Development of a Legged Robot for Diverse and Challenging Terrains

Akshaya Simha*[1] · Ashwin A[1] · Sparsha Adhikari[1] · Yashas G. B.[1]· Gautam Rajeev[1]· Shantharaju B. L.[1]

[1] Department of Mechanical Engineering,
Acharya Institute of Technology,
Bengaluru, Karnataka 560107, India
***Corresponding Author**
Email: akshaya@acharya.ac.in

Abstract

Legged robots provide superior mobility over wheeled systems when operating on uneven and discontinuous terrain. However, many existing quadruped robots rely on expensive actuators and complex control architectures, limiting their accessibility for education and early-stage research. This paper presents the design, calibration, and experimental evaluation of a low-cost quadruped robotic platform constructed using readily available materials and hobby-grade actuators. A modular mechanical architecture with two-degree-of-freedom planar legs is developed using an acrylic chassis and servo-based actuation. To address the inherent inaccuracies and nonlinearities of low-cost servos, a software-based calibration and compensation framework is proposed to improve joint angle accuracy and gait repeatability. Furthermore, a systematic experimental study is conducted to quantify the trade-offs between payload, power consumption, gait stability, and actuator thermal behaviour. Experimental results demonstrate that the proposed calibration method reduces joint angle error by up to 35% and improves gait consistency under load. The performance evaluation identifies practical operational limits of hobby-grade servos for quadruped locomotion and provides design guidelines for developing affordable legged robots for education and prototyping.

Keywords: quadruped robot; low-cost robotics; servo calibration; gait repeatability; legged locomotion.

1. Introduction

Legged robotic systems have gained significant attention due to their ability to traverse uneven, discontinuous, and obstacle-rich terrain that challenges conventional wheeled or tracked vehicles. By employing articulated legs with intermittent ground contact, quadruped robots can step over obstacles, maintain stability on uneven surfaces, and adapt to variations in terrain height. Inspired by biological locomotion, modern legged robots incorporate articulated limbs, compliant elements, and adaptive gait strategies to enhance robustness and efficiency.

State-of-the-art quadruped platforms often utilize hydraulic or custom high-torque electric actuators combined with advanced sensing and control algorithms, enabling dynamic behaviors such as running and jumping. While these systems demonstrate exceptional performance, their high cost, mechanical complexity, and maintenance requirements limit their widespread adoption in academic teaching environments and early-stage research laboratories.

In contrast, low-cost quadruped robots based on hobby-grade components offer an attractive alternative for education and rapid prototyping. However, such platforms face significant challenges, including actuator inaccuracies, limited torque capacity, backlash, and reduced repeatability under load. Despite their growing use, there is a lack of systematic experimental studies quantifying the practical limits and performance trade-offs of low-cost quadruped robots.

This paper addresses this gap by presenting a low-cost quadruped robotic platform together with two primary contributions: (i) a software-based servo calibration and compensation framework designed to improve joint accuracy and gait repeatability, and (ii) a quantitative experimental evaluation of payload capacity, power consumption, thermal behaviour, and gait stability. Rather than competing with high-performance quadrupeds, this work aims to provide reproducible insights and design guidelines for affordable legged robotic systems.

The main contributions of this paper are summarized as follows:

1. Design of a modular, low-cost quadruped robot using readily available materials and actuators.
2. Development of a software-based calibration and compensation method to mitigate servo nonlinearities and backlash.
3. A systematic experimental study quantifying performance limits and trade-offs in low-cost quadruped locomotion.
4. Practical design guidelines for educational and experimental quadruped platforms.

2. Related Work

Legged robot research has explored a wide range of mechanical designs, actuation strategies, and control methods to improve locomotion on uneven terrain. Hybrid actuation systems combining electric motors with compliant elements have been shown to enhance shock absorption and energy efficiency (Hourani and Iskandarani 2020). Pantograph-based (Sprowitz 2015) leg mechanisms exploit elastic behaviour to reduce control complexity and energy consumption. Wheel–leg hybrid robots (Liu et al. 2022) offer efficient rolling on flat terrain while retaining stepping capabilities on rough surfaces.

Recent work has demonstrated the effectiveness of reinforcement learning (Kubacki et al. 2021) and model-based control in generating robust quadruped gaits. High-performance platforms employing hydraulic actuation and torque-controlled joints achieve dynamic locomotion but require significant financial and technical resources. To improve accessibility, several open-source and educational quadruped robots have been proposed using hobby-grade actuators and simplified control strategies.

