output force/torque of the SEA is the spring torque which is controllable by the motor torque [6].

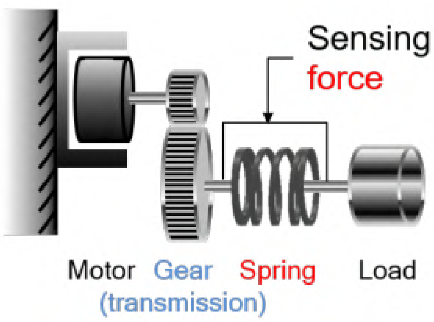



Figure 2.4: Configuration of Force-sensing Series Elastic Actuator (FSEA) [6]

Figure 2.5a depicts the first SEA proposed in [40]. The configuration of the FSEA proposed became popular in most early SEAs, and it was chosen as a general structure as well. The SEA structure proposed in [44] is another FSEA that uses worm gear as the transmission a rotary spring as the elastic element (Figure 2.5b).

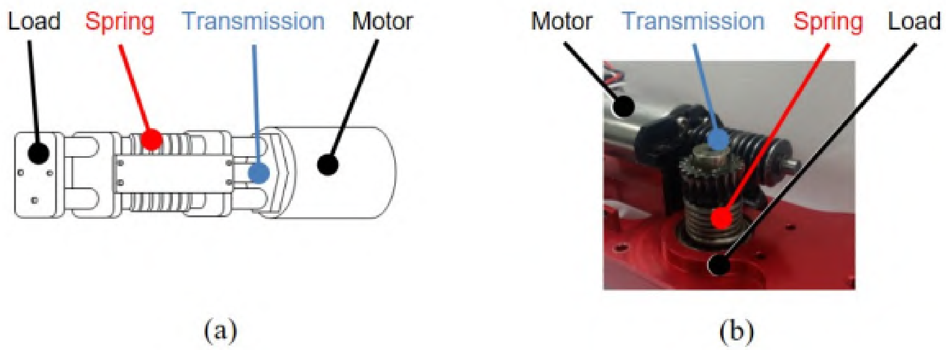



Figure 2.5: (a) first proposed SEA design using FSEA and (b) cRSEA using FSEA [6]

### TFSEA

In Transmitted Force-sensing Series Elastic Actuator (TFSEA), the spring is located at position (3), which is inside the transmission. The TFSEA can be divided into two ways of implementations [6]. Figure 2.6a shows a TFSEA layout in which the spring is positioned between the transmission gears, allowing it to measure the transmitting torque within the gears. Figure 2.6b shows the other TFSEA configuration, where a differential gear such as a planetary gear, and a Harmonic Drive is utilized as the compliant component. In this layout, the motor torque is supplied to the load through the differential gear. The spring is connected to the gear housing that is connected to the differential gear, allowing the spring to measure the torque transmitted by the gear. In this configuration, the position sensors can be coupled to the motor and spring.

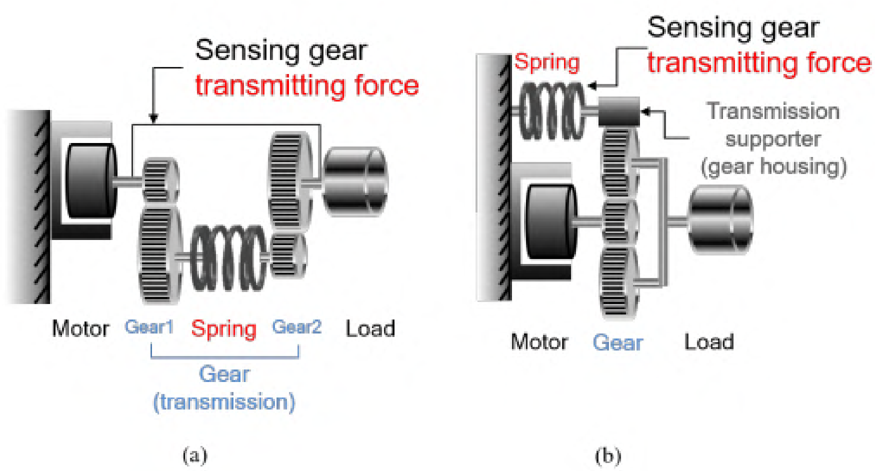



Figure 2.6: Configurations of Transmitted Force-sensing Series Elastic Actuator (TFSEA). (a) "Internal transmitted force of gear" Sensing type and (b) "External transmitted force of gear" Sensing type [6].

### RFSEA

In Reaction Force-sensing Series Elastic Actuation (RFSEA), the spring can be located at positions (1) and (2), before the transmission. The spring can be positioned between the motor stator and the ground. The motor generates a relative torque between the stator and the rotor, which is amplified by the gear transmission and supplied directly to the load. The spring deformation in RFSEA in Figure 2.7a is proportional to the motor's reaction force with respect to the ground. The other type of RFSEA is shown in Figure 2.7b, in which the spring is positioned between the motor rotor and the gearbox. The direct motor torque and the reduced external torque are measured by spring deflection in this situation [6]. The advantages of RFSEA are that it transfers the amplified motor torque directly to the load, the spring deformation is proportional to the reaction force with respect to the ground, and its excellent size and packaging characteristics. Its disadvantage is that internal forces are required to generate the desired output torque.

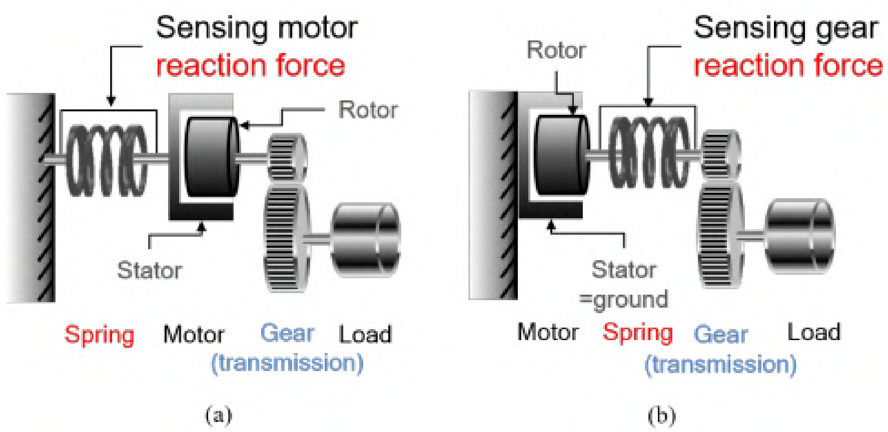



Figure 2.7: Configurations of Reaction Force-sensing Series Elastic Actuator (RFSEA). (a) "Motor reaction force" sensing type and (b) "Gear reaction force" sensing type [6].

The UT-SEA shown in (Figure 2.8) was the developed as the first RFSEA in [47]. The RFSEA structure of Figure 6a was produced by placing a compression spring on the motor stator, and the mechanism used a ball screw to create a prismatic motion using a rotating motor.

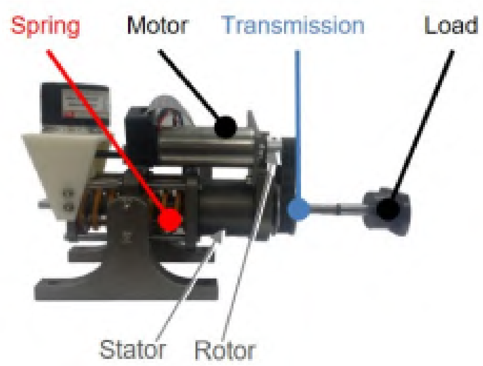



Figure 2.8: First UT-SEA [6]

## 2.2 Previous Designs

### 2.2.1 Spring Flamingo

The Spring Flamingo (Figure 2.9), a planar bipedal walking robot, was the first robot designed using SEA. The SEAs drive a six-degree-of-freedom mechanism in each leg, with three degrees of freedom representing the hip, knee, and ankle [48].

Figure 2.9: Spring Flamingo [7]

### 2.2.2 M2 Robot

The M2 (Figure 2.10), a three-dimensional bipedal walking robot, is a continuation of the work begun with the Spring Flamingo. It has twelve degrees of freedom, six on each leg. The M2 has three degrees of freedom in the hip, two degrees of freedom in the ankle, and one degree of freedom in the knee, only for one leg. This setup allows for three-dimensional movements similar to the Flamingo. The M2 project is far more complicated than the Spring Flamingo [8].

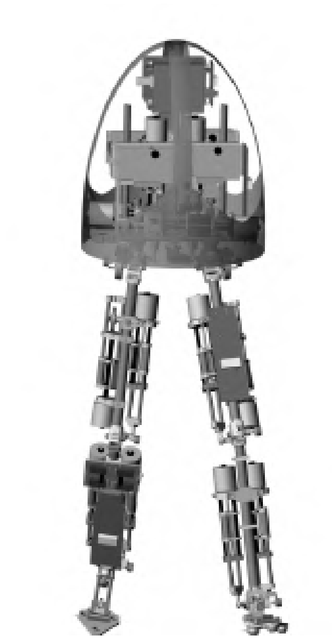


Figure 2.10: M2 Robot [8]

### 2.2.3 Corndog Robot

The Corndog (Figure 2.11), a planar running robot with one front and one rear leg, is another lower limb robot developed with SEA. As a result, it only depicts half of a dog and uses electro-mechanical series elastic actuator [9].

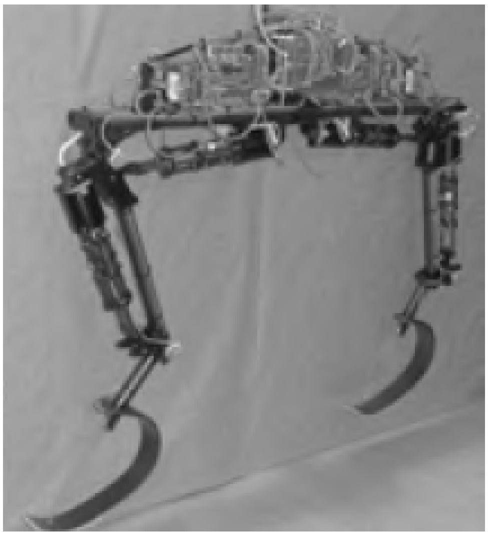


Figure 2.11: Corndog Robot [9]

### 2.2.4 COG Robot

SEA technology is also applied on upper limb robots. The COG robot (Firgure 2.12 is a humanoid with a head and upper torso. Its arms have six degrees of freedom and are actuated by SEAs. Furthermore, COG is capable of hammering and turning a crank [10].


Figure 2.12: COG Robot [10]

### 2.2.5 Exoskeleton for knee assistance

SEAs have been thoroughly analyzed and examined in rehabilitation and assistive technologies, in addition to their use on dynamic robotics. A tiny Rotary Series Elastic Actuator (RSEA) for knee joint assistive exoskeleton (Figure 2.13) is being developed as part of assistive technology for gait rehabilitation. Due to its compactness, a worm gear is chosen for motor reduction, unlike the majority of SEAs that use a motor and gear reduction as the motor part. However, it increases the system's friction, making it more difficult to manage [11].

Figure 2.13: Proposed exoskeleton for knee assistance [11]

## 2.3 What is UT-SEA?

The UT-SEA is a compact, light-weight, and high-power actuator designed to enable energetic and high speed locomotion in electrically actuated legged systems (Figure 2.14). The UT-SEA is a linear actuator that consists of a gear transmission using pulleys.

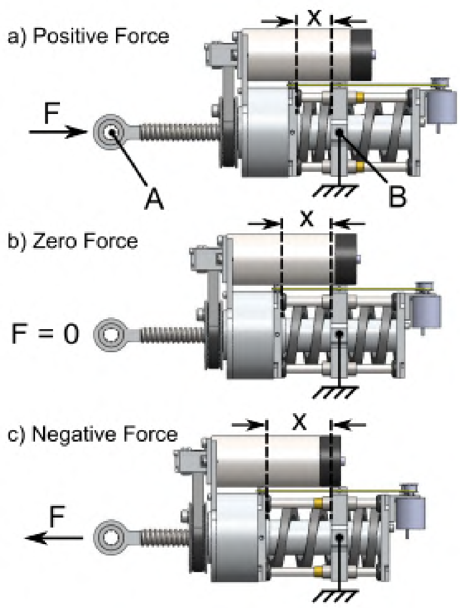



Figure 2.14: UT-SEA Operation [12]

### 2.3.1 Structure of UT-SEA

The UT-SEA implements the RFSEA configuration (Figure 2.7), where the springs are positioned behind the motor stator. The springs in the UT-SEA are usually fixed in place by placing two plates at both ends of each spring, using a total of 3 plates. These plates have to have four holes at their corners to allow four rods pass through them to maintain keeping the plates parallel to each other. These plates normally have grooves for the springs to be fixed on. Next, the motor is hung on a motor mount, which it is connected to the small pulley from the other side. This pulley is connected to the larger pulley using a belt. The larger pulley will then transmit the rotary motion to the ball nut, which is connected to the larger pulley using its flange and casing. The ball nut translates this rotary motion into linear motion by moving the ball screw, it is mounted on, left or right. The ball screw passes through its casing, which is at the center of the springs from one side, and it is connected to the load from the other side.

