Mechanism design, kinematic analysis, simulation and implementation of a legged robot

Ethan Batt
School of Civil and Mechanical Engineering
Curtin University
Perth, Australia
Ethan.Batt@student.curtin.edu.au

***Abstract*—This thesis project outlines the design, analysis and implementation of a modular quadruped robot developed for ease of maintenance and reconfigurability. The project follows a structured design process to achieve a final prototype of the robot that has been based heavily on past literature.**

The following pages of this thesis were previously submitted as part of the Thesis Report assessment for the MXEN4004 Mechatronic Engineering Research Project 2 unit: 1-8.

Keywords—modular, quadrupedal, robot, design, analysis, prototype, reconfiguration.

I. Introduction

A. Background

Legged robots have gained traction in recent years due to their exceptional ability to traverse rugged terrain, outperforming conventional wheeled and crawler robots [1, 2]. Typically, these highly mobile robots are divided into three categories, biped robots, quadruped robots and multilegged robots [1]. Quadrupeds emerge as the main category of legged robots, with greater stability and carrying capacity than bipeds, and better dynamic performance than multilegged robots [1-3]. This balance between agility and stability has contributed to their widespread development in both commercial and research fields, with their applications expanding across military settings, agricultural inspection, disaster recovery, and industrial uses [2].

B. Scope of Work

This thesis aims to design, implement and test a quadruped robot capable of traversing uneven terrain. In this context, uneven terrain refers to moderately irregular natural and urban surfaces, such as grass, pavement, or wooden floors.

The robot will act predominantly as a reconfigurable and modular platform onto which manipulators, loads, or other tools can be fixed. The scope of development encompasses the mechanical design and validation of the robot's leg mechanism, integration of modularity between system components, design of a simplistic electronic subsystem, and a basic control system implementation. Advanced autonomy, perception, tool integration, accessory development and long-term deployment will be considered out of scope for this project.

The project aims to address the challenges, limitations and future work proposed by past literature. Due to the timeframe of this project the end solution will look to solve challenges and limitations brought through mechanical wear and tear, which impacts the robot's performance and operational longevity [2]. To do this it will incorporate a modular approach to reduce maintenance complexity and increase universality as suggested in [4].

C. Outline of the Project

To commence this project a detailed literature review was conducted to evaluate existing quadrupedal robots, their design processes and the technologies they use against the scope of the project. This review outlines the historical progression of legged robots, highlighting key advancements in technologies that have contributed to today's landscape. With this progression, the limitations of technology are explored, highlighting the issues due to wear and tear, maintenance and energy consumption, as well as challenges in the form of societal considerations.

Following an overview of the current landscape surrounding the development of these robots, a deep dive into their key components was completed. The evaluation of leg mechanisms forms a critical part of determining the functionality of these robots [5]. As such, leg mechanisms including prismatic, parallel, serial and compliant structures were investigated for suitability against this project.

The adjustment of these mechanisms forms another key part in the design of a quadruped with the need to consider both the individual leg trajectories and the combined gait sequences. For this project simple trajectories such as sinusoidal and elliptical based paths were compared, whilst sequences for stable and slow movements were identified.

The incorporation of modularity into robotic systems was also investigated, with the effects of structures and the properties of mechanisms outlined in this review. Latticed based structures, with mechanical or magnetic properties were identified as prime candidates for this project.

The analysis of a quadruped's design is also a key subsystem of any robotic project. Static analyses can be conducted to verify the geometries and materials of these designs and can identify how static forces interact with the robot. Kinematic analyses on the other hand help determine the relationship between drive angles, positions, velocities and accelerations, whilst excluding the effects of dynamic forces [1]. Inverse and forward kinematics are often the result of such analyses and provide valuable uses for the control of the robot.

Existing implementations of electronic subsystems that form a part of quadrupedal robots were also evaluated. Within this evaluation the comparison of hobby grade microcontrollers, including ESP32s and RasberryPis, was conducted. Different types of actuators and their drive mechanisms were also investigated, along with the use of sensors such as Inertial Measurement Units (IMUs) and cameras. The power sources and regulators also formed crucial parts of this review.

