Design of a Robotic Leg for a Four-Legged Mule Robot

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ISLAMABAD

19th July 2023

Annex A To NUST Letter No
0972/102/Exams/Thesis-Cert
Dated: 19th July 2023

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Dedicated to my exceptional parents and adored sibling whose tremendous support and cooperation led me to this wonderful accomplishment

Acknowledgements

I'm grateful to Allah Subhana-Watala, my Creator for guiding me through every stage of my effort and for each fresh idea You planted in my head to make it better. Indeed, without Your invaluable assistance and direction, I would have been powerless. It was Your will that everyone who assisted me with my thesis, including my parents and others, thus only You are deserving of recognition.

I am incredibly grateful to my wonderful parents who reared me when I was unable to walk and who have supported me throughout my life in every aspect.

I want to express my gratitude to my supervisor and mentor, Dr. Umar Shahbaz Khan, Professor in Mechatronics Engineering Department, for giving me the opportunity to do a Master thesis under his kind supervision. Dr. Umar was a continual source of encouragement throughout the study effort and was always happy to assist in any manner he could. I want to thank him for giving me the unique opportunity to spend time at the Robot Design and Development Lab (RDDL). I learned about a new research area that guides me in the proper direction. It was a terrific time with amazing people not only as researchers but also as friends. I'm also grateful that Dr. Kunwar Faraz Ahmed Khan, a great researcher in mobile robotics, agreed to join my committee. A big thanks also goes to Dr. Aamir Hamza, Head of the Mechatronics Department, for many fruitful discussions.

In terms of funding, the research was supported by the National Centre of Robotics and Automation (NCRA), which funded a significant portion of the product development.

This work would not have been possible without the contributions and support of countless people, who I wish to thank for the intensive collaboration and all the fun that we had over the past years. They are great colleagues and I'm looking forward to continuing working with them.

And finally, I am deeply grateful to all my friends for all the support they gave me to reach this point.

Abstract

Research in legged robots has recently been an exciting and expanding field of research. Legged robots are becoming more and more robust and stable. But still legged robots are far behind in speed and cost of transport as compared to wheeled robots.

The purpose of this thesis is to improve the energy efficiency and speed of legged robots using biomimicry. As Nature has evolved efficient and optimized solutions over millions of years. Biological systems are studied to understand their mechanisms and apply those principles to design robots that can perform tasks more effectively and efficiently. A model is trained on animal dataset and from that trained model, limb length of the robot is predicted. In this way by emulating nature, the efficiency and functionality of natural systems is channelized to improve the performance of legged robot.

In this thesis, the design, implementation and control of a hybrid walk and roll quadruped robot is presented. The robot's design is based on a combination of a rolling body and four legs, which allows the robot to switch between walking and rolling modes depending on the terrain condition. This allows the robot to make use of both systems to move in an efficient manner. Like on flat surface, robot make use of wheel to get high speed.

The robot's control is based on a combination of kinematic and dynamic models, which allows for a balance between stability and mobility. By leveraging innovative approaches in system design, actuation, and control, this research aims to bridge the gap in the field of Legged Robotics and Wheel Robotics.

The robot's performance and capabilities are also explored by conducting experiments in different modes. The results are analyzed and compared to demonstrate the potential of the hybrid walk and roll quadruped robot in various applications. The results show that due to its adaptability in different conditions by switching between walking and rolling mode, the hybrid walk and roll quadruped robot can achieve a higher speed and energy efficiency compared to traditional quadruped robots.

Keywords—Quadruped Robot, Wheeled Robot, Mechanical Design, Dynamic Locomotion, Static Structural Analysis, Motion generation, Machine learning, Walking Robot, Hybrid Robot

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List of Abbreviations

Here is the list of abbreviations used in this thesis:

DOF	Degree of Freedom
COG	Center of Gravity
CAD	Computer-Aided Design
V&V	Verification and Validation
HMI	Human-Machine Interface
NN	Neural Network
FEA	Finite Element Analysis
IMU	Inertial Measurement Unit
LIDAR	Light Detection and Ranging
HAA	Hip Abduction/Adduction
HFE	Hip Flexion/Extension
KFE	Knee Flexion/Extension
THL	Total hind limb length
COT	Cost of Transport
IDE	Integrated Development Environment
IK	Inverse Kinematics
CAM	Computer-Aided Manufacturing
PWM	Pulse width modulation
MCU	Microcontroller unit
GPS	Global Positioning System
IMU	Inertial Measurement Unit
COM	Center of mass
FK	Forward Kinematics
IKM	Inverse Kinematics Model
ANSYS	Analysis System
IDE	Integrated Development Environment
GPIO	General Purpose Input/Output

CHAPTER 1 : INTRODUCTION

A quadruped robot is a type of robotic system designed to move on four legs, like many animals in the animal kingdom. These robots are specifically designed to mimic the locomotion and movement capabilities of quadrupedal creatures. Quadruped robots are utilized for tasks such as search and rescue operations in rugged terrains or hazardous environments and serve as agile platforms for exploring difficult-to-reach areas. Researchers working on quadruped robots face challenges in developing efficient locomotion control algorithms and optimizing power consumption for longer operational durations. Researchers address the challenges by employing machine learning algorithms, and biomechanical modeling. They also work on optimizing power consumption by using lightweight materials, energy-efficient actuators, and implementing power management strategies such as energy harvesting or intelligent control systems. The purpose of this paper is to improve the cost of transport (COT) and speed of legged robot by biomimicry and addition of wheel to legged robot platform to improve legged robot efficiency on flat surfaces.

1.1 Motivation and Objective:

The goal of designing and developing hybrid walk-roll quadruped robots is to produce robots that can move successfully and efficiently in a variety of situations. The large spectrum is to:

Improved mobility:

Improved mobility is achieved by hybrid walk-roll quadruped robots, which can adapt to various terrains and surroundings by integrating both walking and rolling locomotion. Compared to robots that are restricted to a single method of movement, this enables them to move more effectively and efficiently.

Improved stability:

Quadruped robots are naturally stable, however the addition of wheels to the design can make the robot more stable and less prone to falling over.

Increase speed:

By adding wheels to the design, hybrid walk-roll quadruped robots can move faster than traditional legged robots, especially on smooth surfaces.

Increase endurance:

Walking robots require a significant amount of energy to operate, and by incorporating wheels into the design, hybrid walk-roll quadruped robots can conserve energy and increase the robot's endurance on flat surfaces.

Increase payload capacity:

Adding wheels to the design can also increase the robot's payload capacity, allowing it to carry heavier loads in 2 legs 2-wheel configuration or in all wheel drive.

Increase versatility:

By combining the advantages of both walking and rolling, hybrid walk-roll quadruped robots can perform a wide range of tasks and adapt to different environments, making them more versatile than traditional legged robots.

Overall, the design and development of hybrid walk-roll quadruped robots is motivated by the desire to create robots that can move efficiently and effectively in a wide range of environments, while also advancing the field of legged robotics.

1.2 Quadruped selection

The decision to opt for a quadrupedal design is primarily driven by the need for a legged platform capable of executing a wide range of gaits, encompassing dynamic running on flat surfaces and statically stable climbing on challenging terrain. Having four legs is the minimum requirement for static locomotion with point feet. In contrast, a bipedal robot would necessitate actuated feet elements, which would significantly increase mechanical complexity, end-effector mass, impact losses during landing, and actuator effort for swing leg motion. Another advantage of a multi-contact configuration is the larger footprint, which allows for optimizing actuator efficiency, contact stability, and executing intricate climbing maneuvers by adhering to the ground. Nature itself has demonstrated the efficiency of four-legged designs, evident in the most advanced and large-scale animals.

These factors collectively highlight the numerous advantages associated with quadrupedal platforms.

There are several reasons why researchers and engineers choose to build four-legged robots, also known as quadruped robots, over other types of legged robots:

1. **Stability:**
   Four legs provide a more stable base for a robot, which allows it to navigate uneven terrain and maintain balance more easily.
2. **Maneuverability:**
   Four legs provide more degrees of freedom for movement and allow for a wider range of gaits and maneuvers than two-legged robots.
3. **Efficiency:** Four-legged robots can be more energy efficient than two-legged robots, as they can use a combination of walking and running gaits to move quickly and smoothly.
4. **Biomimicry:** Four-legged animals can move in a wide variety of environments, such as rough terrains and uneven surfaces, thus quadruped robots can be modelled after these animals to mimic the same capabilities.
5. **Versatility:** Four-legged robots can be used in a wide variety of applications, such as search and rescue, industrial inspections, and entertainment, due to the stability and maneuverability provided by the four legs.

Real-world examples: Four-legged animals have been around for a long time and have been able to adapt to many different environments, thus by studying and modeling quadruped robots based on their movements, researchers can have a large pool of data to work with.

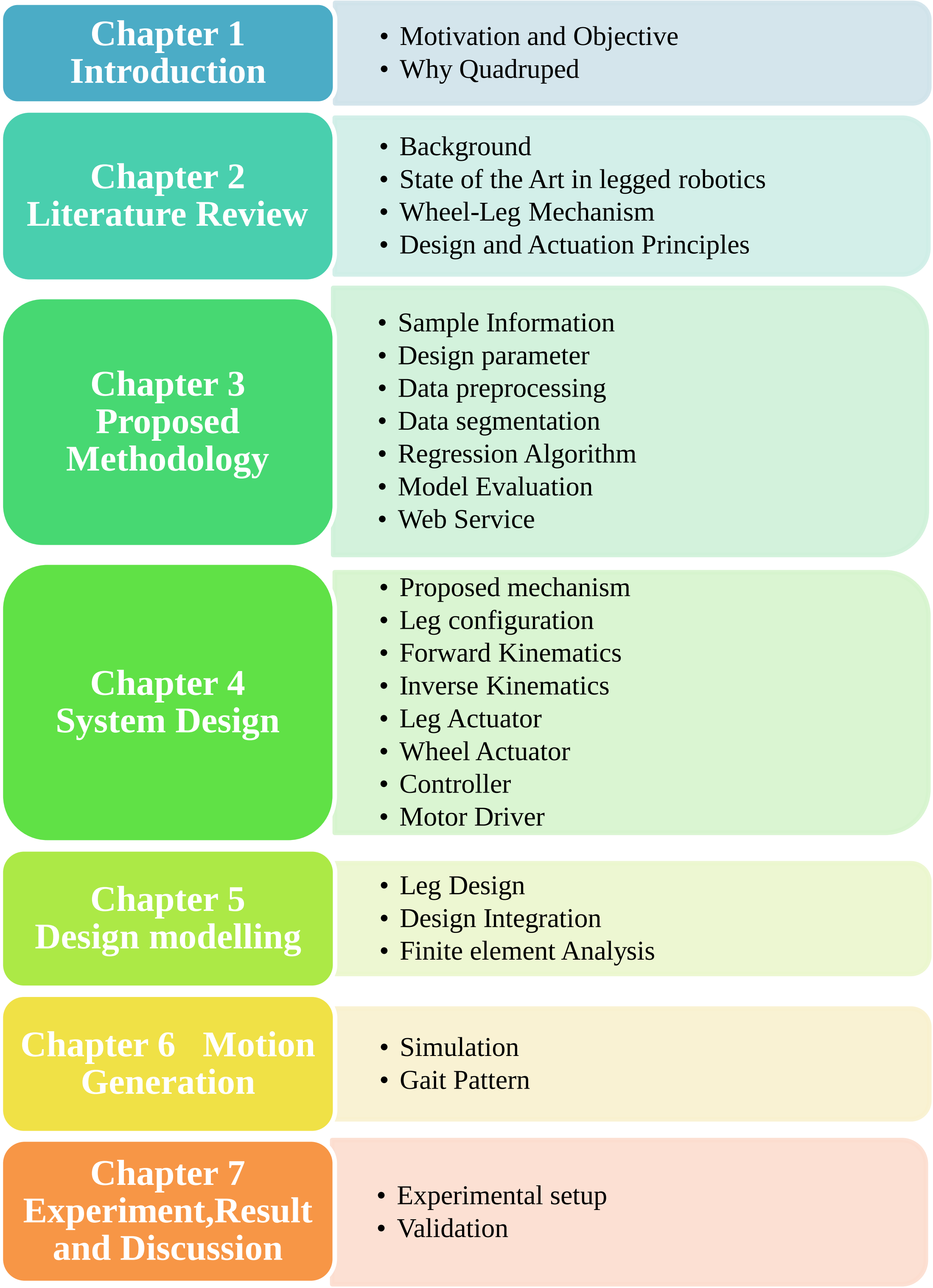


Figure 1.1 Flow chart of the research

CHAPTER 2 : LITERATURE REVIEW

The literature review starts by identifying relevant research articles, conference papers, and academic publications that specifically address topics related to hybrid locomotion, quadruped robots, and related technologies. After analyzing and evaluating selected literature sources special attention is paid to the research methodologies, experimental setups, algorithms, control strategies, and performance metrics. By comparing the findings, strengths, and limitations of each approach gap analysis is conducted. By synthesizing the key findings and identifying research opportunities that have not been adequately addressed in the existing literature. This helps in making the unique contributions this thesis will make in the field of robotics.

2.1 Related Work:

Legged robotics has long captivated human imagination, offering the prospect of constructing systems capable of traversing diverse terrains and operating beyond conventional environments. While it may appear to be a relatively recent scientific pursuit, the origins of legged locomotion can be traced back several centuries. In fact, the earliest concepts for legged vehicles emerged as early as the 15th century.

During the years 1495 to 1497, the renowned polymath Leonardo da Vinci conceptualized and potentially even constructed the initial iterations of an articulated anthropomorphic robot [1]. Figure 2.1 shows the Leonardo da Vinci design of the first articulated anthropomorphic robot. This remarkable creation stands as a testament to da Vinci's visionary ideas and represents a significant milestone in the history of Western civilization.

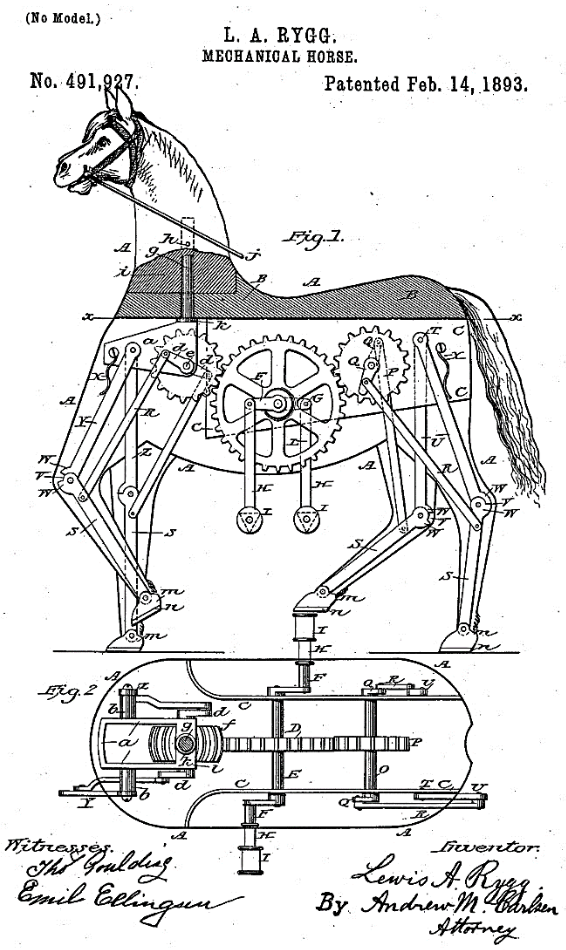


Figure 2.1 Leonardo da Vinci design of the first articulated anthropomorphic robot (Lewis et al. 1893)

Significant advancements in the field of legged robotics emerged during the 1960s and 1970s. A notable breakthrough was the development of the General Electric quadruped which showcased the ability to exhibit various gaits. Figure 2.2 shows the General Electric quadruped robot. This groundbreaking vehicle was created by R. Mosher and completed in 1968.

The General Electric quadruped stood at an impressive height of 3.3 meters, measured 3 meters in length, and weighed around 1400 kilograms. It featured four legs, each equipped with three degrees of freedom (DOF), with one DOF in the knee joint and two DOF in the hip joint. The actuation of these joints relied on hydraulic cylinders, while propulsion was achieved through a powerful 68-kW internal combustion engine.

The development of the General Electric quadruped marked a significant milestone in the progression of legged robotics, demonstrating the potential for creating mechanically complex and dynamically capable legged systems. This pioneering achievement paved the way for further exploration and innovation in the field, inspiring subsequent advancements in legged locomotion research.

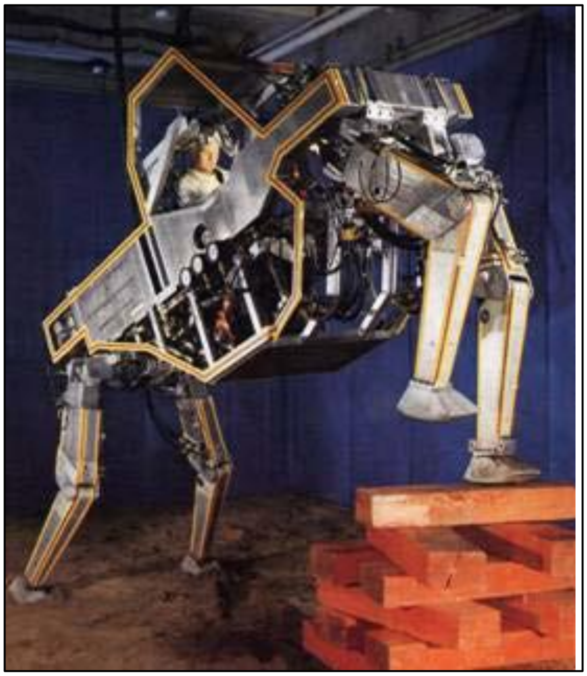


Figure 2.2 General Electric quadruped robot, 1968

Since then, significant progress has been made in the field of walking robots. Today, walking robots are capable of a wide range of movements, including running, jumping, and climbing. They are also capable of adapting to different terrains and environments, and they can be controlled by a variety of methods, including machine learning and artificial intelligence.

2.2 State of the art in legged robotics

Legged robotics is a discipline that is continually developing, with new innovations and advancements being developed all the time. Some of the main fields of legged robots research and development are:

1. **Dynamics Stability:**

   Walking robots must be able to retain stability and balance while moving, which is a difficult challenge. The development of control algorithms and sensor systems that enable robots to retain stability and adapt to shifting surroundings is the major emphasis of this field of study [2].

2. **Locomotion:**

   A variety of locomotion skills for legged robots are being developed by researchers, including walking, running, leaping, and climbing. This involves creating novel actuators that can give robots more strength and mobility, including series elastic actuators [3].