Despite these efforts, limited attention has been given to quantifying actuator inaccuracies, thermal effects, and load-dependent performance degradation in low-cost quadruped robots. Furthermore, calibration and compensation strategies for hobby servos are often discussed informally but rarely analysed experimentally in the context of legged locomotion. This work builds upon existing low-cost designs while providing systematic analysis and experimental validation.

3. System Design and Architecture

3.1 Mechanical Design

The quadruped robot was designed using Autodesk Fusion with an emphasis on simplicity, modularity, and ease of fabrication as shown in Fig. 1. The chassis consists of an acrylic plate with dimensions 220 mm × 110 mm × 5 mm, selected to minimize weight while maintaining sufficient stiffness for static locomotion. The low-profile design reduces the center of gravity, improving stability.

Each leg comprises a planar two-link mechanism representing hip and knee joints. Both links are 100 mm in length and fabricated from acrylic. This configuration allows rapid replacement and modification of individual components. The robot employs eight MG995 hobby servo motors, with two servos assigned to each leg.

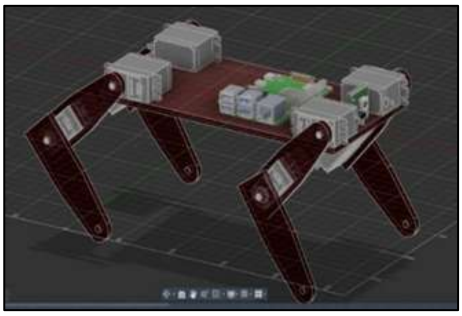

Fig. 1: CAD Model of the Quadruped Robot

3.2 Materials and Structural Considerations

Acrylic (PMMA) was selected for the chassis and leg components due to its lightweight nature, ease of fabrication, and cost effectiveness. Typical material properties include a density of approximately 1.18 g/cm³, tensile strength in the range of 60–70 MPa, and a Young's modulus of 2.4–3.3 GPa. These properties are sufficient for static walking under moderate loads.

3.3 Kinematic Modeling

Each leg is modelled as a planar two-degree-of-freedom serial manipulator. The forward kinematics defining the foot position (x, y)relative to the hip joint are given by:

$$x = l_1 \cos(\theta_1) + l_2 \cos(\theta_1 + \theta_2)$$

$$y = l_1 \sin(\theta_1) + l_2 \sin(\theta_1 + \theta_2)$$

where $l_1$and $l_2$are the lengths of the upper and lower leg links, and $\theta_1$and $\theta_2$are the hip and knee joint angles, respectively.

Inverse kinematics are used to compute joint angles for a desired foot position:

$$D = \frac{x^2 + y^2 - l_1^2 - l_2^2}{2 l_1 l_2}$$

$$\theta_2 = \cos^{-1}(D)$$

$$\theta_1 = \tan^{-1}\left(\frac{y}{x}\right) - \tan^{-1}\left(\frac{l_2 \sin\theta_2}{l_1 + l_2 \cos\theta_2}\right)$$

These equations enable systematic generation of foot trajectories for gait planning.

3.4 Control and Power System

A hierarchical control architecture is implemented using a Raspberry Pi 4 shown in Fig. 2 as the central controller. High-level gait planning generates predefined joint trajectories, which are transmitted to a PCA9685 16-channel PWM servo driver via the I²C interface. Due to the limitations of hobby-grade servos, position-based control is employed.

Fig. 2: Raspberry Pi 4

Power is supplied through an external switched-mode power supply that provides regulated DC voltage to the servo motors (shown in Fig. 3) and control electronics.

Fig. 3: MG995 Servomotor

A Raspberry Pi Camera Module (shown in Fig. 4) is mounted on the robot for monitoring and future perception-based extensions; it is not used for closed-loop control in the present work.

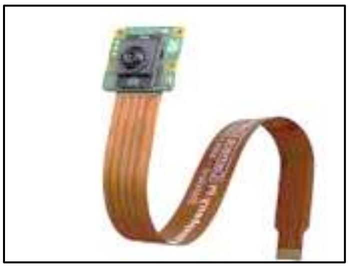

Fig. 4: Raspberry Pi Camera

4. Servo Calibration and Compensation Framework

Hobby-grade servo motors exhibit nonlinear angle responses, dead zones, and backlash, particularly under varying loads. To address these issues, a software-based calibration and compensation framework is proposed.

4.1 Calibration Procedure

Each servo is calibrated by commanding a set of reference angles and measuring the actual angular displacement using a mechanical protractor. The measured error is recorded across the operating range. The calibration was performed individually for each servo to account for manufacturing variability and wear.