The final portion of the literature review outlines control systems to enable stable and versatile movement of quadrupeds. Within this section various open-loop and closed-loop algorithms are detailed.

Following the conduction of thorough research, the theoretical design and analysis of the quadruped robot developed in this project was conducted. This process began with the selection and derivation of parameters of a parallel leg mechanism. To achieve this, a dexterous workspace was defined based on existing implementations in literature.

This workspace could then be applied to generate a foot trajectory path. From the evaluation of research, a sinusoidal gait was chosen and divided into discrete intervals using appropriate formulae. The individual paths of each leg could then be combined and offset in cyclical phase to achieve a walking gait sequence. Within this sequence each leg is lifted for only a quarter of its total duration, enabling the robot to maintain three points of contact at all times.

Next a modular system for the mechanical structure of the robot was developed. This system divided modules into component modularity, which standardises parts between modules, and operational modularity involving the separation of individual operational subsystems. Once a modular structure was defined, the 3D model of the entire robot could be developed and configured into two different arrangements.

With the completion of the mechanical design, a static, kinematic and dynamic analysis could be conducted on the robot. The static analysis allowed for the validation of Polylactic Acid (PLA) as the primary material for this project. The kinematic analysis identified the inverse and forward kinematic equations, applying them to perform a position, velocity and acceleration analysis of a single leg over its predefined workspace. The dynamic analysis identified the torque and force characteristics of each mechanism to assist with the selection of actuators.

After the verification of the mechanical structure, and the identification of loads required by the actuators, the electronic components could be selected. These components were predominantly chosen from their use in literature, with an ESP32 microcontroller, lithium-ion battery, servo motors and an IMU making up the key components. Once the components were selected, a schematic diagram could be created outlining the interaction between components.

The final portion of the design process was to implement an open-loop control system. This system leveraged third-party packages such as Bluepad32 to connect to peripherals and interact with the onboard electronics. The chosen control system works by phase shifting the individual leg trajectories to form a walking gait, with any adjustments to this gait made by the user via the remote.

To test the outlined quadruped robot, a prototype was manufactured and assembled, verifying the geometries of the design. This prototype was then subject to a variety of tests for comparison against the project performance indicators. These tests included power and control system verification, dynamic motion evaluation, carrying capacity validation and energy consumption performance.

The results of the testing indicated that the designed robot closely met the scope of the project. The discussion of future work to extend the project outlines the addition of cameras and the inclusion of closed-loop control.

The design methodology and steps of this project is broadly applicable to the development of almost all robotic and mechatronic systems. The systematic framework of conducting detailed research, developing and analysing a theoretical design, and implementing and testing a prototype, will more times than not, lead to the development of a successful system.

II. Experimental Procedure

A. *Selecting a Leg Mechanism*

The selection of a suitable leg mechanism was made for this project following the completion of a literature review. After comparison with its serial counterpart, a direct-drive parallel leg configuration was adopted. To synthesise the parameters of this five-bar mechanism, the process outlined in [6] was followed. The resulting linkage lengths are provided below for a defined dexterous workspace with a length of 100mm, height of 50mm and offset from body of 50mm.

TABLE I. Leg Mechanism Derived Parameters

Link	Length (mm)
l_1	50
l_2	48.5
l_3	92.8
l_4	92.8
l_5	48.5

B. *Designing a Gait*

To govern the movement of the designed quadruped robot, a foot trajectory and gait sequence pattern were developed. The foot trajectory implements a discrete sinusoidal swing phase and horizontal support phase based on its successful implementation in Standford Doggo [7]. This trajectory is defined by [8] and depicted in the figure below.

