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Research Article

A Novel Miniaturized Implementation of the Minitaur Quadruped: Design, Gait Control, and Experimental Validation

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Abstract

We present the design, fabrication, and experimental validation of a novel miniature quadruped robot, drawing inspiration from the Ghost Robotics Minitaur platform. This work is primarily motivated by the desire to explore the significant benefits of scale reduction for legged locomotion, including lower cost, enhanced portability, and the ability to operate effectively in constrained environments. Our approach meticulously retains the core mechanical and kinematic features of the original Minitaur, adapting them to a much smaller scale. The robot's development involved integrating 3D-printed structural components (PLA), readily available off-the-shelf micro servos, and an Arduino Pro Mini for control. We specifically addressed key engineering challenges inherent in downscaling, such as achieving a compact chassis design, managing power efficiently within strict weight limits, and implementing robust gait control algorithms, including inverse kinematics for trot gait. Quantitative evaluation of the prototype demonstrates its performance with a mass of less than 0.5 kg, achieves forward speeds of approximately ≈ 0.91 Body Lengths per second (BL/s), and a controlled vertical displacment of less than 20 mm, and draws around 1050 mAh at 5 V during continuous motion. A comparative analysis highlights the critical trade-offs when contrasted with the original Minitaur (6 kg, ~5.0 BL/s) and other similar DIY (do-it-yourself) micro-quadrupeds, notably their differing kinematic approaches. Our results conclusively demonstrate that essential locomotion capabilities can be successfully retained in a highly compact form factor, representing a significant advancement in the development of more accessible and versatile legged robotic platforms.

Keywords: legged locomotion, Image processing, Miniaturized quadruped, low-cost robotics.

Minitaur Tabanlı Dört Bacaklı Bir Robotun Yenilikçi Minyatürleştirilmesi: Tasarım, Yürüyüş Denetimi ve Deneysel Doğrulama

Öz

Bu çalışmada, Minitaur platformu temel alınarak geliştirilen minyatür bir dört bacaklı robotun tasarımı ve deneysel doğrulaması sunulmaktadır. Amaç, bacaklı hareket sistemlerinde ölçek küçültmenin maliyet, taşınabilirlik ve dar ortamlarda çalışabilirlik açısından sağladığı avantajları ortaya koymaktır. Tasarım sürecinde orijinal Minitaur'un mekanik ve kinematik yapısı korunarak daha kompakt ve hafif bir mimariye uyarlanmıştır. Yapısal bileşenler PLA malzemeden 3B yazıcı ile üretilmiş, mikro servo motorlar kullanılmış ve kontrol Arduino Pro Mini tabanlı gömülü sistemle sağlanmıştır. Minyatürleştirme kapsamında kompakt şasi tasarımı, güç yönetimi ve tırıs yürüyüş için ters kinematik tabanlı denetim uygulanmıştır. Deneysel sonuçlar, sistemin 0,5 kg'ın altında kütleye sahip olduğunu, yaklaşık 0,91 gövde uzunluğu (BL/s) hız elde ettiğini ve 20 mm'den düşük düşey yer değiştirme sergilediğini göstermektedir. Sürekli hareket sırasında 5 V altında yaklaşık 1050 mAh enerji tüketimi ölçülmüştür. Orijinal Minitaur ve benzer mikro dört bacaklı robotlarla yapılan karşılaştırma, özellikle performans ölçeklenmesi ve tasarım ödünleşmelerini ortaya koymaktadır. Bulgular, temel hareket yeteneklerinin kompakt bir platformda korunabileceğini göstermektedir.

Anahtar Kelimeler: bacaklı hareket, minyatür dört bacaklı robot, ters kinematik, görüntü işleme, düşük maliyetli robotik

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1. Introduction

Legged robots are increasingly valued for their ability to navigate complex and unstructured terrains-environments where wheeled or tracked platforms often fail [1-3]. Among the notable platforms in this domain is the Ghost Robotics Minitaur [4, 5], a compact yet dynamic quadruped robot designed for research, agility, and affordability in legged locomotion. The Minitaur measures approximately 400 mm in length and weighs around 6 kg, while achieving impressive performance such as running at speeds of ∼5.0 BL, jumping, and climbing [4-6]. It features a unique two-degrees-of-freedom (2-DOF) leg structure, powered by direct-drive brushless motors, which enables high torque output, virtual compliance, and integrated sensing. These features make it a powerful and versatile testbed for legged robotics research.

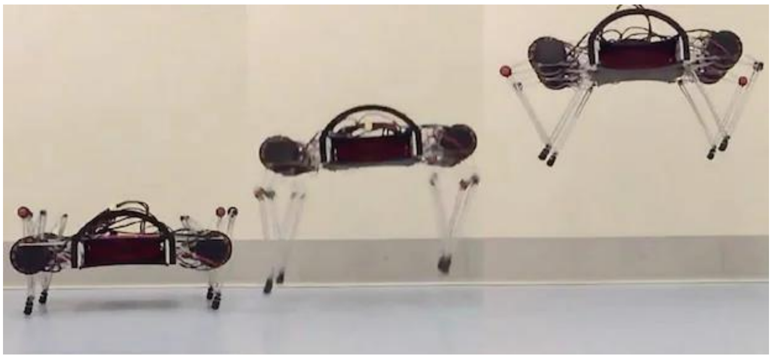

Figure 1.The Ghost Robotics Minitaur quadruped robot, the baseline platform for our work, shown here in a jumping experiment. The Minitaur is approximately 400 mm long, 6 kg in mass, and can achieve dynamic motions via its direct-drive leg actuators [1].