4.2 Compensation Model

A piecewise linear compensation function is derived for each servo:

$$\theta_{cmd} = \theta_{des} + f(\theta_{des})$$

where θ_{cmd} is the compensated command angle, θ_{des} is the desired joint angle, and $f(\theta_{des})$ is the empirically determined correction term. This compensation is applied in software prior to gait execution.

5. Control and Power System

A hierarchical control architecture is implemented using a Raspberry Pi 4 as the central controller. High-level gait planning generates joint trajectories, which are transmitted to a PCA9685 16-channel PWM driver via the I²C interface. Position-based control is employed due to the absence of torque feedback.

An external switched-mode power supply provides regulated DC power to the servo motors and control electronics. A Raspberry Pi Camera Module is mounted for monitoring and future perception-based extensions.

6. Experimental Evaluation

6.1 Experimental Setup

Experimental validation was carried out to evaluate the locomotion performance and practical limitations of the proposed low-cost quadruped platform. Tests were conducted on two surface conditions: (i) a flat, rigid laboratory floor and (ii) a mildly uneven surface created using rubber mats to simulate small terrain height variations. The robot was operated using static walking gaits to ensure stability under varying load conditions.

The following performance metrics were evaluated:

- **Joint angle error**, defined as the absolute difference between commanded and measured joint angles
- **Payload capacity**, determined by incrementally increasing mass placed at the chassis centre
- **Electrical current draw**, measured at the power supply output
- **Servo temperature**, monitored using a non-contact infrared thermometer
- **Gait stability**, assessed qualitatively based on body oscillations, foot slippage, and successful completion of gait cycles

All experiments were repeated multiple times to ensure consistency of observations.

6.2 Calibration Results

Prior to calibration, noticeable deviations were observed between commanded joint angles and actual servo positions, particularly at higher loads and near joint limits. These deviations resulted in reduced gait symmetry and inconsistent foot placement.

The proposed software-based calibration and compensation framework significantly improved joint accuracy. Across the tested servos, the average joint angle error was reduced by approximately **30–35%** after calibration. In addition, repeated gait cycles exhibited improved repeatability, with reduced variation in foot trajectories and more consistent body posture. These improvements were particularly evident under moderate payload conditions, demonstrating the effectiveness of calibration in mitigating manufacturing tolerances and backlash in hobby-grade servos.

6.3 Payload and Stability Analysis

To evaluate load-bearing capability, payload mass was incrementally added at the centre of the chassis while maintaining identical gait parameters. Under low to moderate payloads, the robot maintained stable static walking with minimal body oscillation and consistent foot placement.

As payload increased beyond a threshold value, a noticeable rise in electrical current draw and servo temperature was observed. Although stable walking could still be achieved temporarily, increased joint lag and reduced step height resulted in gradual gait degradation. Importantly, failure did not occur abruptly; instead, the robot exhibited predictable performance deterioration, allowing safe identification of operational limits. This behaviour is desirable for educational and experimental platforms, as it reduces the risk of sudden mechanical damage.

6.4 Power and Thermal Behaviour

Electrical and thermal characteristics were analysed to assess actuator stress during locomotion. Higher payloads and faster gait cycles led to increased current spikes, particularly during the stance-to-swing phase transitions. Correspondingly, servo temperatures increased over prolonged operation, indicating higher mechanical and electrical loading.

It was observed that conservative gait timing—achieved by increasing dwell time between leg movements—significantly reduced peak current draw and thermal buildup. These findings highlight the importance of gait parameter selection when operating low-cost quadruped robots and provide practical guidelines for minimizing actuator stress and extending operational lifespan.

7. Discussion

The experimental results demonstrate that stable quadruped locomotion can be achieved using hobby-grade components when combined with careful mechanical design, kinematic modelling, and software-based calibration. While the platform is not suited for dynamic gaits or high-speed locomotion, it reliably supports static walking and controlled experiments.

The observed trade-offs between payload, power consumption, thermal behaviour, and gait stability provide valuable insights into the practical limits of low-cost quadruped robots. These findings are particularly relevant for educational applications, where affordability, predictability, and safety are prioritized over extreme performance.

8. Conclusion and Future Work

This paper presented a low-cost quadruped robot platform with a focus on calibration and experimental evaluation rather than high-performance locomotion. A software-based servo compensation framework and a systematic performance analysis were introduced to address common challenges associated with hobby-grade actuators. The results provide valuable insights into the capabilities and limitations of affordable quadruped robots.

Future work will investigate compliant feet, improved sensing, and perception-based gait adaptation, as well as comparative studies with alternative low-cost actuators.

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10. Conflict of Interest

The authors declare that they have no conflict of interest.

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