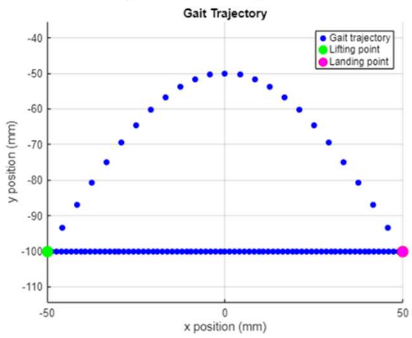

FIGURE I. Sinusoidal gait trajectory

For the gait sequence, a walking pattern was selected to maintain three points of contact with the ground in order to increase stability. In this pattern, the phase of each individual foot trajectory is offset by 25% and consists of a swing phase that takes up a quarter of the gait sequence's duty cycle.

C. *Integrating Modularity*

A key limitation of current quadruped robots arises from the degradation experienced by mechanical components such as leg joints and actuators, as well as the volatility of electrical systems when exposed to water, dust and extreme temperatures [2, 9]. The frequent maintenance that results from such issues, complicates the deployment of quadruped robots, requiring routine field checks and replacement parts to be considered in operational planning, driving up cost and down time [2].

By designing modular components, parts can be readily replaced or upgraded, improving the overall adaptability of the robot's function and increasing the ease of maintenance [2, 10].

The foundation of modularity in this project consists of two distinct stages: component modularity and operational modularity. Component modularity aims to standardise the mechanical framework that operation modules are built upon, whilst operational modularity endeavours to separate the subsystems of the robot into individual modules.

The standardisation of the mechanical framework of this project consists of fundamental volumetric units measuring 85mm x 85mm x 85mm. Each volumetric unit measures is divided into two fundamental components: a wire frame and face plates. The dimensions of this unit were determined through the adjacent connection of two units, housing a single actuator each, where the resultant operational module completely contained the leg mechanism. The units were then scaled to a size that in the event two leg modules are joined, the mechanisms do not collide.

The most significant variation of the face plates implemented for modularity is the connector plate assembly. This assembly leverages bi-gendered mechanical and magnetic connection mechanisms to facilitate the joining of operational modules. The plate also integrates a custom electrical connector to facilitate the transfer of all signals required by the quadrupedal robot. The final assembly of this connection mechanism is depicted below.

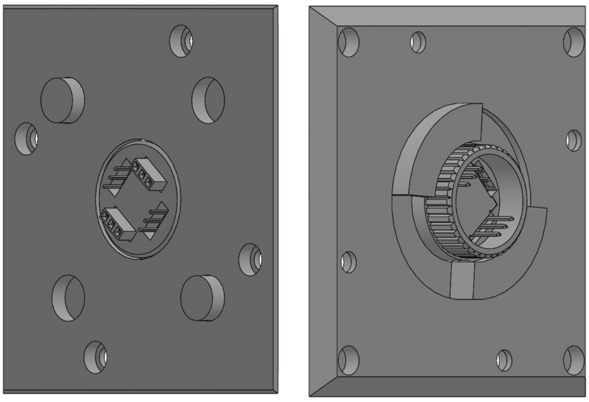

FIGURE II. CONNECTION PLATE ASSEMBLY

Operational modularity in this project was implemented by developing standard modules for the actuators, electronics and spacer assemblies that facilitate close-packed lattices. These modules consisted of a matrix of standardised units and facilitated the reconfigurability of this project. The resulting modules can be arranged in a wide base, square configuration and a narrow footprint configuration for inspection tasks.

D. *Material Selection*

The chosen base material for the predominant structure of the designed quadruped robot was PLA following its successful use in [11]. This material allows for the rapid manufacture of a prototype using 3D printing technology.

E. *Static Analysis*

To verify the material and geometries of the designed components, two stages of a static analysis were completed. The first stage performed an approach taken in [11], which completes a Finite Element Analysis on each component of the leg mechanism to identify the stresses, strains and displacements they experience. Upon the conclusion of this stage, it was verified that the leg mechanism components could withstand up to eight times the robots body weight without failure.

The second stage of the analysis aimed to identify how static loads applied to the feet could be resolved to the actuators. To do this, a reaction force and static frictional force were applied to the foot and resolved onto each linkage, resulting in a moment and force applied to the actuators.