Despite its compact dimensions, the Minitaur remains relatively large and resource-intensive for certain applications. Its mass, hardware complexity, and power demands may pose limitations, especially in constrained environments, low-cost educational settings, or lightweight robotic systems [7, 8]. Therefore, miniaturization of the Minitaur architecture presents a compelling opportunity: reduced cost and energy consumption, safer operation due to lower mass, and improved adaptability for use in confined spaces such as desktop environments or within small vehicles [9, 10].

However, scaling down a complex, performance-focused design such as the Minitaur is non-trivial. Miniaturization introduces several engineering challenges, including mechanical rigidity with thinner structural parts, reduced actuator torque, limited onboard processing, and constrained power delivery [10, 11]. While there exist multiple examples of small-scale quadruped robots built by hobbyists and makers-typically using 3D-printed frames, microcontrollers like the Arduino, and off-the-shelf servos-these are often independent designs rather than scaled versions of established platforms. For example, Technovation's Arduino-powered micro quadruped and Lewin Day’s Hackaday featured robot both utilize 12 SG90 servos (three per leg) controlled by an Arduino Uno, with no attempt to replicate the Minitaur’s distinctive kinematic architecture [12, 13].

Recent advancements in miniature quadruped robotics have gone beyond hobbyist prototypes, highlighting the growing research interest in scaled-down platforms. Notably, the MinIAQ series introduced palm-sized quadrupeds fabricated through lightweight, origami-inspired methods [14, 15]. These works demonstrated that systematic miniaturization of compliant quadruped architectures can be achieved without entirely sacrificing stability or locomotion performance.

In contrast, our approach seeks to preserve the kinematic essence of the Minitaur specifically its two-DOF, five-bar leg structure while scaling down the hardware through accessible components such as SG90 servos and 3D-printed PLA parts. This distinction highlights two complementary philosophies in quadruped miniaturization: one focusing on reimagined morphologies optimized for manufacturability (e.g., origami-inspired MinIAQ robots), and another focusing on faithful downscaling of a proven high-performance design. Our work thus situates itself in the latter, bridging the gap between research-grade robots like the Minitaur and accessible, low-cost prototypes suitable for education and constrained environments.
In addition to the studies discussed above, recent research has placed further emphasis on the mechanical miniaturization and accessibility of quadruped robots. The Q8bot project introduced a sub-smartphone-sized quadruped capable of walking at speeds of up to 5 body lengths per second while remaining lightweight, affordable, and built entirely from easily replicable components [19]. Complementarily, the MEVIUS quadruped demonstrated a scalable mechanical design constructed from sheet metal parts using simple fabrication techniques such as welding and machining. This platform highlights how robust yet compact architectures can be realized through low-cost and widely accessible methods [20]. Together, these contributions extend the discussion of quadruped miniaturization by showing how structural simplicity and compactness can be achieved without sacrificing functionality, thereby reinforcing the relevance of scaled-down Minitaur-inspired platforms.

In this work, we present the first functional miniaturization of the Minitaur architecture. Our miniature quadruped retains the two-actuator-per-leg configuration and draws directly from the original's 5-bar linkage kinematics [5, 6]. The platform is constructed using 3D-printed Polylactic acid (PLA) components, SG90 micro servos, an Arduino Pro Mini, and a lightweight LiPo battery. We implement open-loop control algorithms, specifically inverse kinematics-based gait generation for trotting, and evaluate the robot's performance both qualitatively and quantitatively.

Key engineering challenges addressed include maintaining structural integrity with thin 3D-printed parts, efficient spatial arrangement of onboard electronics, and power management under the limitations of compact components [10, 11]. The resulting prototype, weighing less than 0.5 kg, is experimentally assessed in terms of locomotion speed, power consumption, and gait stability. Results are compared to both the original Minitaur and other DIY micro-quadrupeds to highlight trade-offs and performance benchmarks [6, 8].

The originality of this work resides in its attempt to achieve, for the first time, a systematic miniaturization of the Minitaur's characteristic 5-bar, two-DOF leg architecture within the constraints of low-cost actuation. While most existing miniature quadrupeds are independent hobbyist designs with simplified morphologies, our platform deliberately retains the kinematic essence of the Minitaur and investigates how far its design principles can be preserved under severe hardware and economic constraints. This transition from high-performance direct-drive brushless motors to commodity servo actuators is not merely a pragmatic cost-saving choice; rather, it constitutes an experimental framework to examine the scalability of legged robot architectures. In particular, our results demonstrate a fundamental trade-off: affordability, reduced weight, and accessibility are achieved at the expense of mechanical power density, leading to locomotion modes that rely predominantly on static stability rather than dynamic stability.

Such insights are significant in two complementary respects. First, they provide a scientific contribution to the ongoing discussion of how legged robot designs scale with size, actuator capability, and cost a question that has received little explicit treatment in the literature [12, 16]. Second, they broaden the applicability of Minitaur-inspired designs by situating them within the domain of educational robotics, low-cost prototyping, and resource-constrained environments where safety, affordability, and simplicity are as critical as raw dynamic performance. Thus, the proposed miniature platform is not only a functional prototype but also a case study in the engineering compromises and design adaptations required when translating high-end robotic architectures into more accessible forms.

A critical aspect of this evaluation involves MATLAB-based motion analysis. Through video-based image processing, we extract quantitative gait data-including centroid displacement, step velocity, and vertical oscillation to validate the robot’s real-world behavior. The following sections provide a detailed description of the design process, control methodology, motion tracking framework, and experimental results, culminating in a discussion of the broader implications of robotic miniaturization for research, education, and real-world deployment.

