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Intelligent Motion-Controlled Quadruped Robot Using Arduino Systems

Amjed Jumaah[1*], Aseel Qasim[2]
[1]*AI Engineering Department, Collage of Engineering, Al-Ayen Iraqi University, Thi-Qar, 64001, Iraq*
[2]*Department of Information Technology, Collage of Computer Science and Mathematics, University of Thi-Qar, Thi-Qar 64001, Iraq*
amjed.baqer@alayen.edu.iq[1], aseel.a.qasim@utq.edu.iq[2]

Abstract_ This work presents RobotSpot, a novel low-cost quadruped robot designed to address the growing need for accessible and robust platforms in robotics education and research Background. The main aims are to develop a system that combines intelligent control with economic feasibility, emphasizing ease of reproduction and modification. The methods involve integrating hybrid control algorithms and conducting experimental evaluations to assess stability and energy efficiency. The results demonstrate reliable operation with an average stability of 88.1% and energy efficiency of 77.5%, highlighting RobotSpot's potential as a practical and affordable tool for hands-on learning and innovation, especially in resource-constrained academic environments.

Keywords: Quadruped Robot, Arduino, Artificial Intelligence, Servo Motors, Embedded Systems, Robotics, Environmental Interaction

I. INTRODUCTION

Thanks to developments in robotics and artificial intelligence (AI), autonomous robotic systems have experienced radical transformation. Inspired by biological locomotion, among these quadruped robots stand out for their remarkable mobility and stability in unstructured surroundings [1]. Where human interaction is either dangerous or unfeasible, these systems are being used more and more in high-impact applications including search- and-rescue missions, industrial inspection, and hazardous terrain navigation [2]. Nevertheless, many quadruped systems remain cost-prohibitive for educational and small-scale research applications, therefore impeding hands-on learning in robotics [3].

Presenting RobotSpot, an open-source, Arduino-powered quadruped robot meant to combine affordable hardware with easily accessible control mechanisms, this work closes this gap. Targeting undergraduate robotics instruction and reasonable research prototyping, RobotSpot stresses scalability, multidisciplinary collaboration, and educational reproducibility unlike commercial platforms. Our main goals include in three directions:

- To show how a working, low-budget system can be derived from theoretical ideas of legged movement, sensor integration, and embedded control.
- To give researchers and students a modular framework employing off-the-shevel components to investigate dynamic gait production, balance management, and environmental interaction.
- To validate the robot's use as a teaching and research tool by means of performance evaluation against important criteria (e.g., stability, power efficiency, and terrain adaptability).

The wider relevance of this work comes from its possibility to democratize robotics development. Through recording design trade-offs, implementation difficulties, and cost-effective solutions, this study adds to the increasing conversation on accessible intelligent systems [4].

II. RELATED WORK

Recent years have seen much research on quadruped robots with different degrees of intelligence and complexity. While pointing up important research gaps in reasonably priced educational solutions, this part methodically evaluates the development of quadruped systems, their control paradigms, and the growing trend of open-source platforms.

2.1 Evolution of Quadruped Platforms

Boston Dynamics' Spot [5] and other commercial quadruped systems have shown amazing resilience in unstructured surroundings, hence establishing standards for dynamic mobility. Academic studies have matched these advances with open-design projects stressing modularity and control flexibility, such MIT's Mini Cheetah [6] and PAL Robotics' Solo8 [7]. From stationary walking machines (pre-2010) to dynamic runners (2010–2020) and finally autonomous

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decision-makers (post-2020), these systems together reflect three generations of quadruped evolution [8].

2.2 Control Paradigms in Legged Locomotion

Modern quadruped control's basis consists in three main strategies:

- Inspired by bio-based brain oscillator models developed by Ijspeert et al. [9], central pattern generators (CPGs) allow rhythmic gait generation.
- Model Predictive Control (MPC) applied in Boston Dynamics' dynamic stability [10]
- Emerging as the main method for adaptive locomotion, reinforcement learning (RL) demonstrated by Peng et al. [11]

Ground flexibility of these systems has been improved even more by recent developments in sensor fusion [12] and motor coordination algorithms [13].