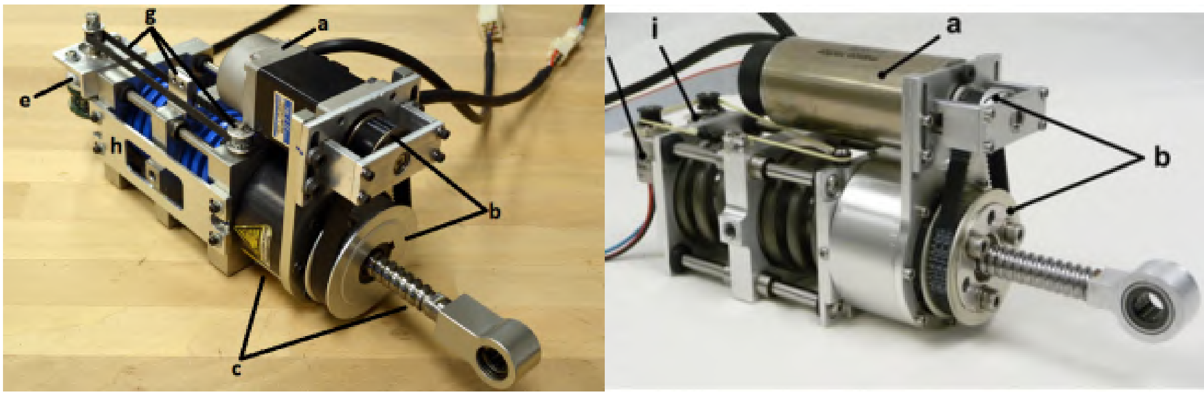



Figure 2.15: UT-SEA implemented examples [13] [12]

### 2.3.2 Operation of UT-SEA

The UT-SEA is operated by its main power source, the motor. When the motor operates, it transmits its motion to the pulleys. Then the pulleys transmit the motion to the ball screw, until the load hits the ground, in this case the Kangaroo leg, and starts making a reaction force. The extra force supplied to the load is transmitted to the springs when the ball screw is pushed to the spring's direction. At this moment, the spring starts absorbing the extra force, and it starts compressing, because the ball nut housing will be pushing the spring housing (the plate it is fixed to), which will result in moving the whole spring housing, resulting in the spring compression. When the motor starts rotating the opposite side, it will move the ball screw to the opposite direction together with the compressed spring. At this instant, the load will be pulled to the other side faster, eventually the leg will jump. When this sequence keeps repeating, the force acting on the load will increase, and it will speed up the movements.

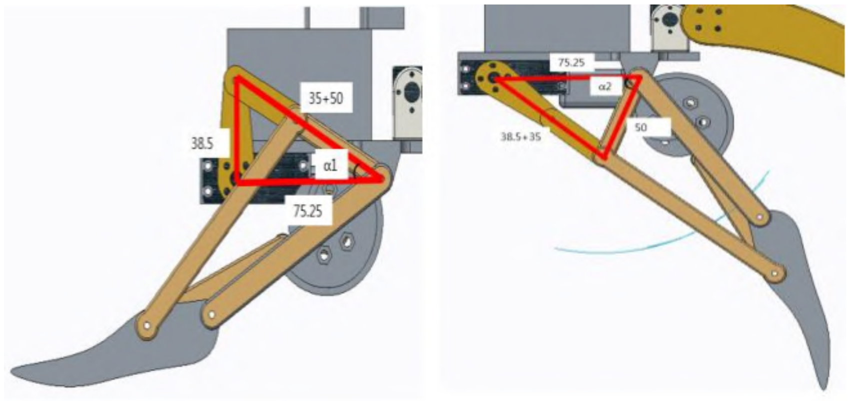
# Chapter 3

# Methodology

## 3.1 Kangaroo Leg Design

For choosing a design for the Kangaroo leg, I did lots of research on the designs, but the designs I found were very limited and not applicable for the SEA that I had to create my own design. The leg will basically be made out of two main links and a knee mechanism (it was added from the third proposed design). My initial and second designs were similar to Figure 3.1, while Figure 3.2 showed me an idea for making the knee mechanism, which appeared to be very complicated.

Figure 3.1: Example 1 [14]




(a)Shrink (b) Stretch

Figure 3.2: Example 2 [15]

### 3.1.1 Initial Design

For the initial design (Figure 3.3), I took ideas from the few designs that I found and decided to make a simple design. I made that design just to visualize the leg and to have the ability to make changes easily, that is why it was composed of only two parts.

Figure 3.3: First CAD Design

### 3.1.2 Second Proposed Design

This design (Figure 3.4) is similar to the first one, but I was thinking of a way to put the SEA on the leg. In this design, the SEA will have a Ball Screw that will be attached to the end of the leg. I changed the foot design, because I wanted to make the leg be mechanically restricted. I thought of adding a link or two around the the leg to help restrict it somehow, but it did not work out.

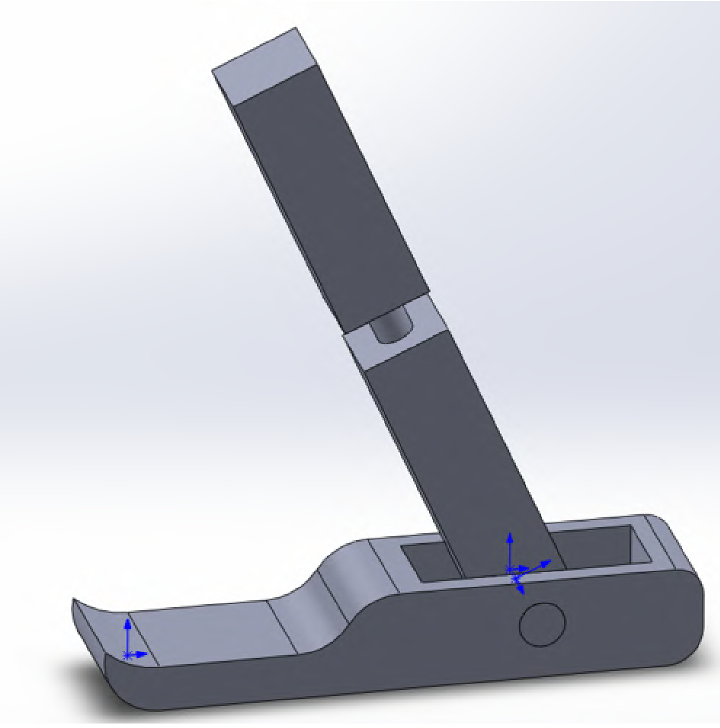


Figure 3.4: Second Proposed CAD Design

### 3.1.3 Third Proposed Design

In this design (Figure 3.5), I implemented the hinge, and got a new idea to put the SEA on the leg. The rectangular-shaped links on the leg are supposed to be guide rails for the SEA to be able to move the leg. The whole actuator itself will be put on the end of the leg, and the ball screw will be attached to a block of Artelon. This way when the ball screw moves linearly, it will move the Artelon block, which is attached to the foot, and the foot should be able to move. This design was not applicable, because the rail guides will not be able to carry the SEA, because it is heavy, and it will be put on a distance from the rails which will create a moment that will be dealing much more force on the rails. So, I had to disregard this idea.

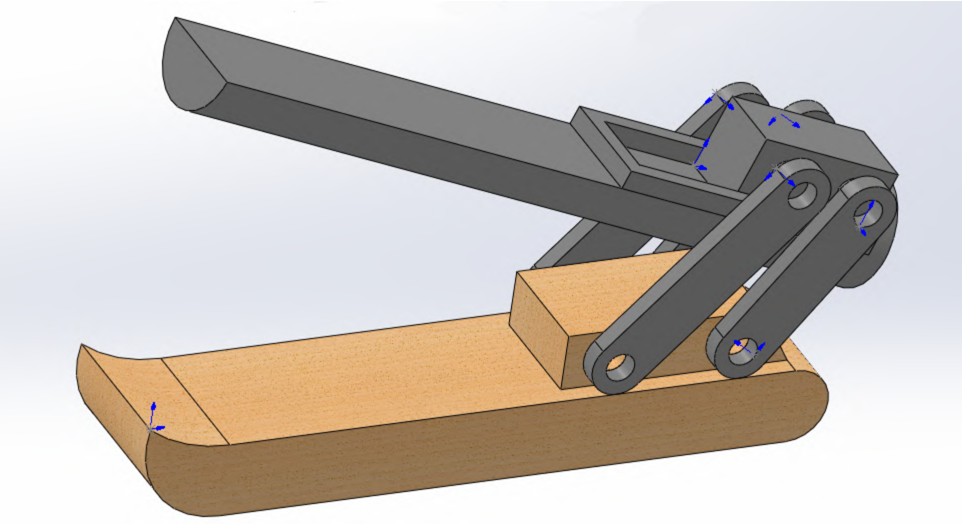


Figure 3.5: Third Proposed CAD Design

### 3.1.4 Final Design

In this design (Figure 3.6), I decided to put the SEA on a wooden plate and attach the ball screw to the end of the leg. The SEA will be put on separate rails, on both sides of the leg, to act as a weight on the leg and actuate the leg as it is supposed to. I implemented the same hinge that I used in the 3rd design (Figure 3.5). I designed the knee mechanism, such that the leg could be attached easily to the actuator.

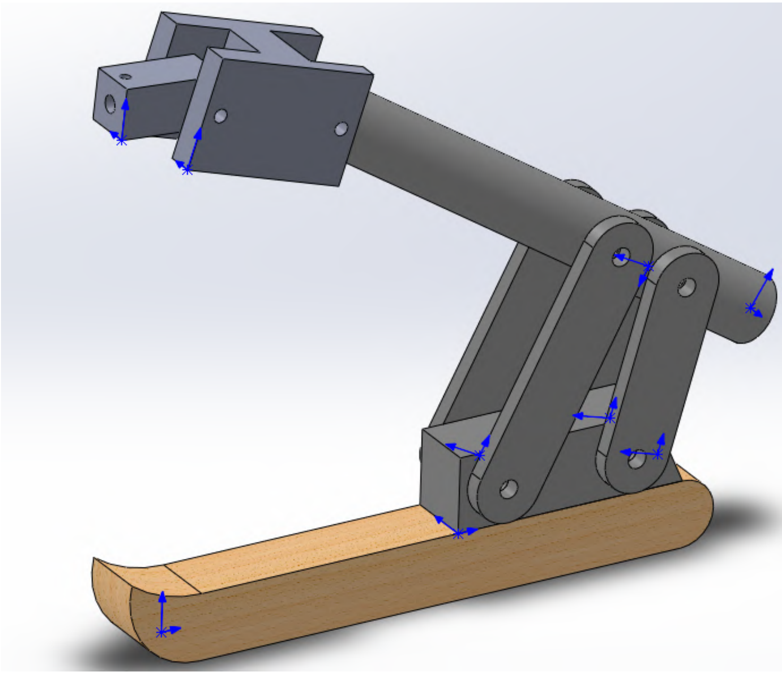


Figure 3.6: Implemented CAD Design

### 3.1.5 Manufacturing the Leg

To manufacture the leg, I used Beech Wood for the foot and Polyamide type 6, also known as Artelon, for the leg, leg holder, and the knee mechanism, and finally aluminium for the knee mechanism. I used the Beech wood because it can carry heavy weights for its small size. For the rest of the leg, I used the Artelon because of its availability and its lightweight, compared to the Beech wood.

I chose the dimensions based on the previous Kangaroo leg designs and actual kangaroos. For choosing the dimensions of the knee mechanism links, I kept trying different dimensions on a CAD application, until the links' dimensions let the leg rotations make sense. The following figures show the CAD designs of each part alone, then the manufactured parts after.

