

DESIGN, DEVELOPMENT, AND REAL-LIFE IMPLEMENTATION OF A HIGH POWER QUADRUPEd ROBOT

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DESIGN, DEVELOPMENT, AND REAL-LIFE IMPLEMENTATION OF A HIGH POWER QUADRUPEd ROBOT

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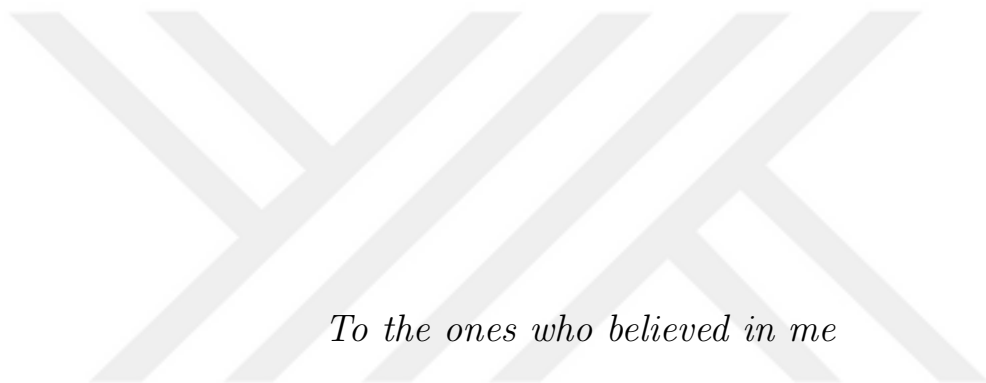
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To the ones who believed in me

ABSTRACT

This thesis presents the design, development, and experimental test of a quadruped with high power-to-weight ratio. In this thesis, three design processes are studied, namely, actuator design, leg mechanism design and torso design. The robot is required to be lightweight and traverse relatively fast without payload. Initially, the dynamic model of the robot was built, and a design optimization study for weight minimization was conducted in accordance with the loading results obtained from simulation studies. In order to obtain enhanced locomotion capabilities, custom actuator units with a high power-to-weight ratio were developed and deployed at the robot joints. With these actuators, the position control method was applied to the robot to control the motion. Moreover, the FEM model of the robot was built, and a design optimization study for weight minimization was conducted in accordance with the loading results obtained from simulation studies. As the main result, two prototypes were built, and quadruped gait experiments were conducted.

ÖZETÇE

Bu tez, yüksek güç-ağırlık oranına sahip dört bacaklı robotun tasarımını, geliştirilmesini ve deneysel testini açıklamaktadır. Bu tezde, eyleyici tasarımı, bacak mekanizması tasarımı ve gövde tasarımı olmak üzere üç tasarım süreci incelenmiştir. Robotun hafif olması ve yük olmadan nispeten hızlı hareket etmesi gerekmektedir. Öncelikle robotun dinamik modeli oluşturulmuş ve buna bağlı simülasyon çalışmalarından elde edilen yükleme sonuçlarına göre ağırlık minimizasyonu için tasarım optimizasyon çalışması yapılmıştır. Gelişmiş hareket kabiliyeti elde etmek için, yüksek güç-ağırlık oranına sahip özel eyleyici üniteleri geliştirilmiştir ve robot eklemelerine yerleştirilmiştir. Bu eyleyiciler ile hareketin kontrol edilmesi için robota pozisyon kontrol yöntemi uygulanmıştır. Ayrıca robotun Sonlu Elemanlar modeli oluşturulmuş ve simülasyon çalışmalarından elde edilen yükleme sonuçlarına göre ağırlık minimizasyonu için tasarım optimizasyon çalışması yapılmıştır. Sonuç olarak, iki prototip inşa edilmiştir ve yürüyüş deneyleri yapılmıştır.

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LIST OF ABBREVIATIONS

COM	Center of Mass
DOF	Degrees of Freedom
DOB	Disturbance Observer
FEM	Finite Element Method
DC	Direct Current
CAD	Computer Aided Design
FE (F/E)	Flexion-Extension
AA (A/A)	Abduction-Adduction
AA	Abduction-Adduction
RF	Right Front
COP	Center of Pressure
ZMP	Zero Moment Point

CHAPTER I

INTRODUCTION

1.1 Motivation

Over the last three decades, robotic systems have been used in several fields, particularly, they are utilized to diminish risk factors for humans. Thus, the development of mobile robotic platforms is a crucial area of research. Wheeled systems and legged systems are the primary focus of these mobile platforms. In recent years, wheeled systems have been successfully used on several tasks. Especially, legged robots possess certain advantages in traversing over unstructured terrain [2]. With the advancements in robotic actuation and control methods, legged robots have become more advantageous in mobility and versatility compared to wheeled systems [3], [4].

The design aspects of these robots may vary according to their tasks and user needs, resulting in different design challenges. As of today, engineers employ various approaches, e.g., detailed mathematical modelling and analysis, mimicking nature, and so on for addressing these challenges [5], [6], [7].

The most common type of legged robots are humanoids and animal-like robots. Quadruped robots are animal-like robot that needs four legs to move. These robots are handy in harsh environments and uneven terrains because of their dexterous and balanced mechanical structures [8]. Moreover, they can be controllable from a distance, thus they can operate in environments that are harmful to human beings. Currently, quadruped robots are being utilized for defense-related or industrial tasks.

While the use of quadruped robots are becoming more and more widespread, their design and manufacturing is not a trivial task. For instance, they include

several active joints, increasing their overall weight and manufacturing costs. Particularly, designing a quadruped robot with high power-to-weight ratio is a very difficult engineering challenge that requires conflicting objectives to be addressed. In the light of this fact, this thesis is aimed at addressing these challenges in a systematic manner, so as to build a state-of-the-art quadruped robot with advanced qualities.

1.2 Literature Survey

In literature, various studies have been conducted in terms of mechanical design, control, and walking algorithms, leg kinematics, and dynamics for quadrupedal robots. In this section, these studies were reviewed under three main topics, ie., actuators, leg mechanisms and control.

1.2.1 Actuator Types on Quadruped Robots

In the case of quadruped robots, a simplistic yet efficient actuator unit is crucial since each joint may require active joints. Thus, the number of actuators employed in the robot depends on the degree of freedom of the robot leg. Besides, actuator type plays an important role on the efficiency of the system and various actuation principles are presented in the literature for quadruped robots.

When it comes to generating high power, some researchers prefer hydraulic actuators. For instance, Semini et al. used linear and rotational hydraulic actuators for all joints on HyQ2Max [9]. Zhu et al. implemented a hydraulic actuator to the active compliant joints [10]. Despite the recent developments [11], these actuators generally lead to heavy-weighted units as they require several peripherals.

Series elastic actuators are known to provide advanced control capabilities using their elastic element between the motor and the mechanical output. In ETH, SEAs (ANYdrive) were implemented on Anymal's joints [12]. Yildirim et al. presented a design approach for the CoEx-SEA module [13]. Despite their merits, these types of actuators may lead to complex designs, and there are still practical issues in implementing these actuation principles in legged robots.

To achieve a more simple and efficient design, Kim et al. [14] proposed a compact actuator unit in which they used a frameless brushless motor and custom-made peripheral design, e.g., transmission, frame, to integrate its mechanical design for increased torque-to-weight ratio tightly. Following this approach, an actuator design methodology will be explained further in detail, which is based on FEM optimization methods.

1.2.2 Leg Mechanisms on Quadruped Robots

Researchers proposed several leg designs and mechanisms which can be grouped into 2 categories: i) direct drive systems [12][15][16], and ii) those that include mechanisms to drive joints [17][18]. For the case of direct drive systems, researchers aim to achieve full range of joint motion. Furthermore, the total weight of the robot could be comparatively less since they do not utilize any additional mechanism. Despite these advantages, the apparent inertia with respect to hip joint axis substantially increases due to knee motor, potentially hampering the controller performance during leg swing. In addition to this issue, locomotion controllers often dictates that the whole mass is condensed around the torso while the legs are relatively lighter [19]. This assumption may not correspond well to the actual dynamics for the case of robots direct drive joints.

To decrease the inertia of the leg, designers avoid assembling actuators onto the knee joints of the robot. For such a robot design architecture, there should be mechanisms to transfer the torque from the actuator to the joints to move the limbs. For instance, researchers used a pulley driven mechanism for the knee joints on Mini-Cheetah [20] and StarETH [21][22] quadruped robots. This mechanism is mounted in the leg's shank, ensuring a compact design structure. In [23][24] researchers developed the quadruped robot in which they utilized a sprawling-type joint on its leg design. Shi et al. [25] designed an elastic joint mechanism for the quadruped robot leg. Gao et al. [26] implemented a series-parallel joint mechanism on the robot leg. Rong et al. [27] developed a system, which possesses three active rotational joints and one passive prismatic joint on its leg. The goal

of this prismatic joint was to absorb impact forces from the ground.

Moreover, some leg designs were inspired by biological structures like bone, muscle, and tendon structures. Bio-inspired tendon-bone structures were implemented on MIT's Cheetah [28] and Eckert's [29] and Ma's [30] quadrupedal robot. Also, in literature, animal-inspired designs are presented like, Cheetah-cub [31] [32], which has a cat-inspired design that uses an actuated spine mechanism and spring-loaded pantograph leg.

Another mechanism that is often employed to transfer power from the actuator to the joint is the four-bar linkage mechanism. This mechanical structure is implemented on Cheetah [28], Laikago, Chituare [33], HyQ [34], HyQ2Max [9] and MiniHyQ [35] leg designs. This mechanism has several advantages: i) Actuators can be installed closer to the center of the mass of the robot, ii) Leg inertia w.r.t. torso can be minimized. This is an important advantage when designing locomotion controllers. Thus, we choose to utilize it in our system.

1.2.3 Quadruped Robot Controllers

Legged robots face various challenges depending on environmental conditions, and they affect robots' performance. For this reason, systems that can realize dynamic locomotion in challenging environments, such as BigDog [36], or possess robust and stable robot controllers [37]. Locomotion control can be covered in two conditions: i) Online pattern generation ii) real-time perceptual feedback [38]. To this end, Rutishauser et al. [39], Maufroy et al. [40] and Barasuol et al. [41] developed CPG (Central Pattern Generator) based trajectory generator. As another example, Moro et al. [7] proposed a trajectory planner with the data collected from a horse with the help of motion-sensing cameras. Kooleen et al. [42] also provided a trajectory planning with a motion capture system. For legged robots, COP (Center of Pressure) based trajectory generators were used in several methods [5], [43], [44], [45], [46], [47]. The COP-based analytical signal generator was designed by Ugurlu et al. [19], which was a fully computational and dynamically balanced COM trajectory planner.

Legged robots should respond appropriately during interacting with the environment [48]. Therefore, physical elastic elements have been introduced to provide smooth movement via with passive and compliant legs [39], [7], [21], [49], [43]. Galloway et al. [50] applied an adjustable passive-compliant system to an animal-like robot. Active adaptive schemes based on sensory feedback is another approach, which increases environmental interaction, and it is widely presented in the literature [51], [52], [53], [54], [5]. Hyon et al. [55] used this method by measuring and using the reaction forces on the robot's feet.

1.3 Methodology

In literature, various design architecture types of quadruped robots are presented. Actuator types, joint and mechanism designs, and controller types are crucial for the development of these robots. Considering these, design constraints are determined, and a design methodology is formed considering these constraints.

Moreover, design constraints could create certain design challenges that must be solved to yield an optimum outcome. In this case, challenges for designing quadruped robots can be categorized as follows: i) light-weight and durable design, ii) designing a compact actuator with high torque output, iii) leg design with minimum weight with sufficient strength.

In the case of quadrupeds with high payload capability, a compact actuator design with a high torque output is crucial since these robots require multiple active joints whilst keeping the total weight under a certain level to avoid unnecessary mass. The most efficient solution would be determining and employing the right commercially available brushless DC motor -gearbox combination and designing the actuator frames and shafts.

Moreover, the weight of the quadruped robot's legs should be contained minimum to decrease the leg's inertia and joint torque requirements. Since all actuators will be placed near the base and close to the center of mass, there must be mechanisms to transfer torque from actuators to the knee joints. Thus, parallel four-bar

mechanisms are suitable for this case because of their compact and stiff structure.

All these design challenges are addressed with a design methodology that was initiated with a rugged design and completed with an optimized design. This methodology requires a series of simulations, FEM analysis, and optimizations. First, dynamic simulations were conducted to obtain each joint's torque and velocity requirements. Then, the first actuator module and rugged quadruped robot were designed based on simulation results. After that, FEM analysis was conducted on these designs to map the stress distribution, and critical areas were found with these results. Topology optimization was implemented on low-stressed parts, and their structures were updated according to this procedure for mass minimization. The first robot prototype was realized with this methodology, and several test runs were executed with this prototype. In order to further lower the total weight, a material analysis was conducted for carbon fiber-onyx 3D printer filament to develop the second prototype. Finally, squatting and walking experiments were conducted on this robot with and without a payload.

CHAPTER II

HARDWARE DESIGN: ACTUATOR UNIT

As mentioned in Chapter (Chapter 1), the actuator unit is the essential element of the quadruped robot. Since the robot has three DOF on each leg, twelve actuator units are implemented in total. Therefore, their weight should be kept minimum in order to design a lightweight quadruped robot.

This chapter aims to present the development of a lightweight actuator unit with a high torque output [56]. In Section 2.1, preliminary simulations and component selection strategy for the actuator will be covered. The mechanical design and optimization methodology of the actuator unit, and its verification, are presented in Sections 2.2 and 2.3. Finally, the composite actuator unit development is explained in Sections 2.4 and 2.5.

2.1 Preliminary Mechanical Analysis

The actuator unit consists of two main elements: a frameless brushless DC motor and a gearbox system. These elements are chosen upon determining the requirements in accordance with the design, and their frames are designed by considering their geometrical structure. Therefore, the design constraints of the actuator unit will be shaped around these elements.

Table 1: Robot Target Specifications

<i>Specification</i>	<i>Value</i>
Target Weight (kg)	35
Max. Target Velocity (m/s)	1
Target Leg Length (m)	0.6
Max. Target Payload (kg)	5

First, the quadruped robot's target specifications were determined by our controller and tabulated in Table 1. In order to determine the design constraints of the actuator unit, a realistic simulation model was constructed in MSC Adams software, considering the robot's specifications as given in Table 1. Three walking simulations were conducted on the quadruped model: i) 1 m/s trot walking, ii) 0,4 m/s lateral walking, and iii) 0,25 m/s trot walking with a 5 kg payload. Joints that exhibited maximum torque demand were considered for further mechanical design steps. These results are shown in Figures 1, 2 and 3.

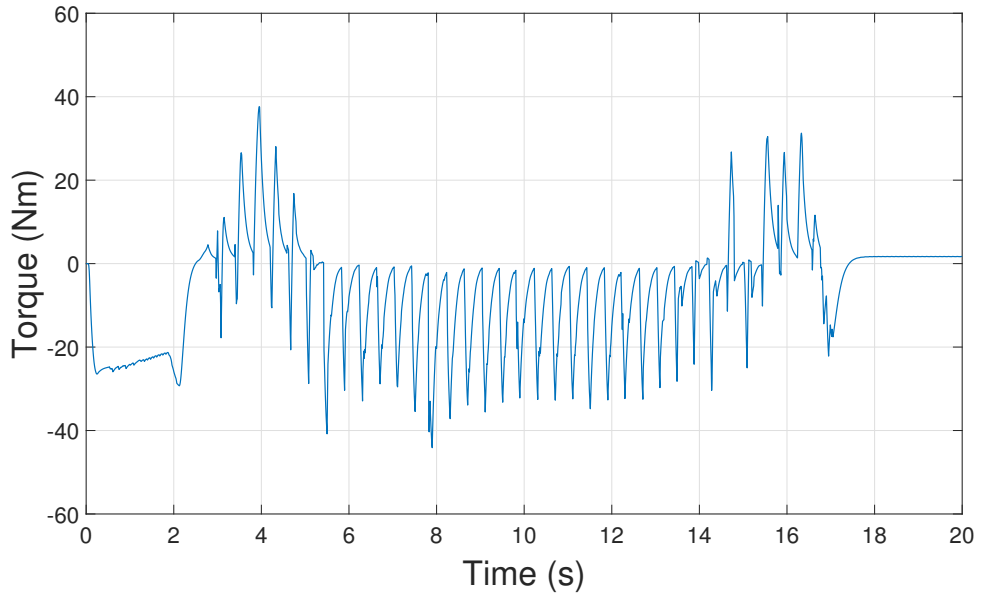


Figure 1: 1 m/s quadruped trot walking

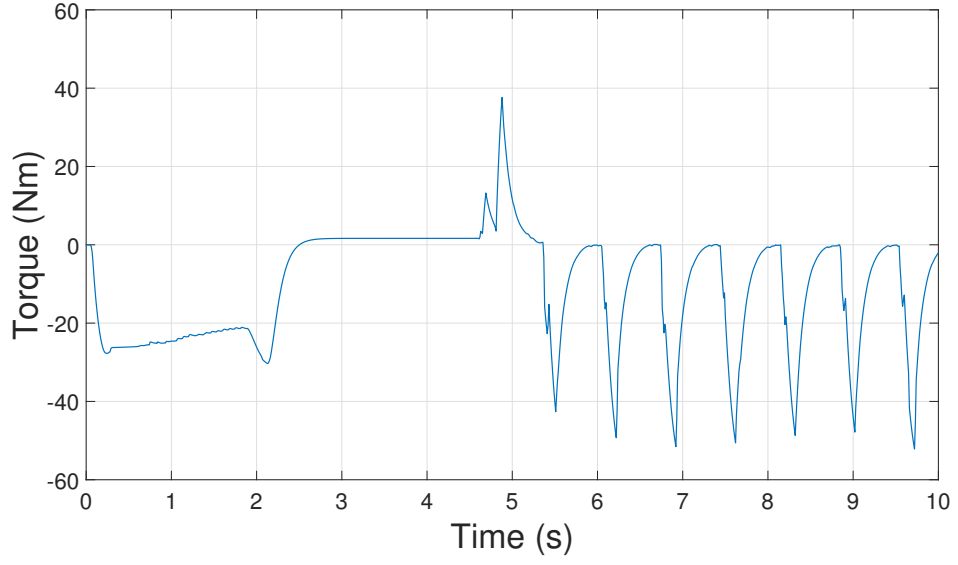


Figure 2: 0.4 m/s lateral walking

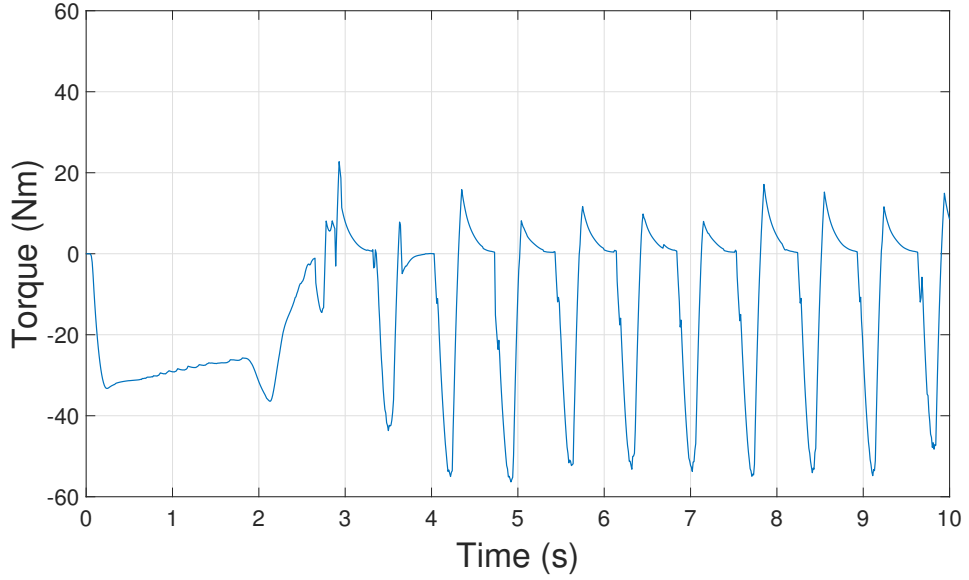


Figure 3: 0.25 m/s trot walking with a 5 kg payload

Assessing the simulation results, the maximum torque requirement for our actuator unit is about 48 Nm. Thus, the brushless DC motor and gearbox will be determined in accordance with these results. Due to its lightweight structure and specifications frameless brushless DC motor was implemented in the actuator. Its specifications are shown in Table 2.

Table 2: Frameless Brushless DC Motor Spec.