F. *Kinematic Analysis*

The completion of a kinematic analysis on an individual leg mechanism for this project was also conducted. Within this analysis the inverse kinematic equations were determined via a method outlined in [6]. These equations are particularly important to calculate the resultant actuator angles from cartesian coordinates defined by the foot trajectory.

Along with inverse kinematics, the forward kinematics for the five-bar linkage can also be derived. These equations use a method dictated in [12] and can be applied to visualise the relationship between the linkages within the leg mechanism. These relationships include the position, velocity and acceleration of the passive joint angles with respect to the actuator angles.

G. *Dynamic Analysis*

The dynamic analysis of a manipulator is utilised to determine the motion of the mechanism that arises from the applied external forces and torques [13]. To begin a dynamic analysis, a static approximation of the dynamic behaviour of a mechanism is often employed to provide an estimate of the behaviour whilst avoiding the complexity of dynamic simulations. The dynamic analysis of the selected leg mechanism over its gait trajectory can be approximated by conducting a static analysis at each discrete interval across this path. To do this, the scenario and equations derived in the static analysis can be applied. The results of this approximation identify a maximum torque and force applied to the actuators of approximately 0.8Nm and 17N respectively.

Following this approximation, a SolidWorks Motion Analysis was run to simulate the forces and torques experienced by the robot in a forward movement. The results of this simulation identify a maximum torque and force applied to the actuators of approximately 0.58Nm and 6N respectively, significantly less than the static estimation.

The final portion of the dynamic analysis calculated the Jacobian matrix of the leg mechanism using the equations defined in [14]. The resulting matrix enables the relation of the joint velocities of the mechanism to the cartesian velocities of the end effector [13].

H. Design of Electronics

Upon completing a literature review it was identified that the minimum requirements for a quadruped robot's electronics subsystem included: a microcontroller, a set of actuators, a driver for the actuators, a power source and a power regulator.

The selection of a microcontroller was completed after comparing alternative hobby breakout boards against the scope of this project. At the end of the comparison an ESP32 DevKitC V4 module was chosen, predominantly due to its inclusion of onboard Bluetooth and WIFI, as well as its relative affordability.

To size and select the actuators for this project, the results of the dynamic analysis were considered, with an applied safety factor of 1.2. The result was the selection of FS5109M servo motors rated at 10 kgcm of torque [15].

The power source of the prototype could then be determined by considering a worst-case scenario at which the actuators operate at stall torque for 20 minutes. This scenario required a total capacity of 4500mAh and thus a 2S 5000mAh lithium-ion battery was selected, similar to the one utilised in [16].

Next, the sensors for the robot were chosen to allow the perception of its surrounding environment. Since the servo motors offer no positional feedback, the state of the robot can be estimated by utilising an onboard Inertial Measurement Unit (IMU) [16, 17]. The IMU selected for this project is Adafruit's ICM-20948, which provides 9 DOF via a gyroscope, accelerometer and compass [18].

Along with the IMU, this project implements a battery monitor to provide insights into the power usage of the robot. For this component Adafruit's INA260 is utilised to avoid overdischarge of the battery, whilst enabling monitoring of the battery voltage and system power draw [19, 20].

A Bluetooth Xbox Controller was utilised as a user control input for the electronic system.

I. Control System

The control system for this project is implemented in C++ using the ESP IDF framework, visual studio code IDE and PlatformIO design environment. This form of implementation was selected due to its ability to integrate third-party packages such as Bluepad32.

To meet the scope and functional requirements of this project, the control system utilised by the quadruped robot was simplified, ensuring reliable control and stability without introducing a large computational overhead. This system combines an open-loop controller, and a state machine, to provide simplistic motion and transition between robot behaviours.

The control strategy utilised in this project, follows an approach similar to that presented in [1], where each leg mechanism follows a predefined gait trajectory with the starting point of this path offset to achieve the desired walking gait pattern. Since the actuators do not provide positional feedback, the control system does not adjust to correct errors between the actual foot position and its desired position, such is the nature of open-loop control [17].

To enable minor variations in the walking pattern, such as changes in step height, body elevation and movement direction, the controller varies gait parameters, including step height, step offset and step length. These changes are actioned by the user through a remote and provide steering via the differential drive of the leg mechanisms.