3. **Adaptability:**

   Legged robots must be capable of adapting to various surroundings and terrains. The development of sensors, control algorithms, and machine learning strategies that enable robots to adapt to new settings and tasks are the main emphasis of this field of study [4].

4. **Energy Efficiency:**

   Walking robots now use a lot of energy to move about, therefore researchers are working on new methods to make them more energy-efficient [5].

5. **Human-robot interaction:**

   Due to the growing proximity of legged robots to people, researchers are developing safe, natural human-robot interactions [6].

6. **Machine Learning and AI:**

   To help legged robots adapt to new settings and tasks and to increase the robot's capacity to navigate and make decisions, researchers are creating machine learning and AI algorithms [7].

7. **Hardware:**

   Legged robot hardware is continually being developed, using new materials and fabrication methods to create stronger, lighter, and more energy-efficient robots [8].

Overall, the state of the art in legged robots is developing quickly, with fresh discoveries and innovations being produced often. Future developments in the subject are anticipated, with legged robots becoming more powerful and adaptable.

In recent years, several significant quadruped robot designs have been created, each with its own distinct traits and abilities. The most prominent designs comprise:

2.2.1 Boston Dynamics' Spot mini:

The Spot Mini is a scaled-down version of Boston Dynamics' Spot quadruped robot. While keeping the agility and adaptability of its bigger version, it is made to be lightweight and small [9].

Spot Mini includes several cutting-edge features that make it suitable for a variety of applications. It also features a variety of sensors that let it navigate and interpret its surroundings, including cameras and LIDAR.

Spot Mini has a high degree of autonomy and can function for long periods of time without assistance from a human. Additionally, it has various safety features including obstacle recognition and avoidance that make operating around people safe.

Figure 2.3 Boston Dynamics-Spot Mini [3]

One of Spot Mini's most noticeable features is its adaptability to many surroundings, including both indoor and outdoor ones. Spot Mini can easily go around obstacles, climb stairs, and traverse tough terrain. Additionally, it has sophisticated control algorithms that enable it to adjust to various activities and circumstances.

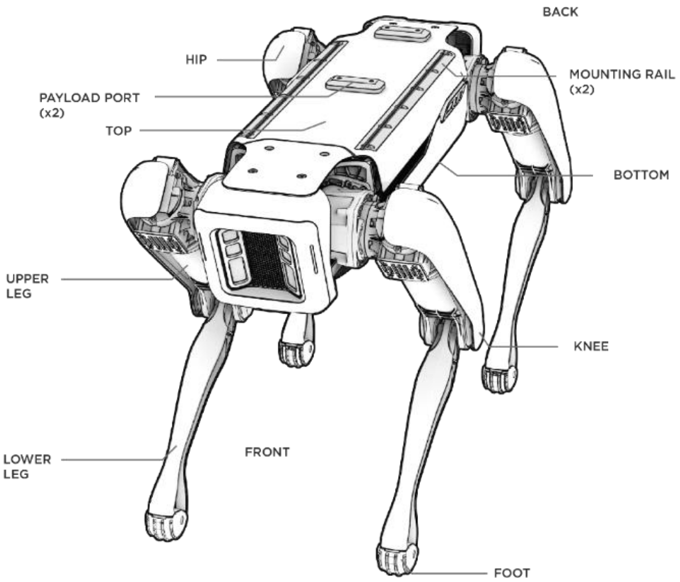


Figure 2.4 Spot-mini specification [9]

Spot Mini has been extensively employed in several studies and applications, including security, surveying, and remote inspection. It is regarded as one of the most advanced quadruped robots on the market because of its small size and cutting-edge capabilities. To meet the needs of commercial sensing and remote operation, Boston Dynamics created the Spot Mini robot as a robust and adaptable platform. Through the client library, it provides the ability to adapt the control system's features and capabilities. The Spot Mini's software framework makes it easy to retrieve visual navigation and perception data, and users may customize application programs to choose the robot's postures and velocities.

Table 2.1 shows the detail specification of a spot mini robot.

Table 2.1 Spot-mini-Specification[9]

Specification	
Weight (kg)	32.5
Payload (kg)	13
Material	Aluminum, steel, and composite materials
Length (m)	1.1
Width (m)	0.5
Default walking height (m)	0.61
Sitting height (m)	0.191
DOFs per leg	3
Hip joint range	120 degrees forward/backward, 45 degrees sideways, and 180 degrees rotation.
Knee joint range	50 degrees forward and 90 degrees backward
Ankle joint range	45 degrees up/down, 35 degrees tilt side to side, and 180 degrees rotation
Upper, lower leg segment lengths (m)	
Maximum speed (mph)	3.6
Actuator	All-electric actuator Peak torque 5.2Nm Max speed 4.2 rad/s
Sensor	Perception sensors including stereo cameras, IMU, and position/force sensors in limbs.
Software	GRPC-based API and Python client library. Spot Software Development Kit (SDK).
Power	564Wh battery (58.8v)
Parent Organization	Boston Dynamics
Country	United States

2.2.2 ANYmal-C:

ANYbotics, a Swiss startup, created ANYmal, a quadrupedal robot. It is intended for use in tough situations including oil and gas installations, thermal power plants, and marine wind farms for industrial inspections, surveys, and monitoring. ANYmal can travel and understand its surroundings thanks to a multitude of sensors that are like cameras, LIDAR, and IMU.

Figure 2.5 ANYmal Quadruped robot [3]

ANYmal has a great degree of autonomy and can function for long periods of time without assistance from a human. It can adjust to various surroundings and terrains thanks to its sophisticated control algorithms. It can move both inside and outside, walk, run, and climb stairs [10].

ANYmal is also outfitted with several security measures that make it safe to function near people, such as obstacle identification and avoidance. It can function in challenging industrial settings including oil and gas infrastructure, thermal power plants, and marine wind farms because of its strong and long-lasting architecture.

The robot also has a strong onboard computer that enables real-time processing of sensor data, decision-making, and job execution. Additionally, the robot may be fitted with different payloads, including cameras, gas sensors, and other instruments, to carry out certain duties.

ANYmal has been used in many different contexts, including as industrial inspections, surveys, and monitoring. It is regarded as one of the most sophisticated quadrupedal robots on the marketplace and is well-suited for usage in demanding industrial applications because of its robust design and superior capabilities.

Because of its extraordinary degree of movement, ANYmal can move objects with its feet, such as doors, and over them. The robot can climb stairs, avoid contacting objects, and change its body height and direction for inspection purposes thanks to its remarkable joint mobility. ANYmal learned its extraordinary movement abilities using machine learning methods. It may, for example, be trained to run in unorganized surroundings, to get up after falling, and to accurately follow predetermined body trajectories. Table 2.2 shows the detailed specification of ANYmal robot.

Table 2.2 ANYmal quadruped robot specification[10]

Specification	
Weight (kg)	30
Payload (kg)	10
Material	Carbon fiber
Length × width × height (m)	0.8 x 0.6 x 0.7
DOFs per leg	3
Ranges of HAA, HFE, and KFE (°)	360°
Torques of HAA, HFE, and KFE (Nm)	40
Upper, lower leg segment lengths (m)	0.3,0.3
Maximum speed (mph)	0.8
Actuator	ANY drive, series elastic actuator
Power	650Wh
Parent Organization	ANYbotics
Country	Switzerland

2.2.3 HyQ:

Italy's Istituto Italiano di Tecnologia (IIT) created the quadruped robot HyQ. It is intended for a range of uses, including environmental monitoring, industrial inspections, and search and rescue operations. It is a quadruped robot with hydraulic legs that can run, walk, and jump.

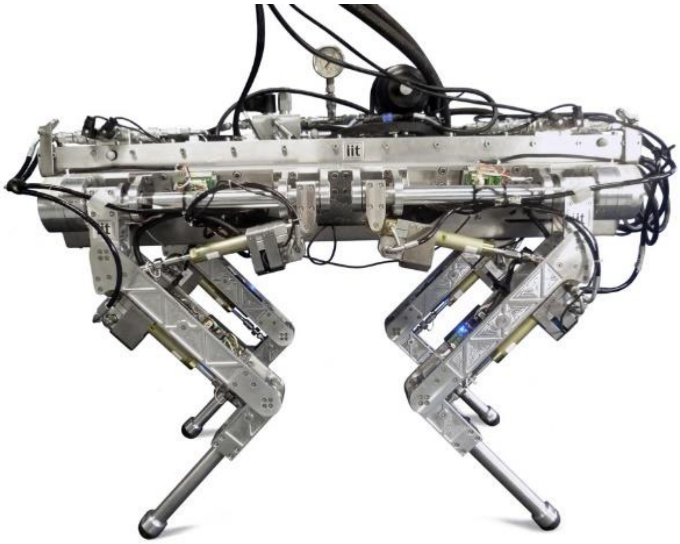


Figure 2.6 HyQ quadruped robot[3]

HyQ has a high degree of autonomy and can function for a prolonged amount of time without assistance from a human. Additionally, it has a variety of sensors including cameras and LIDAR that help it navigate and understand its surroundings.

HyQ can climb stairs, navigate tough terrain, and carry big cargoes, which is one of its most impressive features. Additionally, it has sophisticated control algorithms that enable it to adjust to various activities and circumstances.

High torque and power can be produced by HyQ thanks to its hydraulic actuation system, which is crucial for transporting large cargoes. The hydraulic actuators of the robot can also deliver the fine control and quick motion required for running and leaping [11].

Applications for HyQ have included environmental monitoring, industrial inspections, and search and rescue. It is regarded as one of the more sophisticated quadruped robots in the marketplace and is well-suited for employment in demanding areas because of its tough design and superior capabilities.

The robot is continuously being developed and improved by the IIT team to give it new capabilities like grasping, manipulation, and perception, increase its versatility, and allow it to carry out more difficult jobs. Table 2.3 shows the detailed specification of HyQ quadruped robot.

Table 2.3 HyQ quadruped robot specification [11]

Specification	
Weight (kg)	91
Payload (kg)	10
Material	aerospace-grade aluminum alloy and stainless steel
Length × width × height (m)	1 x 0.5 x 1
DOFs per leg	3 (two hydraulic and one electric)
Ranges of HAA, HFE, and KFE (°)	120 per joint -90→+30 -70→+50 20→140
Torques of HAA, HFE, and KFE (Nm)	Hydraulic actuator 145Nm Electric actuator 140Nm
Upper, lower leg segment lengths (m)	0.35, 0.35
Maximum speed (mph)	4
Actuator	Eight hydraulic cylinders controlled by high-performance servo valves. Four brushless DC motors with harmonic drive gears
Power	Tethered
Parent Organization	Istituto Italiano di Tecnologia (IIT)
Country	Italy

The sophisticated quadruped robots called HyQ-2Max is the next version created by Istituto Italiano di Tecnologia (IIT) for running and jumping. With a total of 8 hydraulically powered actuators and 4 electric actuators, these robots move utilizing a mix of mechanical and electric actuators. All electrical components, including sensors, valves, and actuators, are protected within the mechanical framework to increase dependability and robustness against impacts and dirt. The HyQ-2Max model's core and leg structures are made from a sturdy aluminum alloy suitable for aeronautical use.

The HyQ-2Max has outstanding locomotion skills, reaching top speeds of 1.5 m/s on level surfaces and 0.5 m/s on uneven terrain. It can ascend stairs with a depth of 0.3 m and stepping levels of up to 0.12 m. An excellent quality precise encoder and torque sensors are included in each joint of the robot, allowing for accurate control and feedback while in operation.

2.2.4 MIT Cheetah:

The Biomimetic Robotics Laboratory at the Massachusetts Institute of Technology (MIT) created the MIT Mini Cheetah, a quadruped robot. Despite being smaller, lighter, and less expensive than its bigger sibling, the MIT Cheetah, it nevertheless has the same level of agility and movement.

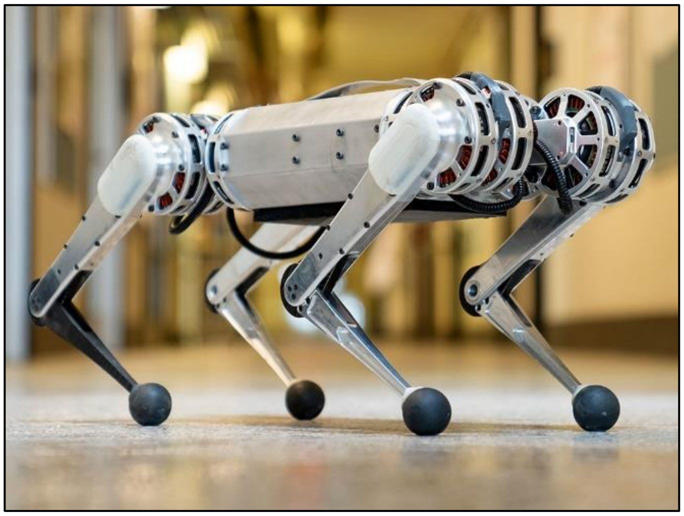


Figure 2.7 MIT-cheetah quadruped robot [3]

The Mini Cheetah is capable of a variety of actions, such as sprinting, jumping, and strolling. Additionally, it has sophisticated control algorithms that let it adjust to various surroundings and terrains. Because of its distinctive design, the robot is incredibly flexible and can shift its legs in any direction to walk forward, backward, sideways, or even flip.

The robot also has several sensors, such as cameras and IMUs, that let it comprehend its surroundings and navigate. It can function for long periods of time without human interaction and has a high level of autonomy [12].

Several safety measures, including obstacle recognition and avoidance, provide the Mini Cheetah with the ability to operate around people safely. Its compact design and cutting-edge capabilities make it ideal for a variety of uses, including exploration, search and rescue, and entertainment.

One of the most sophisticated quadruped robots currently on the market, the MIT Mini Cheetah is employed for a variety of research projects in the fields of control, dynamics, and machine learning. The team is always attempting to increase the robot's speed, torque, and flexibility, among other skills.

MIT has created Cheetah 1, Cheetah 2, and Cheetah 3 family of high-performance quadruped robots. Cheetah 1 weighs 39.406 kg and has a total cost of transport (COT) of 0.51 with a top speed of 6 m/s. Cheetah 2, a vehicle with a top speed of 6.4 m/s, was unveiled in 2015. Compared to Cheetah 1, it has a lower COT of 0.47. The planar serial leg configuration mechanism of the Cheetah 2 allows the actuator to be mounted on the hip while the knee joint is controlled by a linkage system. An ankle joint that is passively flexible is present on each leg.

Additionally, Cheetah 1 has a flexible spine that connects to the back hip joints through a differential gear. This adaptable spine functions like a parallel spring, storing and releasing potential energy as the body moves. The MIT Cheetah 3 is MIT's newest and most sophisticated quadruped robot. The inclusion of abduction/adduction degrees of freedom (DOF) to the hip joint is one of Cheetah 3's notable improvements. Its approximate outline measurements are 0.6 m 0.256 m 0.2 m (length width height), and it weighs 45 kg. The robot has 0.45 kWh of onboard batteries, which give it a runtime of around two hours. The Cheetah 3 trots with a COT as low as 0.45, demonstrating its effectiveness and performance. Table 2.4 shows the detailed specification of MIT cheetah robot.

Table 2.4 MIT Cheetah specification [12]

Specification	
Weight	9 Kg
Payload (kg)	1 kg
Material	Aluminum, plastic protectors
Length × width × height (m)	0.48 x 0.27 x 0.3
DOFs per leg	3
Hip abduction/adduction	±45 degrees
Hip flexion/extension	±90 degrees
Hip internal/external rotation	±45 degrees
Knee flexion/extension	0-135 degrees
Torques of HAA, HFE, and KFE	17 Nm
Upper, lower leg segment lengths (m)	0.21, 0.21
Maximum speed	5.5 mph
Actuator	Custom modular, low-gear ratio, back drivable actuators
Power	lithium-ion battery
Parent Organization	MIT
Country	United States

The four main qualities that researchers are working to improve in legged robots are adaptability, speed, efficiency, and robustness. The capacity to move in a variety of ways, such as running, climbing, and rolling, should be possessed by these robots. They should also exhibit resilient interaction with the environment, handling uncertainty and disruptions well. These four-legged robots should also be able to complete these duties with excellent energy efficiency, quickly moving forward while consuming a small amount of energy.

2.3 Wheel-leg mechanism

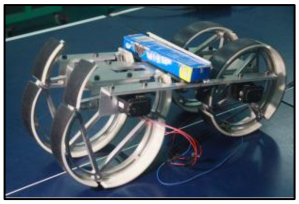
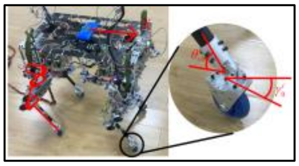
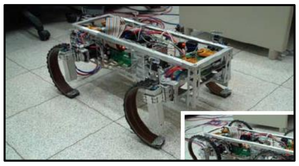
The creation of robotic platforms that combine the advantages of wheeled systems and the versatility of legged movement has gained more attention in recent years. These unusual machines, sometimes known as wheel-leg quadruped robots, provide intriguing options for navigating a variety of settings and overcoming difficult terrains. These robots combine wheeled and leg mechanics to make use of each system's advantages while minimizing its drawbacks. In a variety of applications, including search and rescue operations and exploration missions in dangerous and unstructured areas, this integration of technology creates new opportunities for improving the mobility, agility, and resilience of robotic platforms.

2.4 State of the art in wheel leg robots

The state-of-the-art wheel-leg quadruped robots is the subject of this assessment of the literature, which also examines design concepts, control schemes, locomotion capabilities, and prospective applications. The study seeks to offer insights into the current research environment and serve as a catalyst for new advances in the field of mobile robots by reviewing the development and difficulties in this area.

Hybrid legged and wheel robots have emerged as a fascinating area of research in robotics, combining the benefits of both legged and wheeled locomotion systems. These robots offer the potential to tackle a wide range of challenges by seamlessly transitioning between legged and wheeled modes, enabling efficient mobility on various terrains while maintaining stability and adaptability. Mirroring the movement characteristics of quadrupeds in nature and the characteristics of bone structure, a relatively novel wheel-leg hybrid quadruped robot wheel-leg structure is proposed based on the combination of the wheels and legs. A parallel mechanism is adopted as the structural design [13]. Lywal is a leg-wheel transformable quadruped robot with picking up and transport functions. Lywal is designed by using an innovative 2-DoF transformable wheel-leg mechanism [14]. Design and development of an all-terrain wheel-legged hybrid robot (WLHR) with strong adaptability to the environment. According to the operation requirements in different road conditions, the robot adopts a wheel and leg compound structure, which can realize the transformation of wheel movement and leg movement to adjust its motion state [15]. Inspired by human roller-skating, a new dynamic roller-skating gait of a typical mammalian quadrupedal robot with passive wheels is proposed to promote mobile efficiency [16]. A novel locomotion system with wheels and legs is suggested, and a mobile robot prototype that uses the system is also presented. A novel locomotion system with wheels and legs is suggested, the robot has four legs, and each leg's end is equipped with a wheel. Three joints and a passive wheel are on the front leg. One joint and an active wheel are present in the back leg. Three locomotion modes—wheel mode, hybrid mode, and step mode—are created to optimize the system. On level ground, four wheels are deployed while in wheel mode. When the hybrid mode is used, two active wheels and two legs are employed to go across uneven terrain. The step mode can be used to ascend or descend a big step. HyTRo-I combines two mobility concepts. For example, while wheeled vehicles share higher speed than legged and tracked machines on flat ground, they have relatively lower degree of flexibility than the other two on irregular terrain [17]. Quattroped comparing to most hybrid platforms which have separate mechanisms of wheels and legs, this robot is implemented with a transformation mechanism which directly changes the morphology of wheels (i.e., a full circle) into 2 degree-of-freedom legs (i.e., combining two half-circles as a leg) [18].The hybrid quadruped robots with both wheel and leg mechanisms are shown in Table 2.5.