<i>Spec.</i>	<i>Value</i>
Nominal Torque (N/m)	1.32
Nominal Velocity (rpm)	2300
Weight (kg)	0.709
Nominal Current (A)	11.1
Nominal Voltage (V)	48
Stator Diameter (mm)	75.79
Stator Length (mm)	30.73

In actuator units, gearboxes are required for high torque generation. Harmonic gearboxes are very efficient for robotic applications because of their low backlash value and compact design. Therefore, a harmonic gearbox with a 1:30 gear ratio was chosen as a gearbox element for the actuator unit. While determining this gearbox, a series of calculations were made by using the equations below:

$$\eta_{out\ av} = \frac{\int |\eta| dt}{\int dt} \quad (1)$$

$$\tau_{av} = \sqrt[3]{\frac{\int |\tau^2| dt}{\int \eta dt}} \quad (2)$$

$$L_{50} = L_n \frac{Rated\ input\ speed}{\eta_{in\ av}} \left(\frac{Rated\ Torque}{\tau_{av}} \right)^3 \quad (3)$$

In Eq. (1) average output angular velocity for the actuator unit was calculated using the dynamic simulation data. In this equation, η is the angular velocity, and t is the time. The average torque value was calculated by using Eq. (2), where τ denotes the torque variation. Finally, in Eq. (3) gearbox's lifetime was calculated. L_n was the gearbox's optimal working time. Moreover, rated input speed and rated torque values were taken from the product catalogue. In Tables 3, 4, 5, results of these calculations for all actuator units were given in three different dynamic simulation conditions.

Assessing these results, maximum torque was generated at Hip FE actuators on the legs. The brushless DC motor and (1:30) harmonic gearbox combination

Table 3: 1 m/s Trot Walking

	Leg-1			Leg-2		
	Hip Yaw	Hip Pitch	Knee Pitch	Hip Yaw	Hip Pitch	Knee Pitch
Av. Torque (Nm)	7.98	11.54	11.18	4.00	17.47	7.95
Av. Velocity (rad/s)	0.00	349.07	223.83	0.00	347.52	225.35
Lifetime (y)	1.09E+18	31.4	53.9	3.41E+19	9.1	149
	Leg-3			Leg-4		
	Hip Yaw	Hip Pitch	Knee Pitch	Hip Yaw	Hip Pitch	Knee Pitch
Av. Torque (Nm)	5.09	11.41	9.03	4.44	10.05	7.44
Av. Velocity (rad/s)	0.00	346.03	223.56	0.00	347.85	222.60
Lifetime (y)	3.99E+18	32.8	102.2	5.42E+18	47.8	183.6

Table 4: 0.4 m/s Lateral Walking

	Leg-1			Leg-2		
	Hip Yaw	Hip Pitch	Knee Pitch	Hip Yaw	Hip Pitch	Knee Pitch
Av. Torque (Nm)	13.28	19.90	7.36	14.26	21.01	7.87
Av. Velocity (rad/s)	139.76	63.77	136.01	140.54	63.27	134.95
Lifetime (y)	51.5	33.5	310	41	28.5	255
	Leg-3			Leg-4		
	Hip Yaw	Hip Pitch	Knee Pitch	Hip Yaw	Hip Pitch	Knee Pitch
Av. Torque (Nm)	8.74	15.18	5.85	11.94	16.04	6.34
Av. Velocity (rad/s)	139.76	63.77	136.01	140.54	63.27	134.95
Lifetime (y)	180	75.5	616	70	64	489.5

Table 5: 0.2 m/s Trot Walking With a 5 kg Payload

	Leg-1			Leg-2		
	Hip Yaw	Hip Pitch	Knee Pitch	Hip Yaw	Hip Pitch	Knee Pitch
Av. Torque (Nm)	17.43	25.19	14.16	16.23	29.58	11.05
Av. Velocity (rad/s)	0.89	179.41	168.34	0.89	163.74	150.46
Lifetime (y)	4.E+03	5.9	35.3	4.44E+03	4.0	83
	Leg-3			Leg-4		
	Hip Yaw	Hip Pitch	Knee Pitch	Hip Yaw	Hip Pitch	Knee Pitch
Av. Torque (Nm)	17.45	27.28	7.72	17.47	25.52	11.43
Av. Velocity (rad/s)	0.89	166.76	158.62	0.89	174.01	158.47
Lifetime (y)	3.56E+03	5.0	230.5	3.56E+03	5.8	71.3

are chosen so that they could bear these conditions, as τ_{av} and η_{av} indicates. The further actuator design proceeded by considering these elements.

2.2 Unit 1.0: Mechanical Design

This section will explain the mechanical design methodology of the actuator frames. Our proposed methodology is initiated with a preliminary actuator design that is followed with topology optimization and FEM analysis.

Using dynamic simulation results reported in Section 2.1, ground reaction forces were obtained. After that, a basic CAD model of the robot was constructed by considering simplistic geometries. Using Ansys software, a FEM analysis is conducted on basic robot design, and force reactions on the actuators' output shafts were obtained. Then, further analyses are conducted with these results.

Initially, Al-7075 was selected as the base material for the actuator frames and shafts. Its structural properties are given in Appendix A. Then the initial actuator unit was designed in a CAD environment and given in Figure 4.

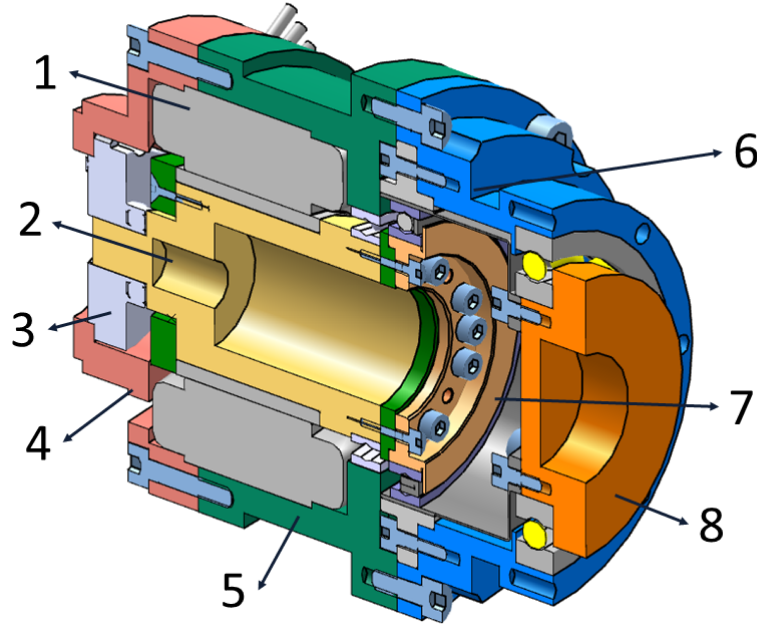


Figure 4: CAD view of the initial actuator design

The actuator unit was designed as two modules: the motor module and the gearbox module. The motor module includes a brushless DC motor (1), a high

resolution rotary encoder (3), and a hollow motor shaft (2). The backside of the motor shaft is tightly integrated to the encoder to measure the angular position of the motor. The front side of the shaft is attached to the gearbox module's harmonic bearing, and the flex spline is fitted to this bearing. The gearbox module includes a harmonic gearbox (7) and an output shaft (8), which are connected to the flex spline of the harmonic gearbox. After the initial design, the motor frame's (5) and gearbox frame's (6) geometrical structures were modified to achieve a decrease in the total length of the actuator and the number of bolts, see Figure 5.

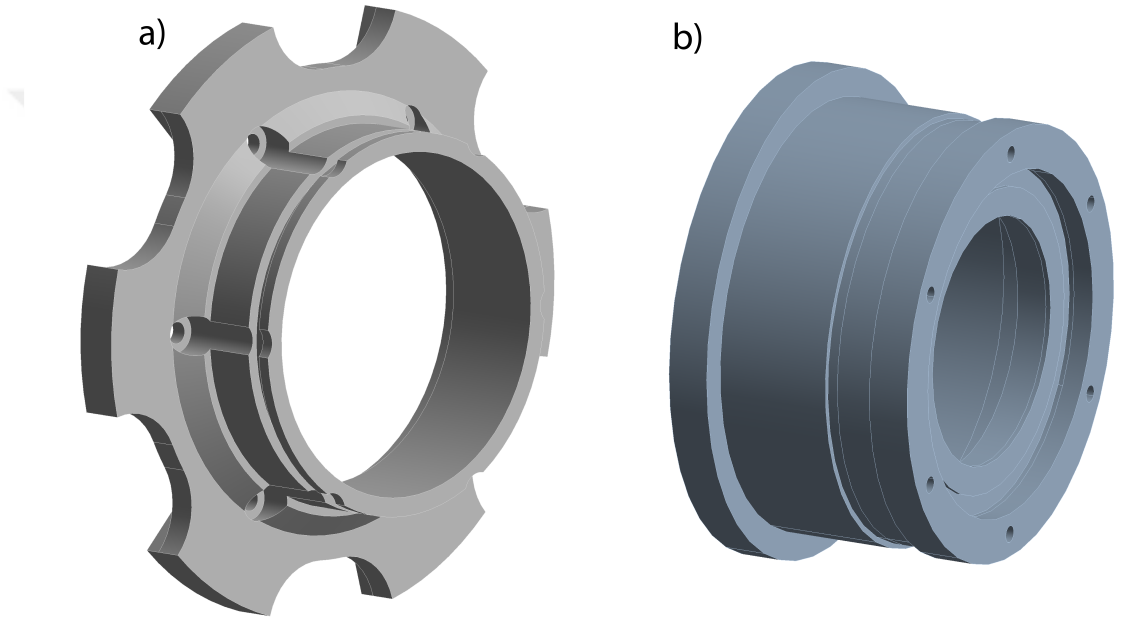


Figure 5: Design changes at the frames a)Motor Frame b)Gearbox Frame

Using Ansys, topology optimization was conducted on these parts (5, 6) to decrease their total weight [57]. The design target of the topology optimization was obtaining the possible lightest geometry for the actuator frames. Due to dynamic forces in the real world that could not be foreseen, the safety factor was decided as 2.3. Therefore, the objective function of the optimization was minimizing the mass with the desired tensile stress constraints. First, the finite element model of the primary actuator frames was constructed with a 1 mm mesh size to ensure two elements at each dimension, and Al-7075 was defined as the base material because of its mechanical properties. Then the geometrical constraints

were determined from the assembly points and bolt connections. Finally, reaction force constraints that were obtained from the dynamic simulation were applied to the FEM model, see Figure 6.

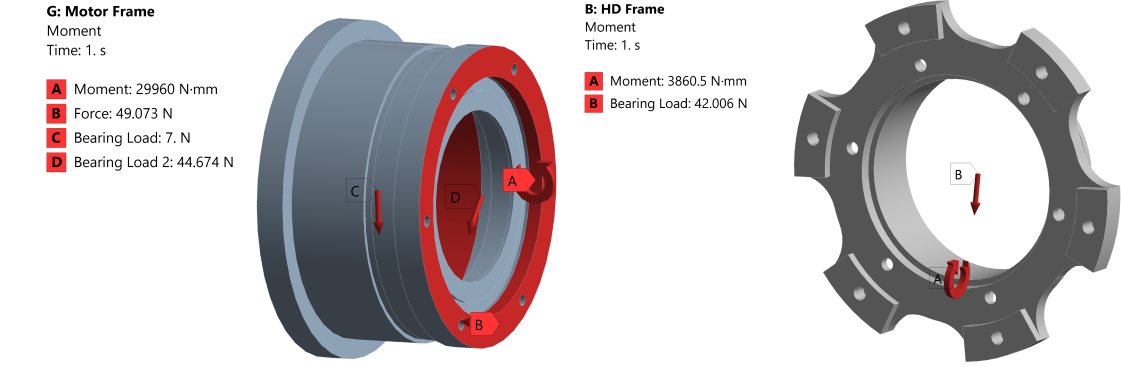


Figure 6: Optimization model of the frames in Ansys environment.

Before conducting the topology optimization, the stress distribution on these parts should be obtained. Therefore, an initial static structural analysis was performed with the given constraints to obtain stress distribution which was presented in Figure 7. As seen in structural analysis results, critical stresses were observed on bolt connection points of the actuator and other fields were safe to be removed. Therefore, the topology optimization was conducted in accordance with the stress distribution.

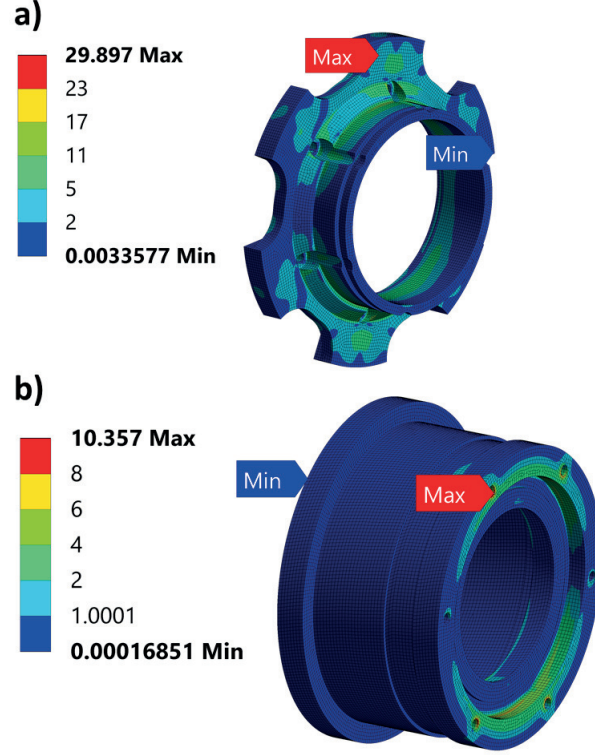


Figure 7: Stress distribution of the frames, a)Gearbox frame b)Motor frame

Solid Isotropic Material with Penalization method [58] was used for this topology optimization. The objective function was constructed around minimization of the mass and also compliance for minimal deflection. Moreover a stress constraint were applied which was 120 MPa regarding the 2.3 safety factor. The objective function converged in 14 iterations for the motor frame and 10 iterations for the gearbox frame to obtain optimal geometry. These optimal geometries were designed again in CAD environment due to manufacturing purposes. These processes is shown in Figure 8.

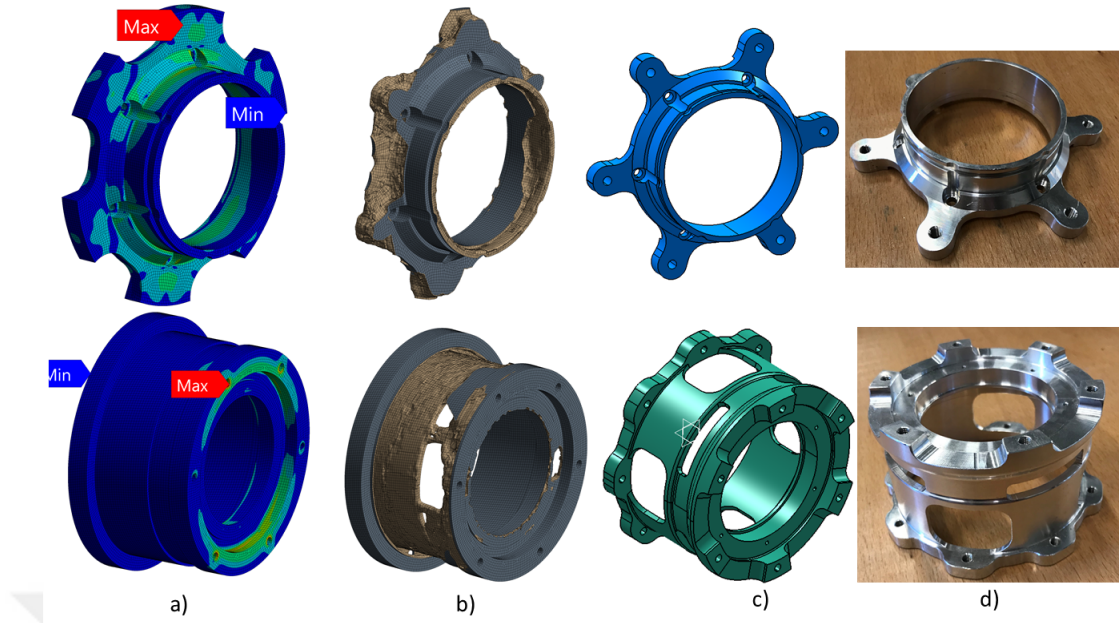
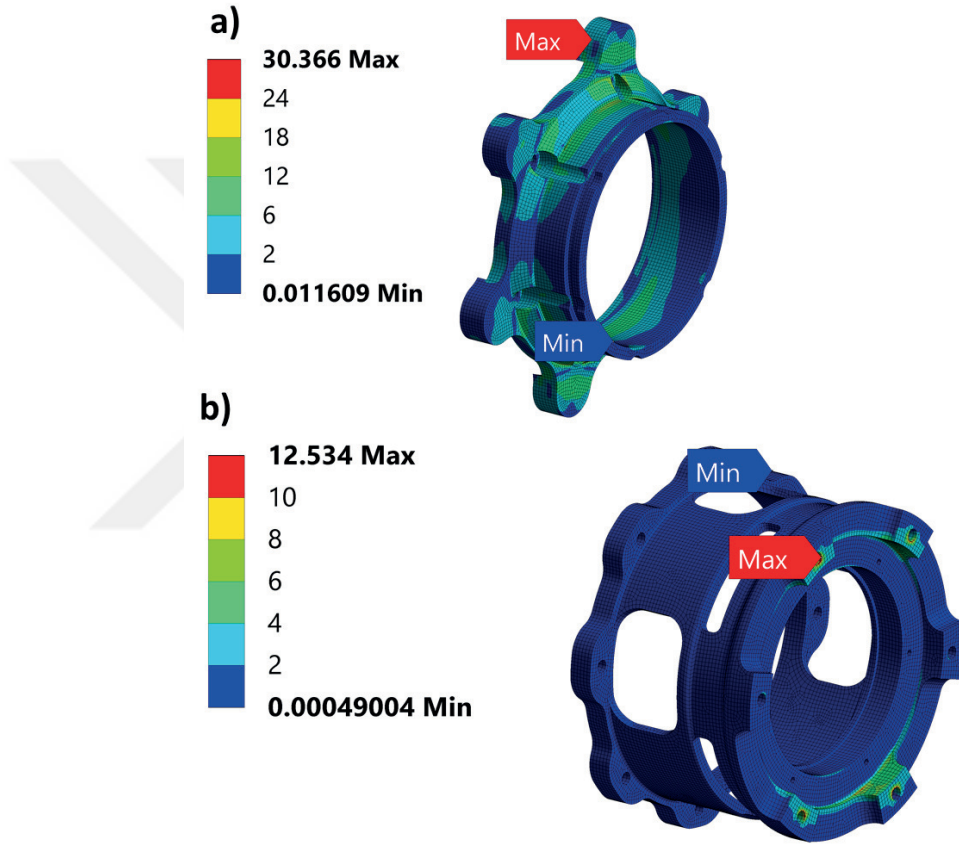


Figure 8: Topology optimization process, a)FEM model of the frames b)Topology optimization results c)New CAD design d)Manufactured frames

Finally, a static structural analysis was conducted on the optimized parts using the same constraints, and as the result, optimized parts did not exceed the safety factor; see Figure 9. The actual unit and its CAD model are depicted in Appendix B. It has a 1.7 kg mass in total. Therefore, 10% mass reduction was achieved for the optimized actuator design. The specifications of this actuator are given in Table 6.

Table 6: Actuator Unit: 1.0 Specifications

<i>Specification</i>	<i>Value</i>
Speed at Rated Power (rpm)	79.16
Max. Continuous Torque (Nm)	48
Peak Torque (Nm)	152
Mass (kg)	1.7
Dimensions (r x L) (mm x mm)	52.5 x 120
Gear Ratio (-)	1:30
Torque-Weight Ratio (Nm/kg)	28.23

**Figure 9:** Stress distribution of the frames, a)Gearbox frame b)Motor frame

2.3 Unit 1.0: Assessment

The actuator unit was experimentally verified with a series of experiments. These experiments were conducted using EPOS Studio software. This software allows online calibration and hall sensor-less commutation. Moreover, current control option is selected, and Figure 10 displays the current control performance.