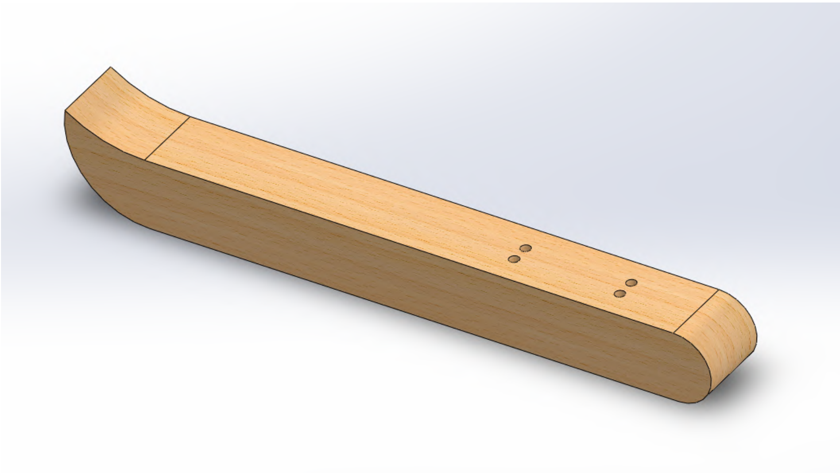


Figure 3.7: CAD Model of the Foot

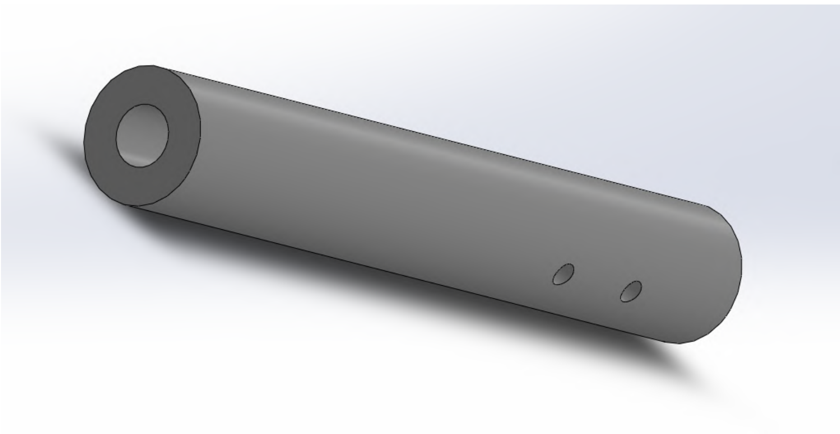


Figure 3.8: CAD Model of the Leg

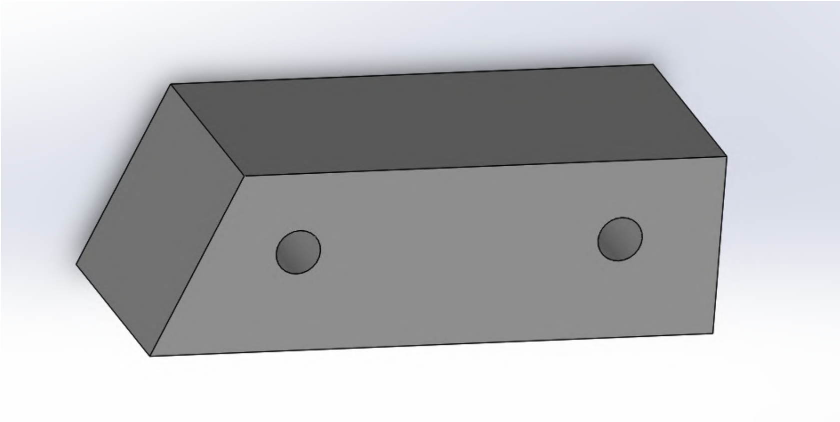


Figure 3.9: CAD Model of the Leg Holder

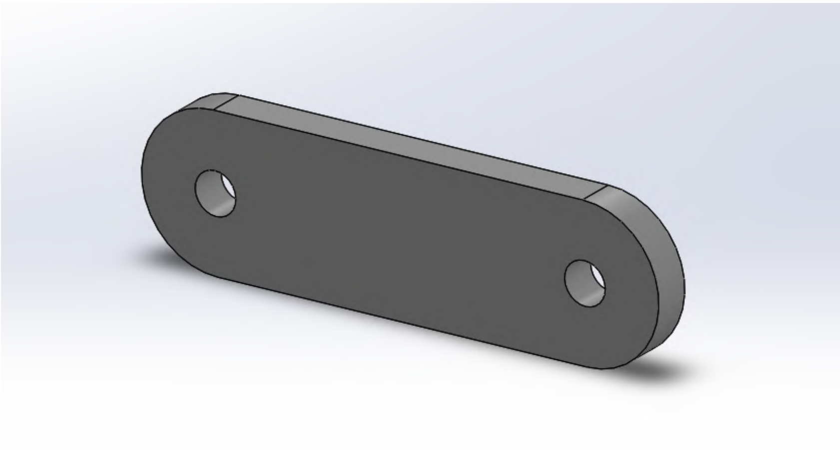


Figure 3.10: CAD Model of the Short Link

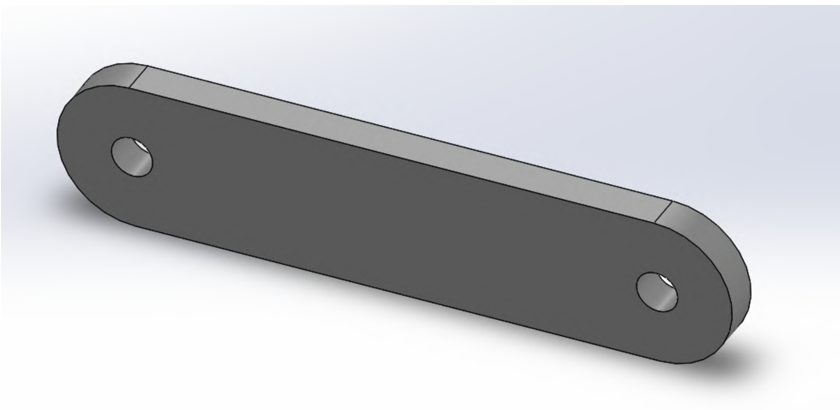


Figure 3.11: CAD Model of the Long Link

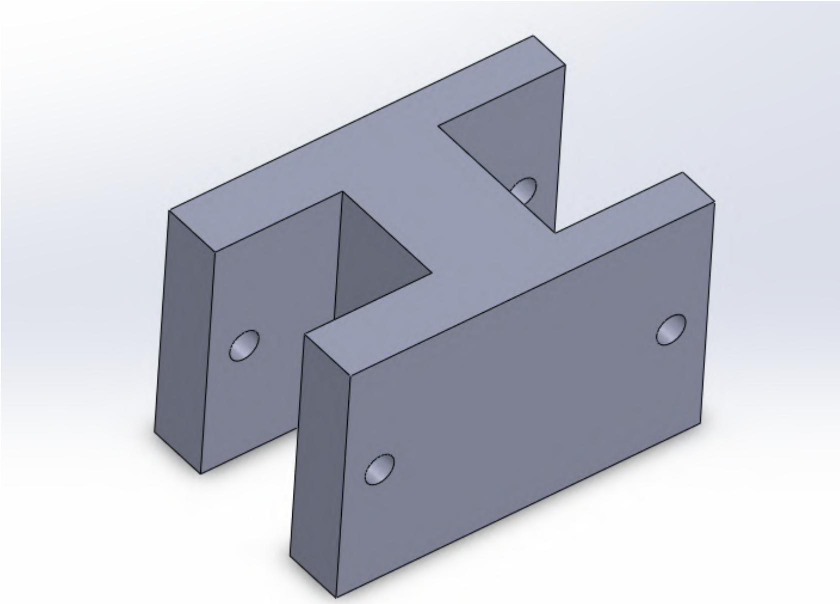


Figure 3.12: CAD Model of H-link

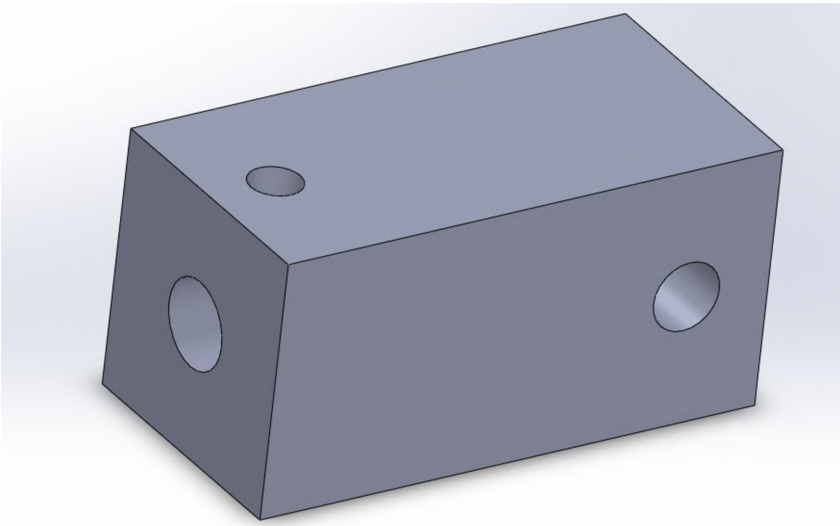


Figure 3.13: CAD Model of connector

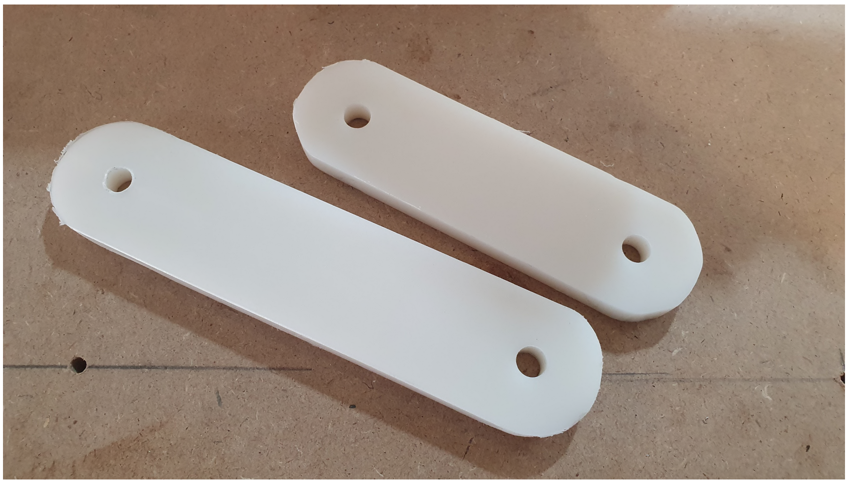


Figure 3.14: Manufactured links

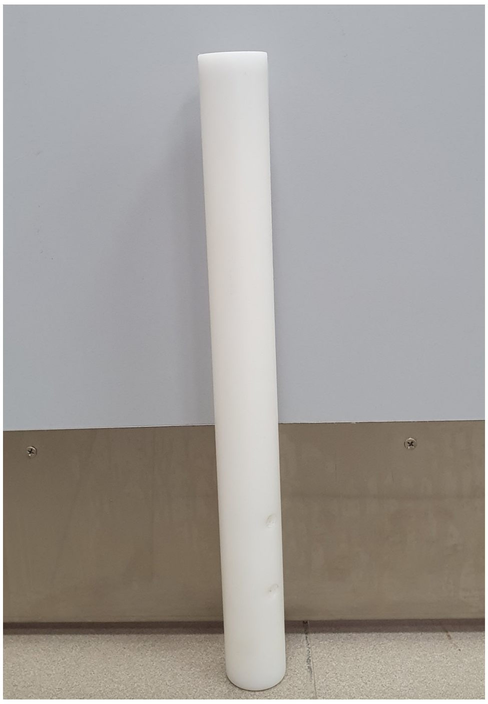


Figure 3.15: Manufactured leg

In this part (Figure 3.16), the leg holder was assembled wrong, because of technical issues. Therefore, I had to assemble it that way, and thankfully it did not do any harm to the complete assembly.

Figure 3.16: Manufactured foot and leg holder

## 3.2 Leg Assembly

In Figures 3.17 and **??**, this is the assembled leg. Its rotation is exactly as the CAD assembly manual analysis.

Figure 3.17

## 3.3 SEA Design

I have chosen to implement the UT-SEA design due to its availability and the number of research papers written about it.

### 3.3.1 Motor Selection

I needed a high torque brushless motor to be able to actuate the leg effectively.Unfortunately, I was not able to find brushless motors in Egypt, and I could not also ship it to Egypt, so I had to use a DC Geared Motor, which will ruin the backdrivability of the actuator. I bought the DC Geared motor (SG775125000-20K) which has a 1.03Nm torque, speed reduced to 250rpm, and operates at 12V 4A.


Figure 3.18: DC Geared Motor

The datasheet of the motor is as follows:

| MOTOR TORQUE/SPEED/CURRENT | |
|---|---|
| Rated voltage | 12VDC |
| No load speed | 5000r/min |
| No load current | 600mA |
| Rated torque | 650gf・cm 63.7mN・m |
| Rated current | 4.0A |
| Rated speed | 3750r/min |
| Stall torque | 2700gf・cm 264.6mN・m |
| Stall current | 14.0A |

Figure 3.19: Motor default parameters [16]

GEARED MOTOR TORQUE/SPEED/CURRENT

| Geared motor name | Rated Volt. V | No Load | | Load torque | | | | At maximum efficiency | | Output power W | Number of gear trains | Gearbox length "L" mm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Current | Speed | Current | Speed | Torque | | | | | | |
| | | mA | r/min | A | r/min | Kgf • cm | N • m | Kgf • cm | N • m | | | |
| SG-7755125000-20K | 12 | ≤500 | 250 | ≤4.0 | 188 | 10.5 | 1.03 | 33.0 | 3.23 | 20 | 2 | 28.5 |

Figure 3.20: Specific motor type parameters (SG775125000-20K) [16]

### 3.3.2 Spring Selection

To select the spring to be used, I bought 3 different springs (low stiffness (Figure 3.21), medium stiffness (Figure 3.22), and high stiffness (Figure 3.23)) to calculate their stiffness and choose the most suitable spring for my application. The spring stiffness will be chosen based on the total weight of the actuator and the leg. The spring's main job will be to absorb shocks and help the motor in actuating the leg.

Figure 3.21: Low Stiffness Spring

Figure 3.22: Medium Stiffness Spring

Figure 3.23: High Stiffness Spring

I, with the help of my colleagues, calculated the stiffness of each spring using a practical method. We added different weights to each spring to measure the deflection of the springs with each weight. Finally, I used this equation:

$$F = kx \tag{3.1}$$

to calculate the stiffness of each spring. Then I plotted the stiffness at each load on a graph. I also calculated the critical damping coefficient of each spring using this equation:

$$b_c = 2 * (\sqrt{k/m}) \tag{3.2}$$

### 3.3.3 Ball Screw with nut

The Ball Screw is a high-efficiency method of converting rotary motion to linear motion by using a recirculating ball mechanism between the screw shaft and the nut. The ball screw requires driving torque of one-third or less, when compared with a conventional sliding screw [49]. This feature makes it ideal for lower motor energy consumption, ensuring improved reliability, efficiency, and resistance even at extremely high loads [50]. Ball bearings within a ball screw roll along the track in a similar way to ball bearings in a standard rotary ball track, therefore eliminating the sliding friction associated with lead screws. The ball bearings are recirculated through the ball nut regularly, spreading the load and gathering up lubricant along the route. Internal friction in a ball screw is very low due to the use of rolling ball bearings, hence ball screws may provide great efficiency and positional precision even at high torque and force loads [51]. Advantages of Ball Screws include [51]:

1. High Efficiency - Less torque required and small in size.
2. High Accuracy - It can offer high positional accuracy and repeatability which is desirable for most applications.
3. Low Temperature - It can function at lower temperatures than other options.
4. Long Life - It can function for more time than other options.

Finally, I chose a 350mm long 12mm diameter ball screw for the actuator since I will not need a longer length (Figure 3.24).