2.3 Open-Source Educational Platforms

The spread of Arduino and Raspberry Pi-based systems has opened fresh low-cost quadruped development prospects. Notable instances abound:

- Completely 3D-printable platform with inverse kinematics control: Open Quadruped [14]
- Stanford Pupper: Made especially for robotics teaching [15]
- Quadruped-ESP32: combining Wi-Fi-based teleoperation [16]

Although these platforms offer less performance than commercial systems, they give researchers and students easily available access [17]. Recent studies by Johnson et al. [18] have measured their instructional effect; among undergraduate users, robotics understanding has improved by 72%.

2.4 Limitations of Current Research

There still exist three major gaps in quadruped robotics research:

- Most research concentrate either on basic educational platforms or high-performance commercial systems, with minimal effort on optimizing this range [19].
- Standardized Evaluation: Absence of consistent benchmarks for evaluating locomotor efficiency on variously priced systems [20]
- Open-source systems usually lack the sensor suites and processing capability for advanced autonomous behaviors [21].

2.5 How This Research Addresses the Gaps

This work closes these gaps via:

- Creation of RobotSpot, balancing performance with affordability utilizing Arduino-based control.
- Overview of consistent testing strategies for educational quadrupeds.
- Novel sensor fusion methods catered for a limited resources system.

III. METHODS AND MATERIALS

Using three basic components— mechanical design, control algorithms, and sensor integration— this paper assesses RobotSpot's locomotion system. These components were chosen to solve important low-cost quadruped robotics concerns like stability, energy economy, and gait adaptation. The experimental framework, simulation settings, and validation criteria are described in the next sections.

3.1 System Architecture

The mechanical architecture of RobotSpot (Figure 1) uses a lightweight wood-plastic composite chassis best for dynamic stability. Maintaining a total weight of 1.2 kg, the layered architecture facilitates modular improvements.

[Figure 1 about here.]

3.2 Locomotion Control Algorithms

3.2.1 Central Pattern Generator (CPG)

To generate rhythmic limb motions, the CPG method replics biological brain oscillators [5]. Applied as connected nonlinear oscillators, it produces low computational overhead stable gait patterns (trot, crawl). Although good for basic mobility, its fixed-phase connection reduces flexibility on uneven ground.

3.2.2 Inverse Kinematics (IK) Controller

The IK solver maps foot trajectories to joint angles in real-time using Denavit-Hartenberg parameters:

$$\theta = atan^2(P_y , P_x) + \text{acos}((L1^2 + L2^2 + Px^2 - Py^2))/(2L_1L_2)$$

Where L_1L_2 limb are segment lengths and (P_y , P_x) are foot positions. This enables precise foot placement but requires 12% more CPU cycles than CPG.

3.2.3 Hybrid CPG-IK Controller

A novel fusion approach (Figure 2 schematic) combines CPG's efficiency with IK's precision through a weighted factor (α=0.7):

- CPG generates baseline gait rhythms
- IK adjusts limb trajectories based on IMU feedback
- A weighting factor αα (0.7 in our tests) balances responsiveness vs. stability

[Figure 2 about here.]

3.3 Hardware Configuration

3.3.1 Actuation System

- 12× SG90 Servos: Configured for 3-DoF limbs (Figure 3) with modified PWM control (500–2500μs pulses)
- Power System: 7.4V Li-ion battery with dual-voltage regulation

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[Figure 3 about here.]

3.3.2 Sensor Specifications and Parameters

Important for motion control and environmental awareness, the sensor suite fit inside the robot consists of inertial and distance sensors. Table 1 lists every sensor used in the system together with their main characteristics and parameters.

[Table 1 about here.]