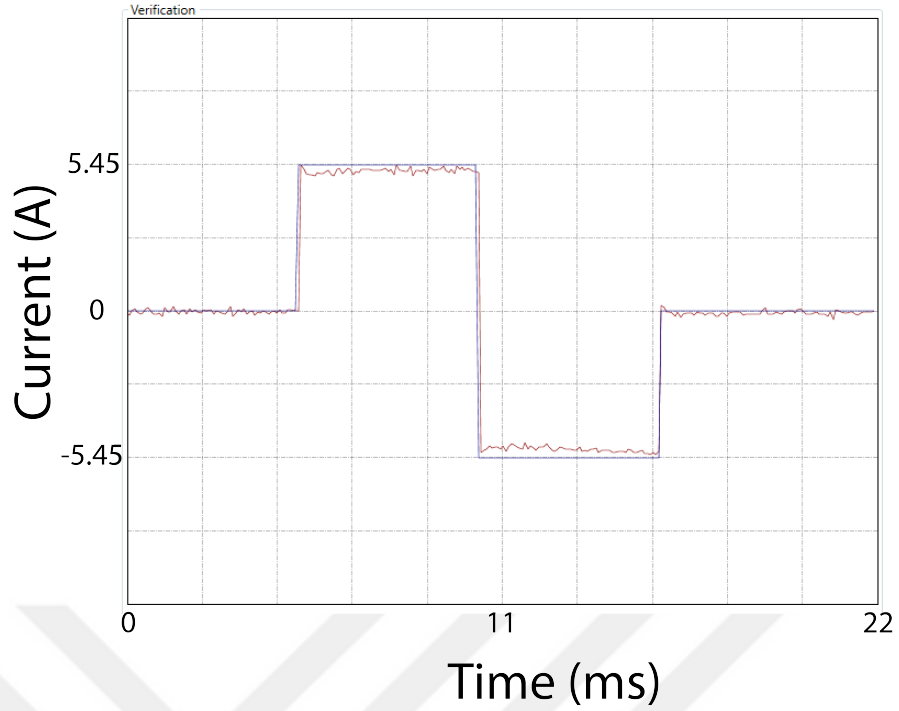


Figure 10: Current tuning data. $P = 5000 \text{ mV/A}$, $I = 5000 \text{ mv/(A*ms)}$

Position control experiment was conducted on the actuator unit to verify its position tracking. A cosine trajectory with a 0.2 Hz frequency and an amplitude of 30° was considered as the input. As the controller, a computed torque control [59] was implemented where the whole body dynamics were considered. In Figure 11, the reference and actual position variations were depicted. Results indicate that the actual position of the actuator can track the reference position well.

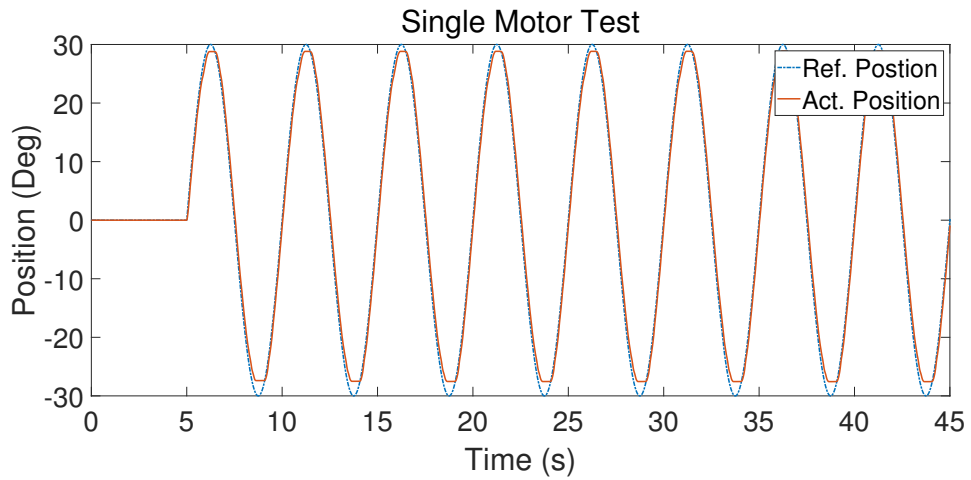


Figure 11: Motor position tracking. Ref: $\pm 30^\circ$ amplitude Frequency: 0.2 Hz.

2.4 Unit 2.0: Mechanical Design

In this section, the design of the composite actuator Unit 2.0 is explained. The composite material is based on a 3-D printed onyx-carbon fiber combination, and its material properties are provided in Appendix A. The architecture of the actuator unit 2.0 is similar to the previous actuator unit, which was explained in Section 2.2. The composite actuator unit is shown in Appendix C.

To increase the mechanical stability of the actuator unit, the motor shaft was extended to the actuator output shaft with the help of an additional secondary shaft. This additional shaft was stabilized with a bearing at the output shaft. Thus, the stiction forces at the actuator were relatively decreased with this improvement.

The steps described in Section 2.2 were followed during the design process. The reaction forces that were required for static structural analysis were obtained from composite robot FEM analysis; see Chapter 4. Afterwards, the same FEM model was created in Ansys software, and the actuator frames' material was selected as the onyx-carbon fiber material. Other parts remained as Al-7075 material to support significant loads. Due to their continuous filament structure, topology optimization is not beneficial with composite materials. Therefore, only static structural analyses were conducted on actuator frames and output shafts. As shown in Figure 12, this analysis is conducted on assembled parts because aluminium supports composite parts in the axial direction. According to the results, the new actuator's weight was decreased to 1.5 kg, and its torque density was increased to 32 Nm/kg; see Table 7. As a result, 0.2 kg mass reduction was achieved at actuator mass, which reflects as a 2,4 kg total mass reduction.

Table 7: Actuator Unit: 2.0 Specifications

<i>Specification</i>	<i>Value</i>
Speed at Rated Power (rpm)	79.16
Max. Continuous Torque (Nm)	48
Peak Torque (Nm)	152
Mass (kg)	1.5
Dimensions (r x L) (mm x mm)	59 x 109
Gear Ratio (-)	1:30
Torque-Weight Ratio (Nm/kg)	32

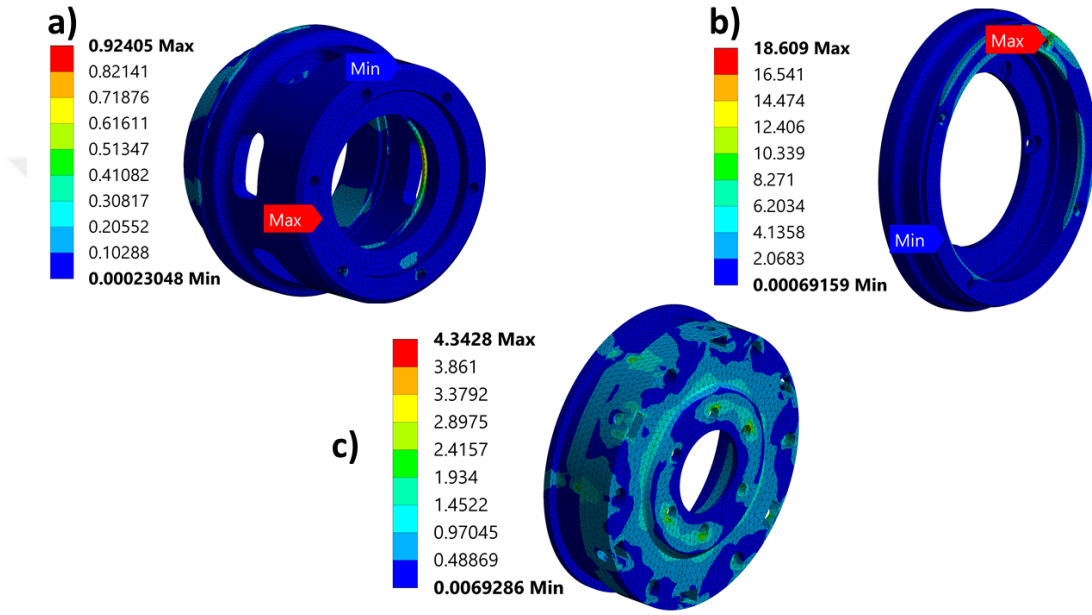


Figure 12: Stress distribution of the parts, a)Motor frame b)Gearbox frame c)Output Shaft

2.5 Unit 2.0: Assessment

The actuator unit 2.0 was experimentally verified using the quadruped robot's single leg. First, a single unit experiment was conducted to test the position tracking of the single joint. The single unit experiment is similar to the actuator unit: 1.0 experiments as explained in Section 2.3. As a result, the actuator could track the reference position, as shown in Figure 13.

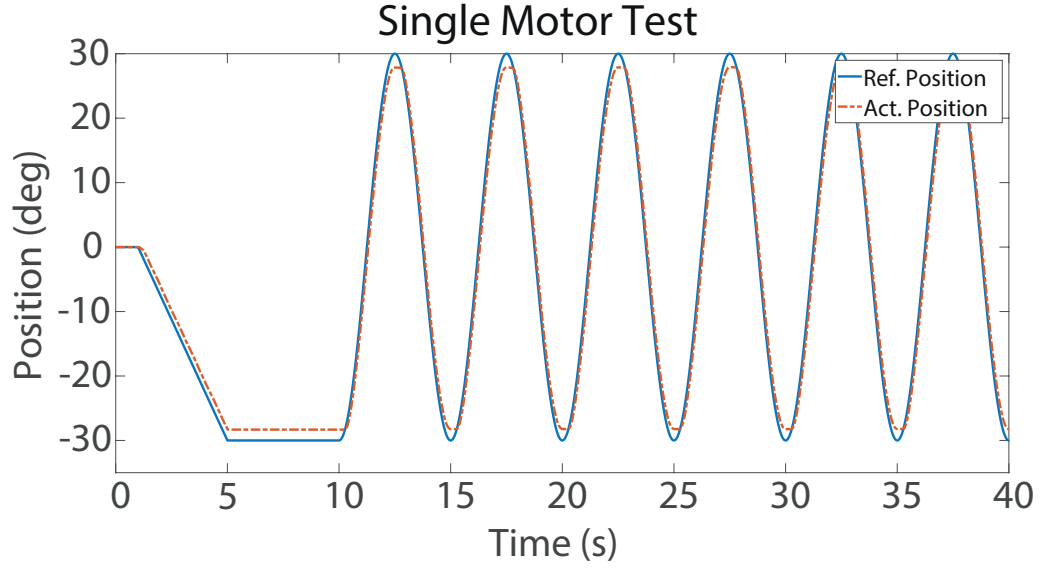


Figure 13: Motor position tracking. Ref: $\mp 30^\circ$ amplitude Frequency: 0.2 Hz.

Then a single leg experiment was conducted to verify the position tracking of the leg in a walking trajectory. The single leg experiment was conducted on the 2 DOF (Hip/FE and Knee/FE) quadruped leg. The trajectory was prepared using the quadruped robot's whole body inverse kinematics [60]. Similar to the previous experiments, a computed torque controller was implemented as well. The results are presented in Figure 14. According to these results, actuators can follow the desired trajectory with a RMS error of 4° . In the light of these results, we argue that a composite material-based actuator unit can work effectively on a quadruped robot.

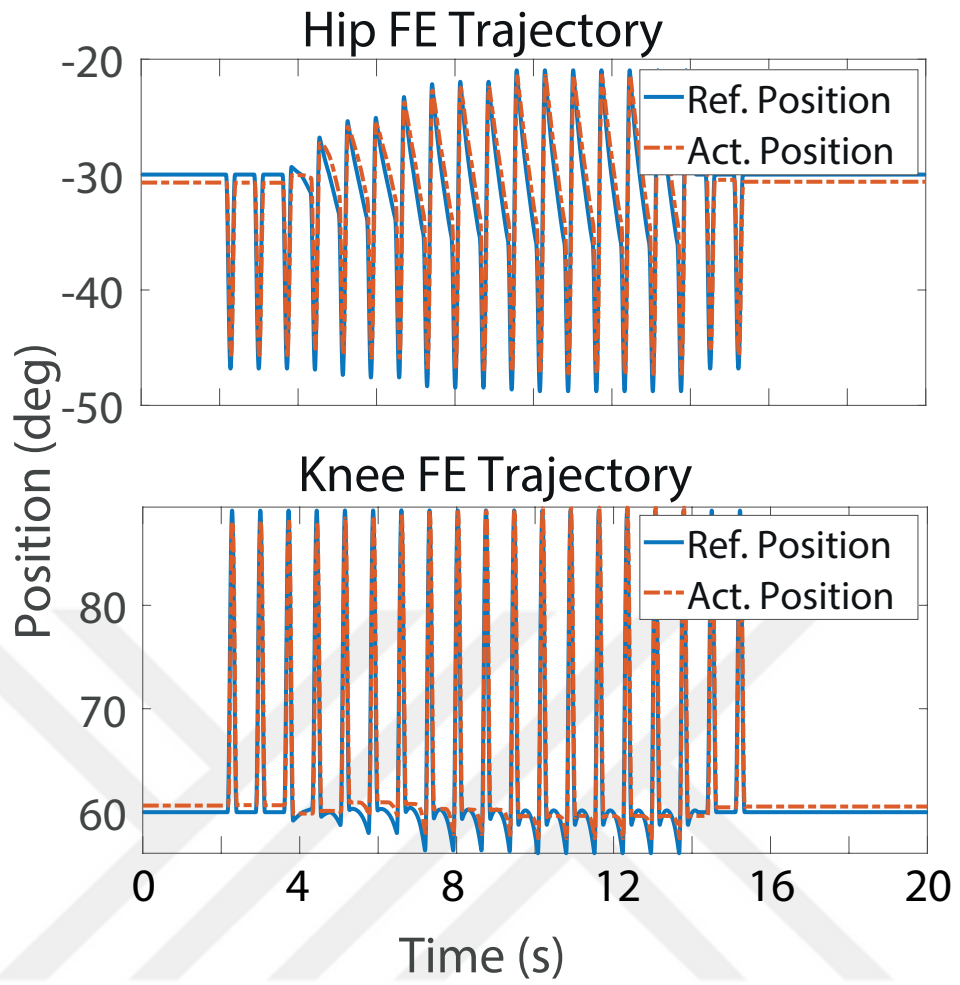


Figure 14: Leg trajectory tracking on joints.

CHAPTER III

QUADRUPED ROBOT HARDWARE DESIGN

In this chapter, design methodology will be explained. First, 3-D dynamic robot simulations and leg structure will be shown in Section 3.1. After that the torso design of the robot will be explained in Section 3.2 and the electronic structure will given in Section 3.3. Finally, leg experiments and the first robot prototype experiments will be explained in Sections 3.4 and 3.5.

3.1 Leg Design

To achieve feasible walking performance in 3-D, a quadruped robot requires 3 DOF (Hip A/A, Hip F/E, Knee F/E) for each leg. Furthermore, all actuators are should be deployed around torso to reduce leg inertia. With this design strategy COM of the robot will remain in the torso. To achieve this goal, a mechanism is required for actuating the knee joint.

Design of the leg structure was initiated with deciding the right mechanism for the knee joint. As mentioned in Chapter 1, four-bar mechanism was the most feasible solution for this case. To verify this information, a dynamic simulation was conducted on ADAMS software and 3 different solution were compared in terms of torque output and range of motion. This mechanisms were listed as: i) Actuators were implemented directly on joints, ii) All actuators are implemented around torso with 2double four-bar mechanism, iii) All actuators are implemented around torso with single four-bar mechanism. These structures are shown in Figure 15.

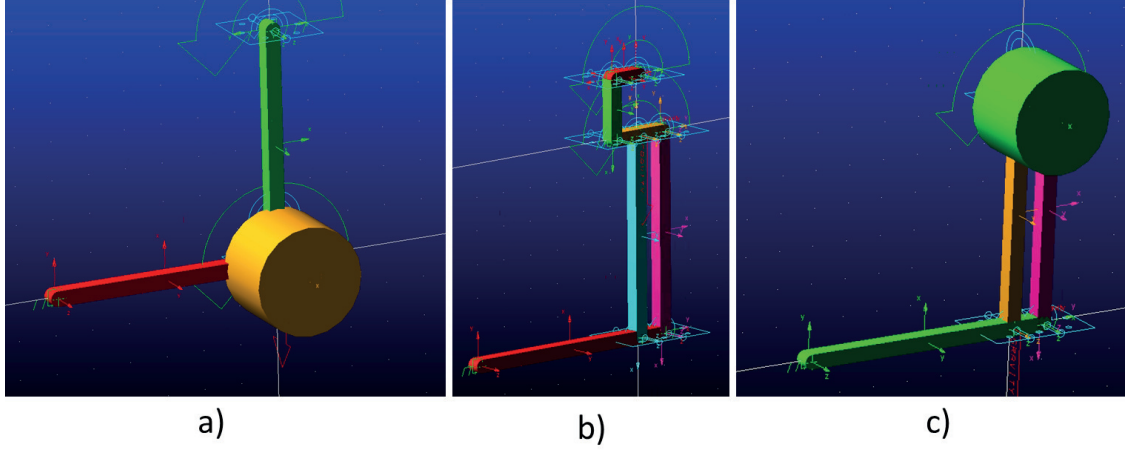


Figure 15: Leg mechanism solutions a)Direct-drive b)Double four-bar mechanism c)Single four-bar mechanism.

In this simulation, same Cartesian trajectories were given to the system and joint torque outputs were compared. As seen in Figure 16, scenario-(a) had more torque output than other solutions but there were not any difference between scenario-(b) and (c). Thus, position difference between Hip F/E actuator and joint were compared in scenario-b to decide which mechanism was efficient.

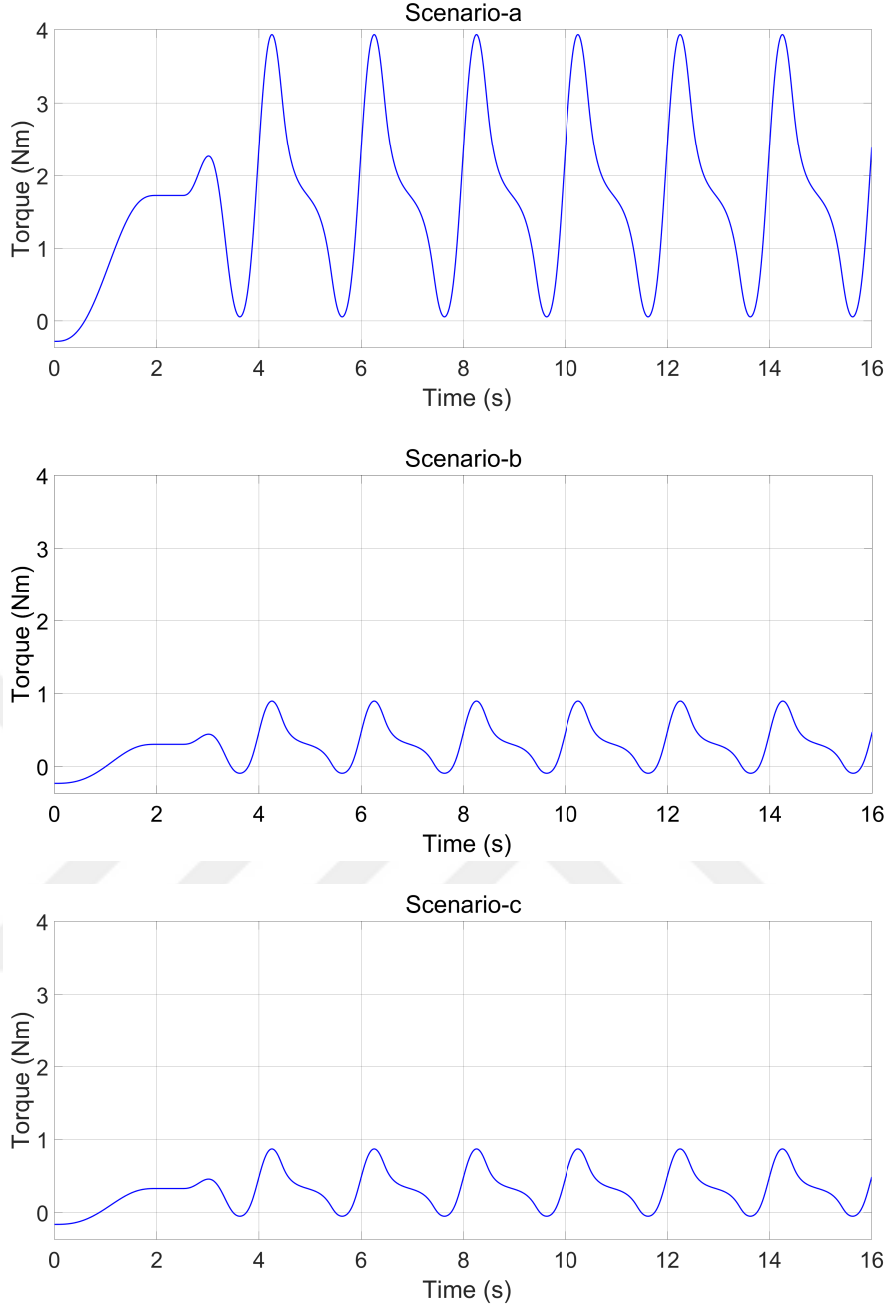


Figure 16: Torque outputs at Hip F/E actuators for all scenarios.

As seen in Figure 17, there were 1 rad position difference between the knee actuator and the knee joint due to the coupling between Hip F/E actuator and Knee F/E actuator. This position difference restricted the range of motion of the knee joint. In the light of these simulations, one four-bar mechanism was chosen for knee joint because of its efficiency in terms of torque generation and range of motion.