Table 2.5 Wheel-Leg mechanism literature review

Paper	Date	Wheel mode	Pictorial view
[13]	2022	Wheel placement below feet	
[14]	2021	Leg-wheel transformable	
[15]	2021	Wheel as feet	
[16]	2021	Wheel below feet	
[17]	2013	Wheel attach to body	
[18]	2010	Leg-wheel transformable	
[19]	2009	Leg-wheel transformable	
[20]	2006	Wheel attach to Feet	

2.5 Design and Actuation Principles

The actuators used to provide movement and control the robot's legs are the subject of much study on quadruped robotics. It is found that there are two types of actuators frequently employed in legged robots when comparing the achievements of previously constructed quadrupedal robots.

1. Hydraulic actuator system
2. Electrical actuator system

2.5.1 Hydraulic actuator system

The development of more effective and potent actuators, as well as control algorithms that can efficiently use the high torque and power offered by hydraulic actuators, has been the primary focus of research on hydraulic actuators in quadruped robots. Along with research on the design and optimization of hydraulic actuators, this covers studies on the dynamics and control of hydraulic quadruped robots.

2.5.2 Electrical actuator system

The development of lighter, more compact, and more effective electrical actuators for quadruped robots, as well as control algorithms that can efficiently make use of the high-frequency capabilities of electrical actuators, have been the main topics of research in this area. Research topics include electrical quadruped robot dynamics and control, as well as the design and optimization of electrical actuators.

Hybrid actuator systems, which combine the benefits of hydraulic and electrical actuators, are also the subject of expanding study. This covers research on hybrid actuator system design, control, and optimization as well as studies on the efficient fusion of hydraulic and electrical actuators in quadruped robots.

Researchers are always attempting to create new actuator technologies and control algorithms that can enhance the performance and capabilities of quadruped robots. In general, research on quadruped robots by the actuator they employed is an active field of research. Table 2.6 shows the Quadruped robots built over the years and the type of actuator they used.

Table 2.6 Quadruped robot comparison [21]

Name of robot	Dimension (m) (L x W x H)	Speed (m/s)	Weight (kg)	Payload (kg)	DOF per leg	Actuator	YEAR
Quadruped	1.05 x 0.35 x 0.95	2.2	38	-	3	E	1990
PV-ii	0.9, 1 (L x H)	0.02	10	2	3	E	2000
PAT rush	0.36 x 0.24 x 0.33	0.6	5.2	-	3	E	2000
AIBO RES-210A	0.3 (L)	0.3	1.4	-	3	E	2004
Little dog	0.3 (L)	0.25	2.85	-	3	E	2007
Qrt2	1 x 0.5 x 1	1.3	60	40	3	Hy	2008
KOLT	1.75 x 0.6 x 0.8	1.1	7.5	-	3	E	2009
Kotetsu	0.34 0.19 ~ 0.25 0.35	0.2	5.2	-	3	E	2010
Hubodog	0.8 (L)	0.5	42	24	3	E	2010
HyQ	1 x 0.5 x 1	1.78	70	-	3	Hy	2011
Scalf 1	1 x 0.4 x 0.68	1.8	123	80	3	Hy	2012
Aidan 3	0.3	0.33	12.3	3	3	E	2013
StarlETH	0.6(L)	1	23	25	3	E	2013
VU Quadruped	0.46 x 0.64 x 0.38	0.23	6.9	9.1	3	P	2014
LS3	1.7(H)	-	590	181	3	Hy	2015
TITAN Xiii	0.21 x 0.55 x 0.34	0.9	5.65	5	3	E	2016
ANY mal	0.8 x 0.4 x 0.7	0.35	30	10	3	E	2016
SPOT	1.1 x 0.5 x 0.84	1.6	30	14	3	E	2016
Laikago	0.57 x 0.37 x 0.6	0.8	24	-	3	E	2017
Mini-Cheetah	0.48 x 0.27 x 0.3	2.45	9	-	3	E	2018

Speed:

The actuators' speed is one of the most important things to consider. Since hydraulic actuators depend on fluid flow to produce motion, hydraulic actuators are often slower than electrical actuators. They often operate less frequently and with a longer reaction time. On the other hand, electrical actuators are frequently quicker than hydraulic actuators. They operate more often and with a quicker response time since they depend on the movement of energy to create motion. They can also be more simply incorporated into the robot's control system and are often more lightweight and compact than hydraulic actuators. Therefore, it is more suitable for rapid and nimble robots. Figure 2.8 shows the speed and 2.9 shows the weight of quadruped using electrical or hydraulic actuator.

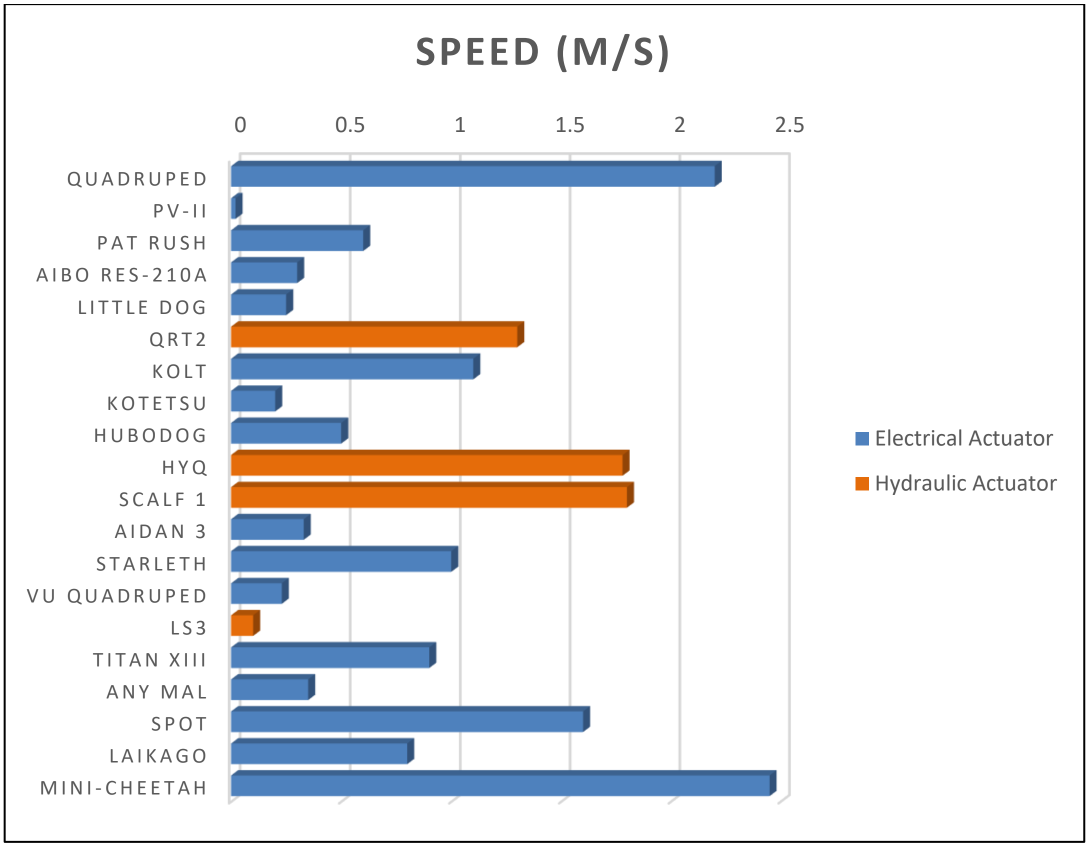


Figure 2.8 Quadruped robot speed comparison chart

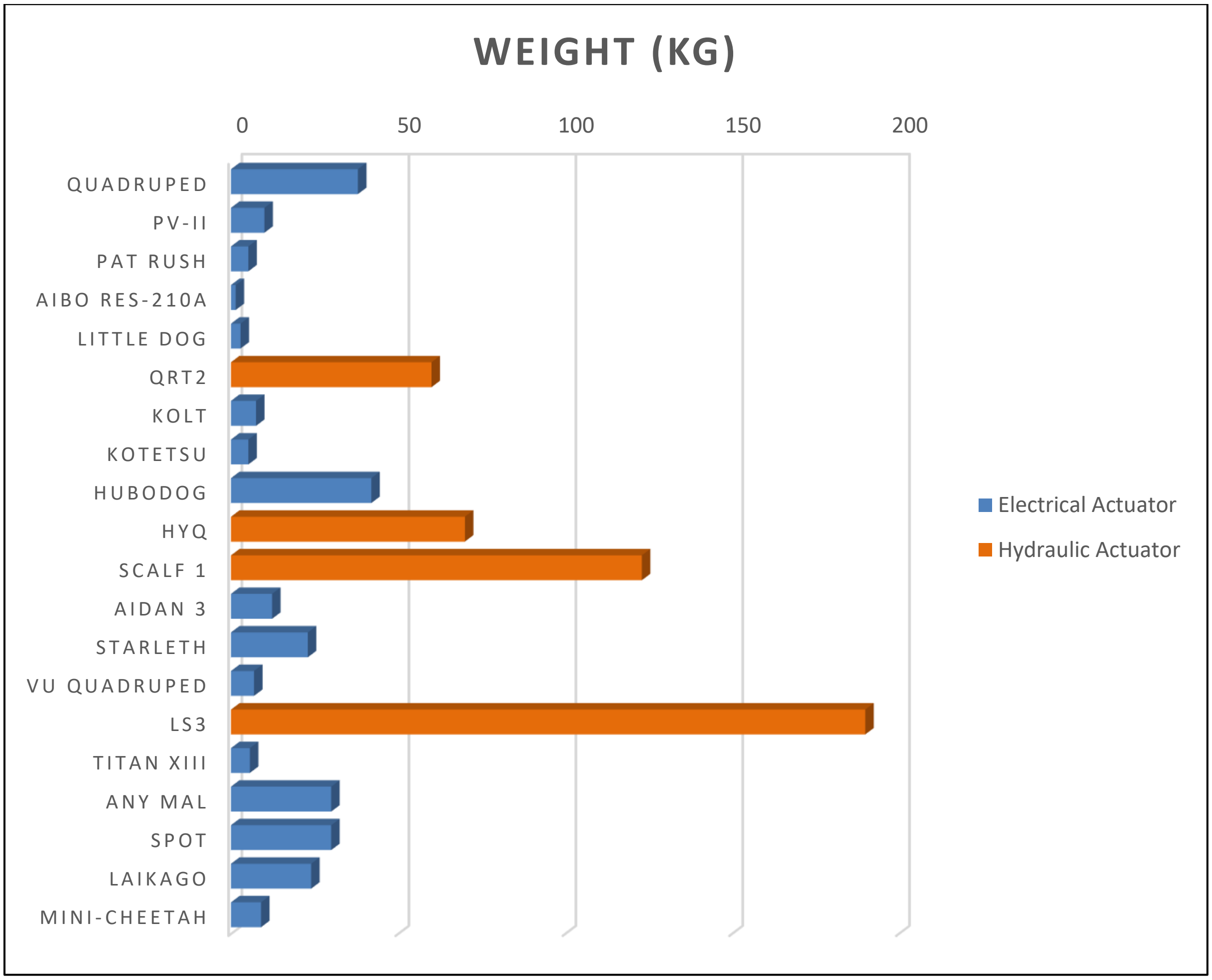


Figure 2.9 Quadruped robot weight comparison

2.2.3 Advantages and Disadvantages:

Legged robots frequently employ both hydraulic and electrical actuators, each of which has benefits and drawbacks.

Pressurized fluid is used by hydraulic actuators to provide force and movement. They may provide a lot of torque and force and are often stronger than electrical actuators. They are therefore ideal for use in legged robots that must lift large objects or carry out powerful motions. They are also effective in dampening vibrations due to their great damping capabilities.

Although they need a different power supply and control system than electrical actuators, hydraulic actuators are typically heavier and bulkier. They can produce heat that has to be dispersed and have higher energy use.

On the other hand, electronic actuators produce force and movement using electrical power. They can be more simply integrated into the robot's control system than hydraulic actuators since they are often lighter and more compact. They can operate at high frequencies and have quick response times, strong controllability, and accuracy.

Electrical actuators, on the other hand, are frequently less potent than hydraulic actuators and might not be appropriate for use in legged robots that must lift large objects or make forceful motions. Additionally, they are less capable of dampening, which could cause vibrations.

Legged robots' choice of hydraulic or electrical actuators ultimately comes down to the needs of the robot and the application for which it will be utilized. As our area of interest is improving the speed and lightweight design, we have chosen an electrical actuator. The comparison based on the parameter important in incorporated electrical actuator in leg mechanism is shown in table 2.7.

Table 2.7 Motor comparison

Parameter	Servo motor	Stepper motor
Precision	Servo motors have low pole count (between 4-12)	Stepper motors, due to their high pole count (usually between 50 and 100) offer precision drive control
Torque/Speed	High levels of torque at high speed	High torque at low speed, at speed they lose nearly all their torque, sometimes up to 80%
Noise	Servo motors can work in AC or DC drive, and do not suffer from vibration or resonance issues.	High vibrations levels and are prone to resonance issues

CHAPTER 3 : PROPOSED METHODOLOGY

Engineers often build robots that are inspired by nature. Nature has evolved efficient and optimized solutions over millions of years. Engineers study biological systems to understand their mechanisms and apply those principles to design robots that can perform tasks more effectively and efficiently. For example, studying the flight of birds has led to the development of more efficient drones and aircraft. Biomimicry is the practice of imitating nature to solve human challenges. Engineers look to the natural world for inspiration and mimic the structures, mechanisms, and behaviors of organisms to create innovative and effective designs. By emulating nature, engineers can leverage the efficiency and functionality of natural systems to improve the performance of robots.

Legged robots are far behind in cost of transport (COT) as compared to wheeled robots. The purpose of this thesis is to improve the energy efficiency and speed of legged robots using biomimicry. A model is trained on animal dataset and from that trained model parameters will be predicted like the limb length. Based on the weight, velocity and other input parameters of the quadruped robot. The limb length will be predicted that can be used for designing the quadruped robot. Figure 3.1 shows the block diagram of the proposed framework.

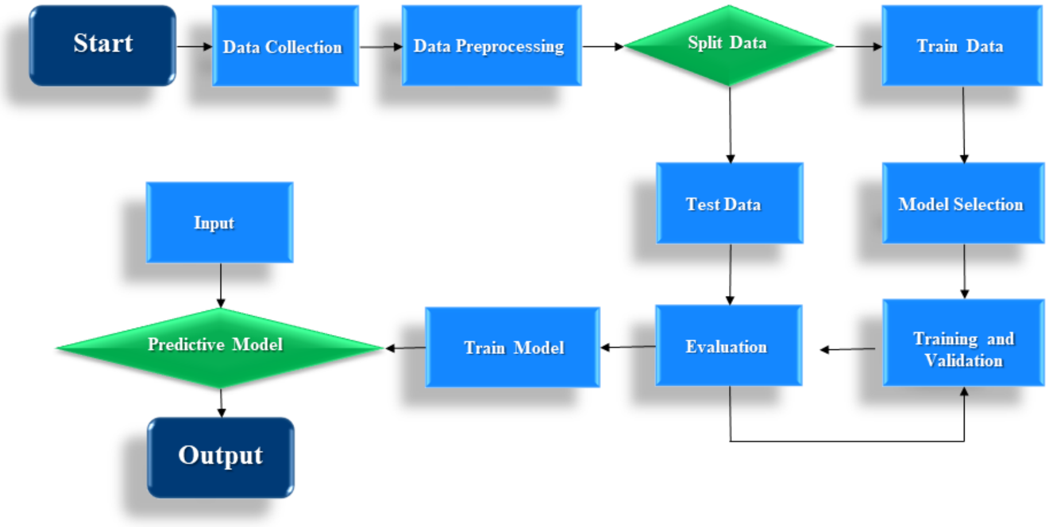


Figure 3.1 Block diagram of the proposed framework

3.1 Sample Information:

The most critical element of using biomimicry approach is the data set. It serves as the foundation upon which models are trained and evaluated. To draw biologically meaningful comparisons concerning the relationship between limb length, speed and weight. A through research is carried out. The search engines used included Google scholar, Microsoft Academic, PubMed, Web of science and Academic Search. The focus of the research is how each of these variables correspond to each other. After researching the literature, the data set is taken from figshare. The database contains the data of 103 species across 38,408 cycles. Recently in 2022, a W category journal is published on this data set which reaffirms the authenticity of this dataset [22].

3.2 Selected Parameter

The parameters through which the performance is evaluated are: Hind limb length, body mass, stride length, stride frequency and speed. Table 3.1 shows the listed parameters and their respective units.

Table 3.1 Selected Parameter

Sr. No.	Parameter	Unit
1.	Hind limb length	m
2.	Body mass	Kg
3.	Stride length	m
4.	Stride frequency	stride/s
5.	Speed	m/s

The chosen parameters and their explanations are given below:

a) **Hind limb length:**
Length of each segment from point center to point center of the hind limb. Add up all the segment length measurements to get the total hind limb length (THL). Start by taking measurements of the femur, gaskin, hind cannon, pastern, and hoof segments of the hind leg.

b) **Bodily mass:**
The sum of a person's bodily weight.

c) **Stride length**:
The distance travelled during movement in a single step or stride. It is the separation between the same foot's placements on two consecutive occasions (for instance, right foot to right foot).