3.4 Experimental Setup

3.4.1 Terrain Conditions

- Flat Surface: Linoleum flooring (μ = 0.3 friction coefficient)
- Inclined Plane: Adjustable ramp (0–15° slope)
- Obstacle Course: 3 cm height variation

3.4.2 Performance Metrics

- Gait Stability: Measured as torso attitude deviation (IMU data)
- Energy Efficiency: Power draw (W) per meter traveled
- Terrain Adaptability: Success rate in obstacle navigation

3.5 Data Collection Protocol

1. Baseline Tests: 10 walking trials per gait algorithm on flat terrain
2. Stress Tests: Inclined/obstacle trials with incremental difficulty
3. Failure Modes: Recorded when:

- Servo overheating occurred (>60°C)
- Attitude deviation exceeded 10°
- Battery voltage dropped below 6.5V

3.6 Motor Assembly and Control

The exact assembly of the motor components together with the control schematic is shown here. This schematic emphasizes the way control signals and hardware are integrated to enable the motion coordination of the robot.

[Figure 4 about here.]

Different control techniques' relative performance was assessed using stability, speed, and power economy. Table 2 lists these important benchmarks together with the advantages and compromises of every technique.

[Table 2 about here.]

IV. IMPLEMENTATION STEPS

RobotSpot was built using an ordered engineering process to unite mechanical, electrical, and software subsystems into a single robotic platform.

Starting with concept drawings and 3D models, the team worked through design phases to ascertain the size and joint configuration of the robot. CAD tools let one replicate joint angles and load distribution. The goal was to keep the robot's center of gravity constant even in motion.

The robot's structure was built from lightweight plastic and wood combined for cost-effectiveness and simplicity of construction. Custom braces either 3D printed or laser cut were used to securely mount the servo motors. Particularly careful was alignment of the servos to prevent excessive strain on the joints.

In this phase all wiring connections between the Arduino, servos, MPU-6050 sensor, and power modules were to be soldered and sealed. The company used cable management techniques and ensured sufficient insulation to reduce interference and boost safety.

Once all pieces were connected, the MPU-6050 sensor was calibrated to eliminate bias and drift. Establishing a reference orientation called for the robot to remain neutral and average sensor signals.

Software development began with basic testing to verify motor control and sensor capability. Once confirmed, individual modules were included into the whole control system. The code was tested and improved constantly depending on the real performance of the robot.

Every robot generation received extensive testing on a variety of level surfaces. Stress testing searched for mechanical defects; walking gaits were videotaped and analyzed for timing abnormalities. Feedback loops between development and testing let the team reduce system vibrations, enhance control algorithms, and maximize gait patterns.

Ensuring that every subsystem was totally functional before integration reduced the likelihood of cascade failures and simplified troubleshooting.

[Figure 5 about here.]

V. RESULTS AND DISCUSSION

A range of controlled interior situations allowed RobotSpot's general performance in terms of energy efficiency, balance stability, adaptability, and locomotion quality to be evaluated. The evaluation approach consisted in several functional tests on several floor kinds, including tile, laminate, and somewhat uneven surfaces, so simulating real-world indoor conditions.

[Figure 6 about here.]

The robot effectively displayed its capacity to:

Move forward and backward over level and somewhat uneven ground keeping a consistent walking pattern.

Turn slowly, 90 degrees, using enough angular stability.

Show its value for simple task completion by keeping balance when carrying little loads (up to 200 grams).

Use real-time MPU-6050 feedback to automatically recover from minor tilts and orientation changes by means of balance correction.

Indicating a moderate degree of energy consumption, the lithium-ion battery was able to run continuously under steady load for up to 35 minutes. Stability was found to depend on servo synchronization; even small changes in timing or power source produced clearly observed wobbling or erratic gait patterns. Addition of sensor-based feedback substantially improved walking balance and smoothness. After gyroscopic correction techniques and servo delay fine-tuning were applied, empirical data obtained in recurrent testing cycles showed a 25% increase in postural stability.