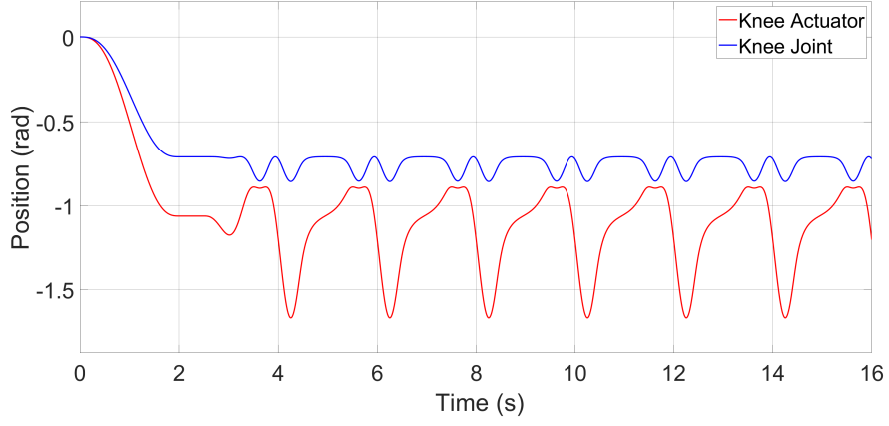


Figure 17: Hip actuator and hip joint positions, scenario-(b). Due to coupling, there is a significant position difference

After these simulations, first robot structure was designed with basic geometries and integrated to Ansys environment for further analysis. First, reaction forces at the joints were obtained by using static structural analysis. FEM model of the entire robot was constructed with 326604 nodes and 81779 elements. Then, revolute joints were implemented on all joints; see Figure 18.

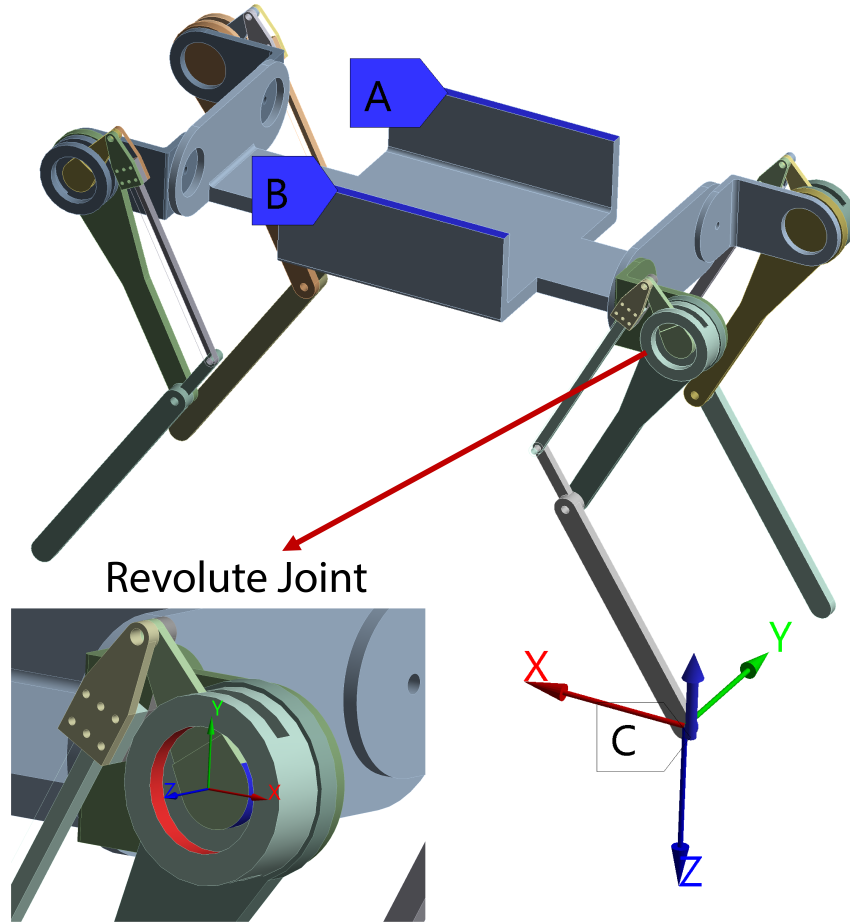


Figure 18: Static structural analysis model.

Joint trajectories (See Figure 19) were applied on revolute joints of the robot. The robot was constrained from A and B sections of the torso. Ground reaction forces (See Figure 20) were applied on C section of the shank. Walking trajectory was a cycloid motion in time period so that 1.5s simulation time was sufficient for further analysis. As a result, all reaction forces at each joints were obtained and they are applied on topology optimization.

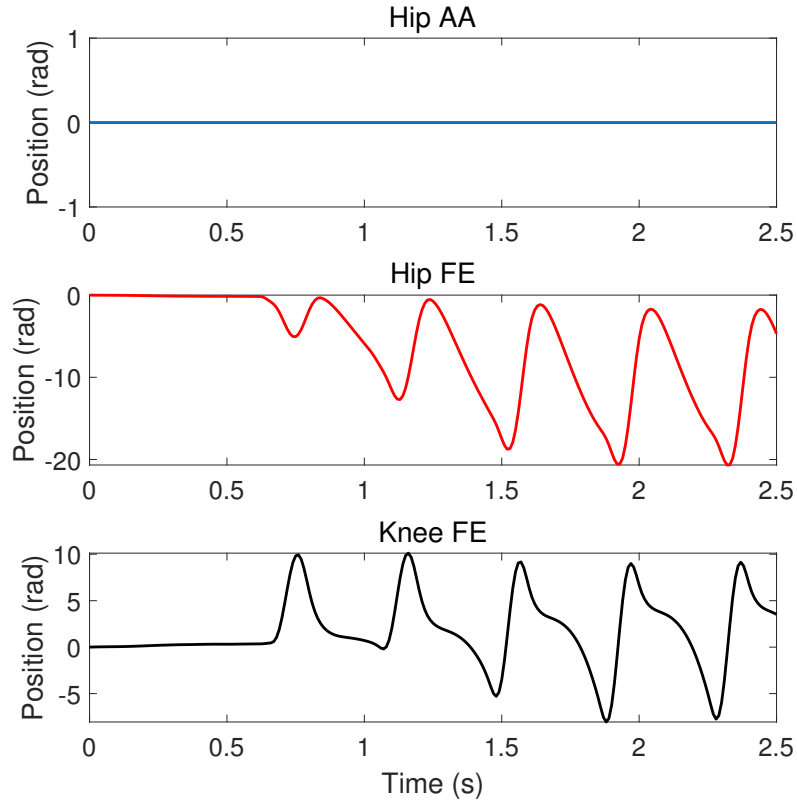


Figure 19: Joint trajectories during the optimization.

The topology optimization steps were explained in Chapter 2. The initial leg parts was designed and stress distribution was mapped. Then the topology optimization was conducted on these parts under 300 MPa constraint to minimize the total weight. In this section, only the thigh's optimization results and post static analysis results were shown; see Figures 21 and 22. The other components' topology optimization results were listed in Table 8. According to results, 310 g weight reduction (20%) was done on each leg which led to a total of 1.24 kg weight reduction on the robot.

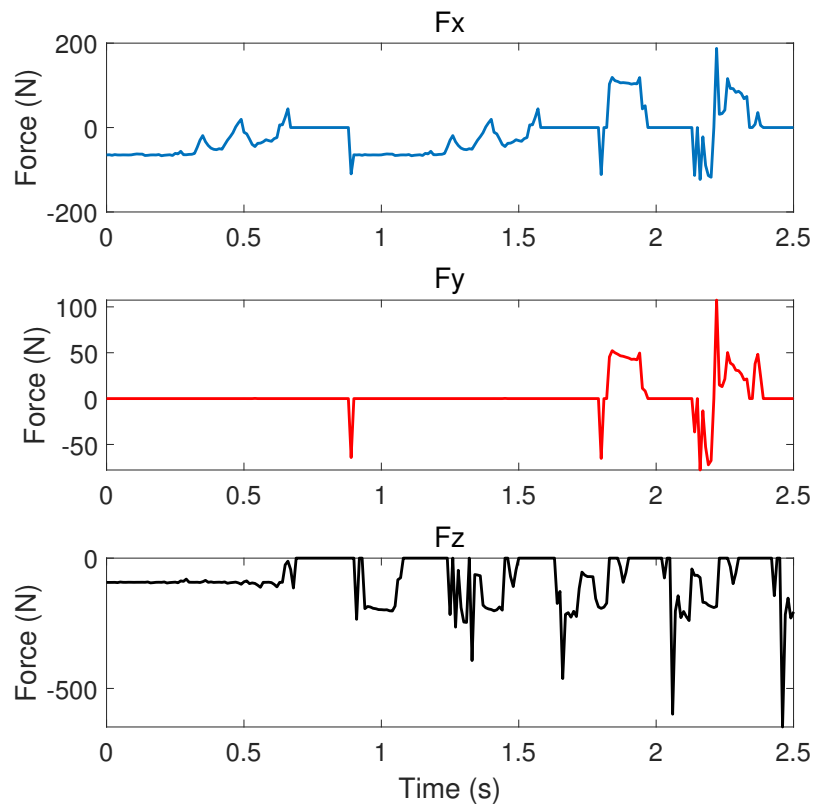


Figure 20: Ground reaction forces on foot

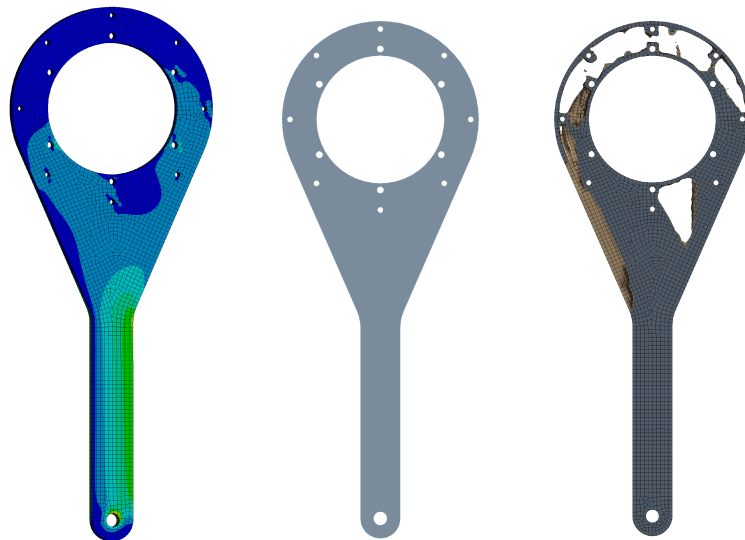
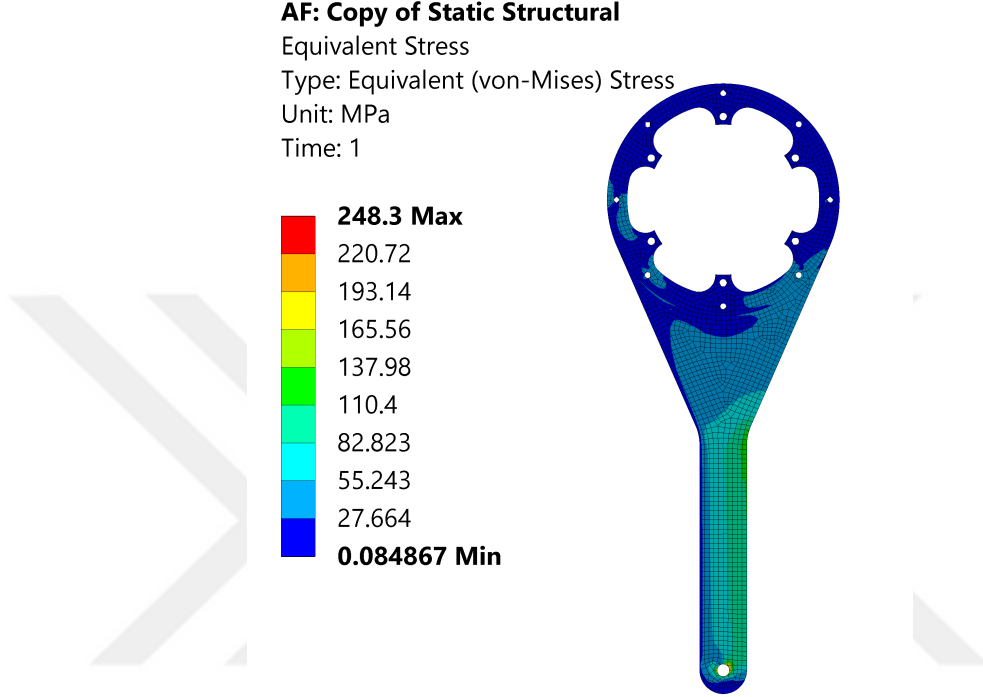


Figure 21: Topology optimization results of thigh.

Table 8: Topology optimization results

Part Name		Von Mises Stress (MPa)	Weight (gr)	Net Weight Difference (g)
Thigh	:	248	430	220
Four-bar	:	65	90	10
Knee	:	23	280	70
Hip	:	210	25	10

**Figure 22:** Static structural analysis results on optimized thigh.

Finally the foot was manufactured with 3-D printer and TPU-95A [61] material was used due to its elastomer structure. For creating a damping effect, gyroid infill was used at the inner structure of the foot. Final design of the leg is shown in Appendix D and it has 1.3 kg total mass.

3.2 Torso Design

The torso of the quadruped robot carries the electrical components and Hip A/A actuators. Because of these components, most of the weight will be accumulated in this structure. Therefore, the design of the torso should be as light as possible to avoid extra weights on robot. To achieve this goal, carbon fiber tubes (see Appendix A) were used on the skeletal structure of the torso.

Front and back walls of the torso are designed using Al-7075 material. Finally, electrical components were implemented in an ABS electrical box. CAD model of the torso (see Appendix E) were integrated in Ansys environment. Then, modal analysis and static structural analysis were conducted on the torso.

In Ansys, torso walls were modelled with 6 DOF shell elements. Carbon fiber tubes were modelled in ACP Pre Post module and each tube had 10 composite layer with 0.2 mm thickness. In modal analysis, it was examined whether the operating frequency coincided with the natural frequency of the body. Moreover, the critical frequency was chosen as 10 Hz or less which is the 1 m/s trot walking trajectory period.

W: Modal

Fixed Support 2

Frequency: N/A

- A** Fixed Support
- B** Fixed Support 2

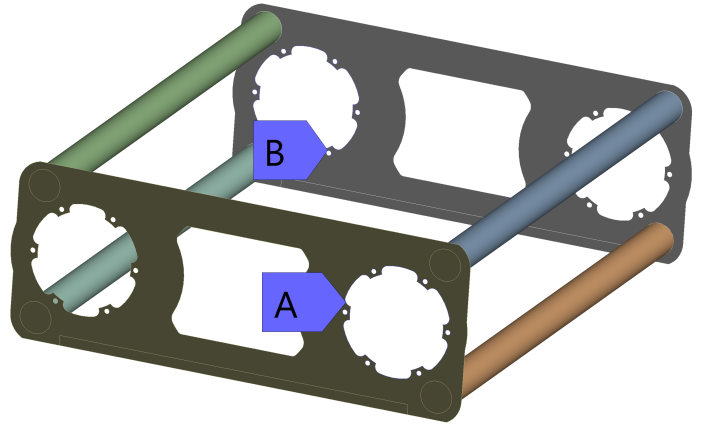


Figure 23: Modal analysis model of the torso.

As seen in Figure 23, modal analysis simulation model was built for the most critical condition during the trot walking. This critical condition was occurred while the quadruped robot's 2 two diagonal feet were on the ground. To simulate this, the torso was constrained from two diagonal Hip A/A joints.

According to modal analysis results, torso has 22.2 Hz natural frequency in Z direction and it can be examined statically rather than using a dynamic analysis.

As a next step, further static structural analyses were conducted on the torso. The analysis model was shown in Figure 24. To simulate floating base effect, the torso was constrained from A (3 directions), B (Y and Z direction) and C (Z direction) nodes. Reaction forces were applied on all Hip A/A joints and electrical components were implemented as a 11.1 kg mass.

U: Static Structural

Displacement 3

Time: 1. s

- A** Displacement
- B** Displacement 2
- C** Displacement 3

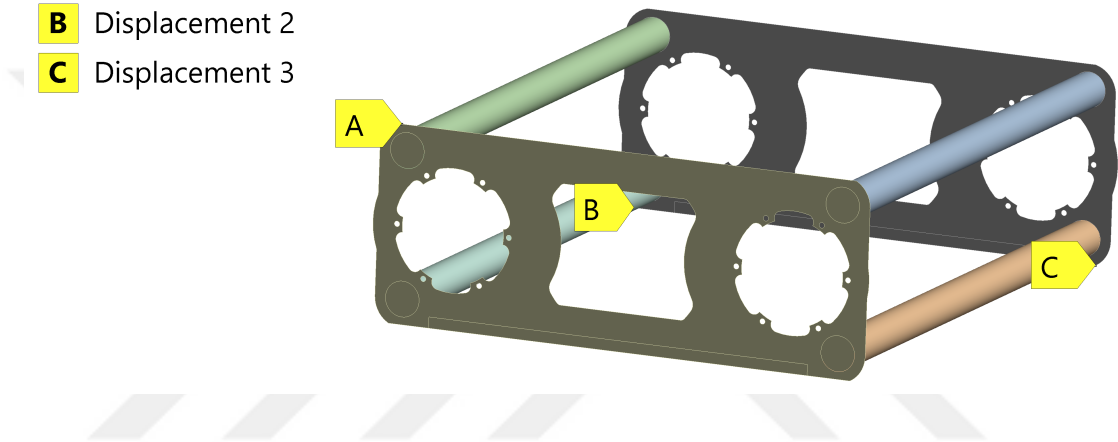


Figure 24: Static structural model of the torso.

Results indicated that Von-Mises stress values were below the yield stresses for isotropic materials as seen in Figure 25. Carbon fiber tubes were interpreted according to Tsai-Wu, maximum stress, maximum deflection and Puck error criteria. As the results we found that, these tubes do not fail under these conditions as the maximum damage criteria was 0.17. Thus, the CAD model of the torso was verified in terms of durability.

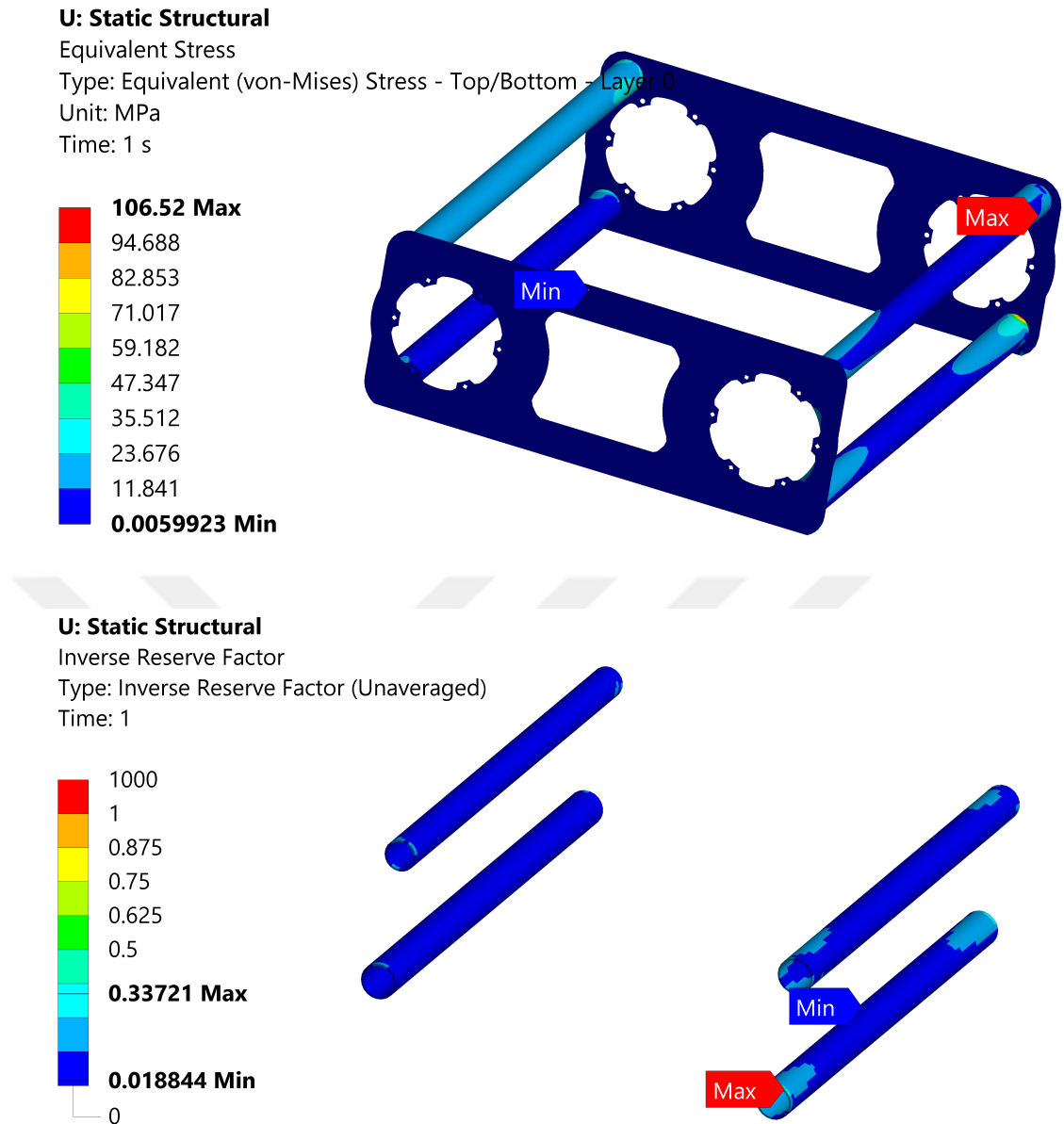


Figure 25: Modal analysis model of the torso.