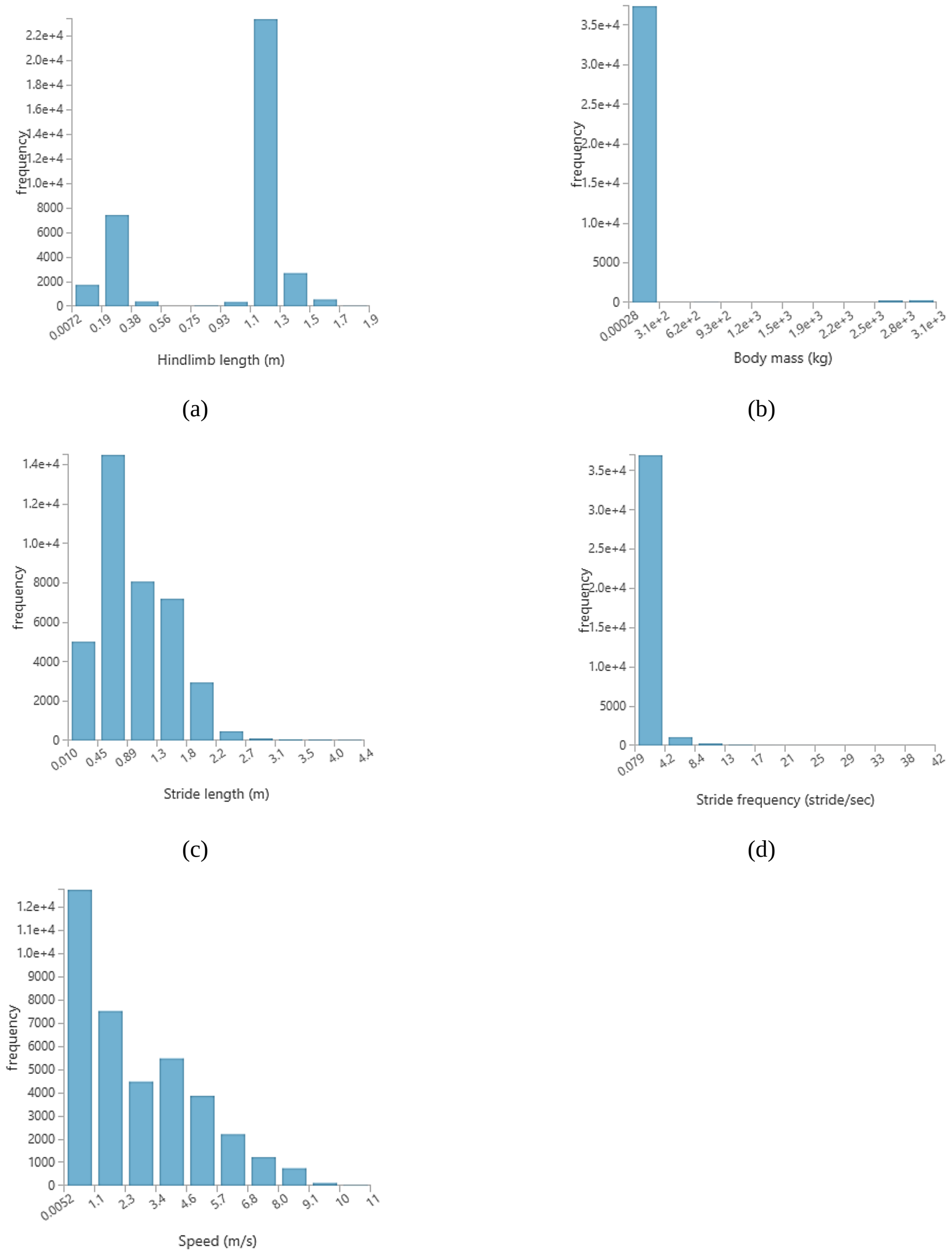
d) **Step frequency:**
The quantity of steps or strides made during locomotion per unit of time.

e) **Speed:**
Rate at which a person moves or travels a specific distance in each length of time.

3.3 Design Parameter:

While designing a quadruped robot, what we are interested is in: what will be the optimum value of hind limb length? Because all the other variables can be changed even after the designing phase. So hind limb length will be our output and all the other variables will be our inputs.

The frequency of data variables provides insights into the distribution of values within a dataset. Like, data variables with low frequency may not carry sufficient information or prediction power. High-frequency variables, on the other hand, highly influence the model. Analyzing variable frequencies can help guide feature selection and prioritize variables with the most meaningful impact. Figure 3.2 shows the frequency of each parameter.



(a)

(b)

(c)

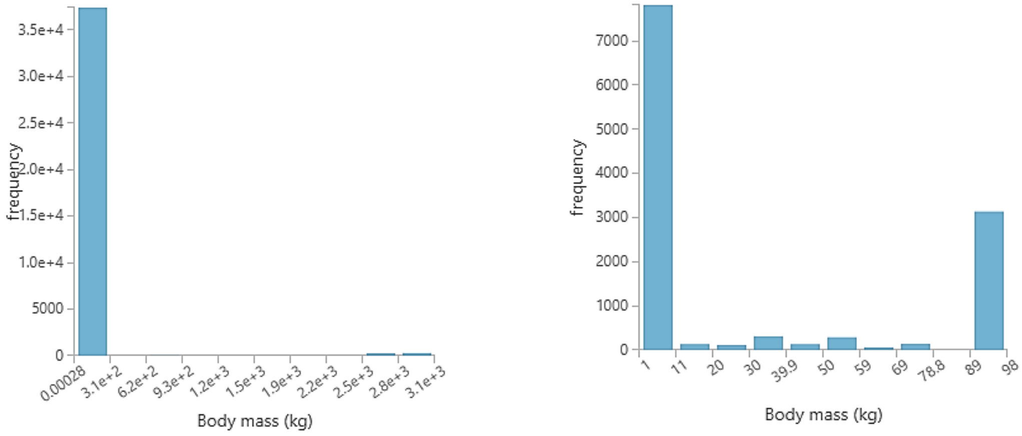
(d)

(e)

Figure 3.2 Frequency of each parameter in dataset: (a) hind limb length, (b) body mass, (c) stride length, (d) stride frequency, (e) speed

3.4 Data preprocessing:

It is observed from the data frequency graph that the large number of species have mass below 1kg. This can make the model biased towards light weight species. So, data cleaning is required to remove the biasness. This is done by removing data of species having weight below 1 kg. After cleaning the data set biasness is being removed but now the model that will be trained will not be for robots having size below 1 kg, which is not a problem as quadruped robots develop over the years are much heavier than 1 kg. Figure 3.3 shows the data before and after cleaning.



(a) (b)

Figure 3.3 Data cleaning: (a) Before, (b) After

3.5 Machine Learning:

The database was constructed and uploaded to Microsoft machine learning studio also known as Azure Machine Learning Studio Classic. It is a cloud-based integrated development environment (IDE) provided by Microsoft for building, deploying, and managing machine learning models. The workflow can be seen in Fig 3.4.

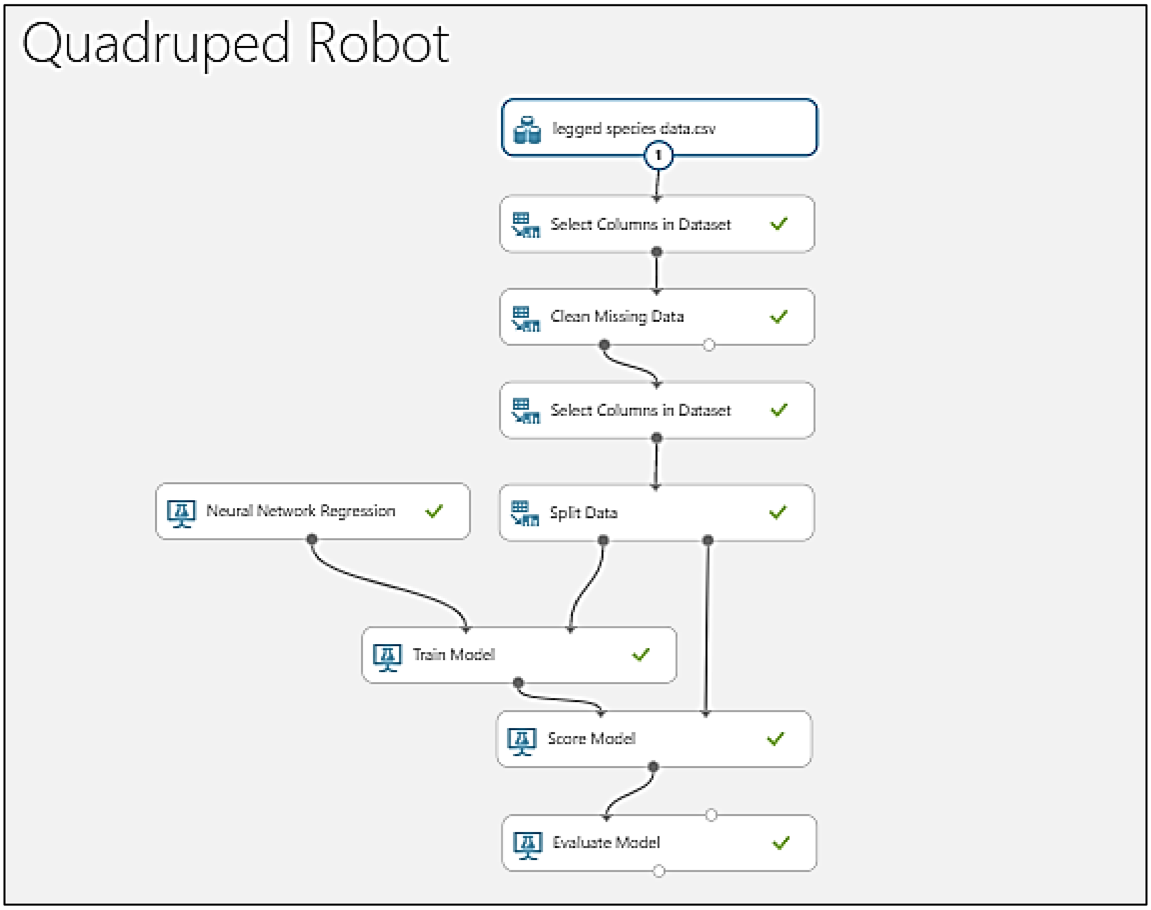


Figure 3.4 Azure Flow chart

3.6 Data Segmentation

In machine learning, splitting data refers to dividing a dataset into separate subsets for training, validation, and testing purposes. The most common splits are typically between the test and training set.

3.6.1 Training set:

The training set is a specific portion of the dataset that is employed to train a machine learning model. During the training process, the model analyzes and learns from the patterns and relationships present within this dataset. By understanding these patterns, the model becomes capable of making predictions or classifications based on new, unseen data.

3.6.2 Test set:

The test set is a crucial component in evaluating the performance of a trained machine learning model. It serves as a benchmark to objectively assess how well the model generalizes to unseen data. The test set consists of data that was not used during the training phase, ensuring an unbiased evaluation. By applying the trained model to the test set, its performance can be measured, providing insights into its effectiveness and ability to make accurate predictions on new and unfamiliar data.

Hold out method:

The strategy used to split the data is the holdout method. This involves randomly dividing the dataset into training, validation, and test sets based on predetermined ratios. The splitting ratio chosen is 70-30 split. As this is a commonly used ratio, 70% of the data is allocated for training, and the remaining 30% is used for testing.

3.7 Regression Algorithm

As we are predicting a numeric value, based on the input numeric values, the model chosen is Regression model. A regression model is a statistical model used to predict or estimate a continuous numerical output variable based on one or more input variables, also known as independent variables or predictors. The goal is to understand the relationship between the input variables and the output variable and make predictions for new or unseen data.

3.7.1 Neural network regression:

Neural networks are well-suited for regression tasks when the relationships between the input features and the target variable are complex or nonlinear. They can capture intricate patterns and dependencies in the data, enabling them to model more intricate relationships than linear regression models. As the relationship between the output and input is complex so the regression model chosen is the neural network regression model. Table 3.2 shows regression model parameters.

Table 3.2 Neural network regression model parameters

Neural Network Regression	
Trainer mode	Single parameter
Hidden layer parameter	Fully connected
Normalizer type	Min-Max
Number of hidden nodes	100
Learning rate	0.005
Number of learning iteration	100
The initial learning weight	0.1

3.8 Evaluate Model

Model evaluation helps to visualize the discrepancies between the actual value and the value, predicted by our trained model. As can be seen in Table 3.3

Table 3.3 Model evaluation

Body mass (kg)	Stride length (m)	Stride frequency (stride/s)	Speed (m/s)	Actual Hind limb length (m)	Predicted Hind limb length (m)	Error
110.87	0.702321	1.356938	0.965361	1.271	1.259279	0.9%

If you examine the frequency of error in each predicted value, most of the errors are below 1%, means the prediction value is very accurate. Figure 3.5 shows the distribution of errors in a prediction model.

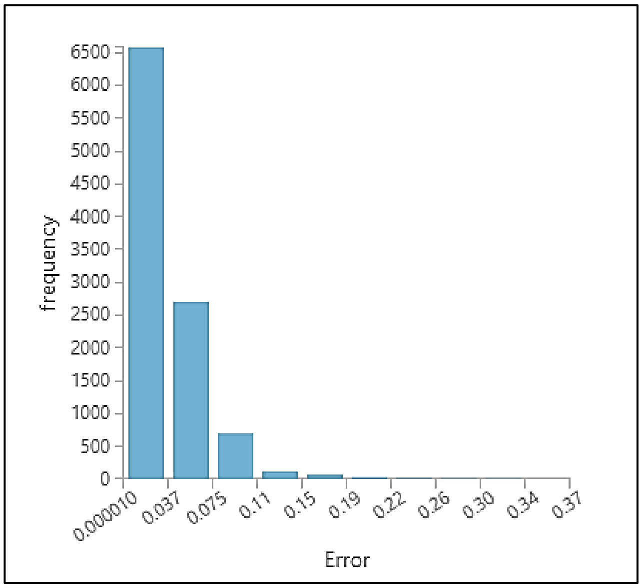


Figure 3.5 Error graph

So, the overall determination rate of this trained model is **98.5531%**

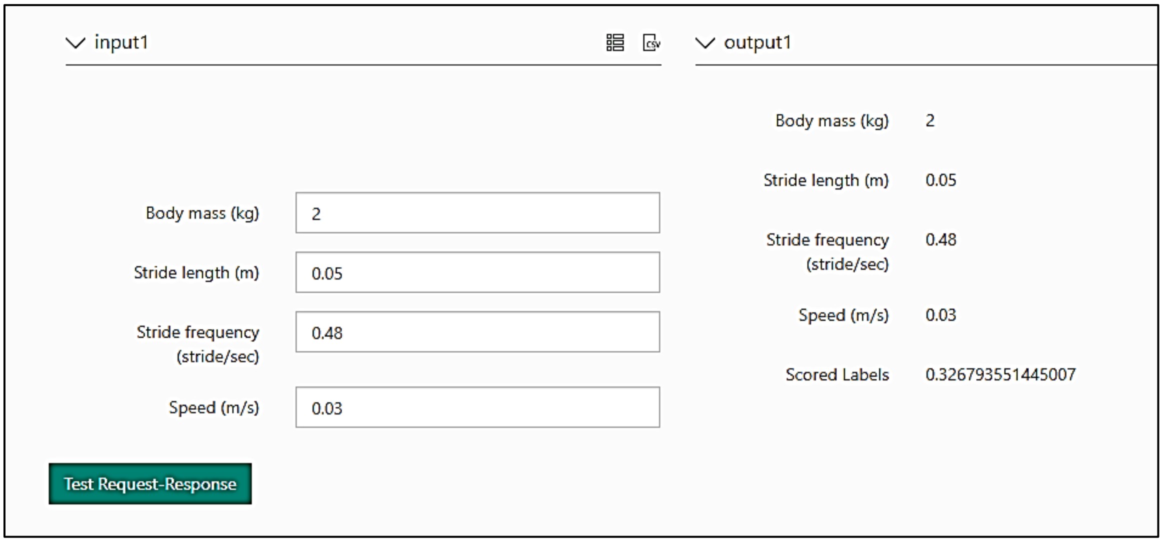
Table 3.4 Trained model Coefficient of determination

Parameter	Value
Mean Absolute Error	0.035814
Root Mean Squared Error	0.04852
Relative Absolute Error	0.107305
Relative Squared Error	0.014469
Coefficient of Determination	**0.985531**

3.9 Web Service

Trained machine learning model is deployed as web services in a scalable and secure manner. This allows us to make predictions. I have given my quadruped input values of body mass, stride length and stride frequency and it gives me the output, hind limb length value of 0.32m which I can use to develop my robodog.

The model is trained and deployed on the Azure web service. So that can be used from anywhere. Just open the Azure web service, a page will open as can be seen in Figure 3.6 and get the predicted hind limb length based on the input parameters.



input1

Body mass (kg) 2
Stride length (m) 0.05
Stride frequency (stride/sec) 0.48
Speed (m/s) 0.03

output1

Body mass (kg) 2
Stride length (m) 0.05
Stride frequency (stride/sec) 0.48
Speed (m/s) 0.03
Scored Labels 0.326793551445007

Figure 3.6 Web service of trained model

CHAPTER 4 : SYSTEM DESIGN

The design principles of their natural equivalents in nature may be immediately applied to the development of legged machines that are designed particularly for dynamic maneuvers. For instance, segments should be constructed as light as feasible to reduce inertia, and heavier elements such as motors, should be positioned near to the main body. These speeds up the swing leg action and lessens impact energy losses upon touchdown. To make the system naturally resilient over landing impacts, to allow passive adjustment, and to allow short-term energy storage, elastic parts should separate actuators and joints. One should strive for an array of flexibility across all joints and carefully connect all the electrical and mechanical systems to achieve maximum mobility.

In this chapter, we demonstrate how the quadrupedal robot followed these broad guidelines for design. We describe the mechanical characteristics of the whole system and each of its four independently operable legs. Wheels are placed just below the knee joint on the tibia of the legs to increase the wheel’s degree of freedom. We place a lot of emphasis on compliant joint actuation because we believe it to be the essential component for integrating adaptability, speed, efficiency, and robustness into a single robotic system. We examine and contrast several wheel configurations and then demonstrate the final hardware implementation. The framework for mechanics and actuation is efficiently designed and tightly integrated to keep the complete robot light and powerful. A brief overview of the electrical setup and the integrated software framework for simulation and control rounds off the chapter.

4.1 Proposed mechanism

We established the following fundamental standards for our prototype robot:

1. Wheels provide quick and effective movement on flat ground; a robot should travel on wheels there.
2. The robot is capable of movement in a discontinuous contact environment.
3. Legs should be employed in uneven terrain since they provide quick and effective movement over uneven terrain.
4. There should also be a hybrid approach in which wheels and legs both can be used.

4.2 Modelling

The system is designed in such a way that hybrid walk and roll quadruped robot involves combining elements of both walking and rolling mechanisms to achieve locomotion. Fig. 4.1 shows the proposed model. A model is the same as, but more accessible than, the system it describes. One goal of the model is to analyze and forecast the impact of device changes. Legged robots are part of the floating base or free-floating system class, which includes systems that are not physically attached to their surroundings, such as a robotic arm, but may move anywhere in space utilizing the earth as support. They have an unactuated base and interact with the surroundings via various and constantly changing contact points to either remain still or move themselves ahead. For the scale of the construction, the mechanical properties are adequate.