2. Material and Methods

The development of the miniature quadruped robot was guided by a set of deliberate engineering constraints, aimed at preserving the original Minitaur’s functional characteristics while achieving significant scale reduction. The design process emphasized structural fidelity, efficient component selection, and compact integration of all subsystems to maintain locomotion capabilities within the limits of hobby-grade hardware. A fundamental requirement was the preservation of the 2-degrees-of-freedom (2-DOF) leg configuration, wherein each leg comprises a pitch (hip) joint and a knee joint. This structure mirrors the Minitaur’s original linkage system and enables the execution of biologically inspired gaits such as trotting through coordinated inverse kinematics. Maintaining this configuration ensured that the miniaturized platform could replicate the movement strategy and mechanical behavior of its larger counterpart. To support miniaturization, the selection of actuators and control electronics was driven by both size and performance considerations. SG90 micro servos were chosen due to their compact form factor, accessibility, and adequate torque for low-mass applications. For central control, an Arduino Pro Mini microcontroller was selected for its minimal footprint and full compatibility with open-source development environments. Despite the constraints imposed by lower torque and limited resolution compared to high-end systems, these components proved sufficient for controlled locomotion at the sub-kilogram scale. The chassis and structural components were fabricated using a consumer-grade FDM 3D printer and PLA filament. This approach provided rapid iteration cycles, low production costs, and customizable geometries tailored to the robot's compact dimensions. Particular attention was given to balancing structural rigidity with minimal material usage, ensuring the frame could withstand the dynamic loads of walking without compromising weight constraints. A key challenge in the design was the integration of electronic components within a constrained volume. The battery, wiring harness, power regulation board, servo connections, and controller had to be compactly arranged within the central body while maintaining serviceability and signal integrity. Efficient spatial planning and modular wiring facilitated clean assembly and minimal interference.

Finally, gait generation and control algorithms were implemented on the Arduino platform using an open-loop inverse kinematics approach. Predefined foot trajectories were encoded based on timing sequences corresponding to crawling and trotting phases. Although no sensory feedback was employed, careful calibration of phase offsets and swing patterns allowed stable execution of the trot gait. The system architecture supports modular extension to other gait patterns or closed-loop refinement in future iterations.

The following section outlines each of these design dimensions in detail, highlighting the trade-offs made to ensure mechanical simplicity, functionality, and reproducibility within the context of a miniature legged robotic system.

2.1. Mechanical Architecture

The miniature quadruped robot is built upon a lightweight and compact chassis, with overall body dimensions ranging between 10 cm and 20 cm per side. This compact form factor enables the robot to operate in confined spaces while preserving mechanical integrity. The structural frame is fabricated from polylactic acid (PLA) using a consumer-grade 3D printer, resulting in a central body weighing approximately 150 grams.

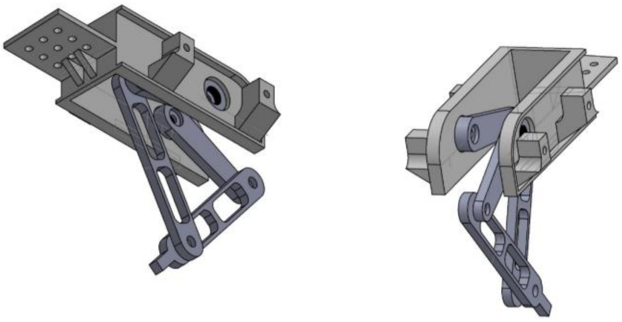

Figure 2. linkage's 3D design

Each of the robot’s four legs is configured with a two-degrees-of-freedom (2-DOF) kinematic linkage, designed to mimic the functional equivalents of hip and knee joints. This arrangement enables vertical lifting and angular bending of the leg segments, thus allowing the foot to reach arbitrary positions in three-dimensional space relative to the body. The leg assembly comprises three linked segments per limb-hip, thigh, and lower leg-extending to a total leg span of approximately 15 cm. Actuation is provided by eight standard micro servo motors, with two servos per leg. Each servo weighs approximately 25 grams and offers a stall torque of around

2 kg·cm, which is sufficient to support locomotion for a robot of this scale. These actuators were selected to provide a balance between torque output, size, and cost, making them ideal for lightweight robotic applications.

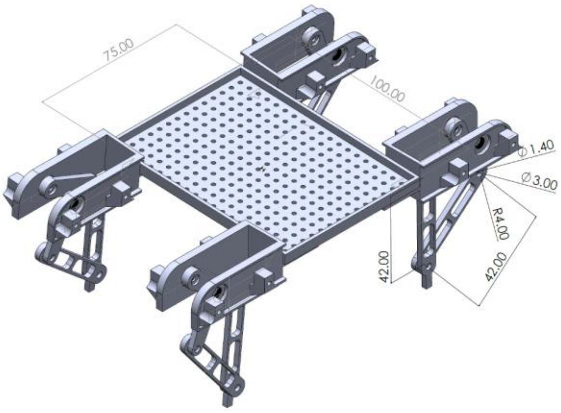

Figure 3. Robot's Dimentions

The joint configuration is such that the hip joint controls vertical lift, while the knee joint governs angular flexion. Although a passive ankle joint may be included in the design, foot orientation and position are primarily dictated by the coordinated motion of the two active joints. This configuration affords sufficient workspace for each foot, enabling the execution of biologically inspired gaits such as crawling and trotting.

From a stability perspective, the robot maintains a low center of mass and operates with at least three legs in contact with the ground at any given time during slow gaits. This provides inherent static stability, as the body's center of gravity remains within the support polygon defined by the stance legs [7]. The mechanical arrangement draws on common design principles seen in other quadruped systems but is adapted here for extreme miniaturization without sacrificing fundamental walking capability.