3.3 *Electronics Design*

The electronic components of the robot were decided by taking into consideration the energy need and control systems of the robot. The overall electronic diagram was shown in Figure 26.

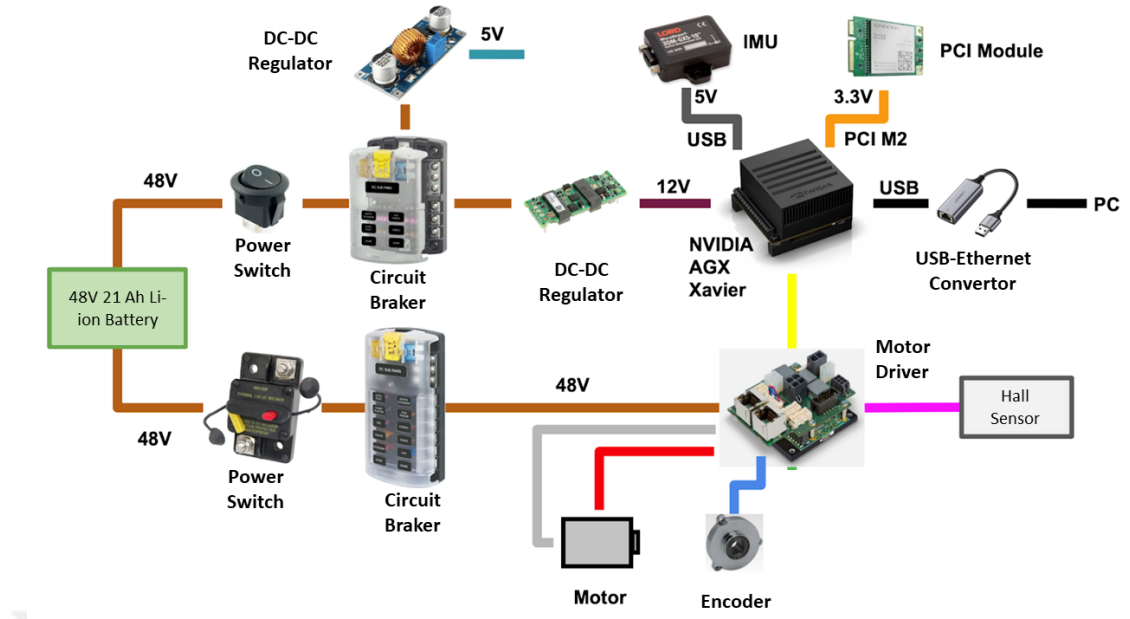


Figure 26: Electronic diagram of the quadruped robot.

NVIDIA Jetson AGX Xavier is chosen as the main controller of the robot, and it is responsible for executing control algorithms. The whole data communication is achieved using EtherCat in which Jetson Agx Xavier is the master and motor controllers are slaves. In this system, high-resolution absolute rotary encoders are used for the position sensing for the joints. Actual view of the electrical system is shown in Figure 27.

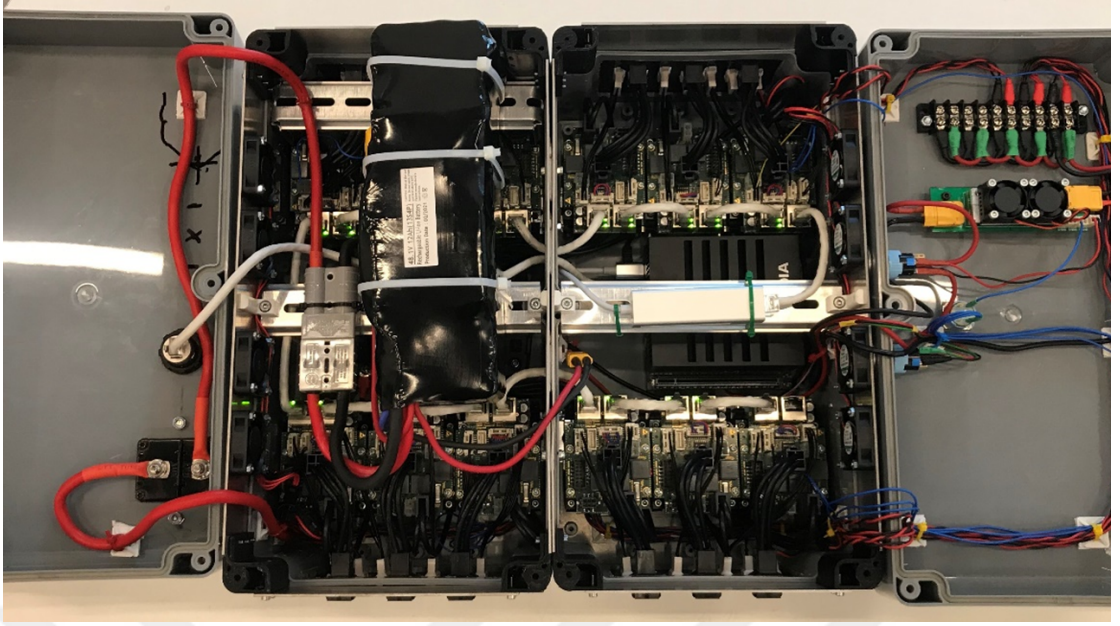


Figure 27: Electronic box of the robot.

3.4 Leg Prototype: Assessment

To verify the design of the leg prototype, two experiments were conducted on the robot leg. In the first experiment, walking trajectory was given to the leg to verify its mechanical structure. In the second experiment, the leg was placed on the ground to observe active compliance control. A test platform was prepared for these experiments as seen in Figure 28. The leg can have moved only on z-axis with the help of sigma profile guide.

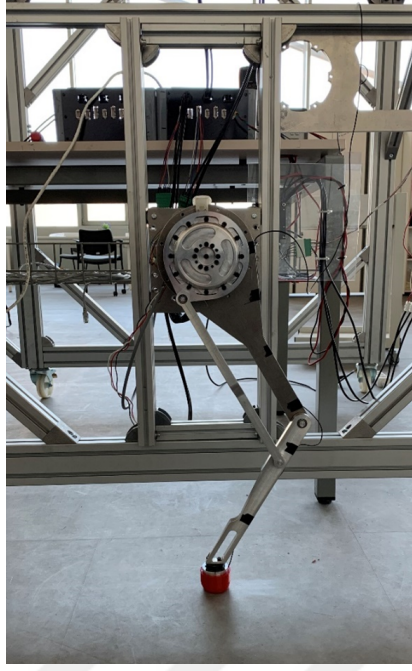


Figure 28: Experiment setup for the robot leg.

First, walking algorithms were tested on the leg while it was being lifted. Then, the the Hip F/E and Knee F/E links of the leg were installed to the test platform. Walking trajectories were applied to the leg and trajectory tracking of the joints were observed. During this experiment, a PD+DOB controller were implemented to the system [62].

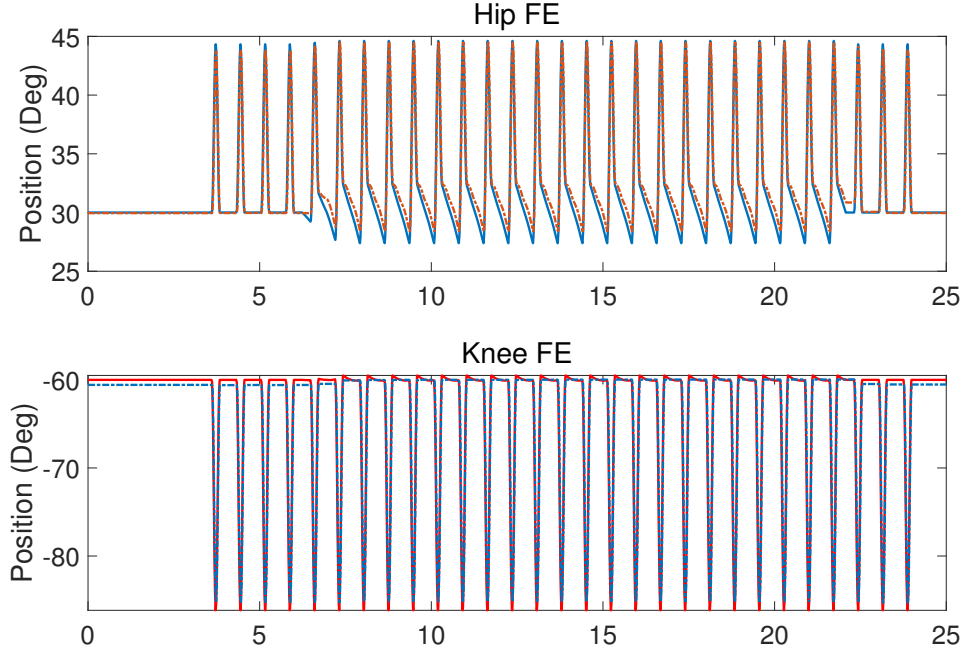


Figure 29: Trajectory tracking of the joints during the leg experiment.

As shown in Figure 29 the maximum errors were 0.52° error at the knee joint, and 1.26° error at the hip joint. Based on this result, we could verify the functionality of the four-bar mechanism.

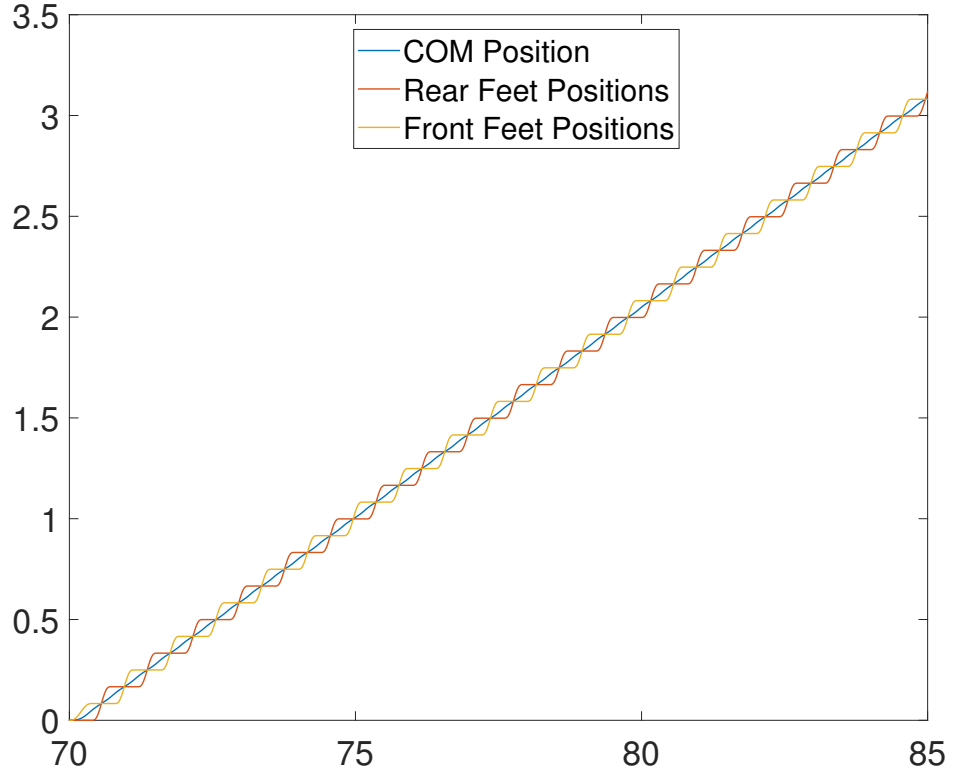
The second experiment was conducted on the ground and the leg can only move along z-axis via sigma-profile guides. At the beginning, the foot's reference trajectory was given as constant value while the leg was on the air. After that, the leg was positioned on z-axis as touching to the ground. In the 4th second, the foot was touching to the ground and leg's COM went from 0.555 m to 0.506 m due to its weight. After that, external forces were applied to the leg. As a result, it could recover its COM position, thanks to the active compliance controller.

3.5 *First Prototype: Results*

After leg assessment, all legs were assembled with the base and electronic parts were connected. Thus, the building of the first prototype was completed and it was shown in Appendix F. The specifications were given in Table 9.

Table 9: Specifications of the quadruped robot

Specification	Value
Mass (kg)	41.5
Degrees of Freedom	12
Length (m)	0.96
Width (m)	0.55
Height (m)	0.74
Max. Speed (m/s)	0.6
Max. Battery Voltage (V)	52
Payload (kg)	4

**Figure 30:** Quadruped robot's COM position according to world frame.

Then, trot walking experiment was conducted on the robot. In this experiment a ZMP based COM trajectory was given to the robot; see Figure 30 [19]. Then

the joint positions of the robot was observed and results were shown in Figure 31. According to experimental results, robot could track the given trajectories and the first prototype could walk.

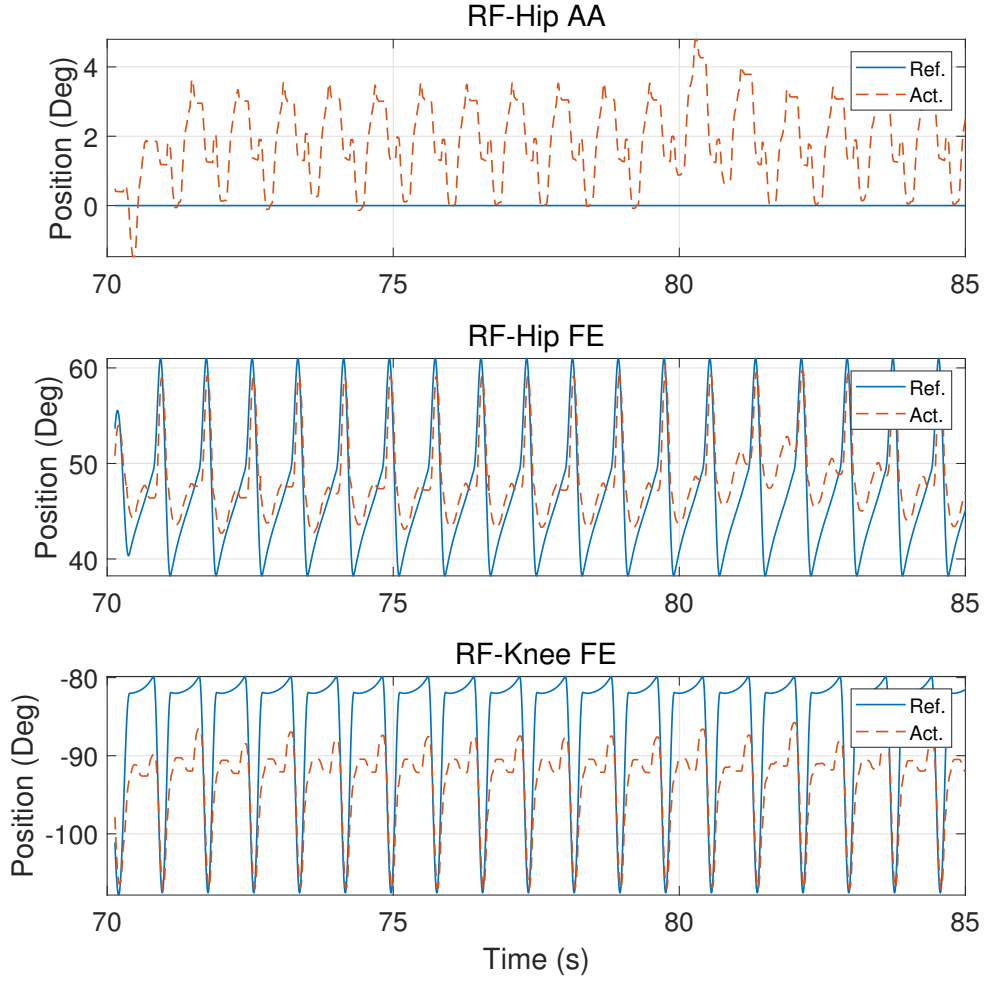


Figure 31: Quadruped joint trajectory tracking of the robot at 0.2 m/s. Results were shown for Right-Front Leg.

In conclusion, the first prototype was experimentally verified. The trajectory and controller algorithms were also verified on this robot. This robot will be used as the baseline for our second prototype.

CHAPTER IV

QUADRUPED DESIGN WITH ADDITIVE MANUFACTURING

In this chapter the second quadruped robot prototype is explained. Development procedures for the additive manufacturing techniques were used for developing the second prototype.

In Section 4.1, material analysis is explained concerning carbon fiber-onyx 3-D material. Leg and torso designs are shown in Sections 4.2 and 4.3. Finally, the second prototype and its assessment is represented in Section 4.4.

4.1 Tension Tests of the Material

In this section, material analysis of the carbon fiber-onyx 3-D material will be explained. This filament is used in industrial carbon fiber 3-D printer. During the printing process, it prints onyx as the main and infill material. Carbon fiber is used as printing composite layers for supporting the part. Note that, their material data are given separately [63], but these data can not be used in FEM analysis due to its layered structure.

To obtain more accurate material data, material test were conducted on carbon fiber-onyx 3-D material in Sabancı University. Three specific test specimen [64] were designed which were used in Tensile Test, Compression Test and Shear Test. Each specimen had onyx and composite layers with same directions.

$$Young's\ Modulus = \frac{\sigma}{\epsilon} \tag{4}$$

$$Shear\ Modulus = \frac{\tau}{\gamma}$$

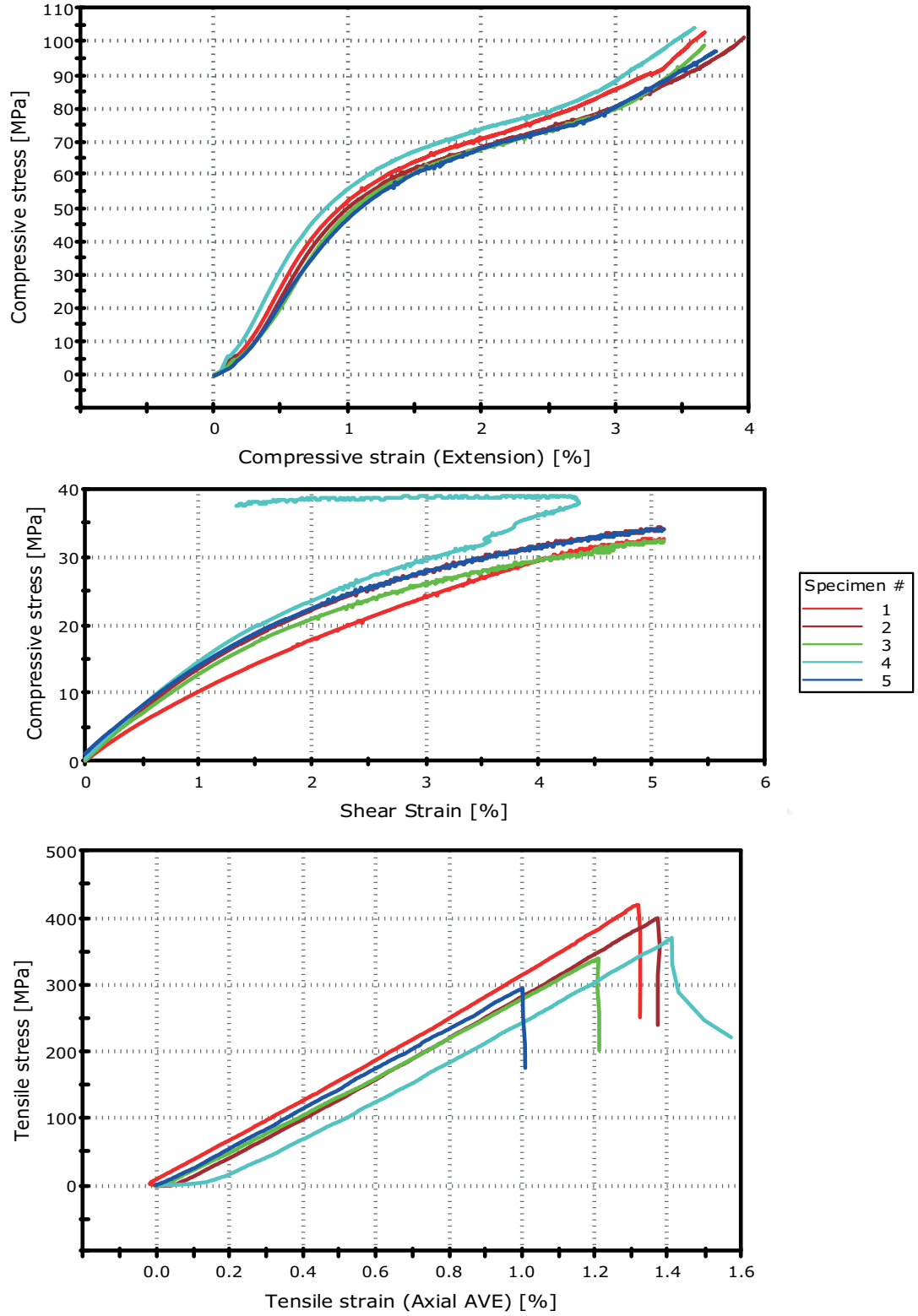


Figure 32: Material test results.