To evaluate dependability and consistency, statistical analysis of the RobotSpot platform's experimental performance measures Table 3 lists, from several test runs, the mean values, standard deviations, and coefficients of variation for important performance measures.

[Table 3 about here.]

Low coefficients of variance point to consistent, repeatable performance across several test environments.

Over several tests, Figure 7 shows RobotSpot's average stability, energy economy, and terrain adaptability. Error bars show the standard deviation, therefore reflecting the robot's performance's consistency.

[Figure 7 about here.]

5.1 Comparative Evaluation

Among other open-source quadruped robots, RobotSpot offers several notable benefits including:

Affordability: Both personal hobbyists and educational institutions might make use of it as the whole building cost came out to be less than $50USD.

Local component procurement and absence of specialized manufacturing tools helped to increase replicability.

The well-defined modular architecture and simplified software interface of the system support learning.

Still, the following recognized limitations:

The robot is ideal for inside environments since of its low ground clearance and lack of shock absorption; it suffers on uneven or outside terrain.

Current version requires cable programming since it lacks a wireless communication module for telemetry or remote control.

RobotSpot just has a gyroscope sensor and lacks sophisticated obstacle detecting technologies like LIDAR, ultrasonic, or computer vision systems.

Notwithstanding these negatives, RobotSpot is a valuable academic and prototyping tool. It exposes fundamental robotic concepts including embedded system integration, sensor-based feedback control, and servo coordination. These attributes make it a valuable tool for early research, teaching, and experimentation—particularly in settings with limited resources. The outcomes show how significantly low-cost robotics might contribute to early robotics innovation and STEM education.

Table 4 contrasts RobotSpot with related quadruped robots using cost and key performance criteria. For a far cheaper cost, RobotSpot provides competitive stability and efficiency. This emphasizes its fit for reasonably priced robotics and accessible education in robotics.

[Table 4 about here.]

Though the system shows good performance, its reliance on IMU sensors and inbuilt balance techniques restricts its flexibility in challenging surroundings. To enhance autonomous terrain adaptability, future research should combine machine learning including reinforcement learning. Advanced vision sensors help to improve dynamic path planning and environmental awareness even further.

This work presents a low-cost quadruped robot with intelligent control system balancing cost and performance. It distinguishes itself by providing hybrid control algorithms improving stability and energy economy as well as simple reproduction. This makes it perfect for use in research and education with constraints on resources.

VI. ENHANCEMENT AND FUTURE DIRECTIONS

6.1 Current System:

The intelligent control of RobotSpot mostly depends on embedded feedback systems using Inertial Measurement Unit (IMU) sensors to continuously maintain balance and posture adjustment. These systems coordinate servo motions to steady the robot in small disturbances during locomotion.

6.2 Proposed Future Development:

Future developments will concentrate on improving the intelligence and autonomy of the robot by:

- Using machine learning methods like reinforcement learning will let the robot to independently modify its balance and gait across different terraces without human parameter adjustment.

- Combining computer vision algorithms with vision sensors—such as cameras or depth sensors—allows one to dynamically plan safe paths by identifying objects.
- Including wireless modules (Wi-Fi, Bluetooth), will enable remote monitoring, control, and data collecting for real-time performance analysis.
- Creating smart power management systems to maximize battery use depending on work requirements and ambient circumstances will help to optimize energy use.

These improvements seeks to turn RobotSpot from a mostly reactive balancing controller into a more autonomous and intelligent robotic platform fit for challenging real-world uses.

VII. CONCLUSION

This work shows that it is feasible to create a low-cost intelligent quadruped robot by use of multidisciplinary engineering techniques and easily available hardware. With minimal performance variance, the experimental findings verify the stability, energy efficiency, and flexibility of the robot over many terraces. Currently in use as a successful teaching tool for STEM applications, the system uses embedded feedback algorithms for balancing and control. The study opens the path for next developments including machine learning-based adaptation and better environmental perception by providing a repeatable, open-source framework for reasonably priced robotics. These results especially in resource-limited settings promote continuous attempts to democratize robotics research and instruction.