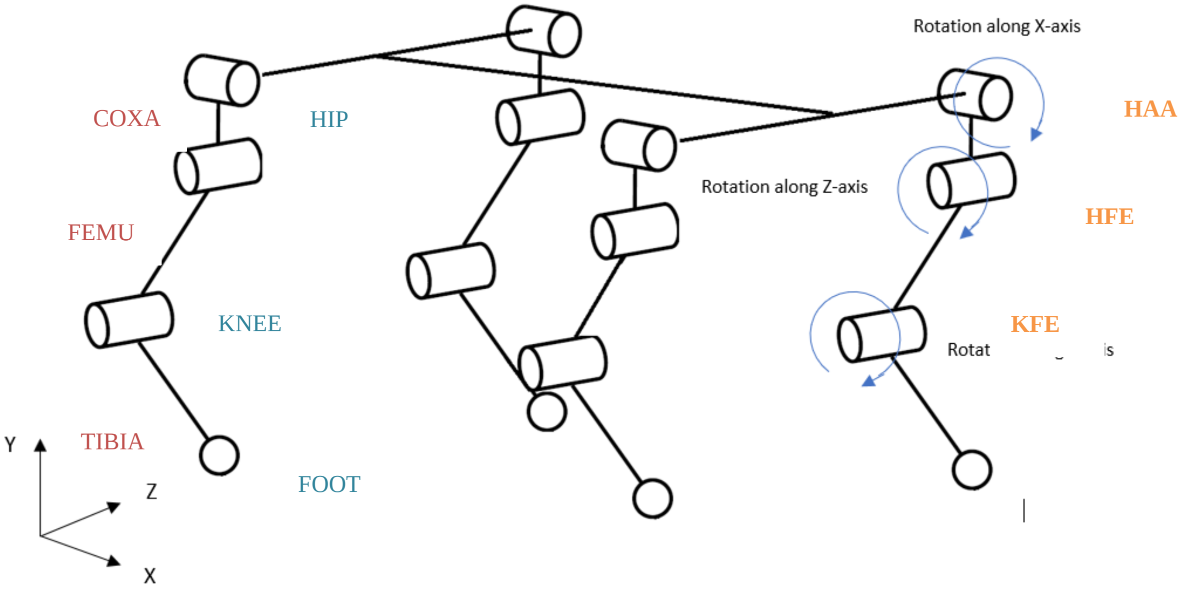


Figure 4.1 Quadruped robot modelling

4.3 Forward Kinematics

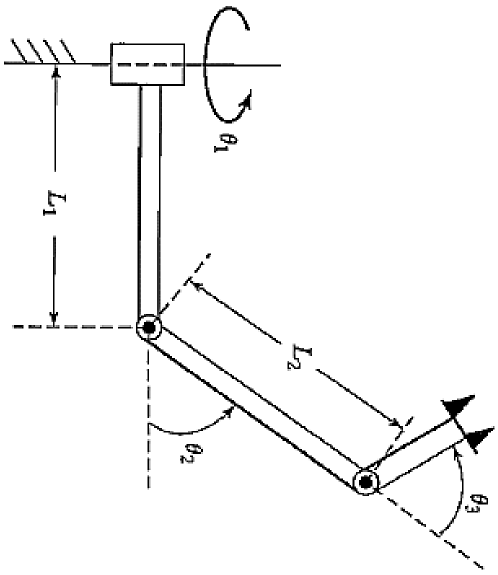


Figure 4.2 Single leg modelling

Table 4.1 DH-parameter

i	**α_{i-1}**	**a_{i-1}**	**d_i**	**Θ_i**
1	0	0	0	Θ_1
2	90°	L_1	0	Θ_2
3	0	L_2	0	Θ_3

$${}_{0}^{1}T = \begin{bmatrix} \cos(\Theta1) & -\sin(\Theta1) & 0 & 0 \\ \sin(\Theta1) & cos(\Theta1) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}_{2}^{1}T = \begin{bmatrix} \cos(\Theta2) & -\sin(\Theta2) & 0 & L1 \\ 0 & 0 & -1 & 0 \\ sin(\Theta2) & \cos(\Theta2) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}_{3}^{2}T = \begin{bmatrix} \cos(\Theta3) & -\sin(\Theta3) & 0 & L2 \\ sin(\Theta3) & \cos(\Theta3) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}_{F}^{B}T = {}_{3}^{0}T = {}_{1}^{0}T\ {}_{2}^{1}T_{3}\ {}^{2}T$$

$$ {}_{F}^{B}T = \begin{bmatrix} c1c23 & -c1s23 & s1 & L1c1 + L2c1c2 \\ s1c23 & -s1s23 & -c1 & L1s1 + L2s1c2 \\ s23 & c23 & 0 & L2S2 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

where?

$$c1 = \cos(\Theta_1)$$

$$s1 = \sin(\Theta_1)$$

$$c_{23} = \cos(\Theta_2)\cos(\Theta_3) - \sin(\Theta_2)\sin(\Theta_3)$$

$$s_{23} = \cos(\Theta_2)\sin(\Theta_3) + \sin(\Theta_2)\cos(\Theta_3)$$

4.4 Inverse Kinematics

Inverse Kinematics is a technique used in robotics and computer graphics to determine the joint parameters of a robot or a character animation based on a desired end effector position and orientation.

Proposed Inverse Kinematics (IK) model attempts to convert some intuitive domain, like XYZ cartesian coordinate system of a quadruped robot, into directly useful values, like motor angles.

Desired values:

1. Hip angle = θ_h
2. Femur angle = θ_f
3. Tibia angle = θ_t

Known values:

1. femur length
2. tibia length
3. coordinates (x, y, z)
4. off_0
5. off_1

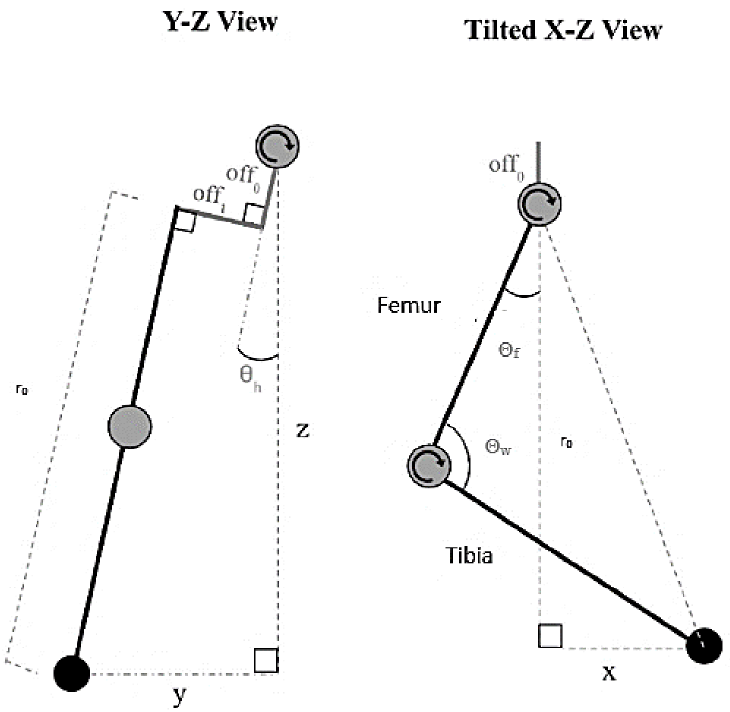


Figure 4.3 Single leg modelling in YZ and XZ plane

4.4.1 Y-Z view

It is important to draw attention to the fact that the view on the right is a tilted X-Z view, which is tilted with respect to r_0. This allows us to carry over the r_0 from our calculations from the Y-Z view.

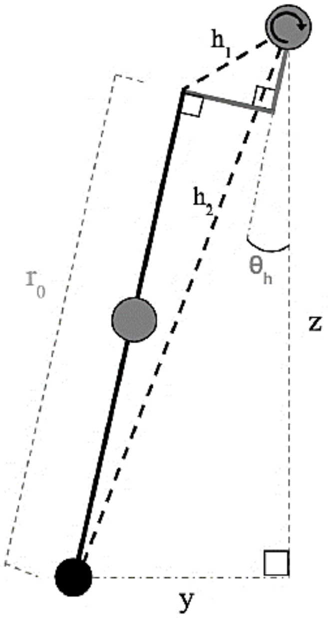


Figure 4.4 Single leg modelling in YZ plane

First, we calculate h_1 and h_2 using Pythagorean Theorem:

$$h_1 = \sqrt{off_0{}^2 + off_1^2} \tag{4.1}$$

$$h_2 = \sqrt{y^2 + z^2} \tag{4.2}$$

For θ_h and r_o

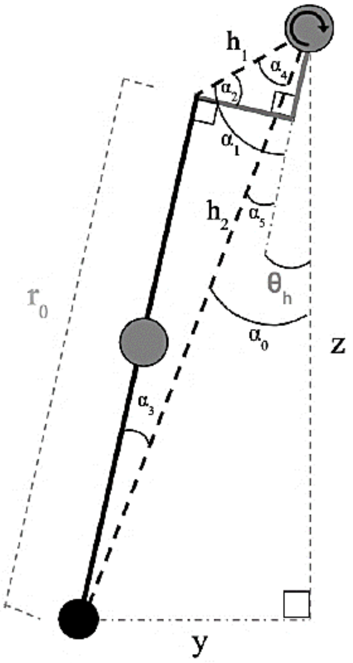


Figure 4.5 Single leg YZ plane parameter

$$\alpha_0 = \arctan\left(\frac{y}{z}\right)$$

$$\alpha_1 = \arctan\left(\frac{off_1}{off_0}\right)$$

$$\alpha_2 = \arctan\left(\frac{off_0}{off_1}\right)$$

$$\alpha_3 = \arcsin\left(\frac{h_1 * \sin\left(\alpha_2 + 90\right)}{h_2}\right)$$

$$\alpha_4 = 90 - (\alpha_3 + \alpha_2)$$

$$\alpha_5 = \alpha_1 - \alpha_4$$

So θ_h becomes.

$$\boxed{\boldsymbol{\theta_h = \alpha_0 - \alpha_5}} \qquad (4.3)$$

By applying Law sines to derive r_0:

$$\frac{r_0}{\sin\alpha_4} = \frac{h_1}{\sin\alpha_3}$$

$$\boxed{\boldsymbol{r_0} = \frac{\boldsymbol{h_1} * \sin\boldsymbol{\alpha_4}}{\sin\boldsymbol{\alpha_3}}} \tag{4.4}$$

4.4.2 Tilted XZ view.

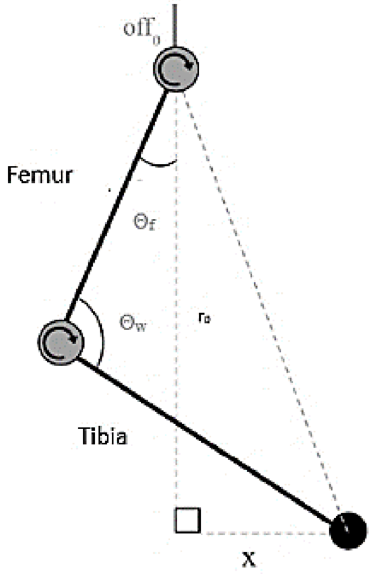


Figure 4.6 Single leg modelling in XZ plane

$$h = \sqrt{r_0^2 + x^2}$$

$$\sin\phi = \frac{x}{h}$$

$$\phi = arcsin\left(\frac{x}{h}\right)$$

By applying Law of cosines to get Θ_f

$$\cos(\Theta_f + \phi) = \frac{h^2 + s^2 - w^2}{2 * h * s}$$

$$\boxed{\boldsymbol{\Theta_f = \arccos\left(\frac{h^2+s^2-w^2}{2*h*s}\right) - \phi}} \tag{4.5}$$

By applying Law of cosines to get Θ_t

$$\boxed{\boldsymbol{\Theta_t = \arccos\left(\frac{w^2+s^2-h^2}{2*w*s}\right)}} \tag{4.6}$$

Thus, given any x y z coordinate (within the bounds of the control range of the actuator), the exact joint angles can be calculated.

4.5 Embedded System:

The innovative idea of ROBODOG necessitates a unique electronics design to take into consideration the components and computing requirements of the robot. Table 3 shows the list of electronic components.

Table 4.1 List of components

Part name	Description
ESP32 Lolin32	CPU
PCA9685 module	Servo motor controller
SPT5430HV-180W 8.4V	12x Servo motors (3 per leg)
DC-DC buck converter	7V-28V to 5V 3A
Wheel motor	DC motor
L298N module	DC motor driver
Power	12V Lipo-battery

As we are developing a small-scale robot for research purposes so ultimate choice is the electrical actuator as they are typically lighter and more compact than hydraulic actuators and can be more easily integrated into the robot's control system. They have good controllability and precision, with fast response times and high-frequency capabilities.

To have full control over the walking mechanism 12 servo motors(3 per leg), requires PCA9685, a 16-channel, 12-bit pulse width modulation (PWM) controller .While four dc motors require four pulse width modulation (PWM) channels that are transformed into the necessary signals for the motor windings through two LM298 H-bridges. Furthermore, the on-board controller must be powerful enough to compute live kinematics and apply closed-loop control. ESP 32 controller is used. The ESP32 expands its versatility by including a Bluetooth 4.2 radio in addition to Wi-Fi compatibility. The ESP32 has twin cores using the 32-bit Xtensa® LX6. Additionally, it has 416KB of SRAM and 128KB of ROM. However, Flash memory, which supports storage capacity of up to 64MB, continues to be provided via an external chip. With a variety of features, such as a wireless antenna, RF, power booster, low-noise audio amplifiers, filters, and a power management module, the ESP32 microcontroller offers a small and integrated solution. The area on printed circuit boards may be utilized effectively because of its compact design. It makes use of TSMC 40nm low power technology, which guarantees ideal RF and power performance while preserving dependability and scalability for a variety of applications.

Fig. 12 shows the schematic diagram.

4.6 Leg Actuator:

When comparing the accomplishments of previously built quadrupedal robots, it is discovered that physical requirements and dimensioning were critical in the design of the mechanical structure. It is difficult to specify the exact weight and size of the robot at first. The availability of components in the marketplace influences the size of the robot. The weight of the robot is determined by the actuation mechanism (electrical or hydraulic) as well as its onboard electronics. Choosing the leg length, on the other hand, is a critical element in robot design and development. Most of the robot's leg length is smaller than the robot's size. Over-proportionately long legs typically collide with each other, and a high proportionally body shape necessitates greater balance while being less nimble.

As we are developing a small-scale robot for research purposes so ultimate choice is the electrical actuator as they are typically lighter and more compact than hydraulic actuators and can be more easily integrated into the robot's control system. They have good controllability and precision, with fast response times and high-frequency capabilities. Hydraulic actuators are generally heavier and bulkier, and they require a separate power source and control system. They also have higher energy consumption and can generate heat, which needs to be dissipated.

Figure 4.7 SPT 5430 servo motor

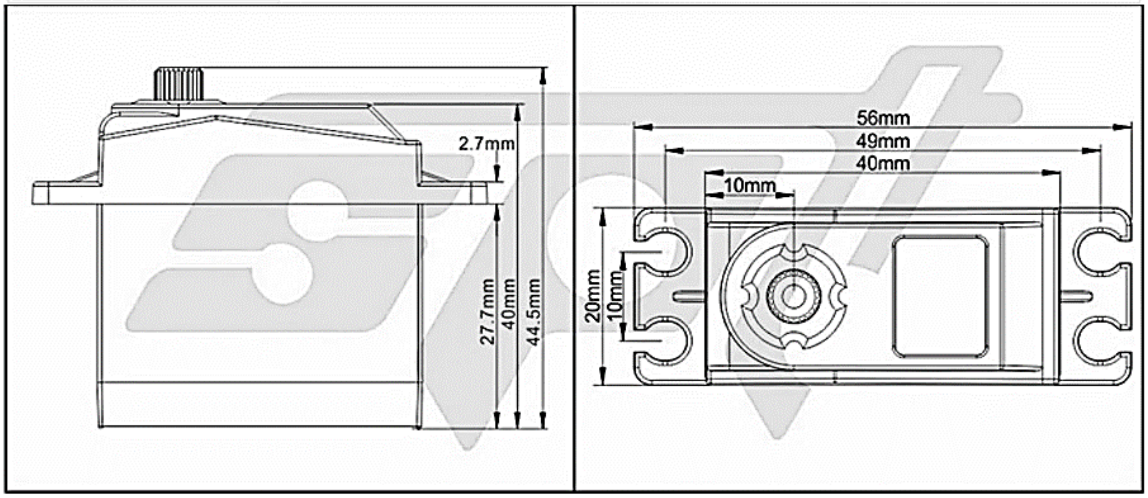


Figure 4.8 Servo motor dimension

Table 4.2 SPT5430 motor specification[23]

Brand	SPT Servo	Potentiometer	Mechanics
Motor	Core	Voltage Range	4.8V/6.0V/8.4V
Neutral Point	1500us	Signal Frequency	330Hz
PWM Voltage	3.3V-5.0V	PWM Voltage	3.3V-5.0V
Feedback Angle	No	Operating Temperature	-10°C - 50°C
Cycle	20ms	Dead band	4us
Default Direction	CCW	Lock	Yes
Remote control Angle	90°	500-2500us Angle	180°/PWM
Quiescent Current	10mAh	Rated Current	1.2A
Blocking current	2.5A	Weight/Dimension	62g/40.5*20*40.5mm
Output Gear	Futaba 25T	Gear Material	All metal Gear
Shell material	Half Aluminum Shell	Bearing	2BB
Connector wire length	260mm	Line definition	Brown-/Red+/Orange
Operating speed	/	6.0V/0.17’’/60°	8.4V/0.15’’/60°
Stall torque	/	6.0V/24.3 kg.cm	7.4V/30 kg.cm

4.7 Wheel actuator:

Due to their accessibility and ease of control, DC motors are chosen for robotic mobility. The torque and mechanical power of the DC motor can be changed by adjusting its speed in accordance with the requirements of the robot.

Mathematical Representation:

The following equation can be used to determine the motor's torque:

$$\tau = \frac{1}{Nw} \times \frac{Dw}{2} \times FT \tag{4.7}$$

where τ is the required torque, N_W is the number of wheels, D_W is the diameter of the wheel, and F_T is the total mechanical force.

F_T is given by:

$$F_T = F_G + F + M_a \tag{4.8}$$

$$F_T = Mg \sin \alpha + \mu \, Mg \cos \alpha + M \, a \tag{4.9}$$

F_G and F_μ represent the gradient force and rolling resistance force, respectively, which are the external forces acting on the wheel as shown in Figure 4.9. M, a, μ, and g represent the payload capacity, constant acceleration, coefficient of rolling friction, and gravity, respectively.