III. Results and Discussion

A. Manufacture and Assembly of a Prototype

Following the theoretical design and analysis of a quadruped robot, a physical prototype was manufactured and assembled. The predominant structure of the robot was 3D-printed from PLA and joined using heated inserts and fasteners. In total the quadruped robot implemented two spacer modules, four actuator modules and an electronics module arranged in the square configuration. A depiction of the prototype is given below.

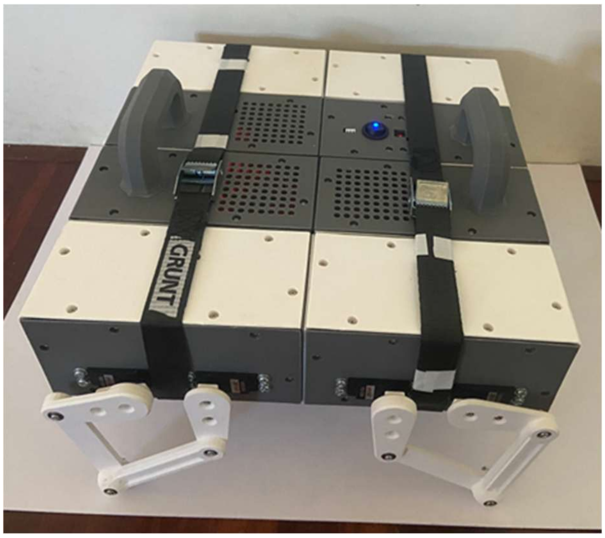

FIGURE III. COMPLETE ASSEMBLY OF PROTOTYPE

The successful manufacture and assembly of the prototype quadruped robot verified the geometric design and fit of individual components has been verified. For the most part, tolerances between components allowed for straight forward assembly.

Deviations from the expected performance were observed in the connection strength between modules in the complete assembly. Whilst individual and partial connections demonstrated acceptable strength and rigidity, the accumulative weight of the entire robot reduced the reliability of module connections.

Although the modules remained joined during the static configuration of modules, the likelihood of failure under dynamic impacts and vibrations was higher than intended. As such, supporting straps were employed to prevent module disconnection throughout the subsequent testing procedures.

B. Power and Control System Testing

Once assembled, the robot was powered on to verify the functionality of the electronics and control system. After receiving power and establishing a connection to a controller via Bluetooth, each input command was systematically cycled through to confirm the correct response was taken by the control system. At the conclusion of this test, each state of the system was correctly activated, with the robot performing the desired movement associated with each state, including the prioritisation of the states, such as the home state.

During this test, the outputs of the IMU, battery monitor and Bluetooth controller via the serial terminal were observed. Each subsystem responded as expected with each sensor providing meaningful data about the robot's current state.

C. Dynamic Motion Testing

Following the construction of the prototype, a variety of tests were conducted to verify the quadruped robot's dynamic performance. The first of these tests was to evaluate the straight line and turning motion of the quadruped on the uneven surfaces outlined in the scope of this project.

To enable quantitative comparisons between each surface, the quadrupedal robot was made to complete the following timed tasks.

TABLE II. DYNAMIC MOTION TEST RESULTS

Surface	Average Time for Forward Straight-Line Motion Over 1m	Average Time for Reverse Straight-Line Motion Over 1m	90° Turn	
			Left	*Right*
Floorboards	21.24s	21.34s	Yes	Yes
Grass	55.86s	54.34s	Yes	Yes
Carpet	22.25s	21.98s	Yes	Yes
Pavement	44.18s	39.16s	Yes	Yes

For each surface, the quadruped robot demonstrated the ability to move in forward, reverse, left and right directions with varying degrees of success. The quadruped's motion was best exhibited on the wooden floorboards and carpet, reaching a maximum velocity of 0.047 m/s and 0.045 m/s respectively. On these surfaces the robot achieved stable and consistent locomotion, which is reflected in the results.