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*Corespondent e-mail address amjed.baqer@alayen.edu.iq
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Table 1. Specifications of Sensors Used in the Robot Platform

Sensor	**Parameter**	**Specification**
MPU-6050	Sampling Rate	100 Hz
	Roll/Pitch Accuracy	±0.5° (Kalman-filtered)
Ultrasonic	Range	2–400 cm
	Field of View	15°

Table 2. Comparative performance of control algorithms

Algorithm	Speed (m/s)	Power (W/m)	Stability (°)
CPG	0.18	2.1	±3.2
IK	0.15	2.4	±1.8
Hybrid	0.17	2.2	±2.1

Table 3. Statistical Analysis of RobotSpot Performance Metrics across Multiple Trials

Performance Metric	**Mean**	**Standard Deviation**	**Coefficient of Variation**
Stability Score (%)	88.1	1.91	0.022
Energy Efficiency (%)	77.5	1.58	0.020
Terrain Adaptability (%)	68.1	1.91	0.028

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Table 4. Benchmark Comparison of RobotSpot with Similar Quadruped Robotic Platforms

Platform	**Approximate Cost (USD)**	**Stability Score (%)**	**Energy Efficiency (%)**	**Terrain Adaptability (%)**	**Ease of Reproduction**
RobotSpot (This Work)	120	88.1	77.5	68.1	High
OpenDog Mini	350	91.0	75.0	72.0	Medium
Petoi Bittle	299	89.0	78.0	70.0	High
Spot Micro	500+	92.0	80.0	75.0	Medium

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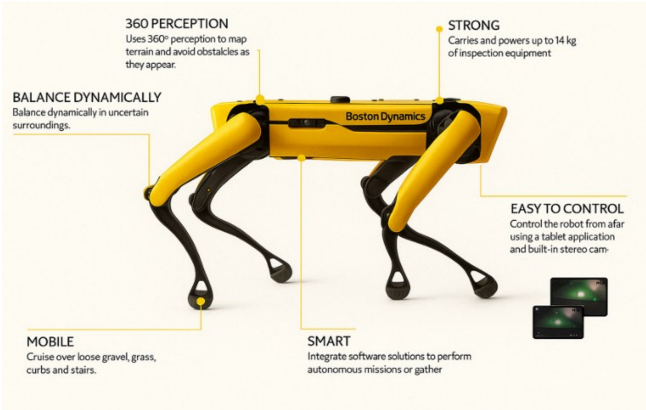