The mechanical power of the motor is calculated using the following equation:

$$P_M = F_T \times V_N \times 1/N_W \tag{4.10}$$

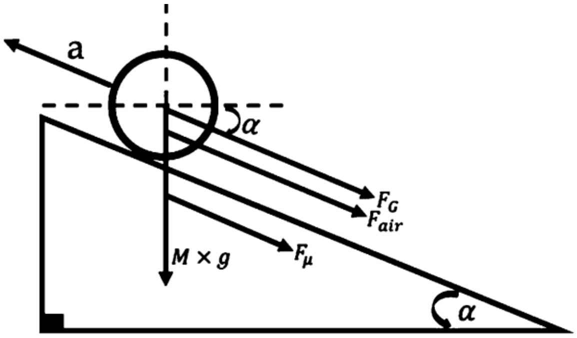


Figure 4.9 Forces acting on wheel on inclined surface [24]

Figure 4.9 shows the vector representation of gradient force (F_G), rolling resistance force (F_μ), force due to gravity (M x g) and air resistance force (F_{air}) acting on the wheel when moved on an inclined surface at an angle “α”.

Here V_N, N_W and D_W represent nominal velocity, number of wheels used and diameter of the wheel, respectively.

Figure 4.10 Wheel motor

Table 4.3 Wheel motor specification

DC Voltage	3V	5V	6V
Current (mA)	100	110	120
RPM (with wheel)	100	190	240
Reduction ratio		48:1	
Noise		<65db	
Weight		29g	

Figure 4.11 Wheel motor dimension

4.8 Controller

With a variety of features, such as a wireless antenna, RF, power booster, low-noise audio amplifiers, filters, and a power management module, the ESP32 microcontroller offers a small and integrated solution. The area on printed circuit boards may be utilized effectively because of its compact design. It makes use of TSMC 40nm low power technology, which guarantees ideal RF and power performance while preserving dependability and scalability for a variety of applications.

The ESP32 is superior to the ESP8266 in several ways even if it does not completely replace it. The ESP32 expands its versatility by including a Bluetooth 4.2 radio in addition to Wi-Fi compatibility. The ESP32 has twin cores, but the CPU architecture is the same as the ESP8266, using the 32-bit Xtensa® LX6. Additionally, it has 416KB of SRAM and

128KB of ROM. However, Flash memory, which supports storage capacity of up to 64MB, continues to be provided via an external chip.

Table 4.4 Controller comparison

Specifications	ESP32	ESP8266	Arduino Uno
MCU	Xtensa Dual-Core 32-bit LX6 600 DMIPS	Xtensa Single-Core 32-bit L106	Single-Core ATmega328P
Wi-Fi	Yes, HT40 802.11 b/g/n	Yes, HT20 802.11 b/g/n	X
Bluetooth	4.2	X	X
Frequency (MHz)	160	80	16
SRAM (KB)	512	160	2
Flash memory (MB)	16	16	0.032
GPIO Pins	36	17	14
PWM	16	8	6
Buses (SPI/I2C/UART/I2S/CAN)	4-2-2-2-1	2-1-2-2-0	1-1-1-0-0
ADC (bit)	12	10	10
Working Temperature	-40 ° C-->125°C	-40°C-->125°C	-40°C-->85°C

4.8.1 ESP32 WeMos LOLIN32

A sophisticated microcontroller board based on the ESP32 microcontroller created by Espressif is called the ESP32 LoLin32. The LOLIN32 ESP32 board has a built-in lithium battery charger circuit that uses the TP4054. It is a fantastic option for battery-powered apps because of its functionality.

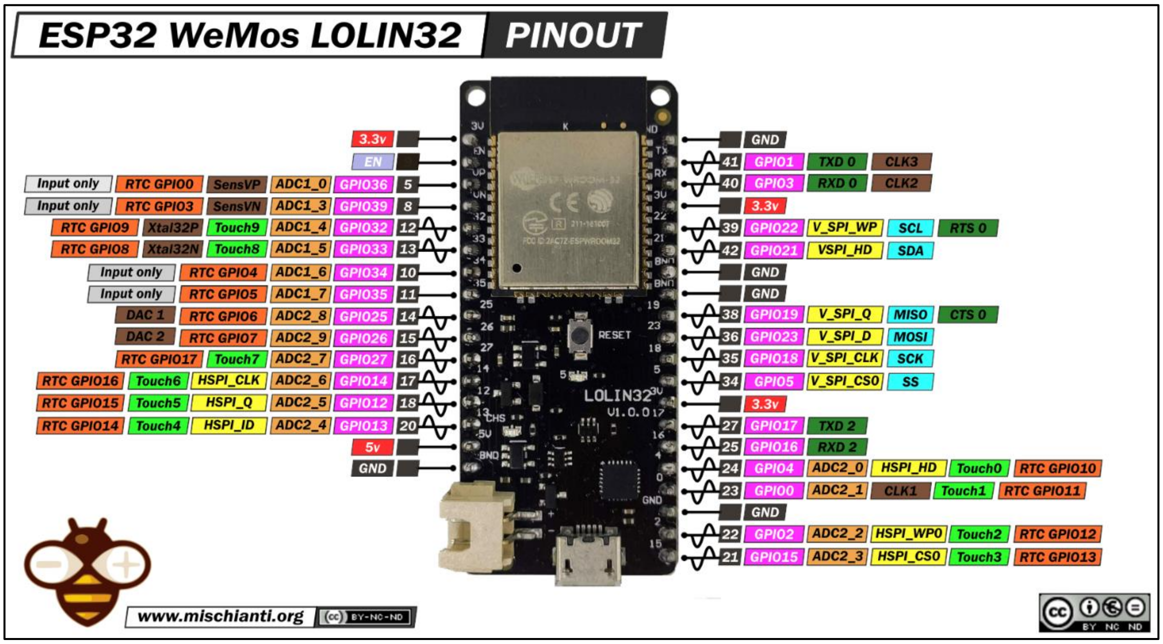


Figure 4.12 ESP32 controller Wemos Lolin32 pin configuration

Some of its notable features includes:

1. **Dual-core CPU:** The ESP32 LoLin32 has a dual-core processor, which increases performance and lets it execute numerous tasks at once.

2. **Wi-Fi and Bluetooth:** Wi-Fi and Bluetooth support are incorporated into the ESP32 LoLin32, enabling it to connect to wireless networks and gadgets. For IoT and wireless communication applications, this makes it perfect.

3. **Low power consumption:** Because of its low power requirements, the ESP32 LoLin32 is appropriate for battery-powered applications.

4. **Large memory:** The ESP32 LoLin32 has a lot of memory, including flash and RAM, which enables it to execute sophisticated programs and store a lot of data.

5. **Variety of Interfaces:** The ESP32 LoLin32 supports several interfaces, including UART, SPI, I2C, I2S, and PWM, enabling it to connect to a variety of sensors and devices.

6. **Secure:** The hardware-based security capabilities of the ESP32 LoLin32, including secure boot, flash encryption, and secure key storage, offer a high level of application security.

7. **Open-source:** The open-source ESP-IDF (Espressif IoT Development Framework), on which LoLin32 is based, has a large community that offers support, libraries, and examples.

8. **Affordability:** The ESP32 LoLin32 is reasonably priced, which makes it available for a variety of applications.

4.9 Motor Driver:

PCA9685, a 16-channel, 12-bit pulse width modulation (PWM) controller. It can regulate a variety of things, including the position of servo motors, the speed of motors, and the brightness of LEDs.

The PCA9685 is managed by an I2C interface, which enables the connection of several devices to a single bus. The PCA9685's unique control of each channel enables fine control of several devices.

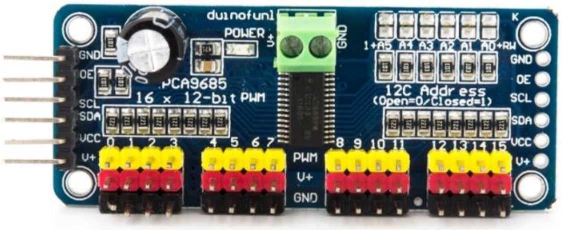


Figure 4.13 Servo driver module PCA9685

Some of the advantages of the PCA9685 include:

1. **High resolution:** The PCA9685's 12-bit resolution enables exact control of the PWM signal's duty cycle, which is crucial for managing devices like motors and LEDs.

2. **High frequency:** The PCA9685 can produce PWM signals at a frequency of up to 1526 Hz, making it possible to operate devices quickly and smoothly.

3. **Low power consumption:** Because of its low power consumption design, the PCA9685 is appropriate for battery-powered applications.

4. **High integration:** The PCA9685 is a small and adaptable device that incorporates an oscillator and an LED driver.

5. **Wide range of applications:** The PCA9685 is a versatile device that may be used to control a variety of devices, including LEDs, motors, and servo motors.

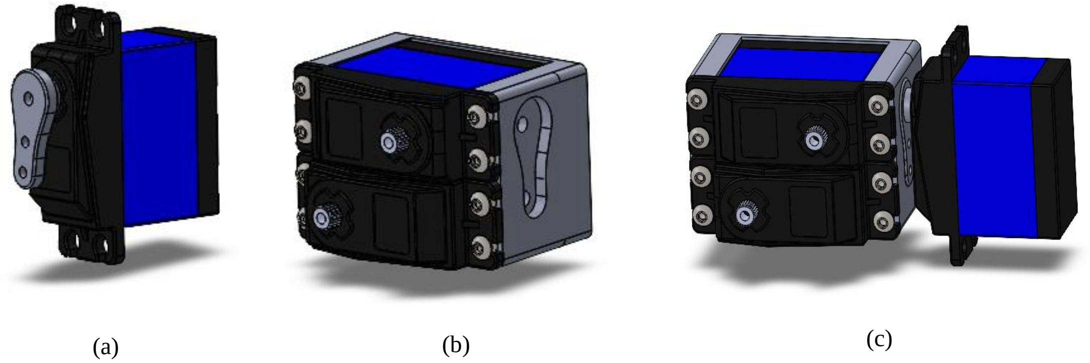
6. **Easy to use:** The I2C interface, which enables straightforward integration with microcontrollers and single-board computers, makes it simple to control the PCA9685.

CHAPTER 5 : DESIGN MODELING

A quadruped robot's design modelling method comprises several essential components. During the conception phase, the robot's overall design, leg configuration, and predicted capabilities are initially envisaged. Then, a complete CAD model with accurate representations of the robot's physical characteristics, joints, and connections is created. To create synchronized and realistic leg motions, kinematics is incorporated into the modelling process. To increase the robot's performance, the design has also been improved for mass distribution, stability, and movement efficiency. After the model has been validated through simulations and analysis, adjustments are made to increase the robot's performance, agility, and adaptability in a variety of scenarios.

5.1 Leg mechanism configuration:

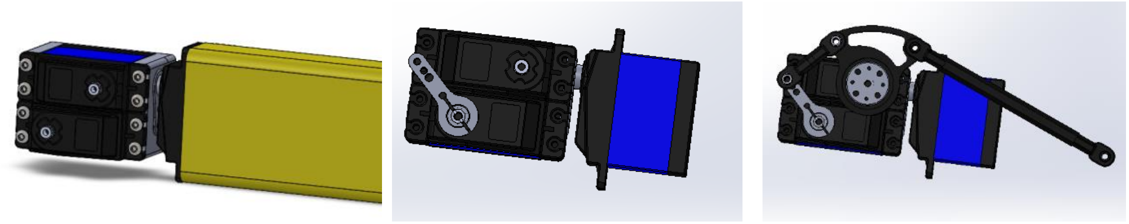
As most of the quadruped robot we study so far has second and third joints in horizontal axis, while the first joint between the torso and the thigh has a vertical axis. So, we stick with that model in our initial design. Instead of placing motors on every joint. All motors are tightly compact, giving a centralized weight. This helps in balancing the robot more easily. Figure 5.1 shows the configuration of motors.



(a) (b) (c)

Figure 5.1 (a) Servo motor 1 (Hip motor), (b) Servo motor 2 and 3 attachment (femur and tibia) and (c) Servo motors configuration

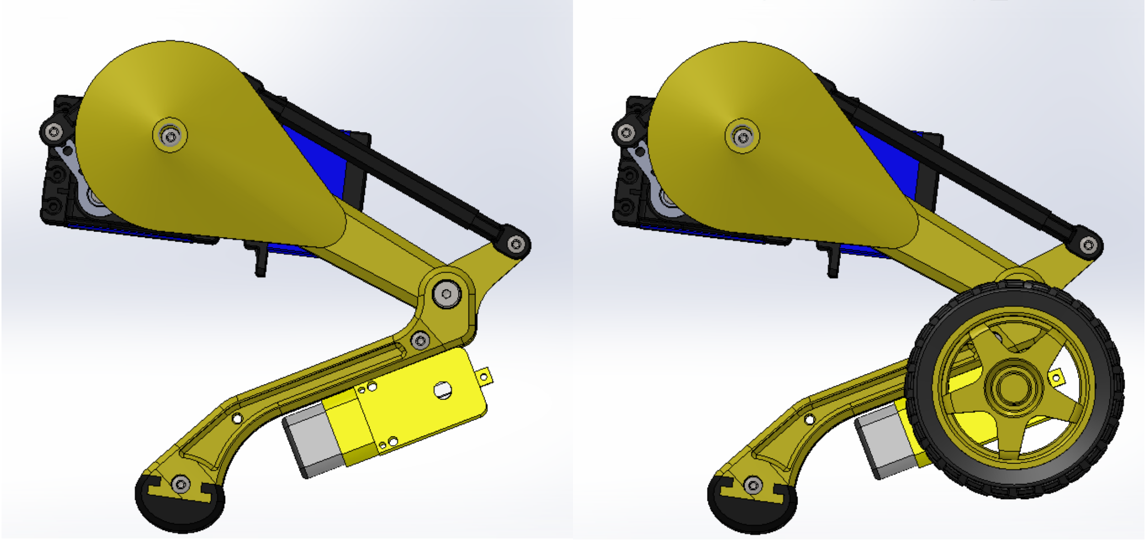
After configuring all the motors, hip motor is attached to body, hip motor allows the robot to rotate on a single point or move the robot goes left and right. Figure 5.2 (a) shows the placement of hip motor on body. As all the motors are compact, we need a bar mechanism for tibia movement. Figure 5.2 (b) and (c) shows how tibia relates with tibia motor.



(a) (b) (c)

Figure 5.2 (a) Hip motor attachment to body, (b) Tibia motor metallic arm and (c) Bar mechanism for tibia movement

Wheels are placed just below the knee joint on the tibia to increase the wheel's degree of freedom. Figure 5.3 shows the placement of wheel on tibia.



(a) (b)

Figure 5.3 (a)Attachment of wheel motor on tibia, (b) Final configuration of front left leg with wheel

In wheel mode the leg mechanism helps in height adjustability as can be seen in Figure 5.4. This allows the robot to keep a low center of gravity for stability at high speed and high center of gravity for obstacle avoidance.

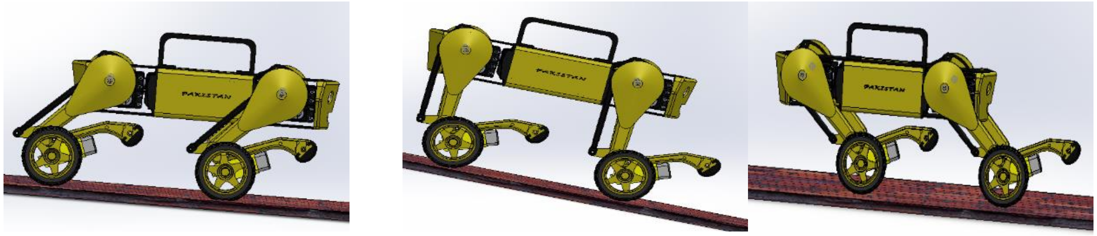


Figure 5.4 Height adjustability in wheel mode

Figure 5.5 shows the exploding view of front left leg with nut, bolt, ball bearing etc.

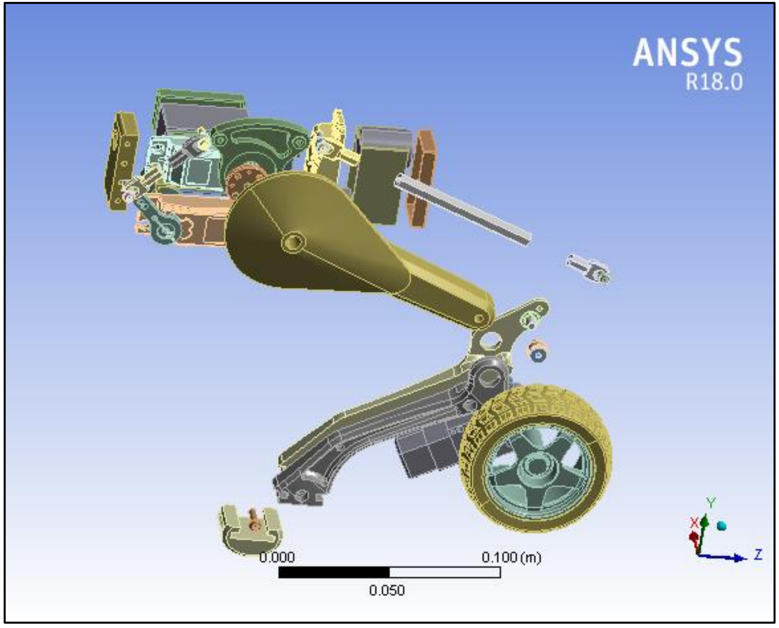


Figure 5.5 Explode view of front left leg.

5.2 System configuration

All four legs have the same design and are modular in nature so that parts can easily be replaced. The figures below show the complete assembly of RoboDog.