The test results are shown in Figure 32. Using these results material properties were calculated by using Eq. 4. In this equation, σ indicates tensile stress, ϵ shows

tensile strain, τ means shear stress, and γ indicates shear strain. Since the load direction is on the compression direction on the robot, compression test results were taken as tensile stress and tensile strain for calculating the Young's Modulus. The material properties are shown in Appendix A. This material was integrated as homogenous material to Ansys for further analysis.

4.2 Leg Design

4.2.1 Limb Design

The new prototype's initial leg architecture was designed by using the first prototype's FEM analysis results in Chapter 3. Following that, the CAD model was integrated in Ansys environment and FEM analysis model was established. The robot model was shown in Figure 33.

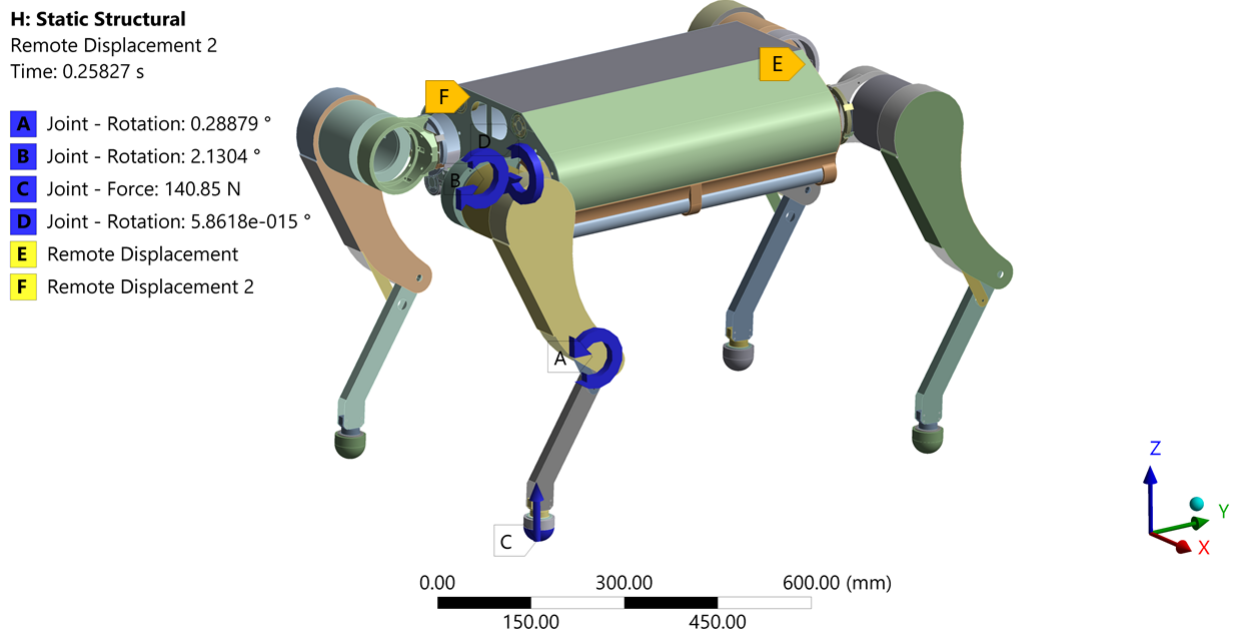


Figure 33: Static structural analysis model of the second prototype.

The joint reaction forces and joint trajectories (See Chapter 3) were used in the the simulation. The robot was constrained from points E and F in 6 DOF. Carbon fiber-onyx material was implemented to composite parts and Al-7075 material was chosen for critical parts. Due to bending moments on the fourbar linkage, it was

decided as the critical part of the robot before the analysis. Considering results in Figure 34, the maximum stress (470.95 MPa) was on hip A/A part of the leg and it exceeds the material's compressive yield stress (100 MPa). Thus, the Al-7075 material was chosen for this part and it was redesigned as the first prototype's hip geometry.

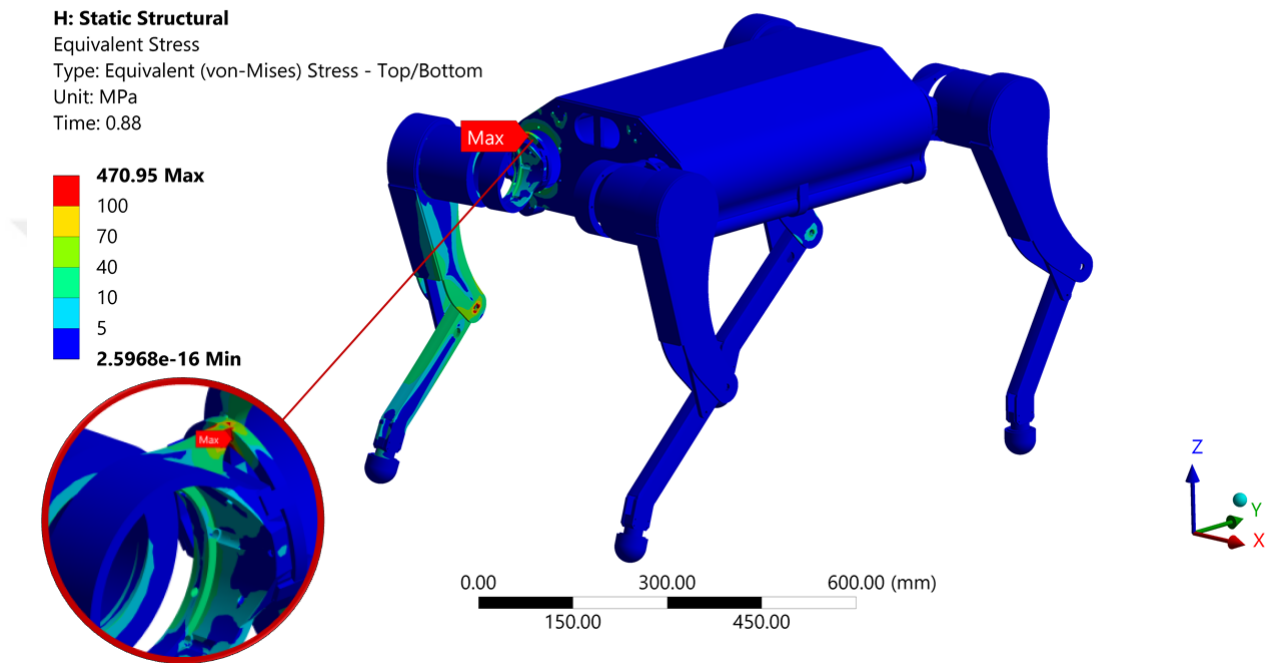


Figure 34: Static structural analysis results and critical area.

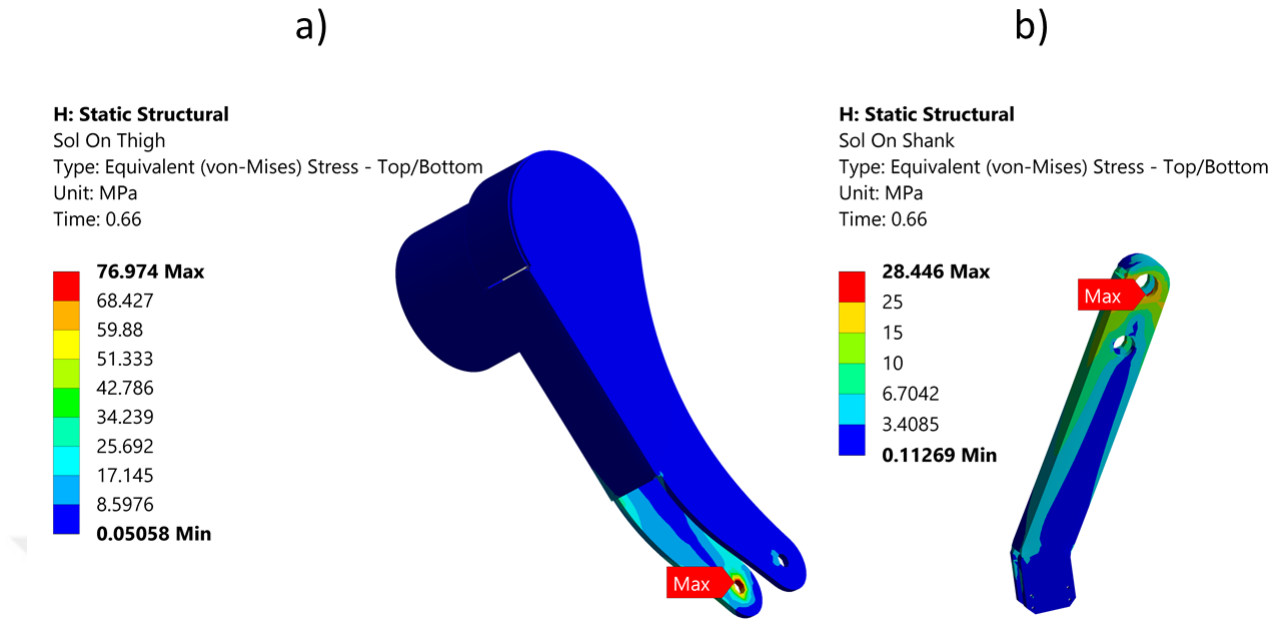


Figure 35: Stress distribution on leg. a)Thigh b)Shank

Furthermore, thigh and shank parts of the leg was evaluated from the results. The maximum stress values are shown in Figure 35. The results indicated that the thigh had 77 MPa and shank had 28.5 MPa maximum stresses which were below the yield compressive stress of the material. Moreover, these stress values were observed at the knee joint of the leg. Since all shafts were Al-7075 material, no major deformation was expected around that area.

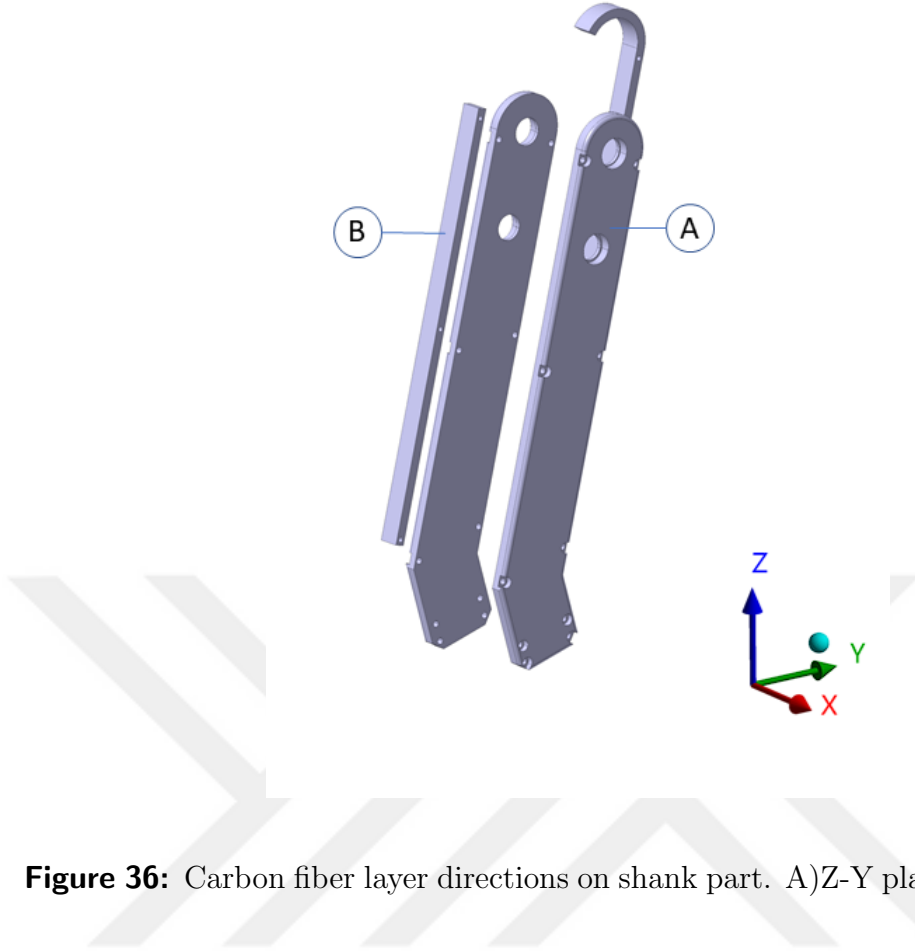


Figure 36: Carbon fiber layer directions on shank part. A)Z-Y plane B)Z-X plane

Using 3-D printer the parts could be manufactured layer by layer. Thus, this manufacturing technique had only allowed to print material in two axis. Since the carbon fiber had resistance only along two axes, all limbs were designed through the combination of 4 sub-parts. Each part had carbon fiber layers in different direction and an example is shown in Figure 36. In doing so, limbs had resistance in three axes. Final leg structure is shown in Appendix G. The fourbar linkage mechanism were implemented in the thigh. As a result, the whole leg weighs 0.85 kg which is 0.48 kg lighter than the first leg prototype, so 36.1% mass reduction is achieved in total for four legs.

4.2.2 Foot Design

An elastic foot was designed and manufactured by using additive manufacturing techniques. As mentioned in Section 4.1, FEM analysis for this method required different approaches in accordance with the material structure. TPU-95A material

was selected for manufacturing with 15% gyroid infill. For this reason, mechanical properties are required to be obtained with experiments.

The foot was manufactured with Ultimaker 3-D printer and had a 15% gyroid infill. Due to its mechanical structure, a gyroid infill was decided to be used in the inner structure. To this end, an impact test was conducted to obtain the damping ratio of the foot. During the impact test, a modal hammer and an accelerometer were used to produce excitation and measure the response. Figure 37 shows the impact test scheme [1].

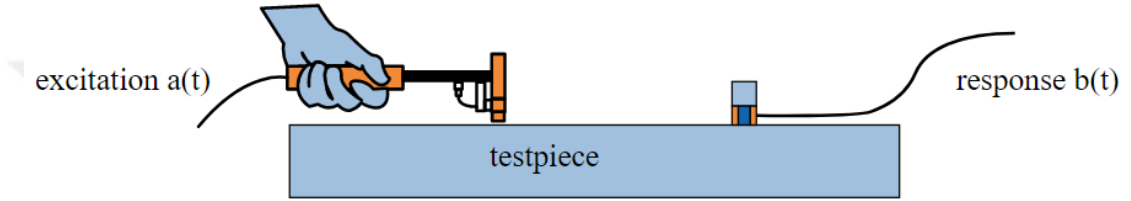


Figure 37: Impact test diagram.

The real experimental setup is shown in Figure 38. It was conducted by using the DEWEsoft Data Acquisition System. The accelerometer was tightly deployed onto a flat plane of the test specimen. Then, it was hit from 3 different nodes with the modal impact hammer. Every point was hit 15 times to obtain a relatively more precise result. The damping ratio was obtained as 0.1 at 62.5 Hz.



Figure 38: Impact test diagram [1].

The CAD model of the foot was built with two separate parts. Due to the mechanical property differences of TPU-95A filament and its gyroid infill structure, the foot was divided into two separate parts as seen in Figure 39.

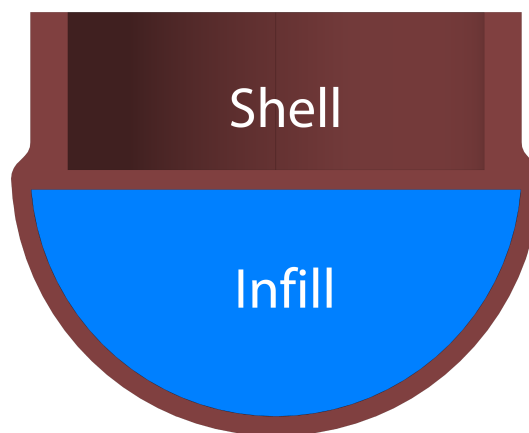


Figure 39: 2D CAD model of the foot. Shell part has 2 mm thickness. Infill part has 25 mm radius with 15% gyroid infill.

Table 10: Homogenization results for TPU-95A gyroid infill.

Specification	<i>TPU 95A</i>	<i>Gyroid</i>
Density (kg /m ³)	1200	181.5
Elastic Modulus (MPa)	67	21

As next step the material properties of the TPU-95A and gyroid infill were implemented. TPU-95A data was taken from the manufacturer's material data sheet. The homogenization method was used to simulate the structure of the gyroid infill. Elastic modulus and density of the structure was calculated using Eqs. 5, 6, 7 [65].

$$p = infill\ ratio * p_{(TPU-95A)} \quad (5)$$

The infill ratio was decided as 0.15. p indicates the material density of the gyroid infill. Since the infill of the foot was constructed with TPU-95A, then its actual density $p_{(TPU-95A)}$ was used for calculating the p -value.

$$f = 0.72 * infill\ ratio^{1.65} \quad (6)$$

$$E = E_{(TPU-95A)} * f \quad (7)$$

Since the infill ratio was 0.15, Eq. 6 was used for calculating the f value, indicating the elastic modulus ratio. Then the gyroid infill structure's elastic modulus (E) was calculated with Eq. 7. Density and elastic modulus values were shown in Table 10.

Following that, the ANSYS model of the foot was built with three main steps. First, a modal analysis was conducted on foot. The step deflection at the top of the foot was seen at 16th mode of the results as seen in Figure 40. Examining the results, it had a 1382.5 Hz natural frequency, and the subsequent analysis was built considering this mode.

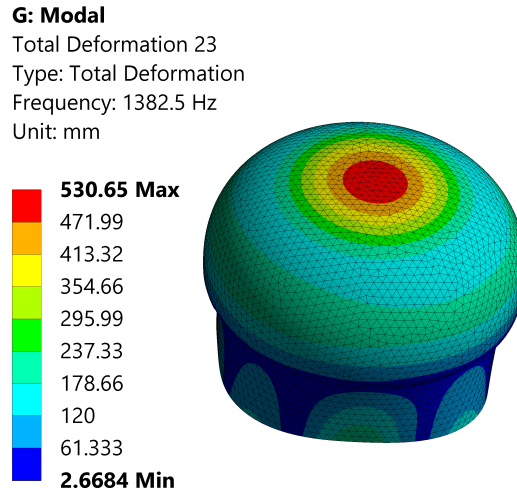
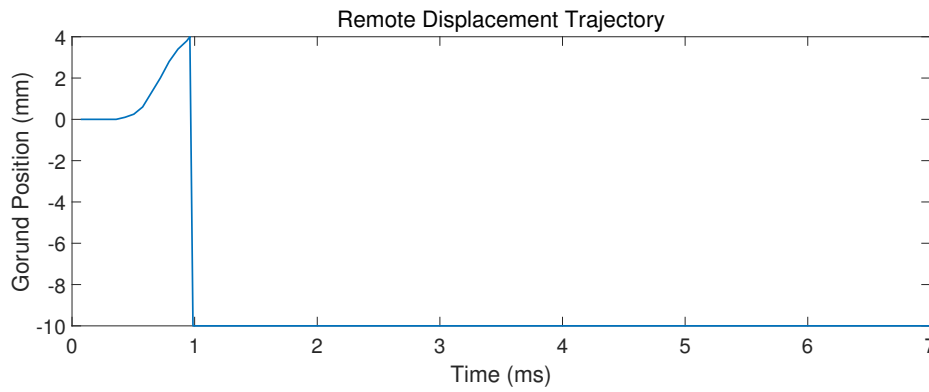


Figure 40: Results of the modal analysis.

The first transient analysis was conducted to obtain force reaction data. A plane ground was designed, and contact connections were formed between the foot and the ground. Moreover, a trajectory was generated, and its time step was decided with respect to the modal analysis results. The period of the 16. mode was 1382 Hz, and it was calculated as 0.72 ms. For transient analysis, the period was decided as 7.2 ms, and the trajectory was constructed using this period.



G: Damped SineStep High Freq

Remote Displacement

Time: 9.36e-004 s

Remote Displacement
Components: 0., 0., 4. mm
Rotation: 0., 0., 0. °
Location: -6., 1.575, -25.5 mm

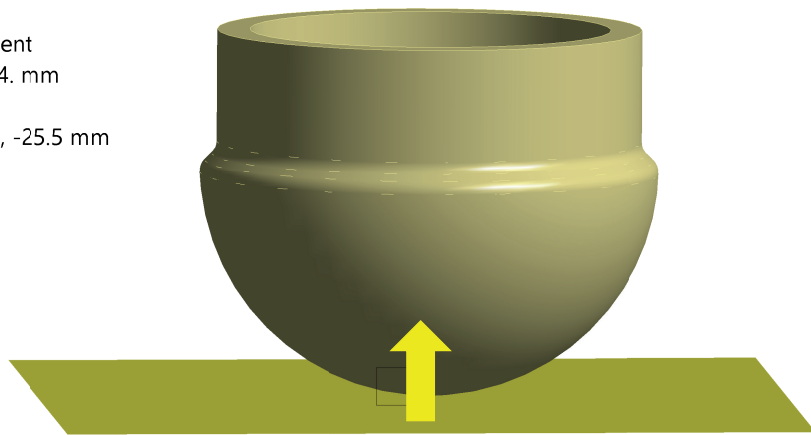


Figure 41: Transient analysis model and the remote displacement. At 1 ms, 4 mm step function was applied to simulate the impact effect.