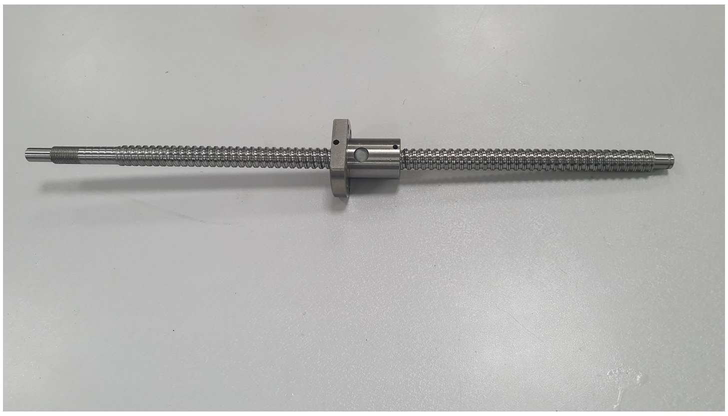


Figure 3.24: Ball Screw with nut

### 3.3.4 Spring Supporters (both ends)

The spring supporters act like a housing for the springs, because the springs will be held horizontally on a height. I used aluminium AL-R-6082 Figure to manufacture these plates.

In (Figure 3.26), the four holes in the corners of the plates will be used to align the plates in a parallel orientation, so the springs can be held in place. The center hole is big enough to hold the spring and let the ball screw housing pass through. The plate was supposed to have a groove for the spring to be held in place, but I decided to use the available aluminium instead of buying a new part and think of another way to hold the spring in place. The eight holes in the middle of the plate were drilled to be able to hold the fix the plate to the side plates (Figure 3.34) using L brackets (Figure 3.27). The final hole at the top center of the plate was drilled to hold an encoder for the feedback system of the actuator.

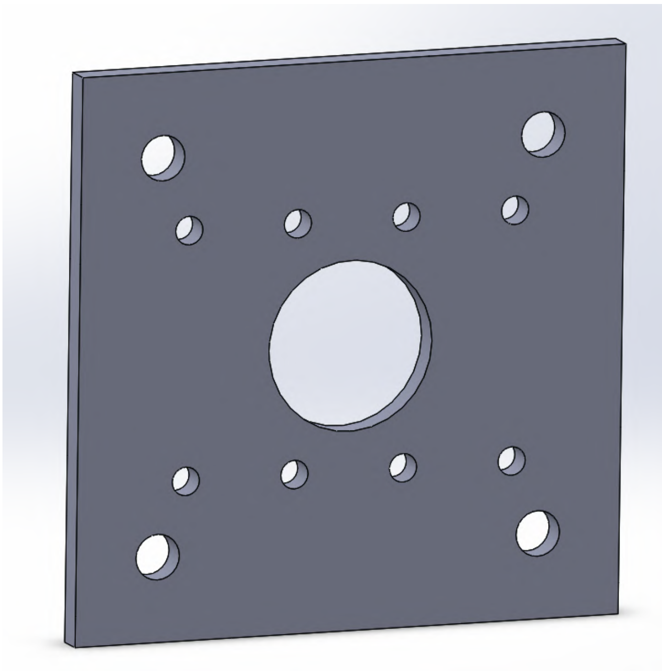


Figure 3.25: Spring Supporter CAD Model

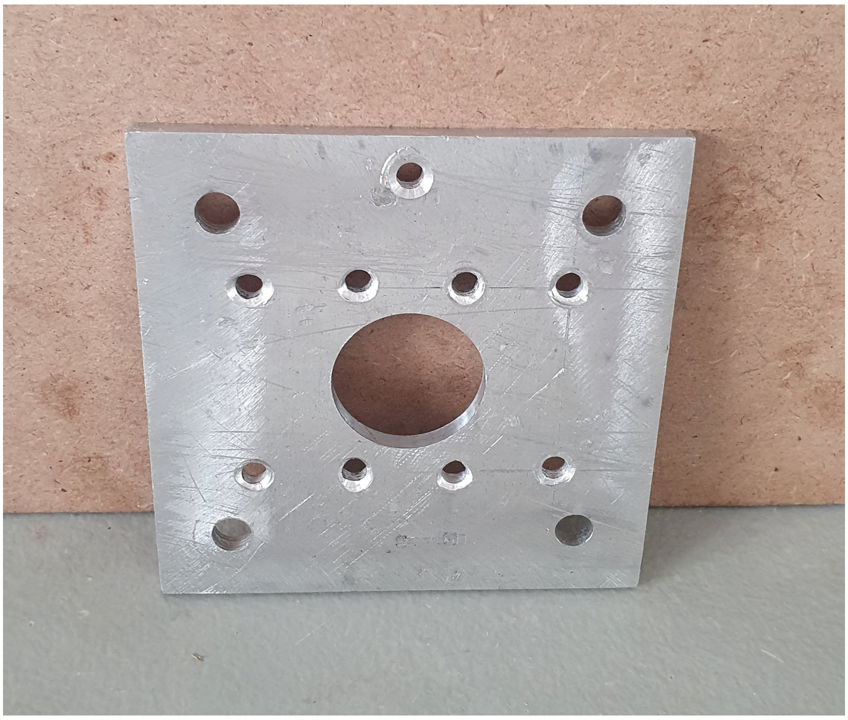


Figure 3.26: Spring Supporter

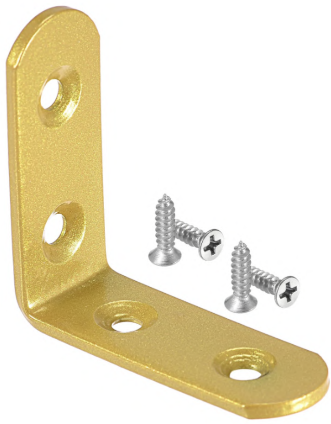


Figure 3.27: L Bracket

I decided to manufacture two 40x60mm plates (Figure 3.28) that will be put on the end of each plate to restrict the springs from deflecting away from their locations. For the spring supporter at the very end, I completely blocked the center hole to restrict the ball screw housing from passing through that side. While for the other spring supporter (near the motor mount), I drilled a hole big enough to only allow the ball screw housing pass by it.

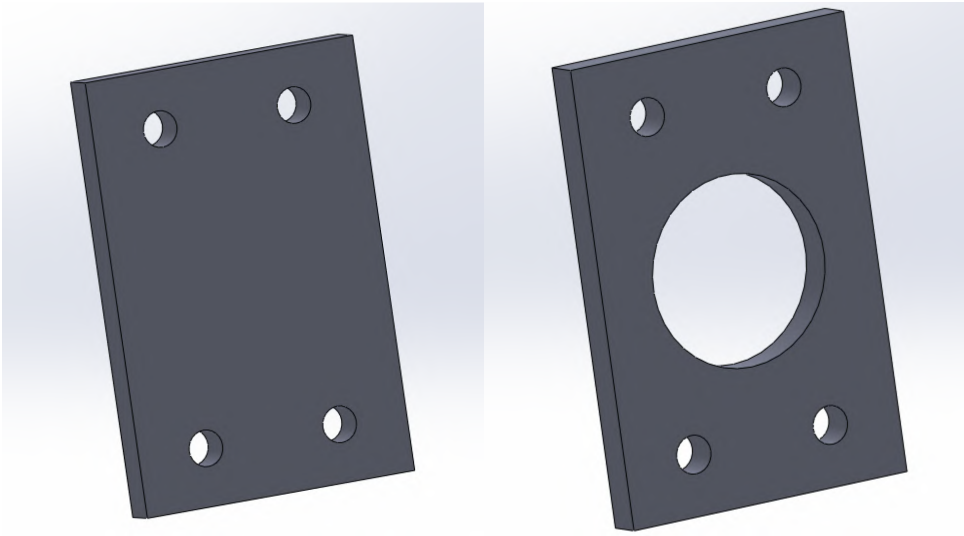


Figure 3.28: Spring holders

### 3.3.5 Middle Plate

To manufacture the middle spring plate (Figure 3.30) , I used Steel Grade 37, so that it could be able to carry the whole actuator from its sides. Its corner holes are bigger than than the spring end supporters, because the linear bearings (Figure 3.31) are to be attached in these holes. The plate has a groove 5mm deep in each side to support each spring from their other end.

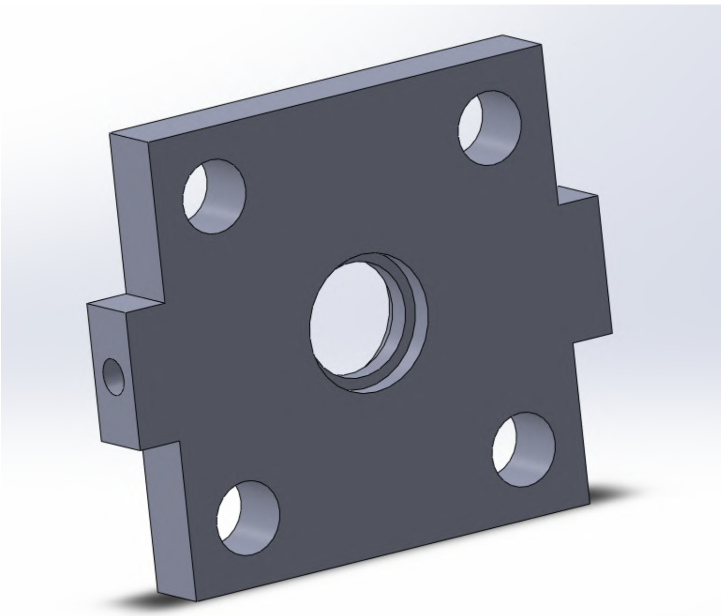


Figure 3.29: Middle Plate CAD Model

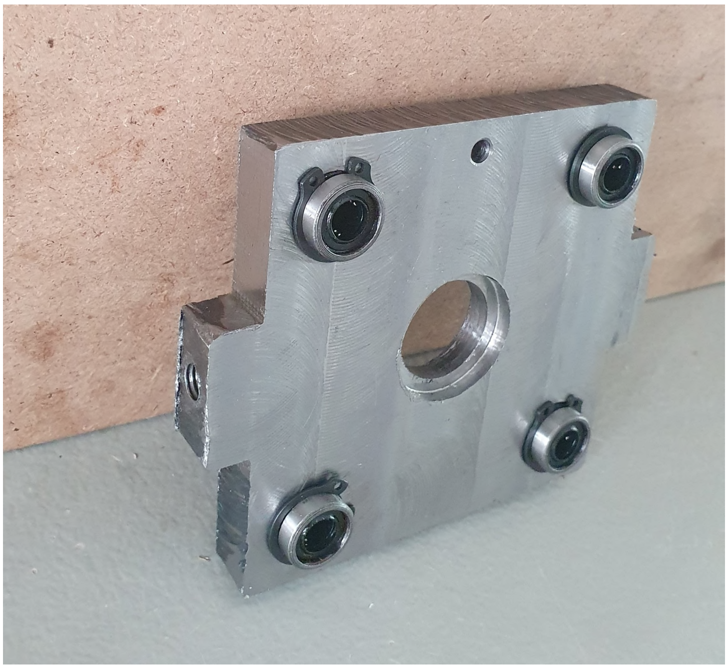


Figure 3.30: Middle Spring Plate

The linear bearings (Figure 3.31) will be used to smooth out the movement of the spring housing when there is an opposing force on the ball screw, which will be transferred to the ball nut housing to push the spring housing, compressing the spring. The linear bearings are fixed in place by using snap rings (Figure 3.32).

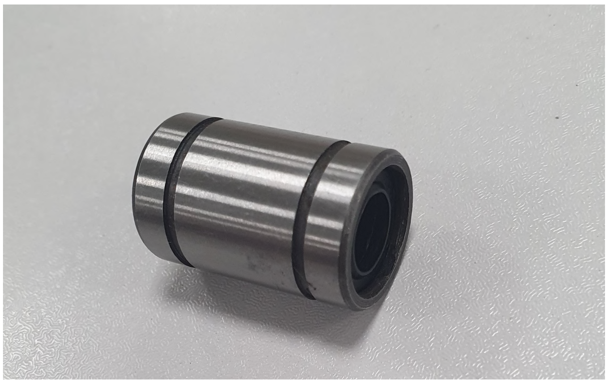


Figure 3.31: Linear Bearing

Figure 3.32: Snap ring

### 3.3.6 Side Plates

The side plates (Figure 3.34) will act as extra supporters for the spring supporter plates, where they will be placed on the sides of the spring housing as in Figure 2.15 (left). The rectangular space in the middle of the plate is made to let the middle plate sides (Figure 3.30) to be held from by connecting to the SEA Holders (Figure 3.37). The eight holes by the middle of the plates are drilled like the holes in the Spring supporters (Figure 3.28), so they can be fixed together with the L-Brackets (Figure 3.27). The plates are manufactured using a 2mm aluminium sheet.