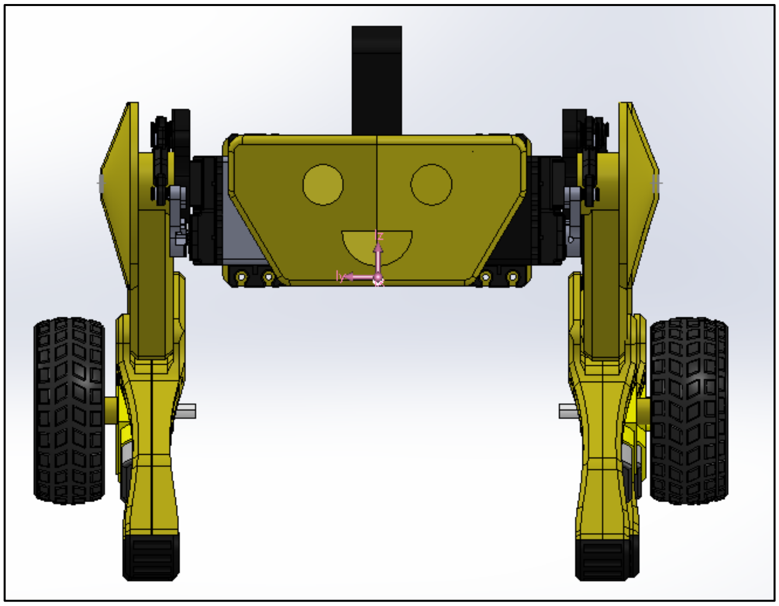


Figure 5.6 RoboDog Front View

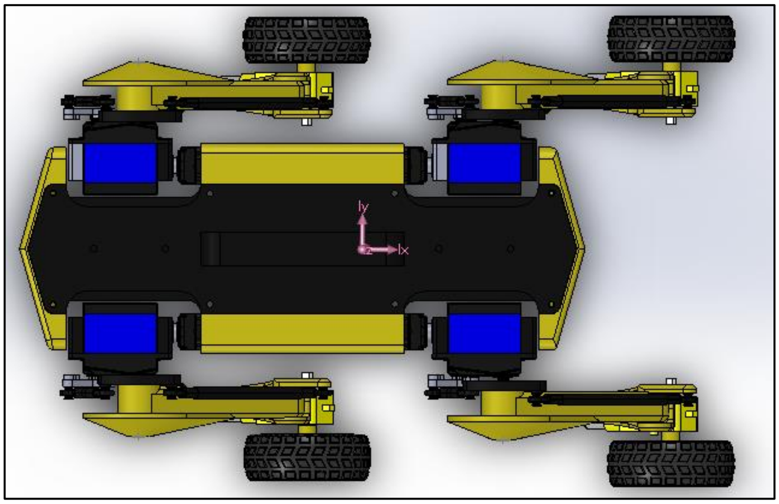


Figure 5.7 RoboDog Top View

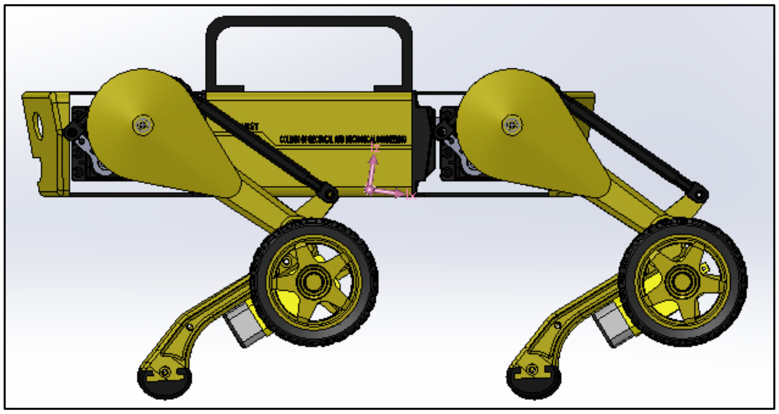


Figure 5.8 RoboDog Side View

5.3 Finite element analysis

ANSYS is a popular software suite widely used for engineering simulation and analysis. For finite element analysis, ANSYS's static structural analysis is employed to investigate how the structure will react to external forces, pressures, or restrictions.

By analyzing these findings, the structural integrity is evaluated by locating possible weak areas and design is optimized. This helps in making educated judgements about material choice.

5.3.1 Meshing

The purpose of meshing is to get accurate results of the part. After importing Solid works file to the ANSYS software, mesh creation is the next phase. The meshing result is shown in Fig. 10. The number of nodes and elements in the mesh are 61316 and 126409 respectively.

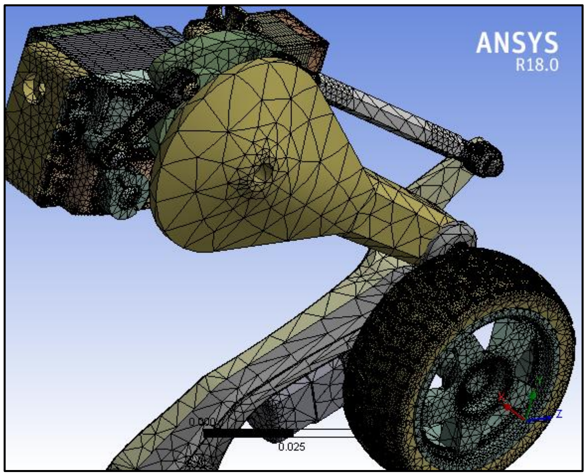
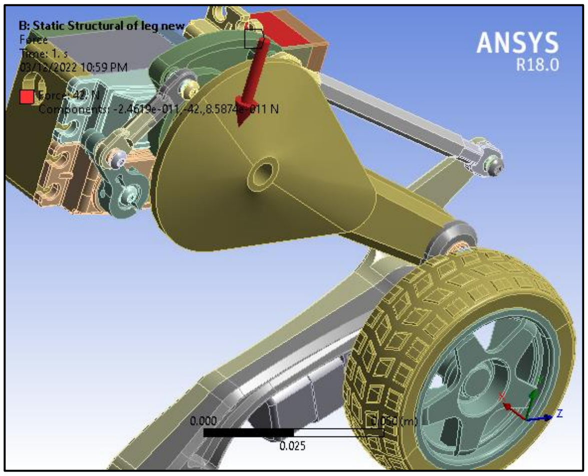


Figure 5.9 Single leg Meshing

5.3.2 Boundary conditions

Finite element analyses heavily rely on boundary conditions. Applying boundary conditions is the next step following meshing. Fixed support is applied at the foot because our goal was to see how much weight leg structure can bear in standing position. Variable force from 0 to 50 N is applied to the motor attached to the body because that’s the points where body weight shifts towards the foot.



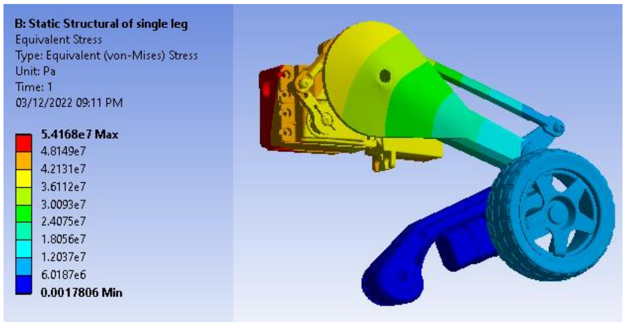
B: Static Structural of leg new
Force
Time: 1. s
03/12/2022 10:59 PM

Force: 42. N
Components: -2.4619e-011,-42.,8.5874e-011 N

Figure 5.10 Applying variable force.

5.3.3 Von-mises stress

By applying a force of 42 N maximum von-mises stress we get is 5.41e^{7} which is equal to yield strength of Polylactic acid. This means if we print our model by fused deposition modeling using PLA material, maximum load a single leg can bear is 42N.

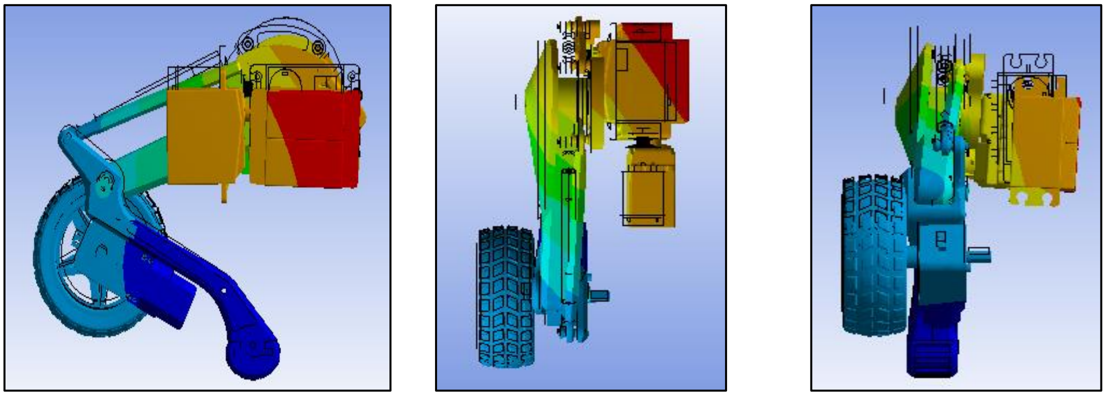


B: Static Structural of single leg
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1
03/12/2022 09:11 PM

Figure 5.11 Von-misses stress of single leg

5.3.4 Total deformation

By applying the force of 42N, figure 5.12 shows the total deformation along X, Y and Z direction. The minimum deformation occurred in the leg is 0 m at 4.51e^{-004} Pa and the maximum displacement occurred is 4.4121e^{-004} m at 1.3726e^{7} Pa.



(a) (b) (c)

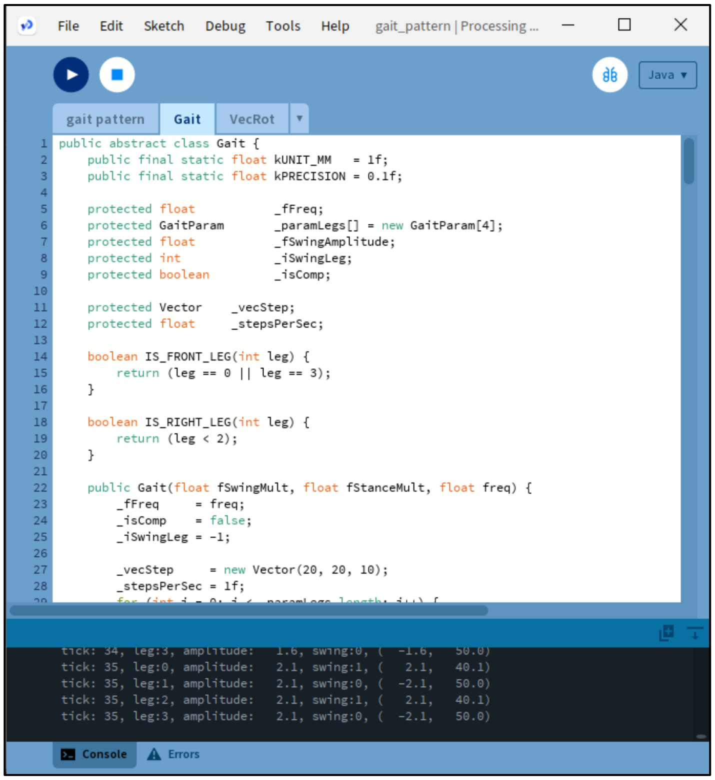
Figure 5.12 Before and after deformation (a) x-axis, (b) y-axis, (c) z-axis

CHAPTER 6 : MOTION GENERATION

Researchers study and evaluate several algorithms and control techniques for producing dependable and stable locomotion patterns in quadruped robots using computer-based simulations. To verify and improve gait generation algorithms, trajectory planning, inverse kinematics, and dynamic control techniques, these simulations reproduce the kinematics, dynamics, and environment of the robot. Prior to applying them to actual quadruped robots, researchers may improve the robot's locomotion performance, flexibility, and robustness through repeated testing and modification inside simulations. The understanding of quadruped robot motion production is being developed quickly thanks in large part to simulation.

6.1 Simulation

In this study, simulation is carried out using processing software. For projects in the visual arts, creative coding, and interactive media, Processing is an open-source integrated development environment (IDE) and programming language. It offers a streamlined programming environment that enables designers, artists, and amateur programmers to produce interactive graphics, animations, and programs.



```
public abstract class Gait {
    public final static float kUNIT_MM   = 1f;
    public final static float kPRECISION = 0.1f;

    protected float            _fFreq;
    protected GaitParam        _paramLegs[] = new GaitParam[4];
    protected float            _fSwingAmplitude;
    protected int              _iSwingLeg;
    protected boolean          _isComp;

    protected Vector    _vecStep;
    protected float     _stepsPerSec;

    boolean IS_FRONT_LEG(int leg) {
        return (leg == 0 || leg == 3);
    }

    boolean IS_RIGHT_LEG(int leg) {
        return (leg < 2);
    }

    public Gait(float fSwingMult, float fStanceMult, float freq) {
        _fFreq     = freq;
        _isComp    = false;
        _iSwingLeg = -1;

        _vecStep     = new Vector(20, 20, 10);
        _stepsPerSec = 1f;
```

```
tick: 34, leg:3, amplitude:   1.6, swing:0, (  -1.6,   50.0)
tick: 35, leg:0, amplitude:   2.1, swing:1, (   2.1,   40.1)
tick: 35, leg:1, amplitude:   2.1, swing:0, (  -2.1,   50.0)
tick: 35, leg:2, amplitude:   2.1, swing:1, (   2.1,   40.1)
tick: 35, leg:3, amplitude:   2.1, swing:0, (  -2.1,   50.0)
```

Figure 6.1 Processing Interface

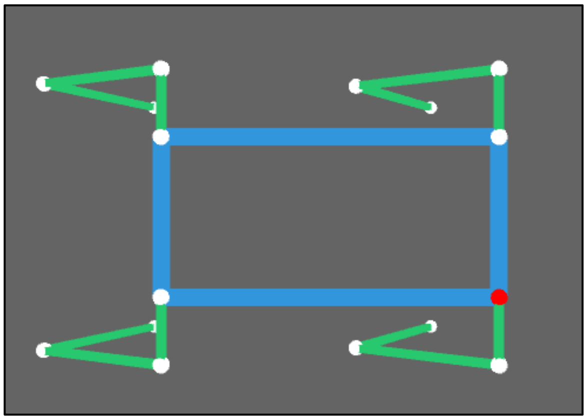


Figure 6.2 Quadruped robot in simulation model Top view

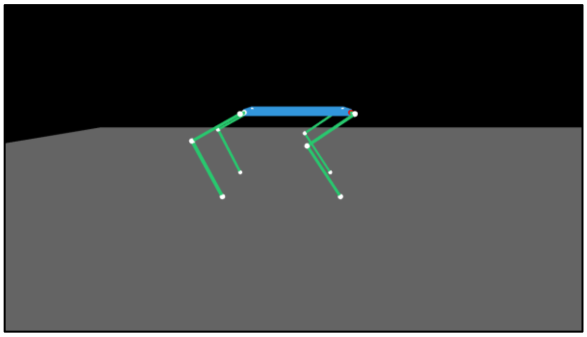


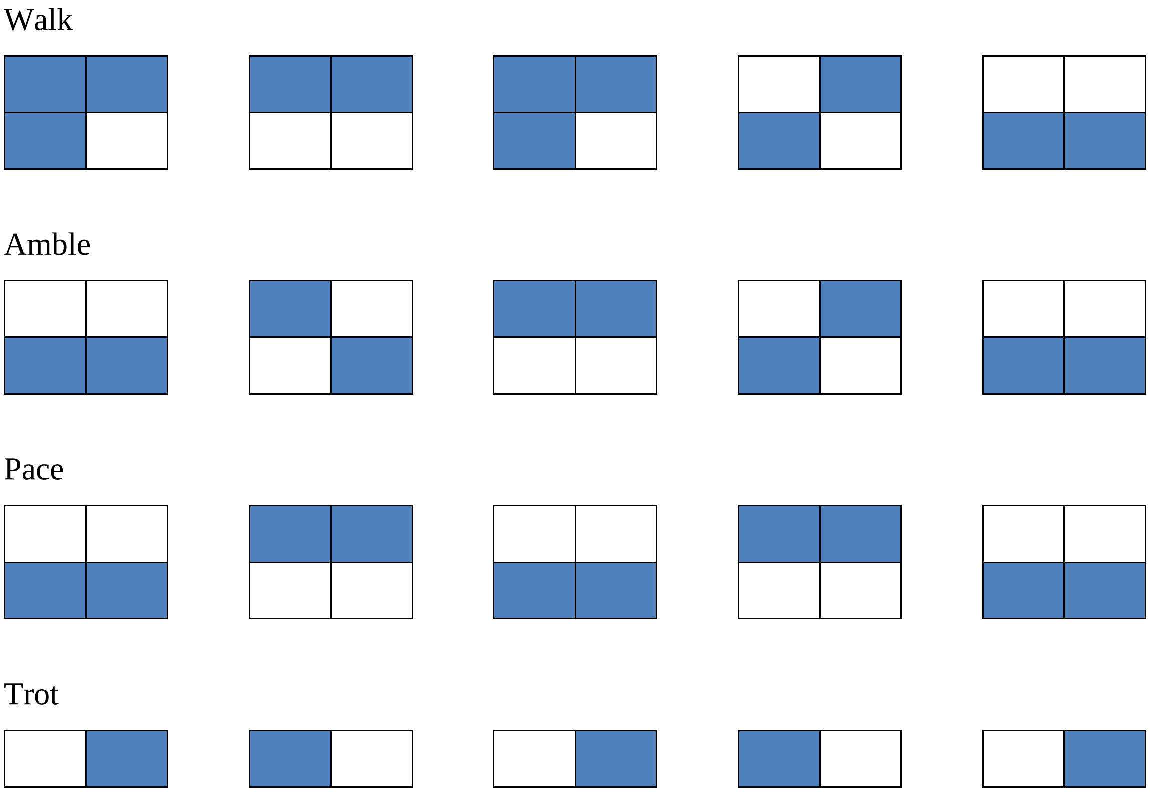
Figure 6.3 Quadruped robot in simulation model side view

6.2 Gait generation

Dogs were one of the quadrupeds used to create gait patterns. The unique arrangement and synchronization of a dog's limbs during locomotion is referred to as its gait. Dogs walk in a variety of gaits. Some of the common gaits are shown in figure 6.5.