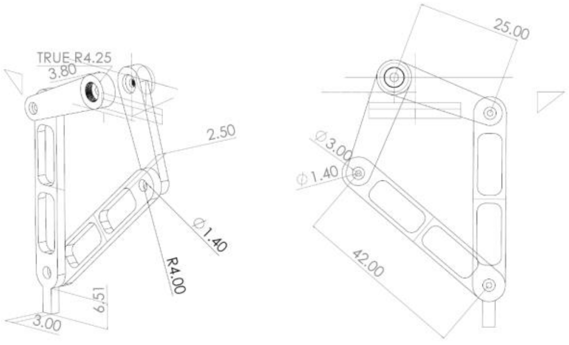

Figure 4. CAD model and dimensional specifications of the 5-bar leg mechanism

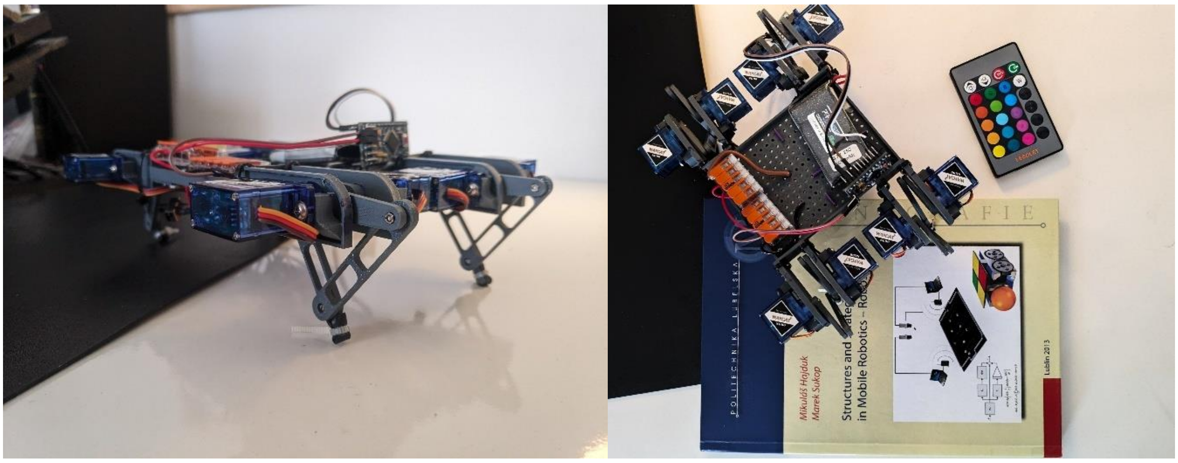

Figure 5. The robot after the manufacturing process. Its size is shown in comparison to a standard book to illustrate scale.

2.1.1. Kinematic Analysis

The quadruped robot is designed with a symmetric leg mechanism, enabling simplified and computationally efficient implementation of both forward and inverse kinematics. Each leg operates as a planar two-degree-of-freedom (2-DOF) linkage, composed of two serially connected rotational joints resembling a hip and knee joint driving two rigid links of lengths l_1 and l_2, respectively. The symmetrical design ensures that both sides of the mechanism contribute equally to the positioning of the foot, enhancing mechanical balance and reducing the computational burden of control algorithms.

Figure 6 illustrates the geometric configuration of a single leg. The angles θ_1 and θ_2 represent the actuated joint angles at the base (hip) of the two mirrored linkages. The passive joints labeled θ_3 and θ_4 are internal angles that describe the configuration of the remaining segments of the linkage. These angles are not directly actuated but are kinematically constrained by the motion of θ_1 and θ_2, due to the rigid and symmetric structure of the leg.

To compute the forward kinematics, which determine the Cartesian coordinates (x, y) of the foot tip relative to the leg's base frame, vector projections are applied along the x and y axes. The fundamental

geometric constraints are given by:

$$\begin{cases} l_1 \cos\theta_2 + l_2 \cos\theta_3 = l_2 \cos\theta_4 + l_1 \cos\theta_1 \\ l_1 \sin\theta_2 + l_2 \sin\theta_3 = l_2 \sin\theta_4 + l_1 \sin\theta_1 \end{cases} \qquad (1)$$

Since l_1 and l_2 are known, and θ_1, θ_2 are actuated variables, the unknowns θ_3, θ_4 can be isolated:

$$\begin{cases} l_2\,(\cos\theta_3 - \cos\theta_4) = l_1(\cos\theta_1 - \cos\theta_2) \\ l_2\,(\sin\theta_3 - \sin\theta_4\,) = l_1(\sin\theta_1 - \sin\theta_2\,) \end{cases} \qquad (2)$$

By solving this nonlinear system numerically, for example using MATLAB, the values of θ_3 and θ_4 can be computed. Then, the position of the foot tip in Cartesian coordinates is determined by:

$$\begin{cases} x = l_1 \cos\theta_2 + l_2 \cos\theta_3 \quad OR \quad l_2 \cos\theta_4 + l_1 \cos\theta_1 \\ y = l_1\, sin\,\theta_2 + l_2\, sin\,\theta_3 \quad OR \quad l_2 \sin\theta_4 + l_1 \sin\theta_1 \end{cases} \qquad (3)$$

This formulation guarantees that both mirrored halves of the leg contribute equally to the final foot position, maintaining the mechanical symmetry of the structure. Moreover, this kinematic consistency is essential for ensuring balance and repeatability across all four legs during locomotion.