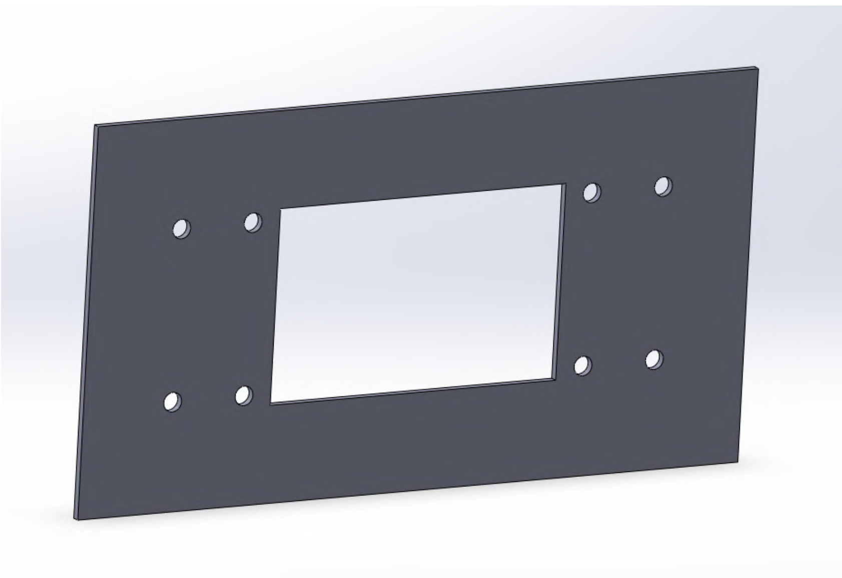


Figure 3.33: CAD Model of Side Plate

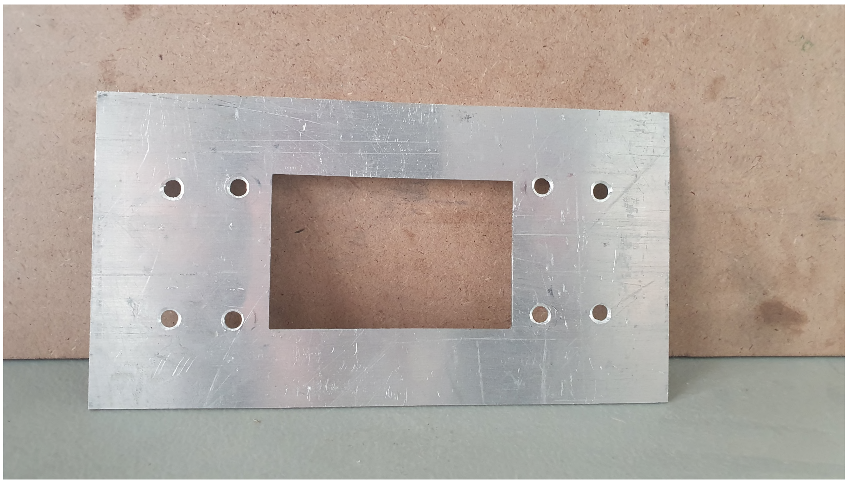


Figure 3.34: Manufactured side plate

### 3.3.7 SEA holder

The SEA holder is the only component that is fixed to the ground, since it will be carrying the whole actuator from the sides of the middle plate (Figure 3.30). This component is important to be able to control the leg. I included this component, because the whole actuator will be placed on a ground plate. If it was put on the leg directly, then that component will have been of no use. I used L-Brackets (Figure 3.27) to fix the SEA Holders on the ground. I used aluminium AL-R-6082 to manufacture the two parts of this component (for both sides). I manufactured the SEA holder using Computer Numerical Control (CNC), because of the needed accuracy to drill the hole for a bearing that will be fixed in there.

Figure 3.35: CAD Model of SEA Holder

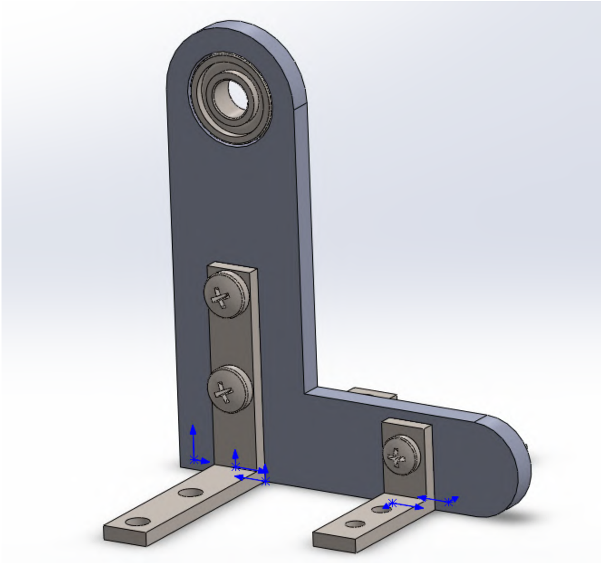


Figure 3.36: CAD Model of Ready SEA Holder

Figure 3.37: SEA Holder with its brackets for ground fixation

There will be a bearing (Figure 3.38) in each SEA Holder hole that will be fixed by pressure to smoothen the actuator motion. Moreover, it will let the leg be able to jump smoother.

Figure 3.38: SEA Holder Bearings

### 3.3.8 Ball Nut Flange

The ball nut flange is needed to transfer motion from the pulley to the ball nut. It will be permanently fixed to the nut by applied pressure. I used aluminium (AL-RO-2011-10) to manufacture the flange (Figure 3.40), because aluminium is light weight, and it is available.

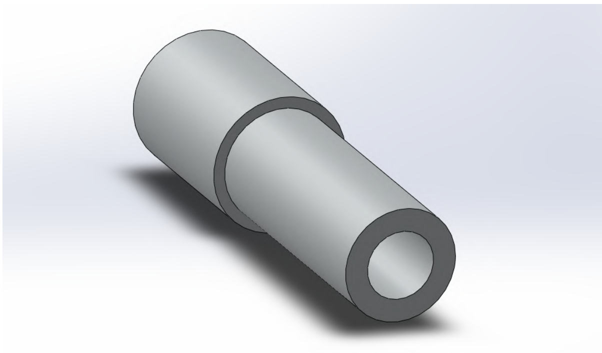


Figure 3.39: CAD Model of Ball Nut Flange

Figure 3.40: Ball Nut Flange

I attached the manufactured flange (Figure 3.40) to the ball screw by pressure and inserted a ball bearing (Figure 3.41) Figure to avoid transmitting the rotation to the Ball Nut Housing (to be talked about later) (Figure 3.42).

Figure 3.41: Flange Bearing

Figure 3.42: Attached flange to ball nut

### 3.3.9 Ball Nut Housing

For the ball nut housing, I used Spring Steel ( 55Cr5 ). I chose this material to be able to push the spring housing and compress the springs without any difficulties.

The ball nut housing will be used to allow the ball nut to transmit motion freely without making disturbances, since there is a ball bearing between the ball nut and the ball nut housing (Figure 3.41). The ball nut housing will also act as a connector between the motor mount (Figure 3.46) and the spring housing using screws.

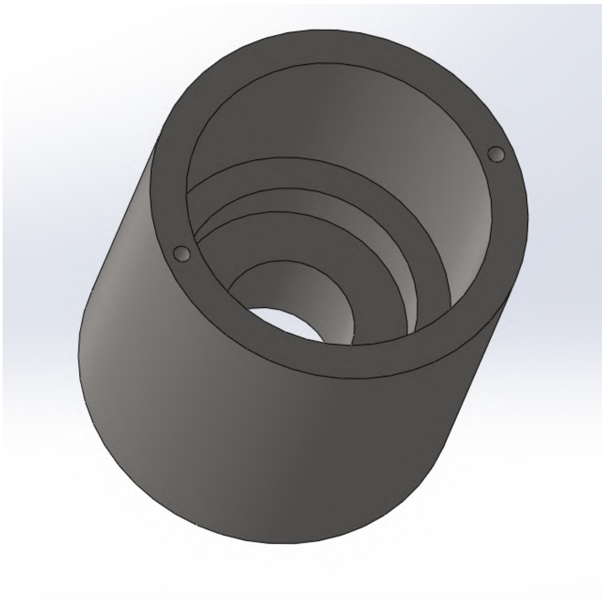


Figure 3.43: CAD Model of Ball Nut Housing

Figure 3.44: Manufactured Ball Nut Housing

### 3.3.10 Motor Mount

This plate will carry the motor while connected to its pulley (Figure 3.46) , and it will hold the ball nut housing, so that it can connect to the spring housing. It will also act as a limiter for the bigger pulley, so it does not shift to the other side. I used aluminium AL-R-6082 to manufacture the motor mount, because I did not need a heavy material, and the aluminium was already available.

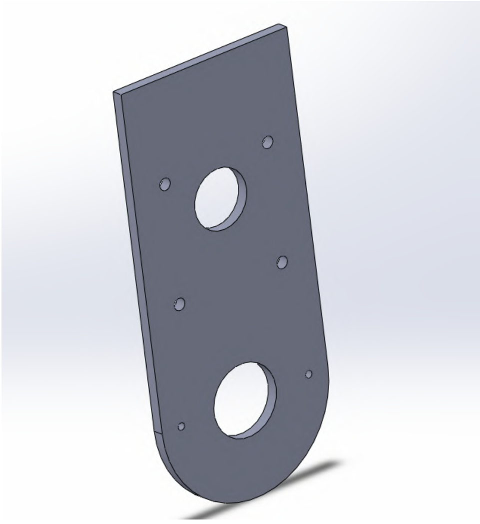


Figure 3.45: CAD Model of Motor Mount

Figure 3.46: Motor Mount

### 3.3.11 Pulleys

To manufacture the pulleys (Figure 3.48) , I used aluminium (AL-RO-2011-50) for the small pulley and aluminium (AL-RO-2011-70) for the bigger pulley. The pulley ratio will be 4:6 to increase the output torque of the motor for better performance.

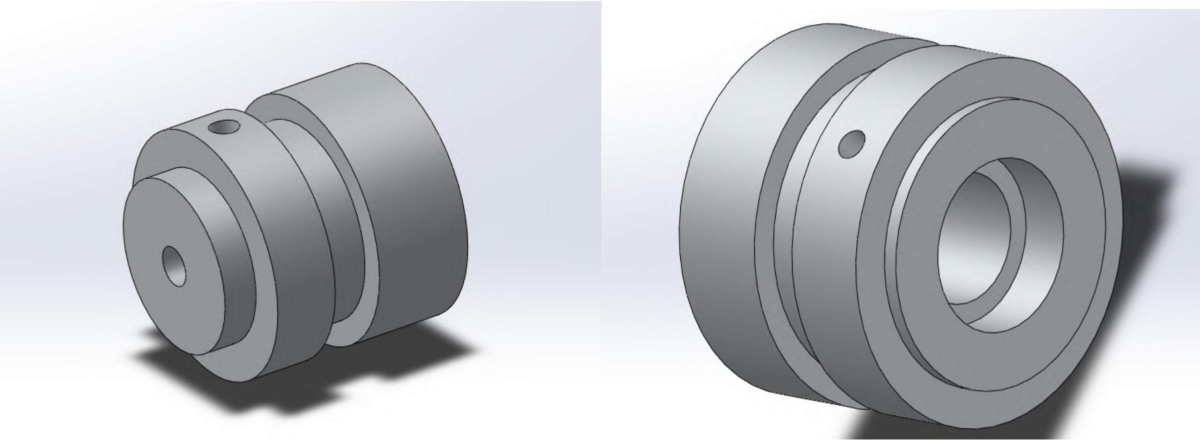


Figure 3.47: CAD Models for the pulleys

Figure 3.48: Pulleys

### 3.3.12 Ball Screw Housing

I manufactured a housing for the ball screw (Figure 3.50) to be placed in the center of the Spring supporters (Figure 3.26) and middle plate (Figure 3.30). It's main purpose is to smoothen the motion of the ball screw inside the spring housing, and it also restricts unnecessary vibrations by making its inner diameter slightly larger than the ball screw. I used Aluminium tube (AL-T-6060-25*15) to manufacture it.

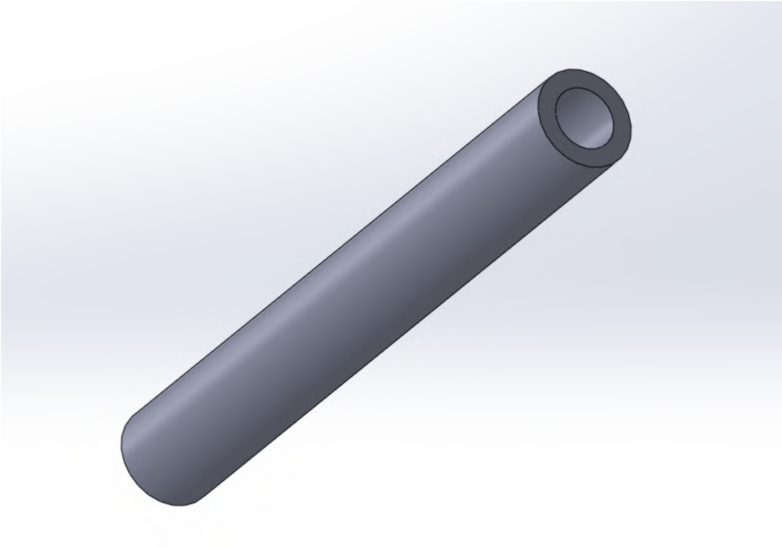


Figure 3.49: CAD Model of Ball Screw Housing

Figure 3.50: Ball Screw Housing

## 3.4 SEA Assembly

In this Figure 3.51, the SEA is completely assembled, and the actuator is ready for operation.