The performance of the robot degraded significantly on uneven surfaces such as grass and pavement surfaces, completing each task with large variations in time. These inconsistencies are caused predominantly by the feet of the robot becoming caught in hollows or gaps in the surfaces, taking extended periods of time to regain directional motion. This behaviour is likely due to the open-loop control system that prevents the robot from adapting its gait to suit variations in surfaces.

This test also aided in the validation of the gait sequency, foot trajectory and inverse kinematic equations. During locomotion, each leg mechanism appeared to follow a sinusoidal trajectory, with the phase offsets of each leg equivalent to a walking gait. The bounds of the inverse kinematics and the lengths of each leg mechanism also prevented the mechanism from reaching any singularity positions in which it couldn't recover.

D. Carrying Capacity

After dynamic motion testing of the robot, a carrying capacity test was conducted to validate the results of the static and dynamic analysis. In both these analyses, it was deemed theoretically possible for the robot to carry a load of up to one body weight.

Given the total weight of the prototype measured 3.5 kg, the theoretical carrying capacity was tested by applying a load consisting of a 3kg weight and a 0.5kg book to the robot. The load was then, lifted and lowered repeatedly to observe the behaviour of the actuators. On the completion of the test, no unusual behaviours were identified, verifying the carrying capacity of up to 100% of the robot's body weight. To prevent any damage to the prototype, the load was not increased further.

E. Power Consumption

Finally, the power consumption of the robot whilst performing a variety of movements was tested. To do this, the robot was placed upon a stand and moved in the forward, reverse, left and right direction over a number of gait cycles. During this test the average time taken to complete one gait cycle was approximately 2.5s.

Using the onboard battery monitor, the voltage current and power draw of the system could be monitored over time. A summary of the average power characteristics for each motion is provided below.

TABLE III. POWER CONSUMPTION TEST RESULTS

Motion	Average Power	Average Current	Average Voltage
Forward	6.14 W	0.87 A	7.31 V
Reverse	5.90 W	0.82 A	7.42 V
Left	5.17 W	0.75 A	7.35 V
Right	4.98 W	0.73 A	7.07 V

IV. CONCLUSION

At the conclusion of this project, a number of design approaches and components have been achieved. The results of these processes include all of the desired deliverables: including 3D models and assemblies of the entire quadruped robot; complete static, kinematic and dynamic analyses with equations and results; a schematic of the electronic components utilised; source code for an open-loop control system; and a physical prototype of the robot. This project extends the deliverables to also incorporate MATLAB scripts for parameter derivation of five-bar linkages, visual simulations of the robot in SolidWorks, and the design pattern for a custom modular connector.

To evaluate the resultant design against the scope of the project, the test results in section 4 can be compared with the outlined performance indicators. The implemented prototype achieves both the stability indicators with a high degree of success, with the ability to stand at any position in its given gait without aid, and the completion of numerous repetitive gait cycles in multiple directions.

A significant implementation of modularity throughout the entirety of the quadruped robot's design is also achieved. Its standardised component modularity allows the same custom connector to be utilised on either ends of a connection, and its volumetric unit geometry prevents issues with reconfiguration due to its uniformity. The segregation of operational components into separate modules allows the robot to achieve various configurations, including a wide base arrangement for carrying loads and a narrow footprint for inspections. The prototype's electrical performance also exceeds the minimum required operating time of 30 minutes by more than ten times, with a forecast battery life of 6 hours.

The performance of the implemented system does meet the movement requirements of traversing a distance of 1 metre and completing a full turn; however, these are completed with various degrees of success. For flat, uniform surfaces, the prototype exceeds, achieving a maximum velocity of 0.047 m/s, whilst maintaining highly stable movements. Relatively uneven surfaces, such as grass and pavement does pose a challenge to the robot, particularly when traversing gaps. Although the robot can complete the set tasks, it does so with a large degree of variation that should be improved upon.

It should be noted that the carrying capacity and use of a Bluetooth controller both exceed the minimum performance indicators. These properties allow for a load up to 100% of the quadruped's weight to be successfully transported on smooth surfaces and enable the control of the robot using both keyboard and game controllers.