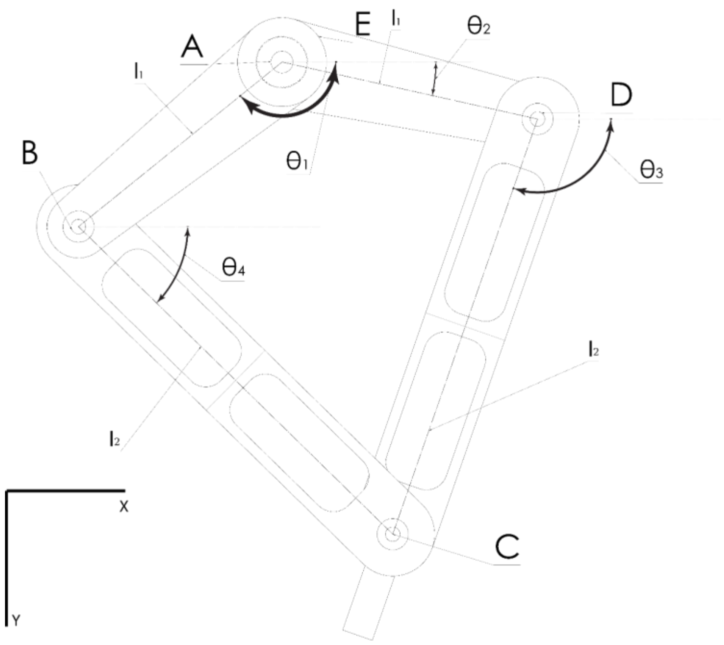

Figure 6. Schematic diagram of the symmetric 2-DOF leg mechanism, showing joint angles θ_1 to θ_4, link lengths l_1,l_2, and the foot tip position in the local coordinate frame.

2.1.2. Velocity Kinematics

To obtain the angular velocities of the passive joints, the system is differentiated with respect to time. Taking the first derivative of equation (2), we derive the following relationship:

$$\mathrm{l}_2 \begin{bmatrix} -sin\,\theta_3 & sin\,\theta_4 \\ cos\,\theta_3 & -cos\,\theta_4 \end{bmatrix} \begin{bmatrix} \omega_3 \\ \omega_4 \end{bmatrix} = l_1 \begin{bmatrix} -sin\,\theta_1 & sin\,\theta_2 \\ cos\,\theta_1 & -cos\,\theta_2 \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \end{bmatrix} \qquad (4)$$

Where $\omega_1, \omega_2, \omega_3, \omega_4$ represent the angular velocities of joints $\theta_1 \sim \theta_4$, respectively.This formulation allows real-time estimation of the passive joint velocities required for foot motion, critical in dynamic gait transitions.

2.1.3. Acceleration Kinematics

$$\mathrm{l}_2\begin{bmatrix}-sin\,\theta_3 & sin\,\theta_4\\ cos\,\theta_3 & -cos\,\theta_4\end{bmatrix}\begin{bmatrix}\alpha_3\\ \alpha_4\end{bmatrix}=-l_2\begin{bmatrix}-\omega_3\ sin\,\theta_1 & \omega_4\,sin\,\theta_2\\ \omega_3\,cos\,\theta_1 & -\,\omega_4\,cos\,\theta_2\end{bmatrix}\begin{bmatrix}\omega_3\\ \omega_4\end{bmatrix}+$$

$$l_1\begin{bmatrix}-sin\,\theta_1 & sin\,\theta_2\\ cos\,\theta_1 & -cos\,\theta_2\end{bmatrix}\begin{bmatrix}\alpha_1\\ \alpha_2\end{bmatrix}+l_1\begin{bmatrix}-\omega_1\,sin\,\theta_1 & \omega_2\,sin\,\theta_2\\ \omega_1\,cos\,\theta_1 & -\,\omega_2\,cos\,\theta_2\end{bmatrix}\begin{bmatrix}\omega_1\\ \omega_2\end{bmatrix} \qquad (5)$$

2.1.4. Inverse Kinematics

Inverse kinematics (IK) is the process of computing the joint angles required to position the foot at a specified target location within the leg's workspace. For the symmetric 2-DOF leg mechanism used in this robot, the analytical derivation of inverse kinematics allows for real-time trajectory generation with minimal computational overhead making it highly suitable for embedded systems such as the Arduino Pro Mini.

Let the desired foot position in the leg's local coordinate frame be defined by the Cartesian coordinates (x, y). The objective is to determine the joint angles θ_1 and θ_2 that achieve this target position.

The process begins by computing the Euclidean distance r from the hip joint to the foot tip:

$$r=\sqrt{x^2+y^2} \qquad (6)$$

Apply the law of cosines to determine the knee angle:

$$\theta_2=\pi-\cos^{-1}\left(\frac{l_1^2+l_2^2-r^2}{2l_1l_2}\right) \qquad (7)$$

Then, compute the hip angle:

$$\theta_1=\tan^{-1}\left(\frac{y}{x}\right)-\cos^{-1}\left(\frac{r^2+l_1^2-l_2^2}{2rl_1}\right) \qquad (8)$$

These analytical expressions enable real-time computation of joint trajectories based on desired footpaths. Given the low-latency requirements of walking controllers, the simplicity of this IK method is advantageous for miniature robot control.

2.2. Electronics and Power Management

The robot's control and power systems are integrated on a compact Arduino Pro Mini microcontroller, chosen for its small footprint, low power consumption, and full compatibility with open-source development tools. The onboard electronics are powered by a single-cell 3.7 V, 1050 mAh lithium-ion battery, which supplies energy through a step-up DC–DC converter that boosts the voltage to a regulated 5 V. To ensure power stability during dynamic operation, the converter output is equipped with capacitive filtering, effectively minimizing voltage fluctuations and suppressing transient dips caused by simultaneous actuator loads.

For user interaction and control, an infrared (IR) receiver module is integrated into the system, allowing wireless selection of gait modes via a standard remote controller. Additionally, status indicator LEDs are employed to provide real-time feedback on operational states, such as power-on, gait selection, and fault conditions. This modular and low-power electronic architecture supports the robot's autonomy while maintaining a lightweight and energy-efficient design, suitable for prolonged untethered operation.

2.3. Control Architecture and Trot Gait Implementation

The quadruped robot employs a lightweight, open-loop control architecture built around an Arduino-based microcontroller, which is responsible for generating predefined locomotion patterns and executing inverse kinematic computations in real time. The robot has four legs, each actuated by two degrees of freedom (DOF) typically corresponding to the hip and knee joints-resulting in a total of 8 actuators and 8 controllable DOF across the entire system. Actuation is achieved via PWM (Pulse Width Modulation) signals sent from the controller to standard servo motors.