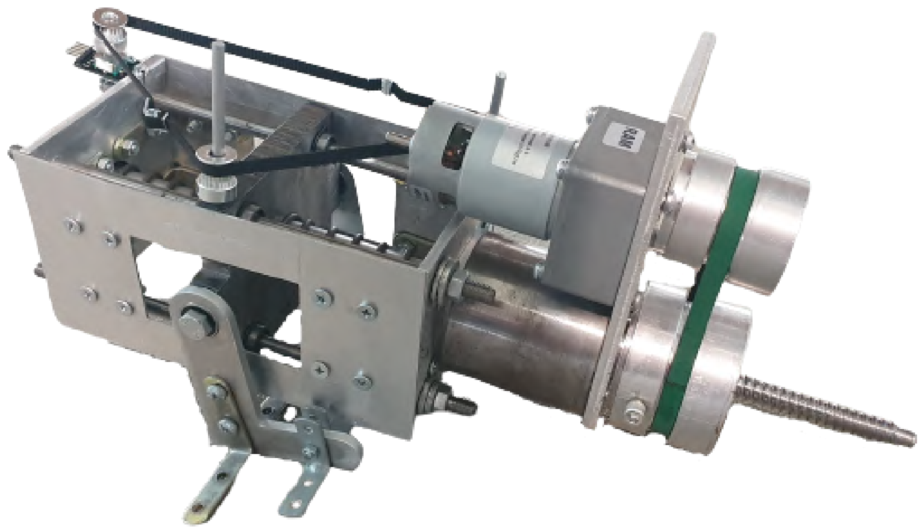


Figure 3.51: Assembled SEA

# Chapter 4

# Results

In this chapter, I will present my spring calculations, findings, and chosen spring. I will also present the final assembly of the leg and the SEA, and the complete assembly of the Kangaroo leg with the SEA. Finally, the implemented working mechanism (it will be updated very soon).

## 4.1 Spring Calculations

After calculating the springs' stiffnesses and damping coefficients, I plotted them in tables (a table for each spring)

Table 4.1: Light Spring starting length=100mm

| | Length(mm) | Mass(kg) | Stiffness(N/m) | Damping Coefficient(Ns/m) |
|---|---|---|---|---|
| 1 | 113.5 | 1.228 | 892.3467 | 48.652 |
| 2 | 136.3 | 3.92 | 1059.372 | 16.606 |
| 3 | 154.2 | 5.955 | 1077.833 | 11.026 |

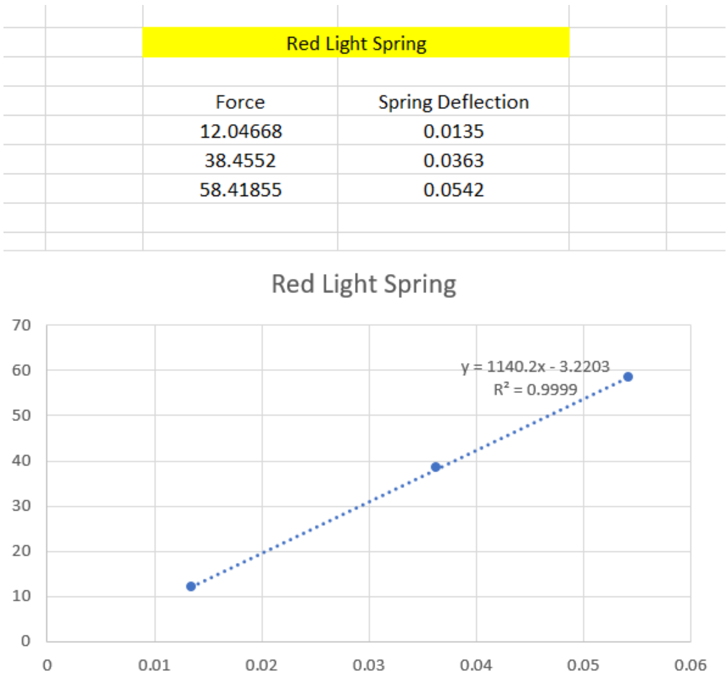
Table 4.2: Medium Spring starting length=101.8mm

| | Length(mm) | Mass(kg) | Stiffness(N/m) | Damping Coefficient(Ns/m) |
|---|---|---|---|---|
| 1 | 111.6 | 1.827 | 1828.86 | 46.815 |
| 2 | 112.2 | 2.78 | 2622.3 | 36.84 |
| 3 | 120.4 | 4.622 | 2437.73 | 21.365 |
| 4 | 129.3 | 6.596 | 2353 | 14.71 |

Table 4.3: Heavy Spring starting length=88.3mm

| | Length(mm) | Mass(kg) | Stiffness(N/m) | Damping Coefficient(Ns/m) |
|---|---|---|---|---|
| 1 | 93.1 | 1.827 | 3733.931 | 66.892 |
| 2 | 99.4 | 4.622 | 4084.85 | 27.656 |
| 3 | 101.2 | 6.596 | 5016.0271 | 21.475 |

I plotted the forces against spring deflections on charts.


Red Light Spring

| Force | Spring Deflection |
|---|---|
| 12.04668 | 0.0135 |
| 38.4552 | 0.0363 |
| 58.41855 | 0.0542 |



Figure 4.1: Force against deflection distance for light spring

| Middle Spring | |
|---|---|
| Force | Spring Deflection |
| 17.92287 | 0.0098 |
| 27.2718 | 0.0104 |
| 45.34182 | 0.0186 |
| 64.70676 | 0.0275 |

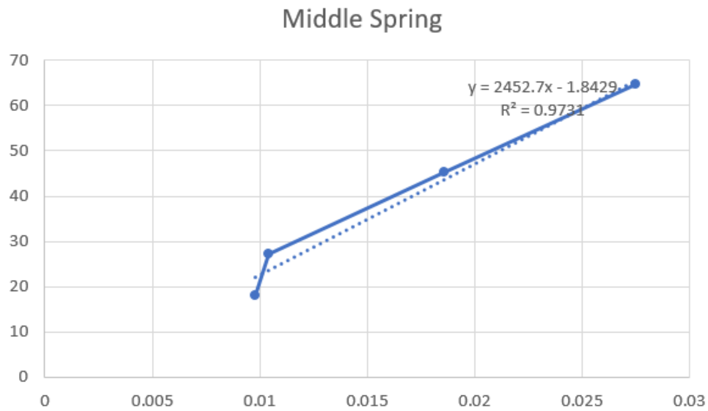



Figure 4.2: Force against deflection distance for medium spring

| Heavy Spring | |
|---|---|
| Force | Spring Deflection |
| 17.92287 | 0.0048 |
| 45.34182 | 0.0111 |
| 64.69695 | 0.0129 |

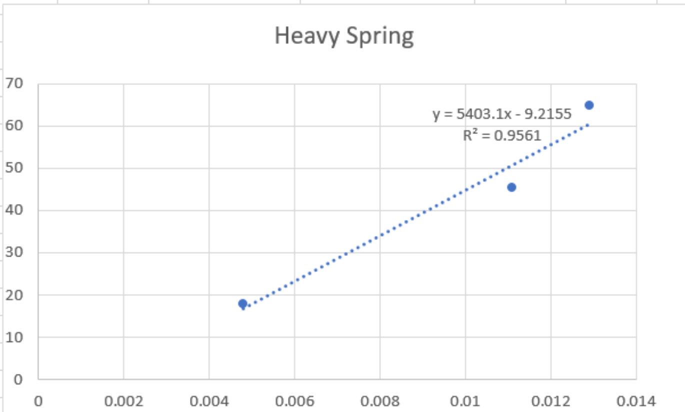



Figure 4.3: Force against deflection distance for heavy spring

Finally, I chose the heavy spring, because its stiffness matched the stiffness needed for my actuator to work effectively.

## 4.2 UT-SEA constants

Table 4.4: UT-SEA Constants

| Constant Description | Value |
|---|---|
| Spring length | 88.3mm |
| Spring stiffness (k) | 4278.27N/m |
| Damping coefficient ($b_c$) | 38.674Ns/m |
| Mass of whole mechanism (leg and SEA) | 7.3kg |
| Motor Power Output (motor) | 20W |
| Motor Voltage | 12V |
| Motor No Load Current | 600mA |
| Motor Rated Current | 4A |
| Motor Rated Torque | 1.03Nm |
| Motor No Load Speed | 250rpm |
| Motor Rated Speed | 180rpm |
| Transmission reduced speed | 120rpm |

### 4.2.1 CAD Assembly

In Figure 4.4, this will be how my final project assembly should look like. The SEA will be hung on guide rails from its both sides,upside down, so that the leg could feel the weight of the actuator.

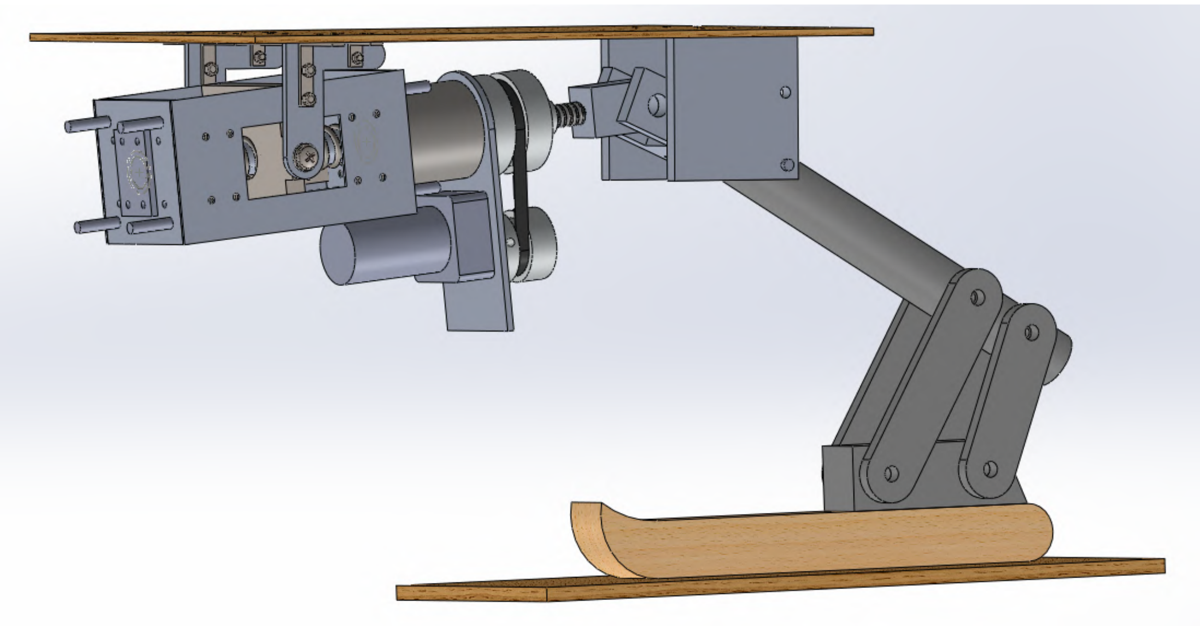


Figure 4.4: Kangaroo leg with SEA

### 4.2.2 Complete Assembly

In Figure 4.5, this is the complete assembly of the system. Now the system is ready for testing. In figure 4.6, This is the top view of the SEA, where I show all the components held tight.

Figure 4.5: Complete Assembly of leg (Side View)

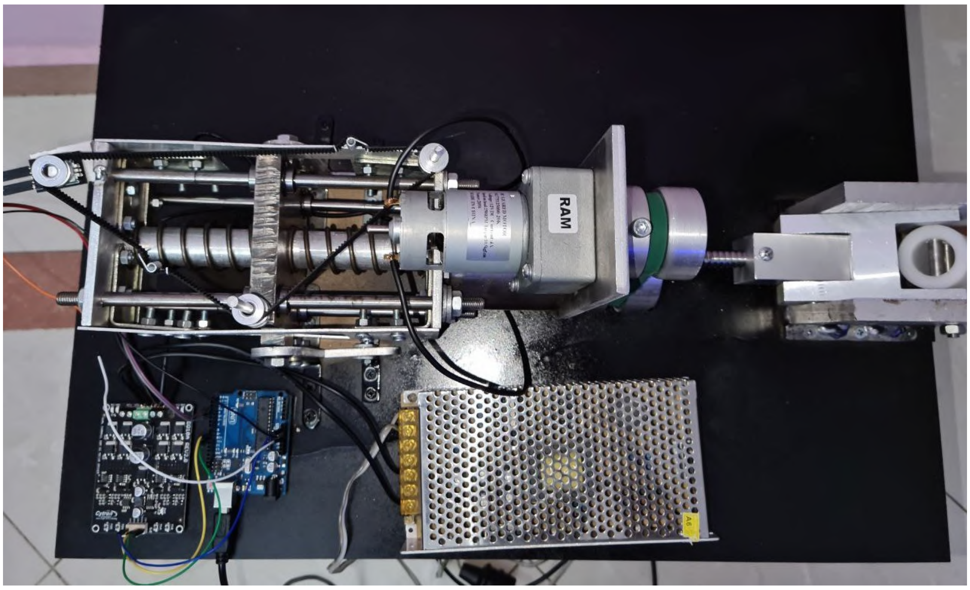



Figure 4.6: Complete Assembly of leg (Top View)

### 4.2.3 Testing the SEA

Figures 4.7 and 4.8 show that the SEA works well, where it compresses the springs in both directions, and the springs react to their compressions and try to push back together with the motor.