Along with comparison to the performance criteria outlined in the scope of this project, the outcome of this project should also consider the economic, environmental and societal impacts it has. From an economic perspective, the total cost of the implementation remained under the allocated budget of $400. This demonstrates the cost-effectiveness of the solution, allowing for replication in similar educational environments.

Although the chosen material may introduce microplastics, the emphasis on modularity in design removes the need for numerous complex parts and facilitates the reuse of components. Furthermore, the energy efficiency of the project exceeds expectations, reducing its reliability on non-renewable energy sources.

From a social standpoint, the project poses minimal effects towards the wider community. The prototype does not include cameras, or store any form of data it collects, thereby eliminating the threat to privacy. Additionally, the default state of the robot is to remain stationary when no input is provided, helping precent collisions due to unintended movement. It is also unlikely that the project will result in job displacement due to its limited functional scope.

Given the success against the performance criteria, it can be concluded that the designed modular quadruped robot is capable of traversing uneven urban terrain. It effectively addresses the need of reconfigurability and reduces maintenance complexity through its integration of modular ideologies to achieve rapid assembly processes.

V. Future Work

The main limitation identified in this project is the use of a simplistic open-loop control system, which prevents self-stabilisation and adjustments to the robot's motion. To combat this issue, it is suggested that a two-stage process be implemented. The first of these stages should integrate the existing IMU sensor into a closed-loop control system such as PID, Fuzzy or ZMP control. The second stage of this solution involves the addition of cameras and processing units to allow the robot to function autonomously.

Other welcomed inclusions to this project could consist of an improved connector design that addresses misalignment issues, a server application hosted on the ESP32 microcontroller to form a user interface, and the development of a digital twin for extensive simulation in software such as MSC ADAMs.

Acknowledgment

I would like to acknowledge my thesis supervisor Dr. Masood Khan for his support, guidance and patience throughout the completion of this project. Thank you for taking the time to point me in the right direction and provide me with valuable knowledge and suggestions for my thesis project.

I would like to thank all the teaching staff and students within the Mechatronics and Computer Science departments. Thank you for your friendliness and your assistance throughout my degree.

Finally, I wish to express my gratitude to my parents, partner and my family. I would not be where I am today without their unwavering love and support.

References

[1] M. Lu, B. Jing, H. Duan, and G. Gao, "Design of a Small Quadruped Robot with Parallel Legs," *Complexity,* vol. 2022, no. 1, p. 9663746, 2022, doi: https://doi.org/10.1155/2022/9663746.

[2] Q. Li, F. Cicirelli, A. Vinci, A. Guerrieri, W. Qi, and G. Fortino, "Quadruped Robots: Bridging Mechanical Design, Control, and Applications," *Robotics*, vol. 14, no. 5, doi: 10.3390/robotics14050057.

[3] J. Zhang, D. Zhang, and Z. Guo, "Research on quadruped robots: Review and Prospect," New York, NY, USA, 2023 2023: ACM, pp. 38-45, doi: 10.1145/3606843.3606850. [Online]. Available: https://dl.acm.org/doi/pdf/10.1145/3606843.3606850

[4] Y. Fan, Z. Pei, C. Wang, M. Li, Z. Tang, and Q. Liu, "A Review of Quadruped Robots: Structure, Control, and Autonomous Motion," *Advanced Intelligent Systems,* vol. 6, no. 6, p. 2300783, 2024/06/01 2024, doi: https://doi.org/10.1002/aisy.202300783.

[5] Y. Zhong, R. Wang, H. Feng, and Y. Chen, "Analysis and research of quadruped robot's legs: A comprehensive review," *International Journal of Advanced Robotic Systems,* vol. 16, no. 3, p. 1729881419844148, 2019/05/01 2019, doi: 10.1177/1729881419844148.

[6] T. Demjen *et al.*, "Design of the five-bar linkage with singularity-free workspace," *Robotica,* vol. 41, no. 11, pp. 3361-3379, 2023, doi: 10.1017/S0263574723001042.