The control framework relies on a closed-form inverse kinematics model, derived from the symmetric geometry of the leg linkage. This model maps each desired foot position (in the local body frame) to a unique pair of joint angles for that leg. During operation, the controller generates target foot trajectories as a function of time, and for each time step, it solves the corresponding inverse kinematics to obtain the joint commands.

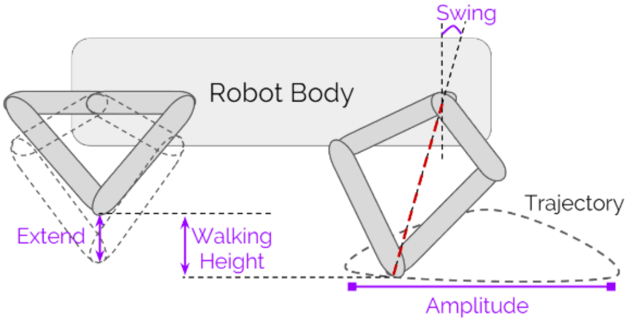

Figure 7. Trajectory and phases [17].

The robot exclusively utilizes a trot gait in this study, chosen for its balance between simplicity and speed. The trot is a symmetrical gait where diagonal leg pairs move in unison-specifically, the front-left and rear-right legs swing forward simultaneously, alternating with the front-right and rear-left legs. At any given point in the cycle, two legs are in the swing phase while the other two remain in stance, providing dynamic support along a diagonal axis.

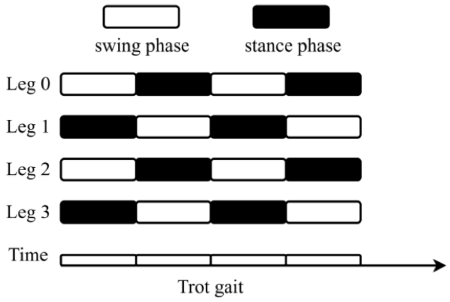

Figure 8. Stance phase and swing phase of trot gait [18].

Each gait cycle is time-divided into two equal halves, implementing a 50% duty cycle: each leg spends half of the cycle in stance and the other half in swing. The controller executes the gait as a phase-based generator, where diagonal leg pairs are offset by approximatly 160 degrees. Foot trajectories for the swing phase follow a predefined "lift–advance–lower" path-lifting the foot vertically to a fixed height, moving it forward horizontally, and smoothly returning it to the ground. These trajectories are generated without sensor feedback, resulting in a purely open-loop control scheme.

2.4. Motor Limitations and Stability Considerations

The miniature quadruped retains the 2-DOF leg architecture and 5-bar linkage of the original Minitaur. However, unlike the original platform which uses high-power direct-drive brushless motors to achieve fully dynamic gaits the miniaturized robot employs SG90 micro servo motors. These actuators provide lower torque and speed, inherently limiting locomotion to statically stable gaits rather than dynamic motion cycles. This constraint is a deliberate engineering trade-off, prioritizing compactness, affordability, and reproducibility. We explicitly clarify that the purpose of this work is systematic miniaturization while preserving the kinematic design, not replicating the full dynamic performance of the original Minitaur. Future upgrades with higher performance actuators or closed-loop control could extend the platform toward dynamic stability studies.

3. Results and Disscussion

3.1. Motion Analysis Methodology

To evaluate the locomotion of the miniature quadruped robot, we developed a custom image-processing routine in MATLAB for analyzing foot and body motion from video recordings. The goal was to extract two-dimensional position data for each marker (attached to the robot's feet and body) and use this information to compute kinematic parameters such as velocity and vertical stability.

The MATLAB code utilized a standard RGB camera (connected as winvideo device) operating at a resolution of 640×480 pixels. A sequence of frames was captured while the robot executed the trot gait. The key parameters included a frame sampling interval of 4 and a total acquisition window of 50 frames.

The algorithm performed marker-based object detection using color segmentation and centroid estimation. Each marker (red, green, blue) was detected using channel subtraction between its RGB component and the grayscale frame, followed by median filtering, binary thresholding, and morphological filtering (via bwareaopen). The centroids of valid objects were extracted using regionprops, and their positions were annotated in the live video stream for visual verification.

For each detected marker, the centroid coordinates (in pixels) were stored in matrix data, along with the corresponding frame number, marker type (1=red, 2=green, 3=blue), and timestamp normalized by total acquisition time. This enabled precise extraction of position-time data for kinematic analysis.

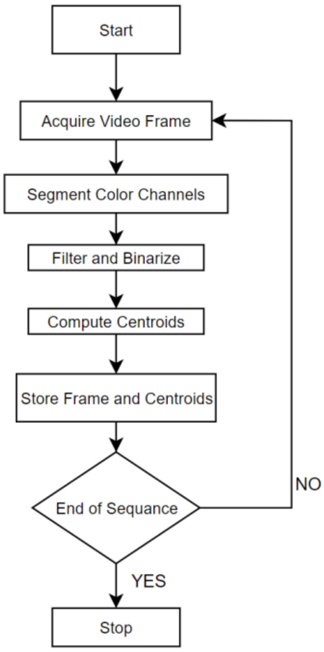

Figure 9. Flowchart of the MATLAB algorithm for video-based marker tracking and motion data extraction.

3.2. Marker Detection and Data Extraction

The marker tracking algorithm is designed to extract the positions of color-coded markers from video frames using a structured image processing pipeline. Initially, the video stream is initialized, and frames are continuously captured until a predefined number is reached. For each frame, the red, green, and blue channels are individually processed by subtracting the grayscale version of the frame, followed by median filtering to reduce noise. The resulting difference images are then binarized using predefined thresholds and filtered by area to eliminate small artifacts. After segmentation, the algorithm applies region-based analysis to identify valid markers and calculate their centroids. These centroids, along with frame index, color ID, and object ID, are stored in a matrix. Finally, the time dimension is normalized relative to total acquisition time, enabling accurate temporal analysis of each marker’s trajectory. This structured data serves as the basis for evaluating gait patterns, velocity, and stability metrics.