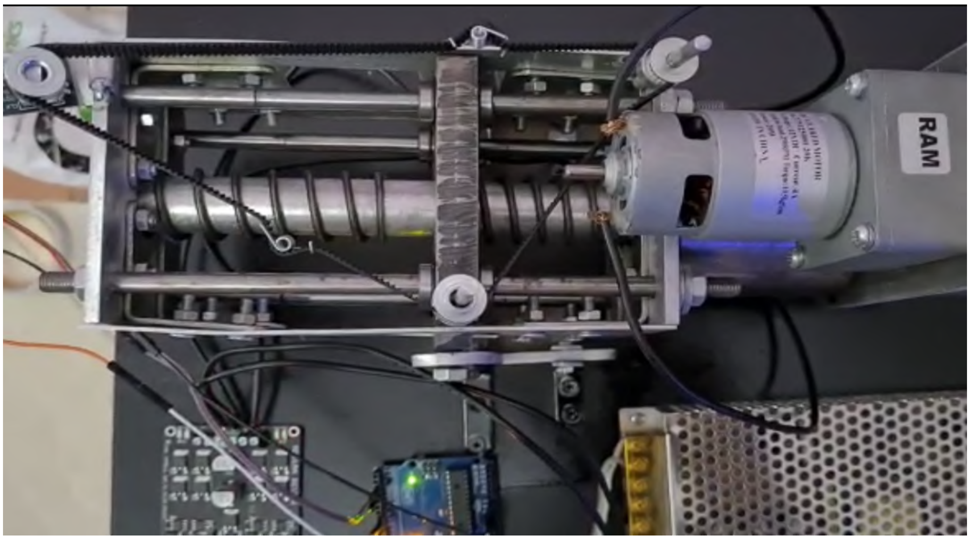



Figure 4.7: Compression of the right spring

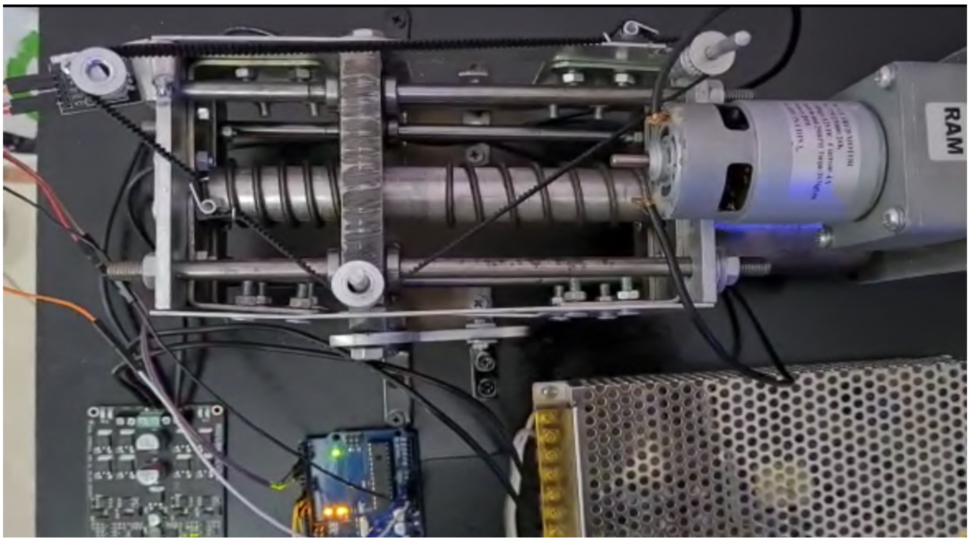



Figure 4.8: Compression of the left spring

### 4.2.4 Testing the Motion

The motion was not as good as expected, but it successfully compressed the spring, which proves that the system is working as it should. It's only drawback is the backdrivability, because the motor used was a DC geared motor not a brushless motor.

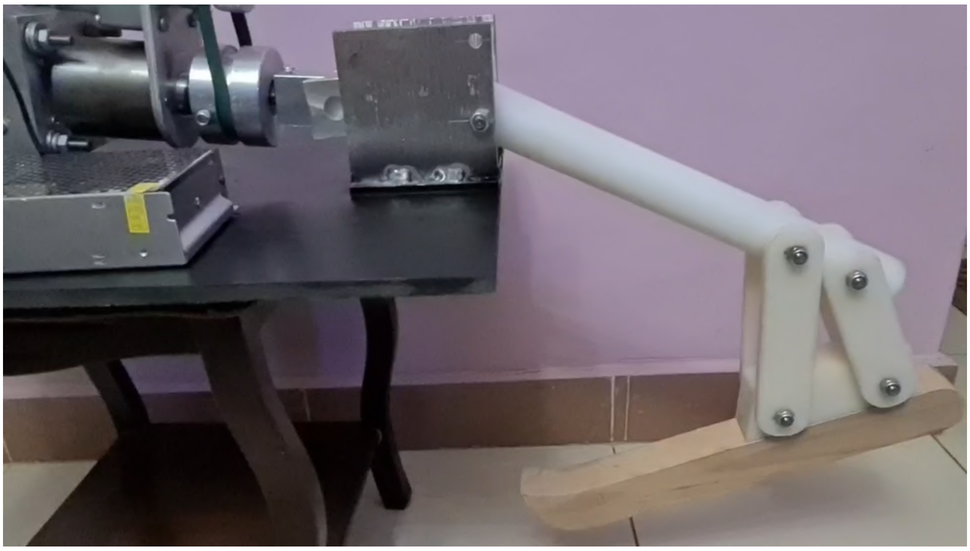


Figure 4.9: Upward motion

Figure 4.10: Downward motion

# Chapter 5

# Conclusion

Robotics is about turning ideas into action. It is a field of engineering that creates systems that mimic humans, animals, and even insects. Robotics has numerous advantages, including the ability to work in dangerous environments where humans are not permitted and the ability to attain repeatable precision. Next, there are industrial robots, which are becoming increasingly popular in the manufacturing industry, as most, if not all, operations of product production are now automated. They perform programmable and repetitive tasks such as picking, placing, welding, cutting, and, most crucially, assembling, which has led to the fast proliferation of industrial robots throughout the world. Rigid robots have actuators for each joint and are rigidly attached. To grip an object, these robots require precise control of rigid joints. They're built of tough materials that have consistent qualities. In contrast to rigid body motions in traditional mechanisms, compliant mechanisms are flexible structures that provide a desired motion by undergoing elastic deformation. The compliant robots are divided into two groups: active compliance and passive compliance. An active compliance scheme can substantially influence the dynamic behavior of a system without changing the physical qualities of the robot by varying the parameters of the virtual springs, such as stiffness and damping coefficient. The internal mechanical structural compliance of the robot base, linkages, joints, and driving mechanism is known as passive compliance. The introduction of passive compliance in robotic joints increases both the efficiency and stability of their dynamical movements as well as their manual manipulation capabilities. The addition of physical springs to a mechanism is exactly the what is meant by passive compliance. SEA is an actuator that is based on passive compliance. It is a type of actuator that combines a high-performance torque control with an elastic element (often a spring) that is instrumented within a rectangular enclosure. Because the friction is practically unnoticeable at the output, the actuator has a high back-drivability and low impedance. Another benefit is that the springs absorb the shocks, making the actuator shock-resistant. The springs may also store and release energy, making harmonic applications more efficient. There are various types of SEAs, but the most popular one is the UT-SEA, which utilizes the RFSEA. The

RFSEA is a type of SEA, where the spring is fixed to the ground followed by the motor, then its gear transmission, then finally the load. In RFSEA, the motor generates a relative torque between the stator and the rotor, which is amplified by the gear transmission and supplied directly to the load. The UT-SEA operates when the motor starts. The motor will transmit rotary motion to the pulleys which will then be translated to linear motion by the ball nut. Then, eventually, the spring will be compressed by absorbing continual shocks. Lastly, the leg should jump when the motor rotates the other direction along with the compressed spring's force. I calculated the spring' stiffness and damping coefficient, and manufactured the UT-SEA and the leg. For the final step, I attached the leg to the SEA and started testing the SEA and the leg motion. The SEA worked as it should, and the leg motion was not as good as it has to be, since it needs a few adjustments in design, but it was able to follow a good motion path.

# Chapter 6

# Future Work

To improve the current actuator and Kangaroo leg, it is recommended to implement some ideas:

- the use of brushless DC motor for smoother performance.
- implementation of the FSEA Configuration.
- placing the SEA on the leg directly or manufacturing a hip that will be able to carry the actuator.
- implementation of a control system to precisely control the leg's position and force.

# Appendix

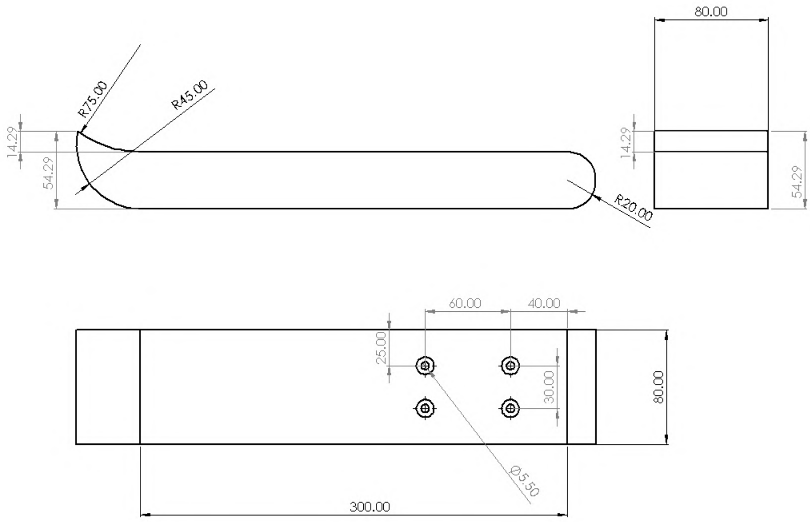



Figure 1: 2D Drawing of the foot (All dimensions are in mm)

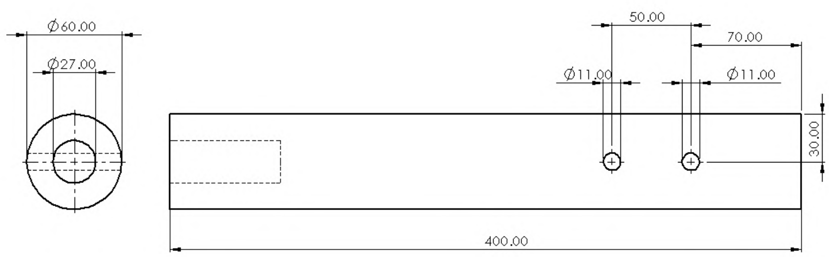



Figure 2: 2D Drawing of the 2nd part of the leg (All dimensions are in mm)

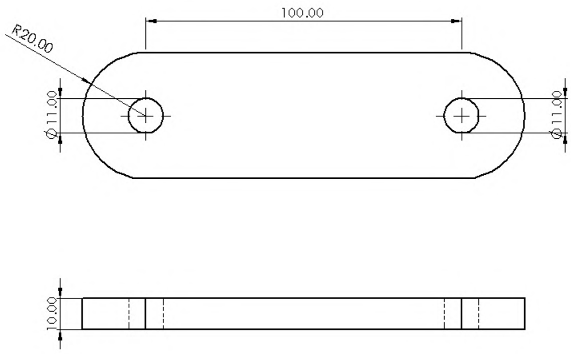



Figure 3: 2D Drawing of the short link (All dimensions are in mm)

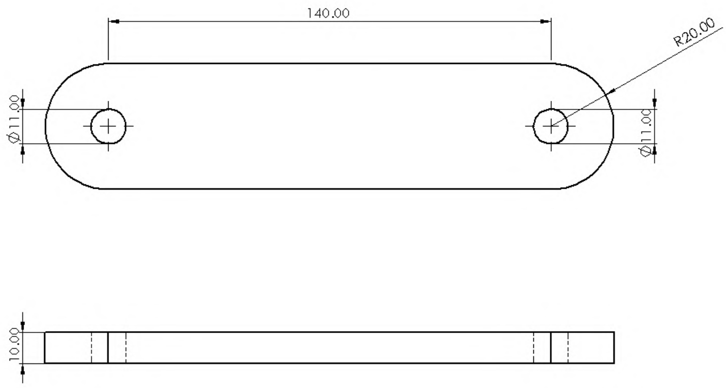



Figure 4: 2D Drawing of the long link (All dimensions are in mm)

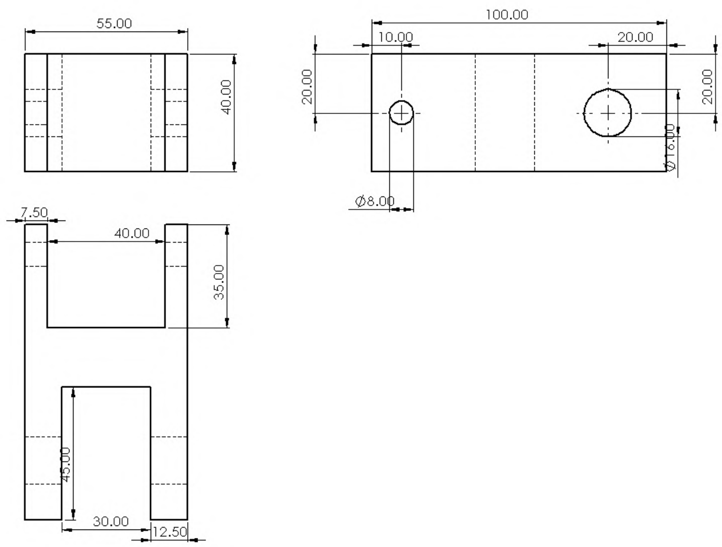



Figure 5: 2D Drawing of the H-Link (All dimensions are in mm)

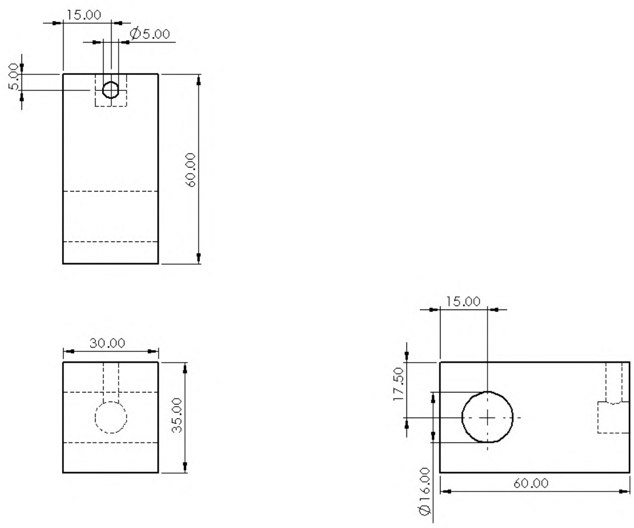



Figure 6: 2D Drawing of the leg connector (All dimensions are in mm)