[7] N. Kau, A. Schultz, N. Ferrante, and P. Slade, "Stanford Doggo: An Open-Source, Quasi-Direct-Drive Quadruped," in *2019 International Conference on Robotics and Automation (ICRA)*,

20-24 May 2019 2019, pp. 6309-6315, doi: 10.1109/ICRA.2019.8794436. [Online]. Available: https://doi.org/10.1109/ICRA.2019.8794436

[8] G. Yadav, S. Jaiswal, and G. C. Nandi, *Generic Walking Trajectory Generation of Biped using Sinusoidal Function and Cubic Spline*. 2020, pp. 745-750.

[9] A. Hamrani, R. M. Munim, M. Telusma, M. Dwayne, and L. and Lagos, "Smart quadruped robotics: a systematic review of design, control, sensing and perception," *Advanced Robotics,* vol. 39, no. 1, pp. 3-29, 2025/01/02 2025, doi: 10.1080/01691864.2024.2411684.

[10] Y. Zou, D. Kim, P. Norman, J. Espinosa, J.-C. Wang, and G. S. Virk, "Towards robot modularity — A review of international modularity standardization for service robots," *Robotics and Autonomous Systems,* vol. 148, p. 103943, 2022/02/01/ 2022, doi: https://doi.org/10.1016/j.robot.2021.103943.

[11] J. Kim, T. Kang, D. Song, and S.-J. Yi, "Design and Control of a Open-Source, Low Cost, 3D Printed Dynamic Quadruped Robot," *Applied Sciences*, vol. 11, no. 9*,* doi: 10.3390/app11093762.

[12] H. D. Eckhardt, *Kinematic design of machines and mechanisms*. McGraw-Hill, 1998.

[13] J. J. Craig, *Introduction to robotics: mechanics and control, 3/E*, 3 ed. Pearson Education India, 2019.

[14] L. Erwin-Christian, C. Valentin, D. Tivadar, O. Alexandru, T. Elida-Gabriela, and S. Melania-Olivia, "Optimal Synthesis of Five-Bar Linkage Based on Singularity-Free Workspaces with Predefined Shapes," *Robotics*, vol. 13, no. 12*,* doi: 10.3390/robotics13120173.

[15] FeeTech, "PRODUCT SPECIFICATION FS5109R," 02/08/2021 2021. [Online]. Available: https://www.feetechrc.com/Data/feetechrc/upload/file/20210827/6376565881266889439933525.pdf

[16] S. E. Schoedel, A. J. Fuge, B. Kalita, and A. Leonessa, "Development of an Affordable and Modular 3D Printed Quadruped Robot," 2022. [Online]. Available: https://doi.org/10.1115/IMECE2022-95700.

[17] Y. Shi, S. Li, M. Guo, Y. Yang, D. Xia, and X. Luo, "Structural Design, Simulation and Experiment of Quadruped Robot," *Applied Sciences*, vol. 11, no. 22*,* doi: 10.3390/app112210705.

[18] B. Siepert and K. Rembor, "Adafruit TDK InvenSense ICM-20948 9-DoF IMU," Adafruit, 22/01/2025 2025. [Online]. Available: https://learn.adafruit.com/adafruit-tdk-invensense-icm-20948-9-dof-imu

[19] B. Xia, J. Fu, H. Zhu, Z. Song, Y. Jiang, and H. Lipson, "A Legged Soft Robot Platform for Dynamic Locomotion," in *2021 IEEE International Conference on Robotics and Automation (ICRA)*, 30 May-5 June 2021 2021, pp. 11812-11819, doi: 10.1109/ICRA48506.2021.9561018. [Online]. Available: https://doi.org/10.1109/ICRA48506.2021.9561018

[20] Y. Chen, J. E. Grezmak, N. M. Graf, and K. A. Daltorio, "Sideways crab-walking is faster and more efficient than forward walking for a hexapod robot," *Bioinspiration & Biomimetics,* vol. 17, no. 4, 046001, 11/05/2022 2022, doi: 10.1088/1748-3190/ac6847.