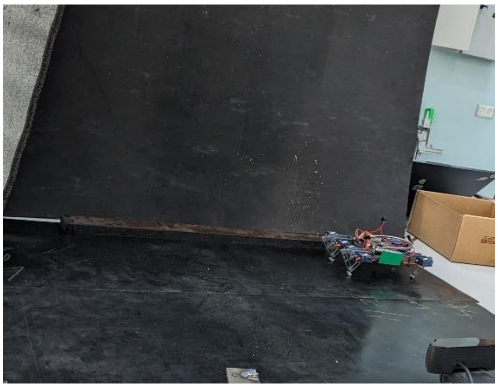

Figure 10. Experimental and analysis setup used during testing

3.3. Velocity Estimation

The horizontal displacement of the body marker was plotted as a function of time. From this, the average forward velocity was calculated using linear regression for three trials. The results are summarized in Table 1.

Table 1 Estimated forward speed across three gait trials.

Trial	Speed (m/s)	BL/s
1	0.1729	0.99
2	0.1733	0.99
3	0.1317	0.75
Average	**0.1593**	**0.91**

The robot demonstrated a consistent and stable forward gait in Trials 1 and 2. Trial 3 showed a slightly reduced speed, which was attributed to the presence of an unexpected small obstacle in the robot’s path, momentarily affecting its stride. Despite this, the overall results align with the design expectations, confirming the system's robustness and repeatability.

3.4. Vertical Stability

Vertical displacement of the body centroid was analyzed to evaluate balance and motion consistency. The recorded trajectory exhibited smooth, periodic oscillations with an amplitude range of approximately ±5–10 mm. These minor vertical fluctuations are characteristic of the trot gait, resulting from the alternating stance phases of the diagonal legs. The verical’s motion profile remained stable throughout each trial, indicating that the robot preserves vertical equilibrium and avoids excessive body tilting or oscillation during locomotion.

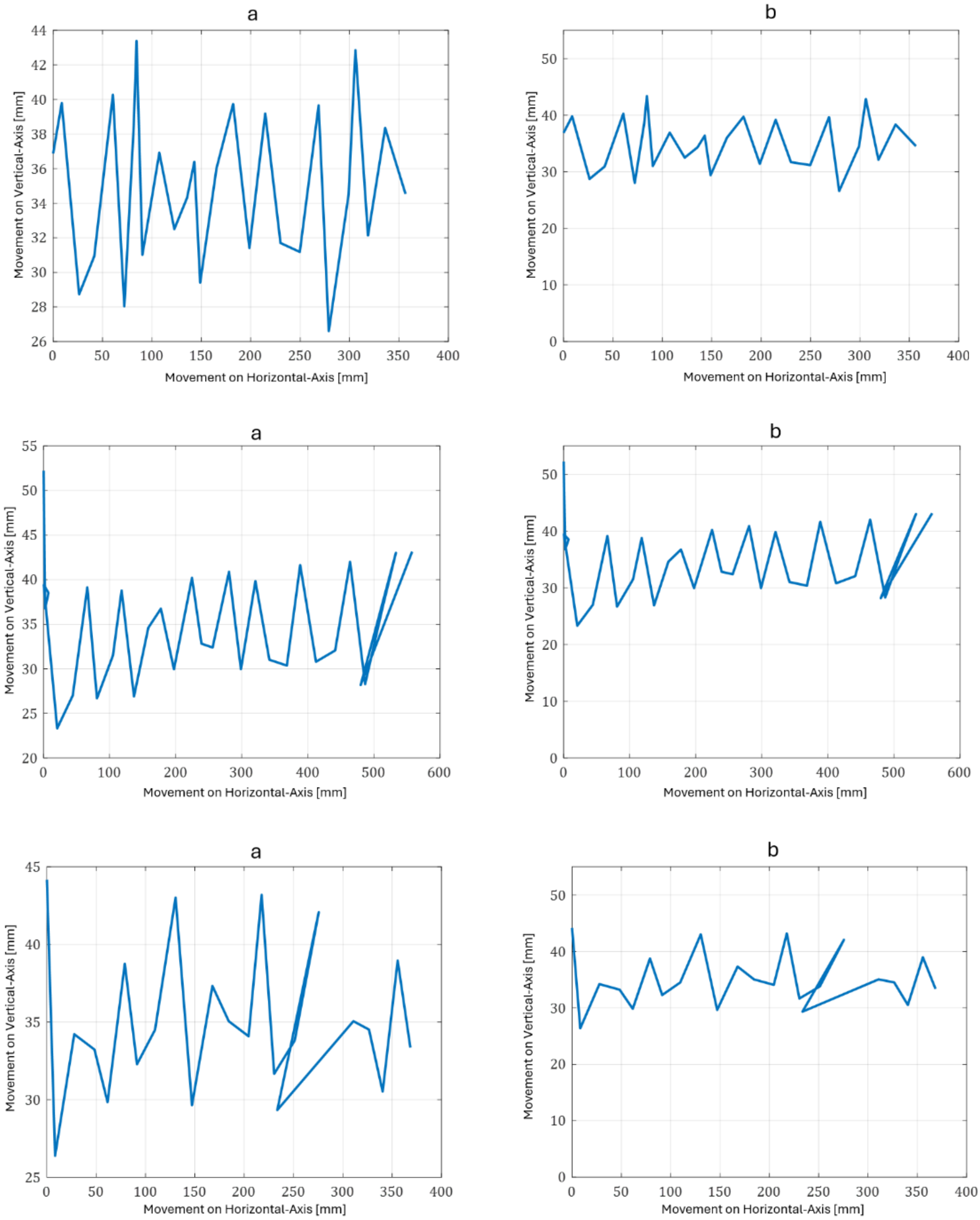

Figure 11. Vertical displacement during three experimental trials with respect to different reference frames: a) relative to the robot's chassis center; b) relative to the ground

3.5. Discussion

The miniature quadruped robot successfully demonstrated stable and repeatable trot gait locomotion using a fully open-loop control strategy. The mechanical structure proved lightweight yet sufficiently rigid, and the 8-DOF configuration (2 DOF per leg) enabled coordinated motion through simple trajectory planning.