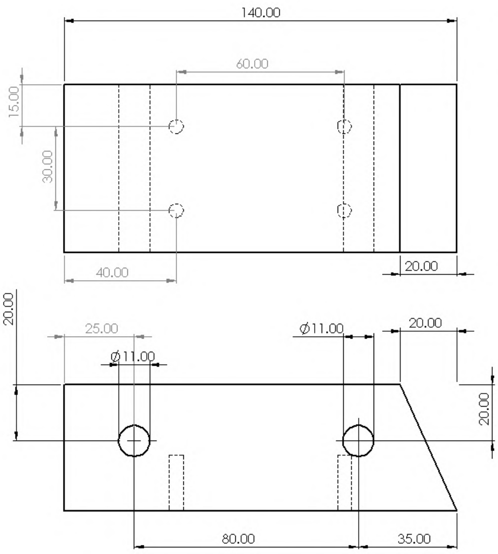



Figure 7: 2D Drawing of the leg holder (All dimensions are in mm)

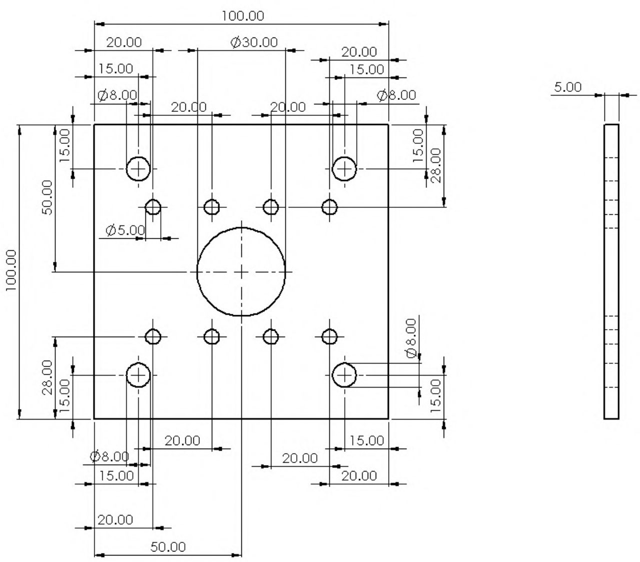



Figure 8: 2D Drawing of the spring supporter (All dimensions are in mm)

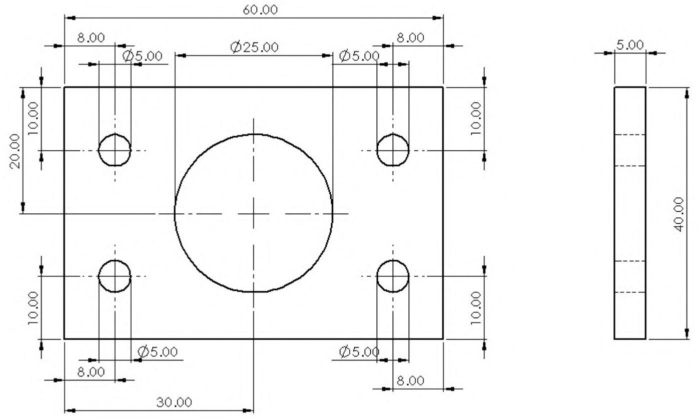



Figure 9: 2D Drawing of the spring 1st spring holder (All dimensions are in mm)

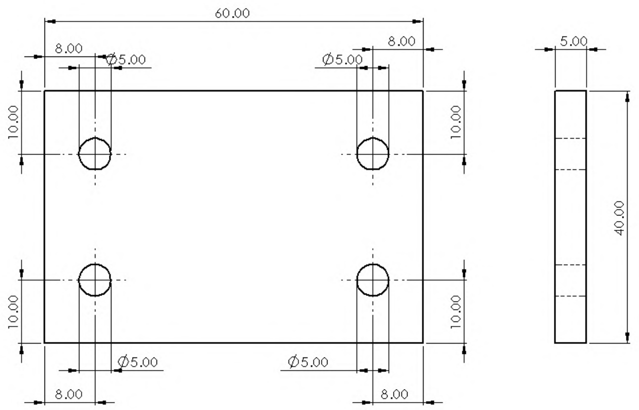



Figure 10: 2D Drawing of the 2nd spring holder (All dimensions are in mm)

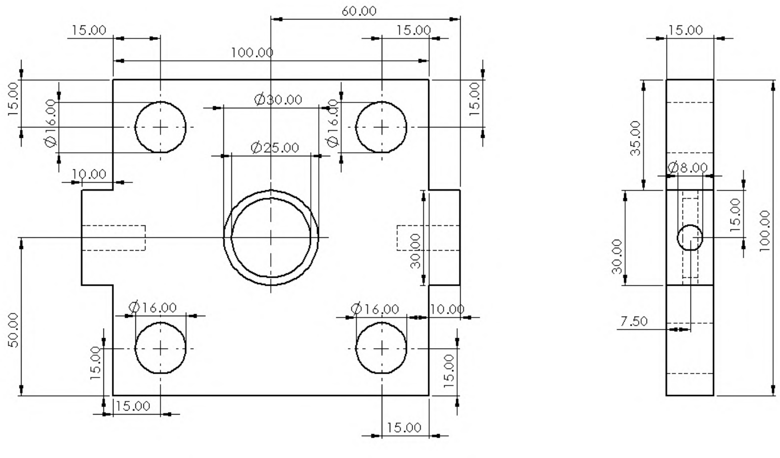



Figure 11: 2D Drawing of the spring middle plate (All dimensions are in mm)

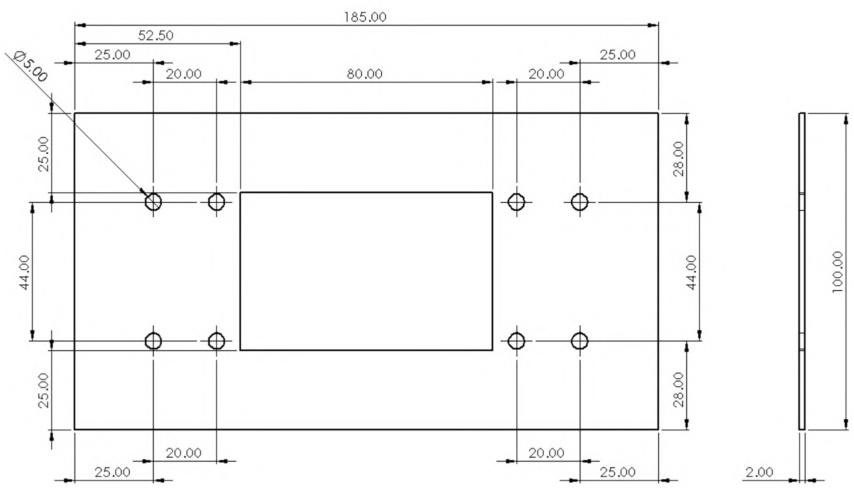



Figure 12: 2D Drawing of the side plate (All dimensions are in mm)

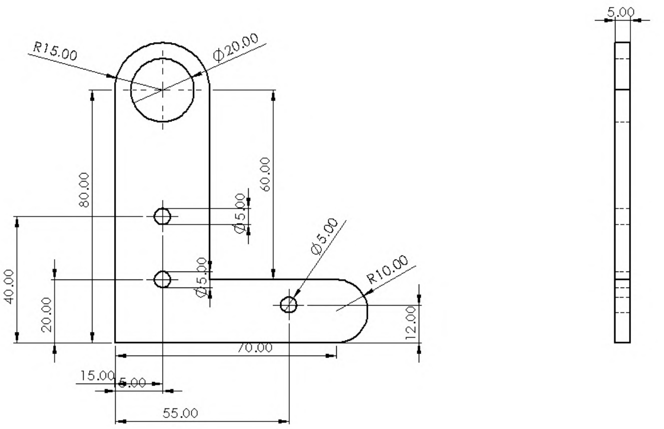



Figure 13: 2D Drawing of the SEA holder (All dimensions are in mm)

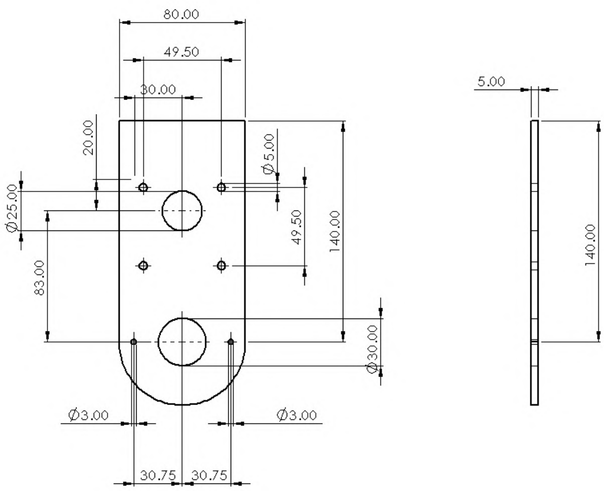



Figure 14: 2D Drawing of the motor mount (All dimensions are in mm)

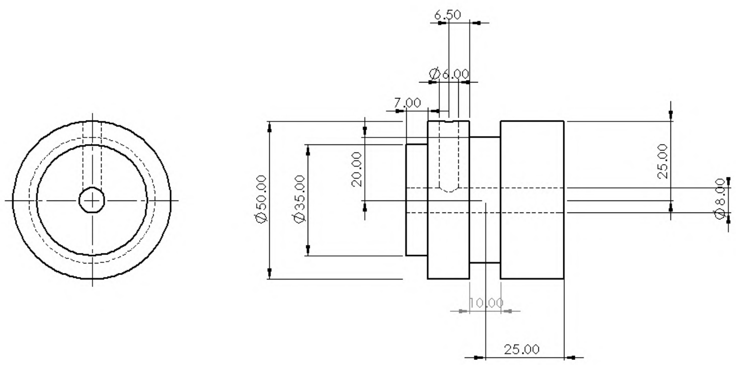



Figure 15: 2D Drawing of the small pulley (All dimensions are in mm)

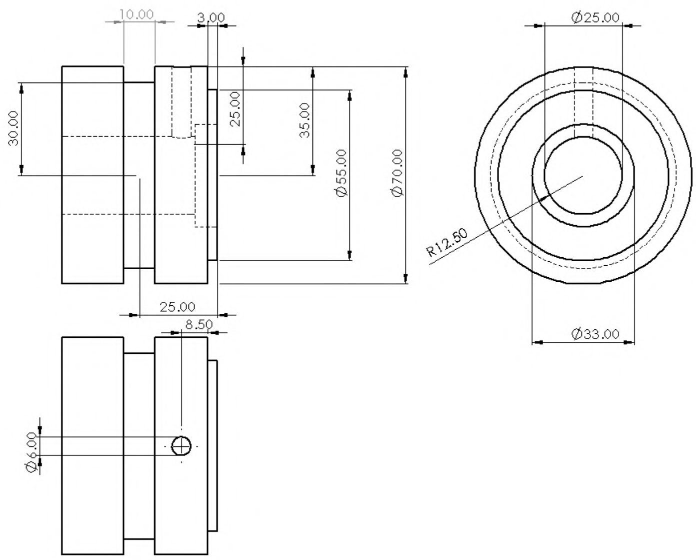



Figure 16: 2D Drawing of the large (All dimensions are in mm)

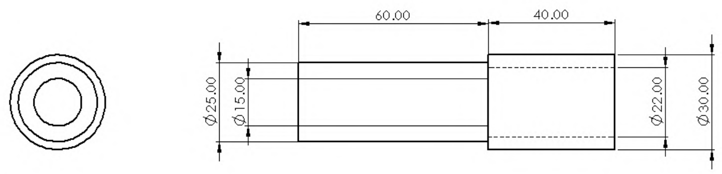



Figure 17: 2D Drawing of the Ball Nut flange (All dimensions are in mm)

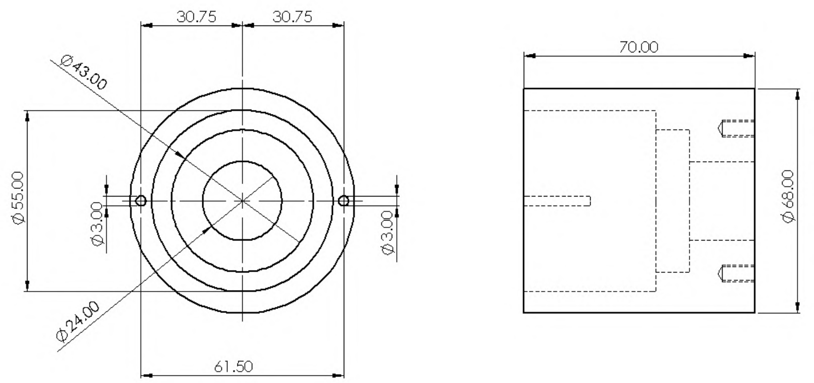



Figure 18: 2D Drawing of the Ball Nut housing (All dimensions are in mm)

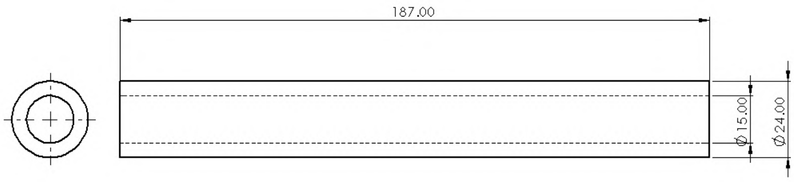



Figure 19: 2D Drawing of the Ball Screw housing (All dimensions are in mm)

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