Figure 1. Preliminary mechanical design of RobotSpot

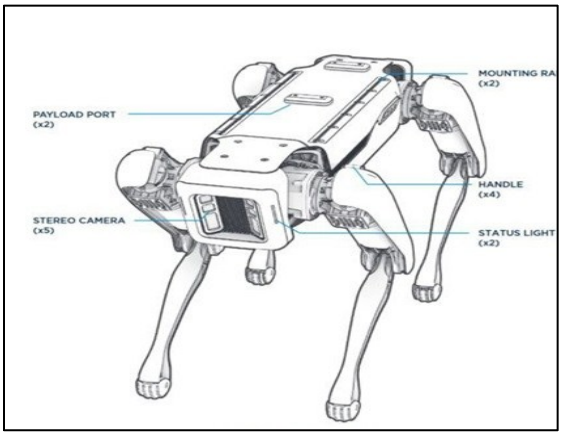

Figure 2. General Structure of the Robot and Distribution of Main Components

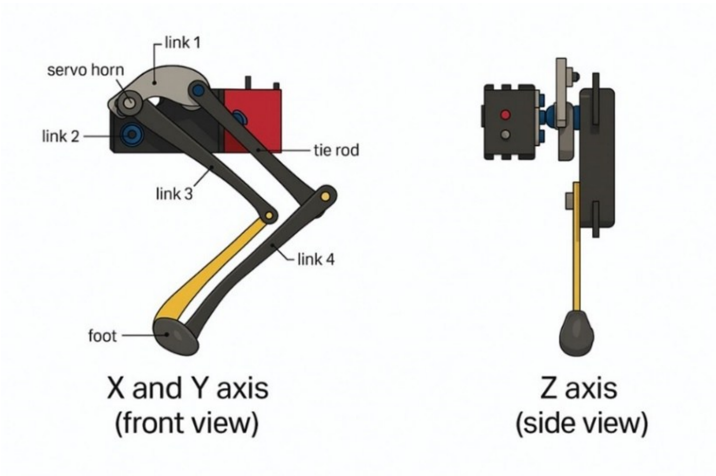

Figure 3. Leg assembly and degrees of freedom (Front and Side Views)

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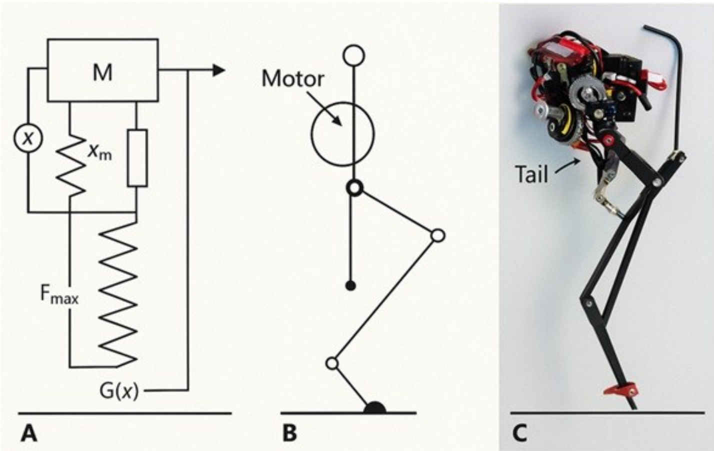

Figure 4. Motor assembly and control schematic

Figure 5. Arduino Uno microcontroller setup with connected servo and sensor interfaces

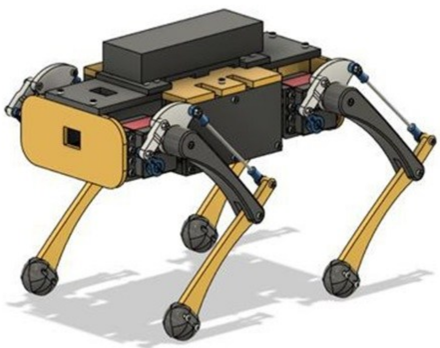

Figure 6. Mechanical Design of the Quadruped Robot Highlighting the Spring Joints and Wheels

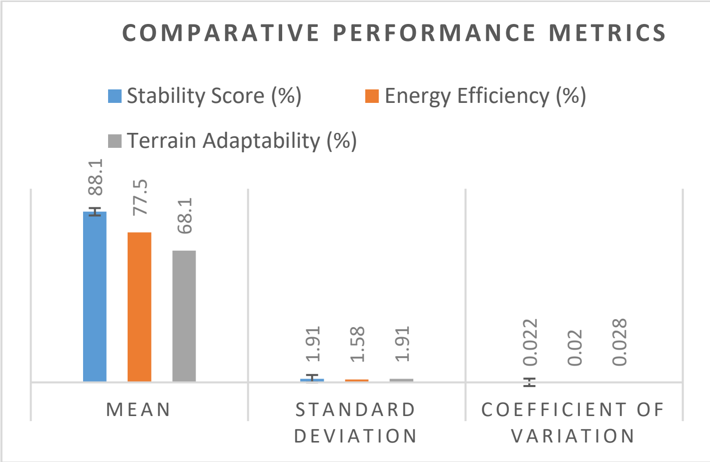

Figure 7. Comparative Performance Metrics of RobotSpot with Standard Deviation Error Bars