Following subsequently, the analysis model was built, as seen in Figure 41. The trajectory was given as a small displacement with respect to the ground. To simulate an impact, the foot was constrained to steady still. The damping ratio was implemented as 0.1 at 62.5 Hz as obtained from the impact test. The force reaction of the foot was obtained from the transient analysis results. The same analysis was run to determine the force absorption without the damping property. Thus, the system behaved statically, and the force reaction was observed. The force reaction and directional deformation data were given in Figure 42 for both analyses. As seen ground reaction forces graph, the maximum reaction force is 11% less with the damped foot. Since the deflection of the damped foot is converging

to 0 mm according to without damped curve in the foot deflection graph, the damping effect of the foot is verified. Observing these results, the foot could dampen while walking, and less reaction force would be transferred to the leg.

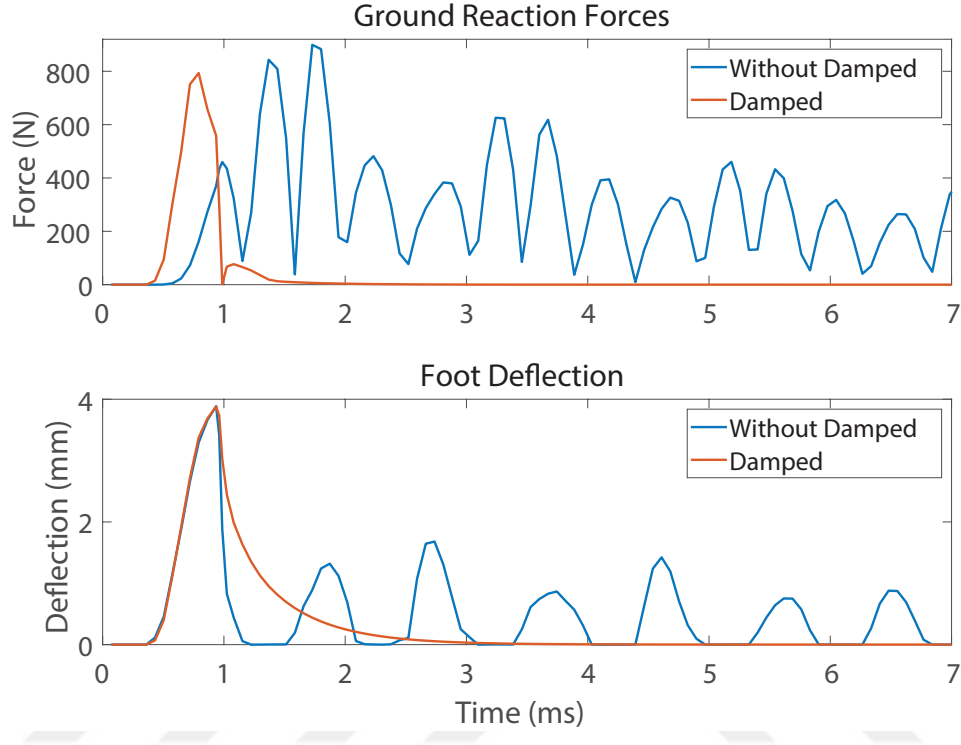


Figure 42: Transient analysis results and damping effect.

In conclusion, a foot structure was manufactured using additive manufacturing method. TPU-95A material was used for this design because of its mechanical properties. The gyroid infill structure and its mechanical behavior with TPU-95A were studied. Further studies will be conducted on this topic to investigate different infill ratios and their damping effect on the foot.

4.3 Torso Design

The structure of the composite torso is similar to the first prototype; see Chapter 2. However, there are design changes in geometry for the new torso. This torso is designed like a closed box to protect electrical components and A/A actuators.

In Section 4.2, whole robot analysis were explained and the stress distribution on torso was obtained. In that simulation, carbon-fiber material was implemented

on the walls of the torso initially. The maximum stress was 28.5 MPa at bolt assembly points as seen in Figure 43.

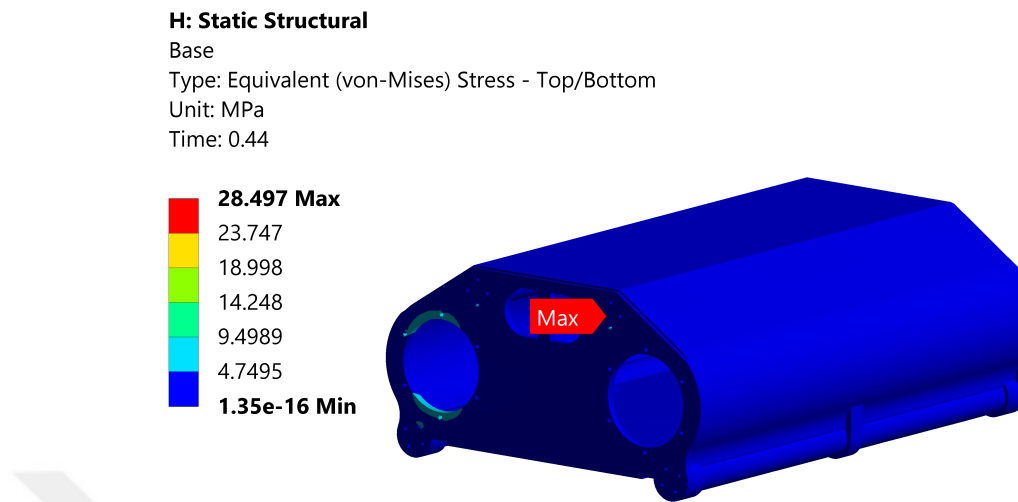


Figure 43: Von Mises stress distribution on composite torso.

Due to the high cost of the carbon-fiber material based manufacturing, the base material of the walls were changed to ABS plastic material. Moreover, the design was updated by considering the manufacturing processes. The new CAD assembly of the base is shown in Appendix H. Moreover, static structural analysis was conducted on the torso to verify its endurance. The analysis model was constructed as same as the torso analysis in Chapter 2.

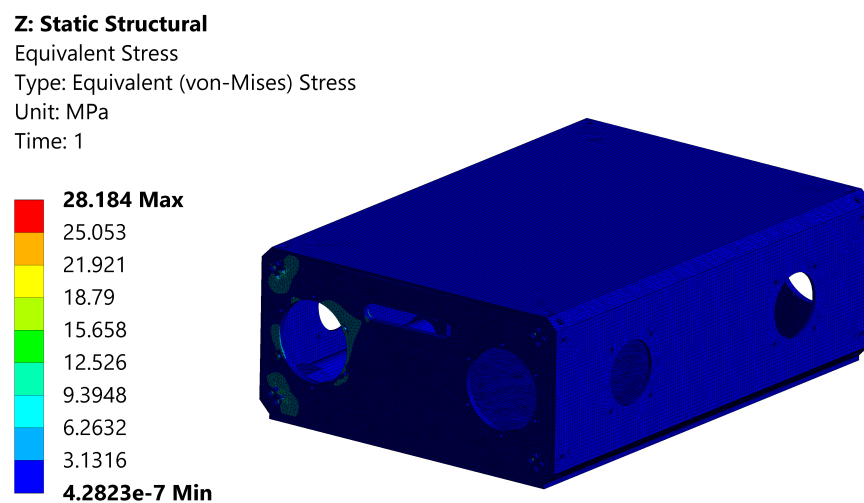


Figure 44: Von Mises stress distribution on composite torso.

As shown in Figure 44, the maximum stress is 28.2 MPa. However, these stresses occur at bolt connections with carbon-fiber tubes. Therefore, the torso was durable per the analysis results.

4.4 Second Prototype: Results

All carbon fiber-onyx parts were manufactured with 3D printer. It was considered that, every part had at least 2 carbon fiber layers during the 3 D printing process, as shown in Figure 45.

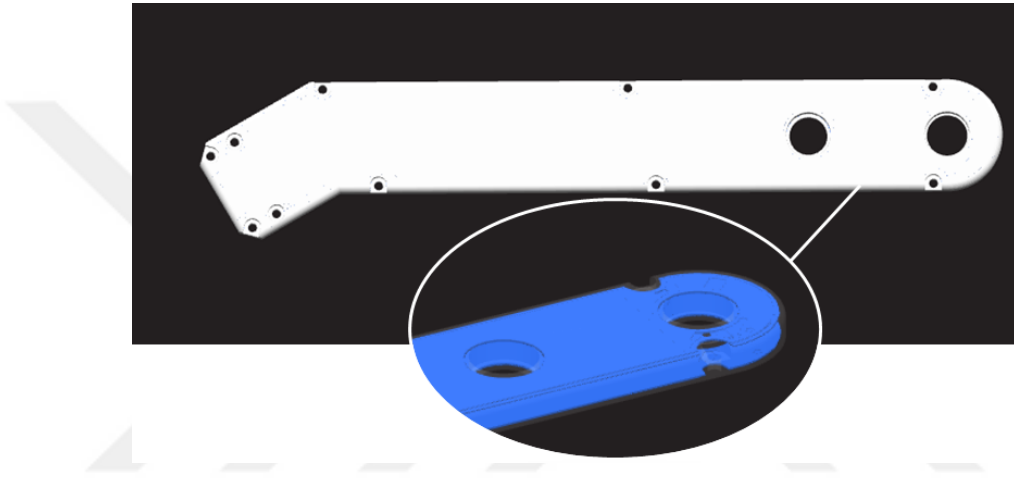


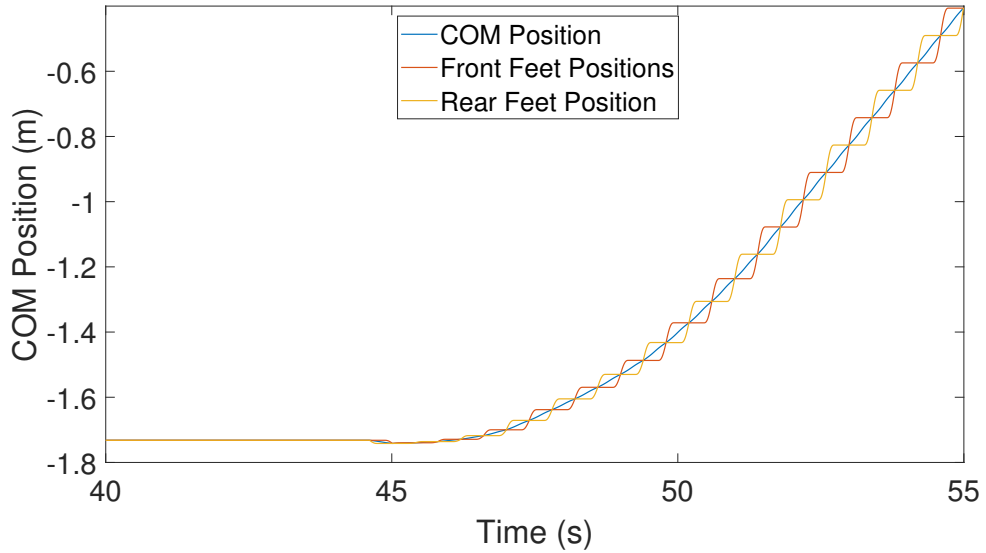
Figure 45: Internal view of the shank in 3-D printer interface. Blue layers are the carbon fiber layers.

Following the manufacturing process, all legs were assembled to the torso and electronic components were integrated. Consequently, the second prototype is built and the actual view of the robot was shown in Appendix I. The specifications of the second prototype are given in Table 11.

Table 11: Specifications of the second prototype

Specification.	Value
Mass (kg)	37
Degrees of Freedom	12
Length (m)	0.91
Width (m)	0.54
Height (m)	0.71
Max. Speed (m/s)	0.6
Max. Battery Voltage (V)	52
Payload (during walk)(kg)	15+

Due to the lack of ABS material during the pandemic outbreak, the torso was manufactured with polycarbonate which had the same strength property with ABS. However, the manufacturer's polycarbonate material was heavier than the ABS. This lead to 4 kg heavier base than the calculated value. Thus, the mass of new quadruped robot was measured as 41 kg.

**Figure 46:** Quadruped robot's COM position with respect to world frame.

Trot walking experiments were conducted on the robot with and without payload. In the first experiment, joint trajectory tracking was observed during 0.3 m/s trot walking. The results (see Figure 47) indicated that the robot could track the given trajectory (see Figure 46 for COM trajectory.). Due to the large amount of data, results were shown between 40s-55s.

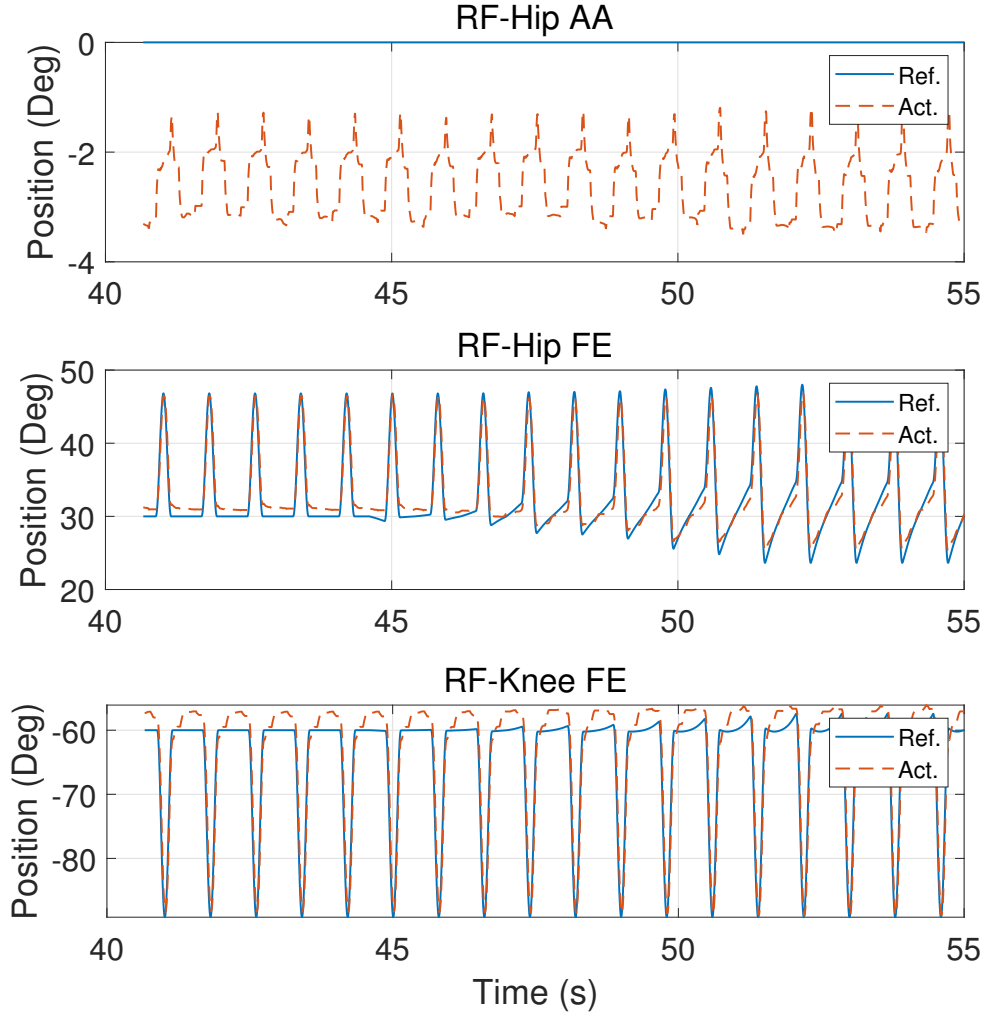


Figure 47: Quadraped robot's joint trajectory tracking at 0.3 m/s. This results were taken from Right-Front leg's joints.

In the second experiment payload capacity was observed during the 0.2 m/s trot walking. At first, the experiment started with 4 kg payload, then it was increased to 15 kg. It was observed that robot could walk with 15 kg payload at the 0.2 m/s speed.

CHAPTER V

CONCLUSION

This study presents the design, development, and experimental test of a quadruped robot with a high power-to-weight ratio. The design steps are explained as follows: 1) Integrated actuator design, 2) The first prototype of a quadruped robot, 3) The second prototype of a quadruped robot.

An integrated design methodology for a compact actuator with high torque to weight ratio was proposed. An initial model was designed, and a topology optimization was conducted on the actuator frames. New frames were designed according to optimization results, and structural verification was done on these parts. The new design had 10% less mass according to the initial design and a 28.23 Nm/kg torque-weight ratio. Actuator unit 1.0 was experimentally verified and implemented in the robot. Another design approach is material optimization on the actuator unit. In this method, actuator frames were redesigned with respect to onyx-carbon fiber combination and additive manufacturing requirements. Also, stability was increased by adding an extra shaft to the actuator unit. The final design was verified in terms of strength in the Ansys environment. After the verification, the actuator unit 2.0 was manufactured by a 3-D printer and experimentally verified.

The first prototype of the quadruped robot was developed by starting with the leg design. To begin with, dynamic simulations were conducted to decide the simplest and mechanically the most efficient design for the knee joint mechanism. During this process, the joints' total torque generation and range of motions were evaluated. To this end, a four-bar mechanism was decided to be employed between the knee F/E actuator and the knee joint. An initial design of the quadruped robot was designed with simple geometries, and static structural analysis was

conducted to obtain joint reaction forces on the robot. Moreover, initial limbs were designed, and topology optimization was conducted on these parts to minimize their masses. With topology optimization, the total mass of the limb was reduced to 1.3 kg, which was a 20% mass reduction. These optimized limbs were verified with FEM analysis to ensure their durability. After the manufacturing process, their mechanical structures were experimentally verified. The final piece of the robot was the torso which included most of the electrical components. The torso consisted of carbon fiber tubes with AL-7075 walls as a skeletal structure. The electrical components were placed in the ABS electrical box, which was assembled in the skeletal structure of the torso. To obtain the natural frequency of the torso, modal analysis was conducted. According to the analysis result, the torso was statically analyzed, and its strength was verified. So, the torso was manufactured, and electrical components were assembled in the torso. After these design steps, the whole robot was realized, and its mechanical structure was experimentally verified via trot walking tests.

The second prototype of the quadruped robot was developed via additive manufacturing techniques with composite materials. A carbon fiber-onyx combination was used as the base material of the robot. Due to its filament base material structure, tension tests were conducted to verify its exact mechanical properties. Moreover, its Young's Modulus and Shear Modulus values were calculated according to material test results. Then, the FEM model of the second prototype was built in the Ansys environment, and this material was implemented on limb parts. Same constraints and trajectories were applied to the robot, and static structural analysis was conducted. Critical parts were updated and verified according to boundary conditions. It was considered that composite parts only carry loads on two axes, and limb parts were designed as four minor parts to support loads in all directions. Thus, the second leg prototype was 0.48 kg lighter than the first leg prototype. The foot of this robot was manufactured from TPU-95A material with a 15% gyroid infill. The mechanical behavior of this design was examined via

impact test and modal analysis. As a result, the material characteristic and the damping value of the foot were obtained. With transient analysis in the Ansys environment, the foot's damping behavior was observed from reaction forces. The final piece of this prototype was the torso which was modeled as a closed box to protect electrical elements and A/A actuators. The skeletal part of the torso was constructed with carbon-fiber tubes and ABS walls. Then, static structural analysis was conducted on the torso to verify its mechanical structure in terms of strength. Due to the lack of ABS material during the pandemic outbreak, polycarbonate was used for torso walls, which have similar mechanical properties as ABS but are 4 kg heavier. After the assembly, trot-walking experiments were conducted on the robot to verify its mechanical structure.

To sum up, two high-powered quadruped robot prototypes were developed. Different design approaches were applied while developing these robots. Additive manufacturing techniques and their materials' behaviors were studied. Finally, two robot prototypes were verified experimentally with trot walking experiments.