LEFT BACK	LEFT FRONT
RIGHT BACK	RIGHT FRONT

Figure 6.4 Leg Configuration legend



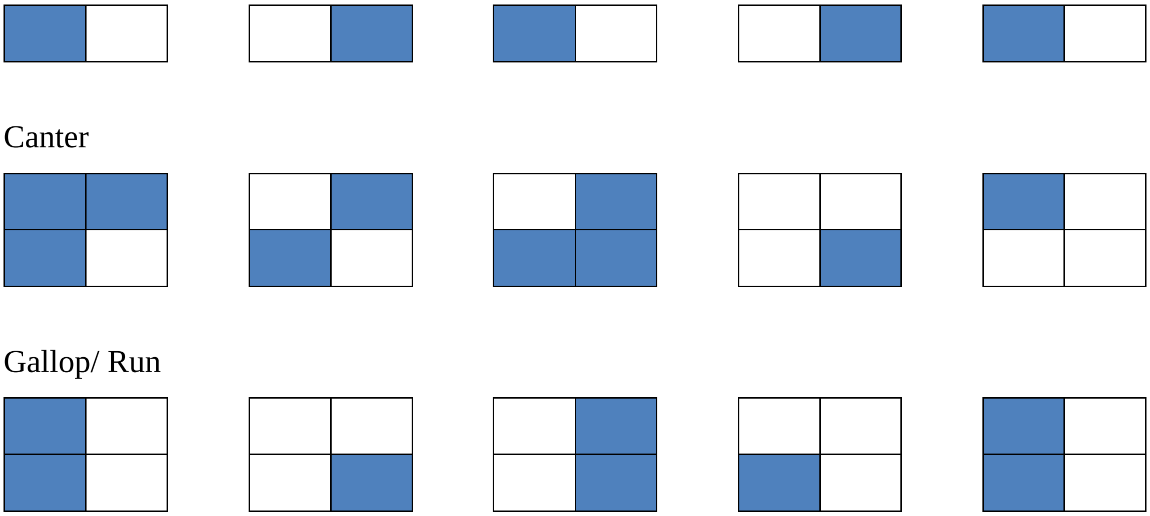
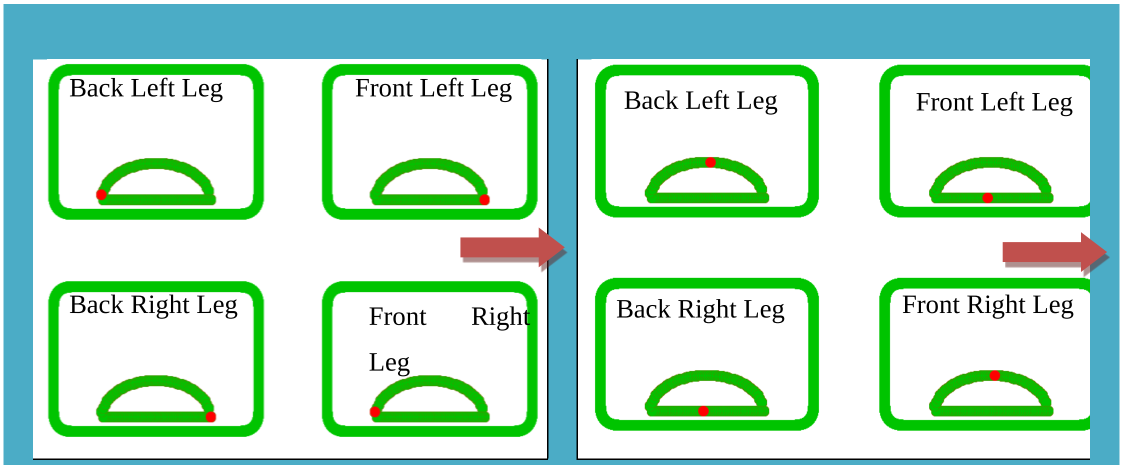


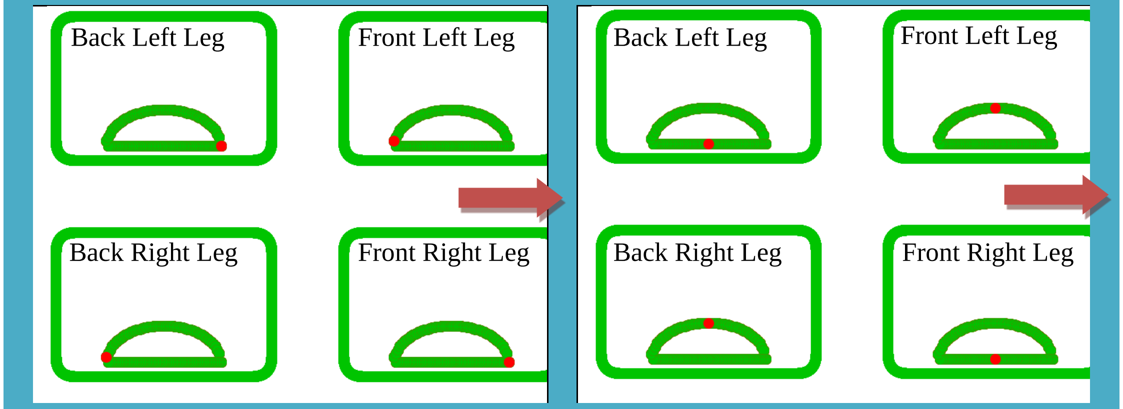
Figure 6.5 Different Gait of Dog

Figure 6.6 shows the gait generation in simulation software and after gait generation these gaits are implemented on RoboDog model in solid works simulation as shown in Figure 6.7.



(a) All legs on the ground

(b) Front right and left back leg in the air



(d) All legs on the ground

(e) Front left and back right leg in the air

Figure 6.6 Gait generation in processing software

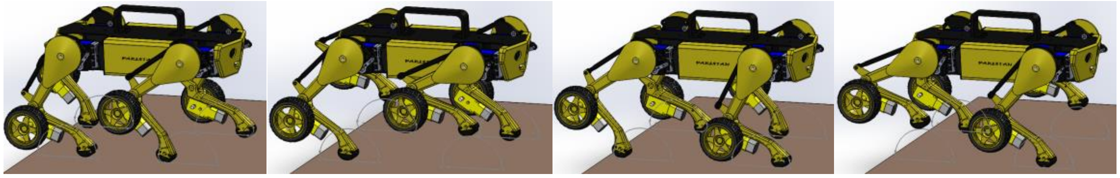


Figure 6.7 Quadruped robot walk simulation.

CHAPTER 7 : ROBDOG-A HYBRID QUADRUPED ROBOT

The initial objective was to design and control a versatile, efficient, and robust quadrupedal robot that integrates various locomotion capabilities. Our aim was to create an electrically driven robot capable of performing a range of gaits, including static walking, dynamic running, and wheel rolling. We recognized the importance of addressing these aspects holistically, understanding their interconnected nature, and promoting progress at their intersection.

To achieve these goals, we sought to consolidate existing solutions that employed compliant actuation into a single device. This involved incorporating leg mechanisms inspired by bio-inspired research to enhance the robot's natural dynamics, as well as integrating wheels to enhance speed, efficiency, and robustness on flat surfaces. The result is RoboDog, a quadruped robot featuring four identical and symmetrically designed articulated legs connected to a rigid main body.

7.1 RoboDog Specification:

With a body length of approximately 0.3 m, limb length of 0.3 m, and a total weight of 2 kg, As can be seen Fig 7.1 and 7.2, the RoboDog closely resembles the overall dimensions of a small-sized dog.

(a) (b)

Figure 7.1 RoboDog in (a) wheel mode (b) walking mode

Table 7.1 provides the detailed specifications of RoboDog.

Table 7.1 RoboDog specification

Specification	
Weight (kg)	2
Payload (kg)	0.5
Material	PLA
Length × width × height (m)	0.3 x 0.2 x 0.2
DOFs per leg	3
Ranges of HAA, HFE, and KFE (°)	90°
Torques of HAA, HFE, and KFE (Nm)	3
Upper, lower leg segment lengths (m)	0.15,0.15
Maximum speed (mph)	0.07
Actuator	SPT 5430HV
Power	Lipo-battery
Parent Organization	NUST College of EME
Country	Pakistan

Figure 7.2 RoboDog walk

CHAPTER 8 : EXPERIMENT, RESULT AND DISCUSSION

A series of tests using the quadruped robot Robodog serve as the capstone of the hardware, actuation, and control development study reported in this thesis. The quadrupedal robot can execute numerous gaits, from static walking to dynamic running and rolling over diverse terrain, by integrating the component construction pieces that were previously demonstrated.

We first show through a set of performance tests that the hardware and actuation are reliable and strong enough for both static and dynamic locomotion activities.

The tests focus on static low-speed walking. The quadruped always has three or more of its legs in touch with the ground, therefore balancing the robot is not a problem. On the other hand, the multi-contact arrangement enables the use of various load distributions. We contrast joint torque and contact force minimization's impacts on energy efficiency and slippage resilience. We demonstrate how easily joint torque and position saturations may be integrated, and we lay out an interpolation technique for a seamless shift in the contact condition.

The evaluations of the energy usage in flexible long-distance trotting serve as the intriguing discussion point for the experimental section's conclusion. Without making any changes to the controller implementation, all techniques and results are examined in simulations (Sim) and verified in hardware experiments (Exp). To work within the constraints of the hardware and actuation, it is necessary to carefully adjust the desired behavior and control parameters.

8.1 Experimental Setup

RoboDog is allowed to walk 1m on flat surface and its time, voltage and current is measured to find out the velocity and cost of transport. In the second phase robot rolls on the wheel covering the same distance and its input parameters are also recorded. Experiments were conducted with on board lithium batteries. Voltage is measured before and after an experiment to check how much power it consumes. Equation 8.1 shows the power consumption formula of a battery.

$$\text{Power} = \frac{Battery(mah)*Voltage*time\ taken}{1000*hrs} \tag{8.1}$$

The cost of transportation measures how energy-efficient it is to move a vehicle from one location to another, which represents a measure of the effectiveness of robot locomotion. Equation 8 shows the formula of cost of transport [25].

$$\text{CoT} = \frac{P}{m*g*v} \tag{8.2}$$

where P denotes the power consumption at any given moment, m denotes the robot's weight, g denotes the gravitational acceleration, and v denotes the robot's speed.

The CoT depends on the kind of robot, robot gait, and local terrain characteristic. The CoT is solely determined from the local terrain property because the experimental platform and locomotion gait are fixed. Table .1 shows the Robodog performance evaluation.

Table 8.1 Performance evaluation

	Wheel mode	Legged mode
Distance covered	1m	1m
Voltage difference	0.01	0.11
Time taken	7s	90s
Velocity	0.14 m/s	0.01 m/s
Power consumed	$1.9\text{x}10^{-5}$	0.00275
Cost of transport	$6.9\text{x}10^{-6}$	0.014

8.2 Validation

This section assesses two crucial performance metrics of RoboDog, namely speed and cost of transport.

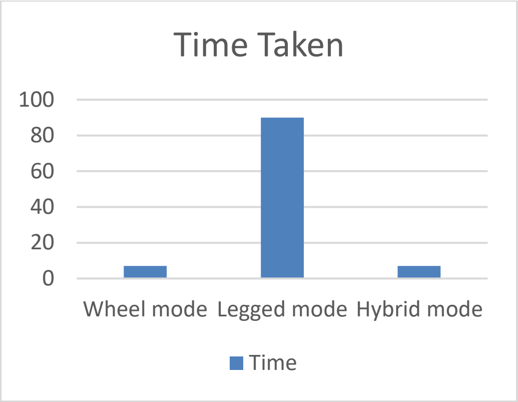


Figure 8.1 Time taken to reach 1m.

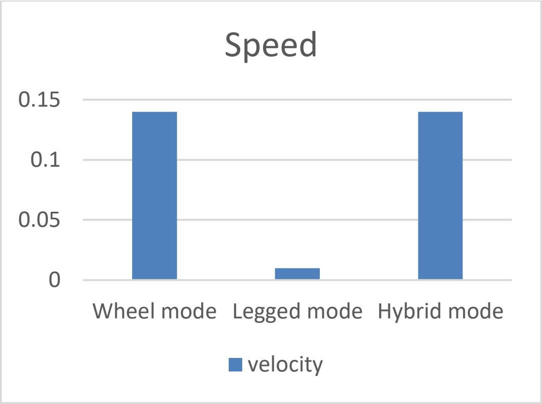


Figure 8.2 Speed comparison

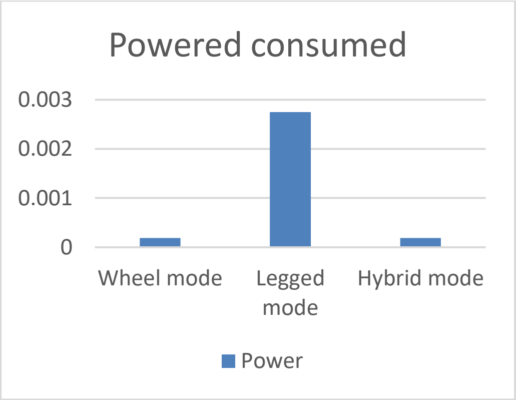


Figure 8.3 Power consumed

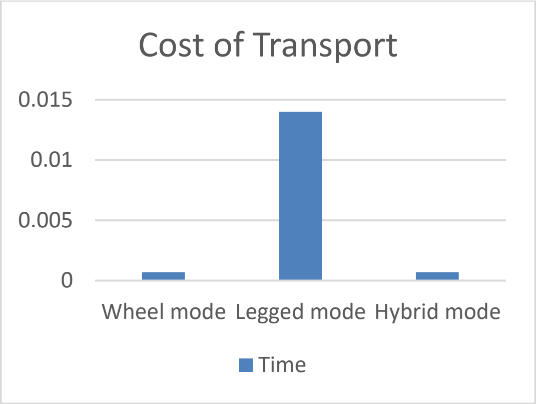


Figure 8.4 Comparing Cost of Transport

CHAPTER 9 : CONCLUSION

The thesis project began with the aim of designing and developing a quadrupedal robot that emulates the locomotion capabilities of natural animals in its size range. Through inspiration from nature and leveraging advancements in system engineering, we successfully constructed and controlled a legged robot capable of executing various gaits, including rolling and running. Our primary objective was not to merely replicate existing theoretical findings, but rather to create a robotic system that seamlessly integrates versatility, speed, efficiency, and robustness into a single device. By bridging the gap between wheel-based and legged robotics, we devised a solution that capitalizes on the strengths of both systems, resulting in a robot that surpasses conventional standards in all these aspects.

The development of the Hybrid walks and roll quadruped robot introduces a multitude of opportunities for future research. By creating a versatile platform capable of locomotion in various terrains, we establish a connection with the extensive community focused on navigation and planning. Currently, we are in the process of integrating perception capabilities through camera systems, enabling the development of advanced gait planning algorithms. These algorithms will facilitate the robot in conquering challenging obstacles and performing tasks in areas that are traditionally inaccessible by conventional means of transportation.

One of our objectives is to make this robot widely available to other research laboratories that lack access to such sophisticated devices. Given its user-friendly nature and low maintenance requirements, we aim to foster collaboration and empower other researchers to explore the possibilities enabled by this platform. Our collective vision is to extend the deployment of these robots beyond the confines of laboratory environments, allowing them to perform practical tasks that involve dynamic motion execution and contact point planning.

An important trend in robotics research is the application of machines in dynamic environments and their collaboration with human operators. We believe that numerous potential applications await such solutions, and we are enthusiastic about contributing to this field.

REFERENCES

[1] LEWIS, A. (1893). MECHANICAL HORSE (U.S. Patent No. 491,927). U.S. Patent and Trademark Office.

[2] Won, Minkyu, Tae Hun Kang, and Wan Kyun Chung. "Gait planning for quadruped robot based on dynamic stability: landing accordance ratio." Intelligent Service Robotics 2 (2009): 105-112.

[3] Tan, Jie, et al. "Sim-to-real: Learning agile locomotion for quadruped robots." arXiv preprint arXiv:1804.10332 (2018).

[4] Hao, Qian, et al. "Stability-guaranteed and high terrain adaptability static gait for quadruped robots." Sensors 20.17 (2020): 4911.

[5] Kitano, Satoshi, et al. "TITAN-XIII: sprawling-type quadruped robot with ability of fast and energy-efficient walking." Robomech Journal 3 (2016): 1-16.

[6] Fujita, Masahiro, and Hiroaki Kitano. "Development of an autonomous quadruped robot for robot entertainment." Autonomous robots 5 (1998): 7-18.

[7] Lee, Chenghwa, and Dawn An. "Reinforcement learning and neural network-based artificial intelligence control algorithm for self-balancing quadruped robot." Journal of Mechanical Science and Technology 35 (2021): 307-322.

[8] Espinal, Andrés, et al. "Quadrupedal robot locomotion: a biologically inspired approach and its hardware implementation." Computational Intelligence and Neuroscience 2016 (2016).

[9] Moses, Jeremy, and Geoffrey Ford. "See Spot save lives: fear, humanitarianism, and war in the development of robot quadrupeds." Digital War 2 (2021): 64-76.

[10] Hutter, Marco, et al. "Anymal-a highly mobile and dynamic quadrupedal robot." 2016 IEEE/RSJ international conference on intelligent robots and systems (IROS). IEEE, 2016.

[11] Semini, Claudio, et al. "Design of HyQ–a hydraulically and electrically actuated quadruped robot." Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering 225.6 (2011): 831-849.

[12] Seok, Sangok, et al. "Design principles for highly efficient quadrupeds and implementation on the MIT Cheetah robot." 2013 IEEE International Conference on Robotics and Automation. IEEE, 2013.

[13] Zhang, Haolin, et al. "Structure design and motion control of a hybrid quadruped robot with wheels and Legs." 2022 8th International Conference on Mechatronics and Robotics Engineering (ICMRE). IEEE, 2022.

[14] Xue, Yongjiang, et al. "Lywal: a leg-wheel transformable quadruped robot with picking up and transport functions." 2021 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2021.

[15] Zhao, Jianwei, et al. "Design and research of all-terrain wheel-legged robot." Sensors 21.16 (2021): 5367.

[16] Chen, Jiawei, Kun Xu, and Xilun Ding. "Roller-skating of mammalian quadrupedal robot with passive wheels inspired by human." IEEE/ASME Transactions on Mechatronics 26.3 (2020): 1624-1634.

[17] Lu, Dongping, et al. "Design and development of a leg-wheel hybrid robot “HyTRo-I”." 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE, 2013.

[18] Tadakuma, Kenjiro, et al. "Mechanical design of the wheel-leg hybrid mobile robot to realize a large wheel diameter." 2010 IEEE/RSJ international conference on intelligent robots and systems. IEEE, 2010.

[19] Shen, Shuan-Yu, et al. "Design of a leg-wheel hybrid mobile platform." 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE, 2009.

[20] Takahashi, Masashi, Kan Yoneda, and Shigeo Hirose. "Rough terrain locomotion of a leg-wheel hybrid quadruped robot." Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006. IEEE, 2006.

[21] Biswal, Priyaranjan, and Prases K. Mohanty. "Development of quadruped walking robots: A review." Ain Shams Engineering Journal 12.2 (2021): 2017-2031.

[22] Granatosky, Michael C., and Eric J. McElroy. "Stride frequency or length? a phylogenetic approach to understand how animals regulate locomotor speed." Journal of Experimental Biology 225.Suppl_1 (2022): jeb243231.

[23] https://alexnld.com/product/spt-servo-spt5430hv-180-30kg-high-voltage-high-speed-digital-servo-for-rc-car-robot-fixed-wing/

[24] Ali, Abdullah Haider, et al. "Motor Parametric Calculations for Robot Locomotion." Engineering Proceedings 20.1 (2022): 8.

[25] Prágr, Miloš, Petr Čížek, and Jan Faigl. "Cost of transport estimation for legged robot based on terrain features inference from aerial scan." 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2018.