Throughout testing, only the trot gait was implemented and evaluated. This diagonal gait configuration allowed the robot to move efficiently, with two legs in contact with the ground at all times. The gait planner was designed using fixed-phase offsets and predefined swing trajectories. These were computed using inverse kinematics equations and executed through timed PWM signals. While closed-loop feedback was not used, the kinematic and motion tracking analysis indicated the controller's effectiveness.

The trot gait inherently requires more precise timing than static gaits such as crawl. Although it offers higher speed and agility, it also reduces the margin for balance. This was evident during testing: while the robot maintained overall stability, minor deviations in phase timing or leg alignment could occasionally cause vertical deviation. Nevertheless, the vertical displacement remained within acceptable bounds, as observed in MATLAB-based measurements.

One key advantage of the chosen gait implementation was modularity. Each leg followed the same foot trajectory, with coordination achieved solely by assigning specific phase offsets. This made the gait system scalable and easy to modify. Importantly, the foot trajectory was chosen to match a "lift–forward–lower" pattern that is simple to implement and avoids unnecessary foot drag.

During experimental trials, performance remained consistent. The MATLAB tracking system confirmed repeatable motion patterns, and the system showed resilience even in the presence of minor disturbances (e.g., the obstacle encountered in Trial 3). These findings highlight the reliability of the current open-loop approach, even without onboard sensing or feedback.

However, several limitations were observed. The use of standard hobby-grade servos limited the attainable gait speed and torque. At higher speeds or on irregular terrain, closed-loop control with IMU or force feedback would be necessary. Additionally, integration of onboard autonomy (e.g., visual sensors or terrain recognition) could extend the robot’s capabilities beyond scripted gaits.

Table 2. Comparative overview of the original Minitaur and the miniaturized platform

Feature	**Original Minitaur**	**Miniaturized Platform**	**Remarks / Engineering Trade-offs**
Actuation	High-power direct-drive brushless motors	SG90 micro servos	Transition from high-torque actuators to hobby-grade servos reduces dynamic capabilities but ensures affordability and compactness.
Weight	~6 kg	<0.5 kg	Significant mass reduction improves safety, portability, and suitability for constrained environments.
Leg DOF	2 (hip & knee per leg)	2 (hip & knee per leg)	Preserved kinematic architecture maintains the ability to execute biologically inspired gaits.
Gait Type	Dynamic locomotion; feet may lift off the ground	Statically stable trot; feet maintain ground contact	Limited by servo torque and speed; trade-off between dynamic stability and low-cost actuation.
Control Architecture	Closed-loop feedback with high-rate sensing	Open-loop inverse kinematics	Simplified control sufficient for stable trotting; future integration of sensors and feedback possible.

Power & Electronics	High-capacity batteries, custom drivers	Single-cell LiPo, Arduino Pro Mini	Ensures minimal footprint and low power consumption; constrains peak torque delivery.
Speed	~5 body lengths/s	~0.91 body lengths/s (experimental)	Reduced speed is a direct consequence of lower actuator power and statically stable gait.

In the present study, the gait generation framework is derived solely from the kinematic analysis of the legs, under the simplifying assumption that the robot's body remains approximately parallel to the ground plane. Consequently, the presented trajectories cannot be considered a complete gait control strategy in the strict dynamical sense, as they do not incorporate body pitch, roll, or yaw dynamics. This limitation arises from the deliberate choice to constrain the design to low-cost, miniature hardware without onboard inertial sensing. Therefore, the locomotion patterns should be regarded as open-loop, kinematic gait generation under static body assumptions, rather than full dynamic gait control. Future iterations of the platform will integrate inertial measurement units and closed-loop stabilization to extend the framework toward dynamic gait regulation.

In summary, the trot gait implementation on this miniature quadruped successfully balances simplicity and performance. The robot achieves reliable, symmetric gait cycles using minimal hardware and no feedback, validating both the mechanical design and the control approach. This platform forms a solid foundation for future work in terrain adaptation, gait optimization, and sensor integration.

4. Conclusion

This research presented the design, implementation, and analysis of a miniature quadruped robot that performs stable trot gait locomotion using an open-loop control strategy. The project demonstrated that with a simplified mechanical structure, basic servos, and well-defined kinematic trajectories, reliable diagonal leg coordination can be achieved.

- Mechanical and Control Validation: The robot successfully achieved stable trot gait locomotion using a fully open-loop control strategy, validating both the mechanical design and the control approach.
- Performance and Repeatability: MATLAB-based motion tracking and analysis verified the accuracy and repeatability of the robot's performance, showing a consistent forward velocity and controlled vertical displacement. The robot's behavior aligned well with theoretical models, even in the absence of real-time sensory feedback.
- Scalability and Accessibility: This study contributes an effective and accessible approach to small-scale legged locomotion. The platform can serve as a foundation for further development, including sensor integration, adaptive gaits, and autonomous navigation systems.
- Future Work: Future improvements will focus on enhancing gait versatility, increasing speed through stronger actuators, and enabling real-time feedback-based motion adaptation in more complex environments.

Ethics in Publishing

There are no ethical issues regarding the publication of this study

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