APPENDIX A

MATERIAL PROPERTIES

Table 12: Al-7075 Material Properties

<i>Specification</i>	<i>Value</i>
Density (kg/m^3)	2770
Young's Modulus (MPa)	71000
Poisson Ratio (-)	0.33
Yield Stress (MPa)	619
Shear Modulus (MPa)	1193

Table 13: ABS Material Properties

<i>Specification</i>	<i>Value</i>
Density (kg/m^3)	1010
Young's Modulus (MPa)	1190
Poisson Ratio (-)	0.3
Yield Stress (MPa)	27.6
Shear Modulus (MPa)	457.7

Table 14: Carbon Fiber Material Properties

<i>Specification</i>	<i>Value</i>
Density (kg/m^3)	1420
Young's Modulus X Direction (MPa)	61340
Young's Modulus Y Direction (MPa)	61340
Young's Modulus Z Direction (MPa)	6900
Shear Modulus XY (MPa)	3300
Shear Modulus YZ (MPa)	2700
Shear Modulus XZ (MPa)	2700
Poisson Ratio XY (-)	0.04
Poisson Ratio YZ (-)	0.30
Poisson Ratio XZ (-)	0.30
Compressive Yield Stress X (MPa)	-509
Compressive Yield Stress Y (MPa)	-509
Compressive Yield Stress Z (MPa)	-170
Shear Stress XY (MPa)	125
Shear Stress YZ (MPa)	65
Shear Stress XZ (MPa)	65

Table 15: Carbon Fiber-Onyx Homogenous Material Properties

<i>Specification</i>	<i>Value</i>
Density (kg/m^3)	1200
Young's Modulus (MPa)	2600
Poisson Ratio (-)	0.3
Yield Stress (MPa)	100
Shear Modulus (MPa)	640

APPENDIX B

ACTUATOR UNIT: 1.0

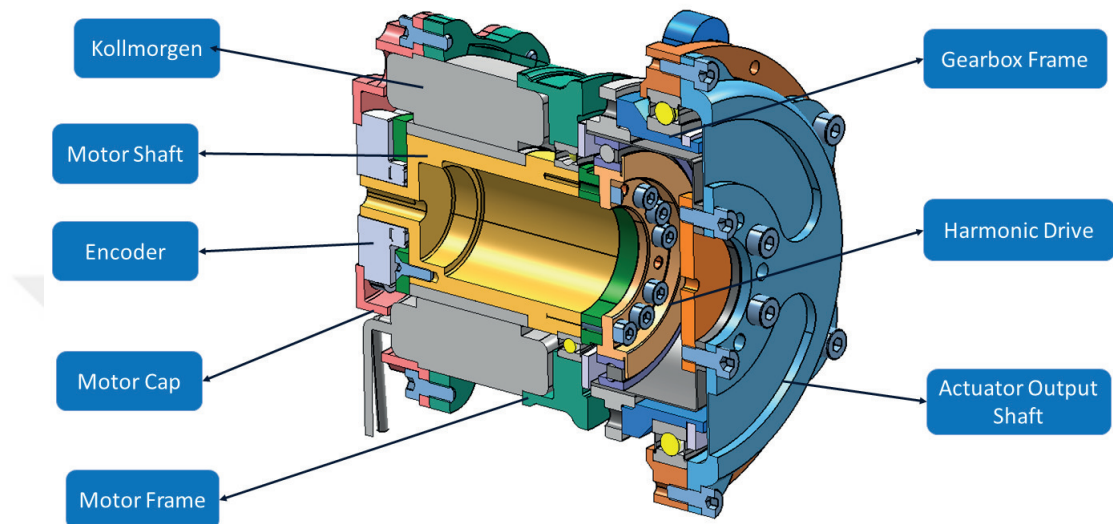


Figure 48: Actuator Unit: 1.0

APPENDIX C

ACTUATOR UNIT: 2.0

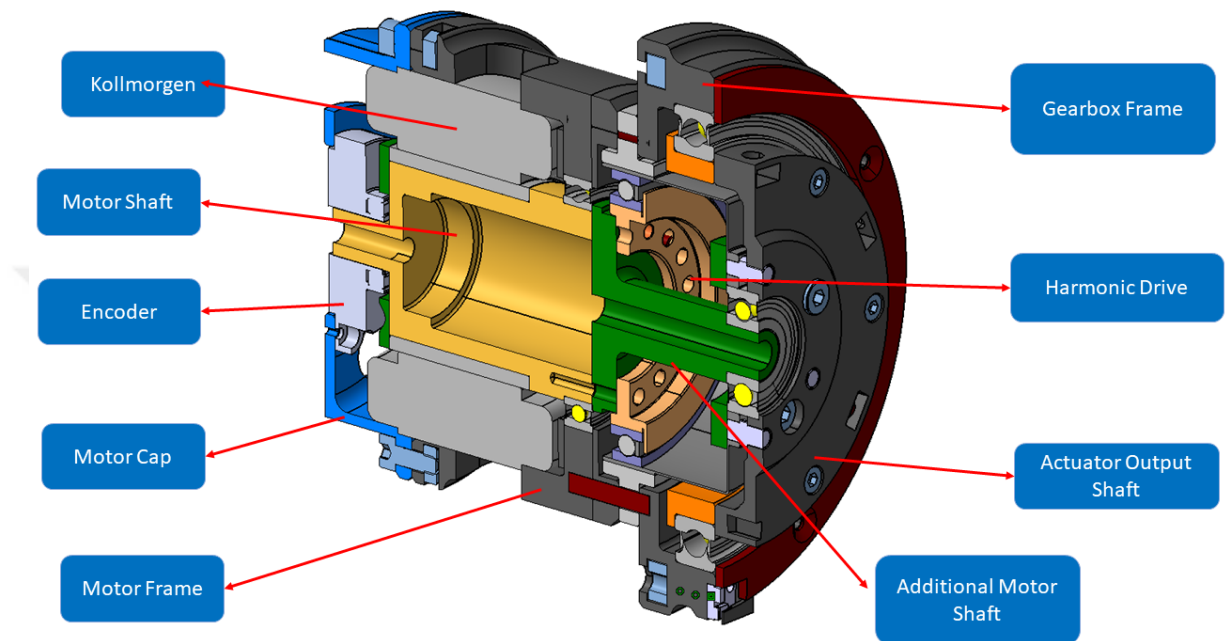


Figure 49: Actuator Unit: 2.0

APPENDIX D

LEG STRUCTURE

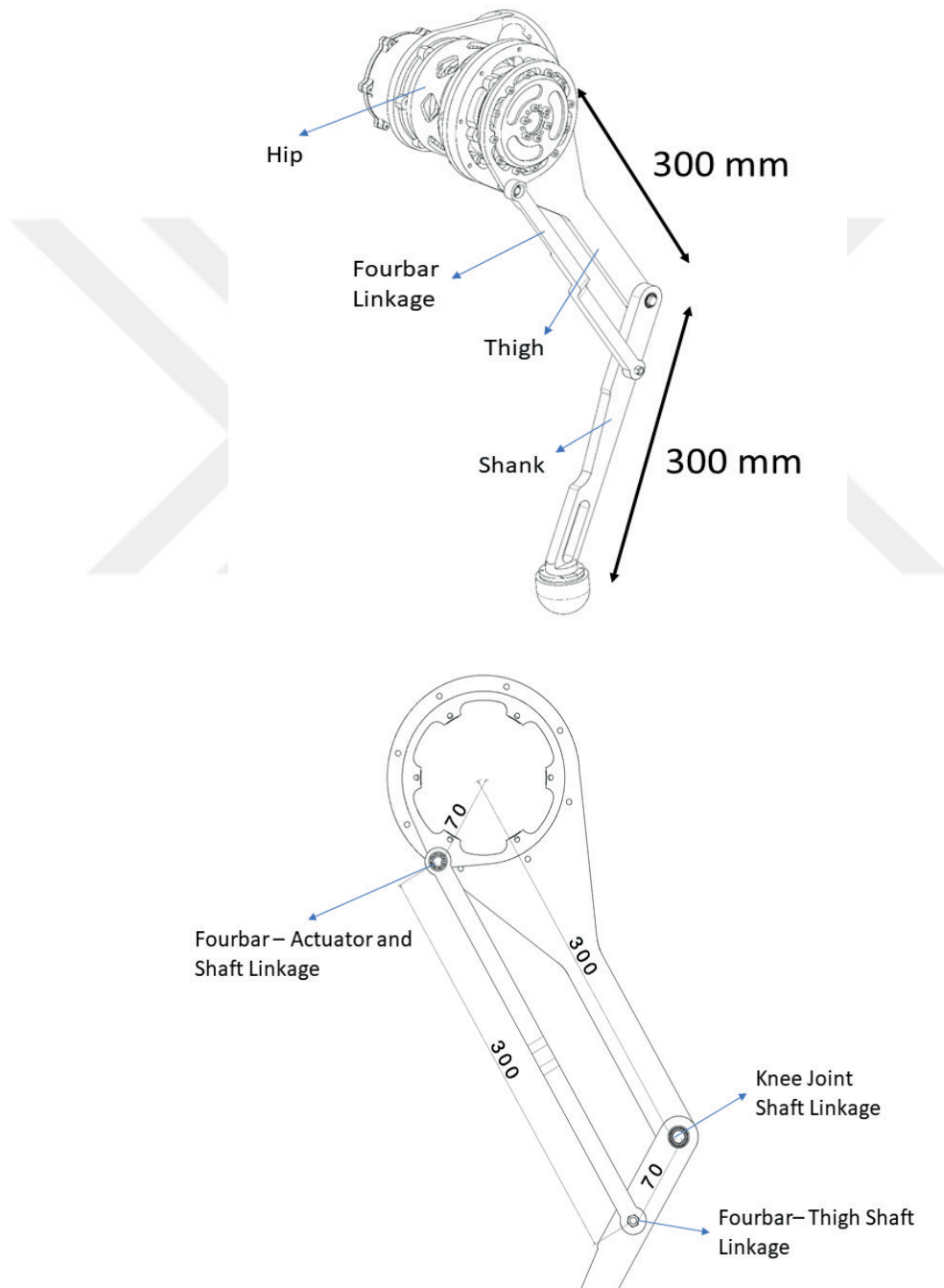


Figure 50: Leg Structure

APPENDIX E

CAD ASSEMBLY OF THE TORSO

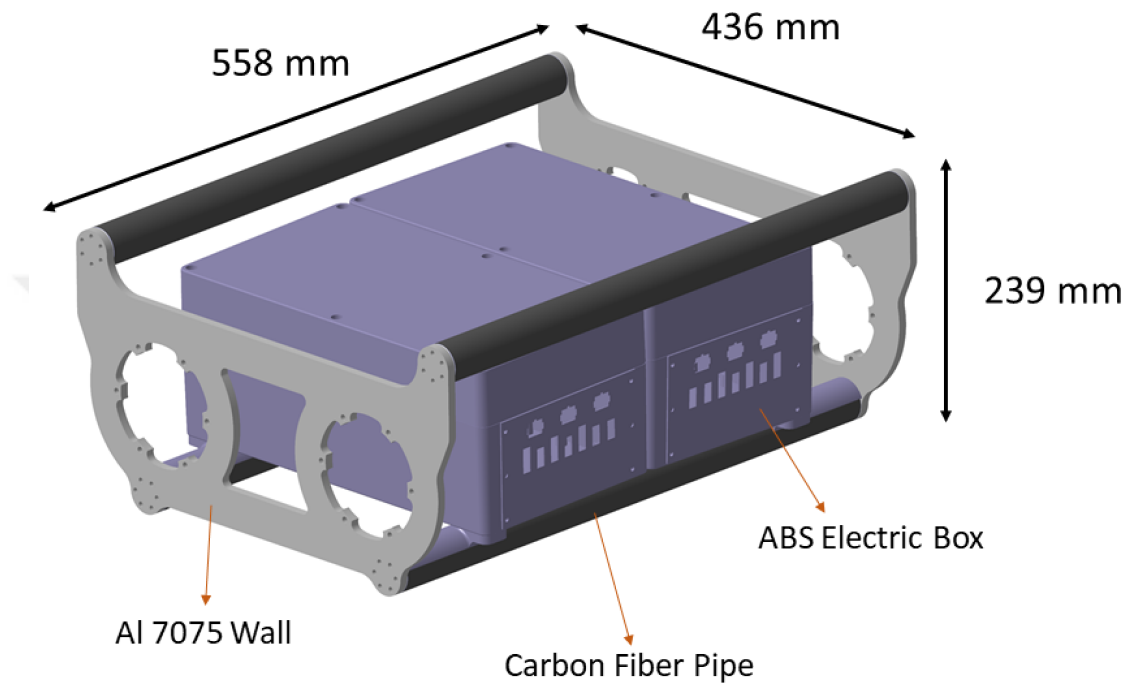


Figure 51: CAD Assembly of The Torso

APPENDIX F

FIRST PROTOTYPE

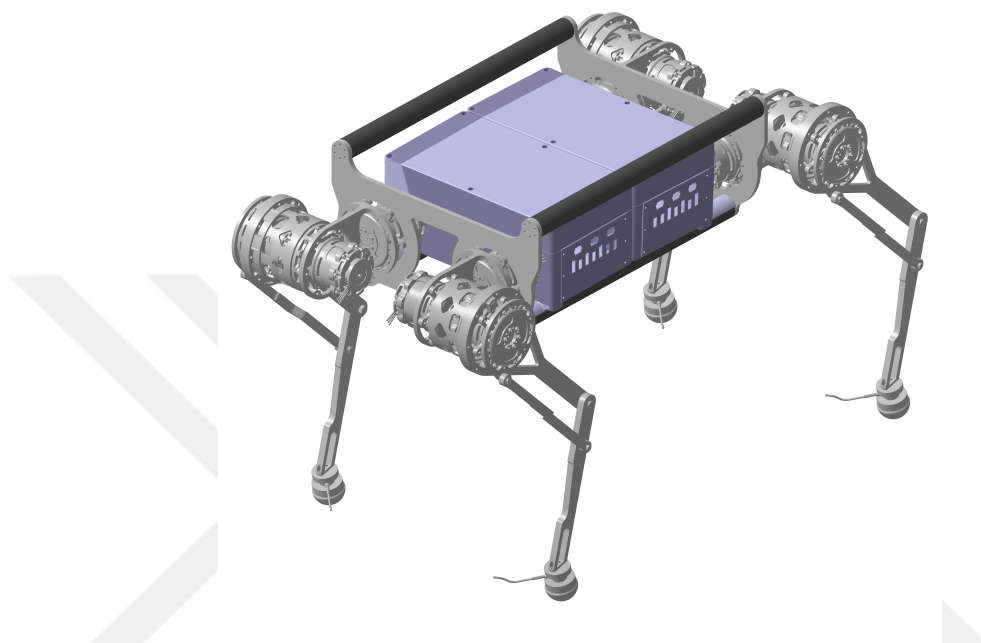


Figure 52: CAD view

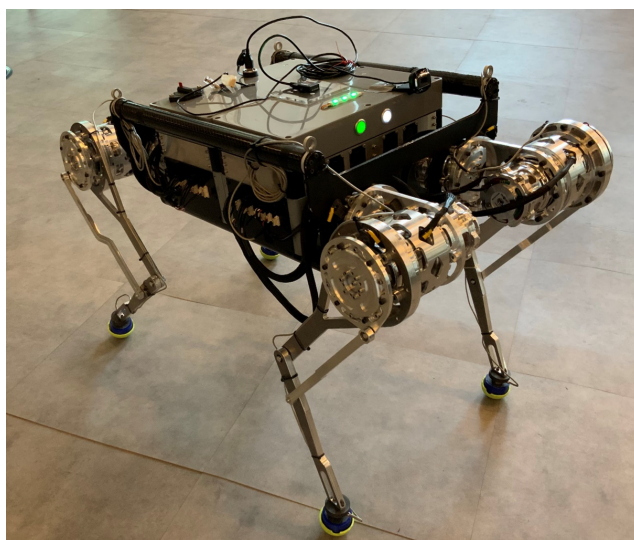


Figure 53: Actual view

APPENDIX G

COMPOSITE LEG STRUCTURE

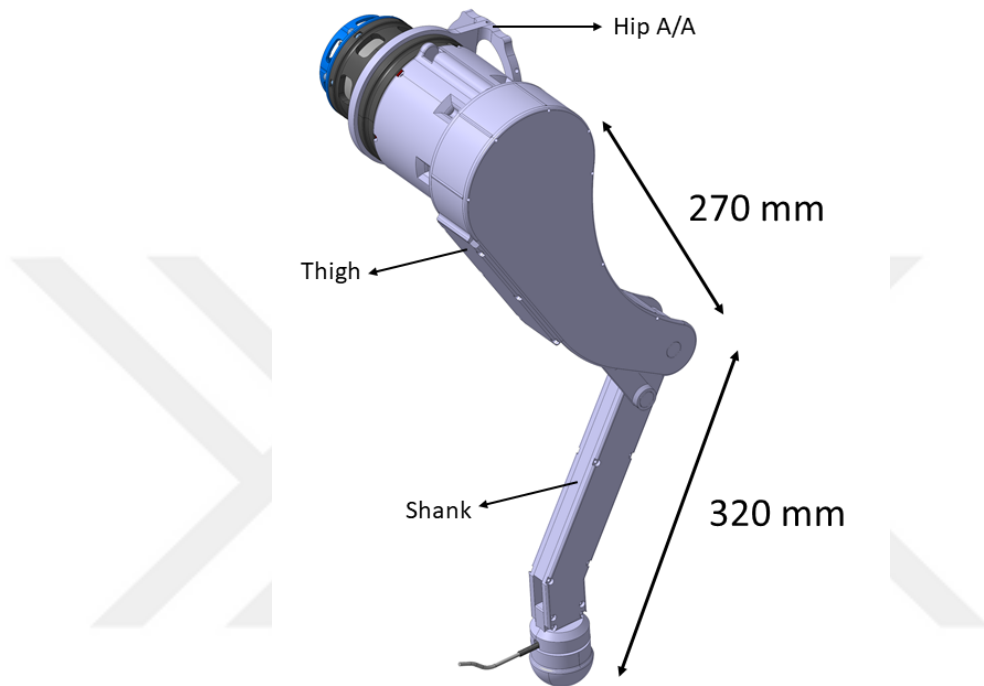


Figure 54: Composite Leg Structure

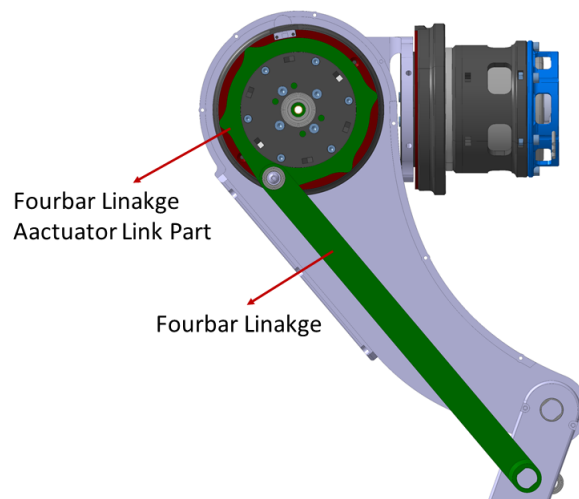


Figure 55: Four-bar Linkage

APPENDIX H

CAD ASSEMBLY OF THE SECOND PROTOTYPE'S TORSO

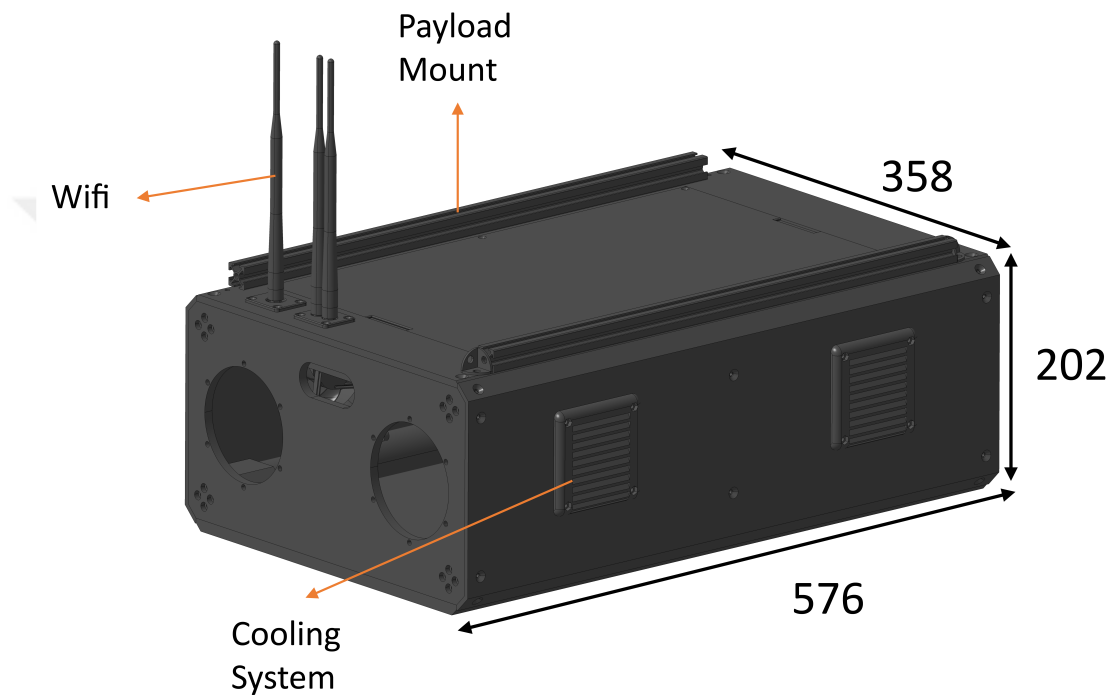


Figure 56: CAD Assembly of The Second Prototype's Torso

APPENDIX I

SECOND PROTOTYPE



Figure 57: CAD view



Figure 58: Actual view

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