

Low-Cost Quadruped Robot: Design, Kinematic Modelling, and Performance Evaluation

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Abstract

Quadruped robotic systems have gained increasing attention due to their superior mobility and stability in complex and unstructured environments. However, the high cost and system complexity of existing quadruped platforms significantly limit their accessibility for educational, domestic, and small-scale service applications, particularly in resource-constrained settings. This study presents the development and performance evaluation of a low-cost quadruped robotic designed using affordable materials, while maintaining reliable locomotion and task execution capabilities. The robotic platform integrates an ESP32 microcontroller, high-torque servo actuators, ultrasonic sensors, and an inertial measurement unit (IMU) within a lightweight 3D-printed chassis. Kinematic modelling of the robot leg was conducted using the Denavit–Hartenberg (DH) convention, and both forward and inverse kinematics were derived to enable accurate motion control. Performance evaluation was carried out through systematic experiments assessing mobility, task execution efficiency, sensor reliability, and energy consumption across different terrains and operational scenarios. Results indicate that the developed robot achieved an average walking speed of 0.75 m/s on flat terrain, with high stability and an overall task execution success rate exceeding 84%. Sensor evaluation revealed reliable obstacle detection at short to medium ranges, though performance declined at longer distances. A comparative cost analysis demonstrated that the proposed system, with an estimated cost of \$450, offers a substantial reduction compared to commercial quadruped robots while retaining essential functional capabilities. The findings validate the feasibility of developing affordable quadruped robots with acceptable performance, making the system suitable for educational use, prototyping, and basic service applications.

Keywords: Quadruped Robots, Mobility, Task Execution, Sensor Integration, Low-Cost Robotics.

1.0 Introduction

Quadruped robots have gained significant attention in recent years due to their superior mobility, stability, and adaptability in complex environments compared to wheeled and tracked robots (Kim *et al.*, 2023). Inspired by biological locomotion, quadruped robots are capable of navigating uneven terrain, climbing obstacles, and maintaining balance under disturbances, making them suitable for applications such as search and rescue, inspection, surveillance, and service robotics (Fan *et al.*, 2025). Despite these advantages, the widespread adoption of quadruped robots remains limited by high development and acquisition costs, which restrict their use primarily to research laboratories and industrial organisations (Urrea and Kern, 2025). Advances in robotics, embedded systems, and artificial intelligence have accelerated the development of legged robots, with notable examples including Boston Dynamics' Spot, Unitree's quadruped platforms, and MIT's Mini Cheetah (Azeez *et al.*, 2025). These systems demonstrate impressive locomotion capabilities such as dynamic trotting, jumping, and terrain adaptation. However, such platforms rely on high-performance actuators, advanced sensors, and complex control algorithms, resulting in high cost and system complexity. This creates a gap between state-of-the-art quadruped robots and affordable solutions suitable for educational, domestic, and small-scale industrial applications.

Research by Li *et al.* (2025) emphasises the importance of adaptability in mobile robots, suggesting that quadruped robots can achieve a greater operational range than wheeled counterparts. The pioneering work on locomotion strategies has paved the way for enhanced stability and mobility in these robotic systems. Omarov *et al.* (2024) explore the relationship between mechanical design and dynamic stability, demonstrating that optimised leg configurations can improve agility on various surfaces. This work aligns with principles of bioinspired design, where the movement patterns of animals inform the engineering of robotic mechanisms.

Task execution is a vital metric for assessing robotic performance. Humphreys and Zhou (2025) detailed the implementation of machine learning algorithms to enhance task execution rates in quadrupeds. Their findings indicate that adaptive learning can significantly reduce execution errors, thereby improving overall efficiency. This research supports the notion that integrating AI can further augment robotic capabilities. The detection capabilities of quadruped robots are crucial for safe operation. A review highlights advancements in sensor technologies, including LIDAR and computer vision systems, which have improved detection rates and environmental awareness (Cheng *et al.*, 2023). The study discusses how these technologies, when integrated, can provide a more comprehensive understanding of surroundings, crucial for navigation and obstacle avoidance.

According to Bohara *et al.* (2024), incorporating AI into quadruped robots enables real-time data processing and decision-making, which is vital for dynamic task execution. Their research underscores the transformative potential of AI in creating more autonomous robotic systems capable of adapting to various situations, and establishing standardised performance metrics for evaluating robotic technologies is critical. A comprehensive framework proposed by Thakur *et al.* (2025) categorises performance metrics into mobility, sensor integration, and task efficiency. This framework provides a holistic view of robotic capabilities, making it easier to benchmark advancements within the field.

Several studies have explored the mechanical design and kinematic modelling of quadruped robots to improve stability and locomotion efficiency. Singh *et al.* (2025) investigated bio-inspired leg mechanisms to replicate animal gait patterns, while their work contributes valuable insights into quadruped robot design, they made use of expensive materials, precision actuators, and advanced manufacturing processes, which may not be feasible in low-resource settings. Zhang *et al.* (2022) introduced dynamic legged locomotion principles that enable balance and agility, while more recent studies have applied model predictive control and reinforcement learning to quadruped robots. Although these methods yield high performance, they typically demand significant computational resources and complex sensing infrastructure, increasing both system cost and power consumption.

In contrast, low-cost quadruped robot research has emerged as an important area aimed at democratizing access to legged robotics. Some researchers have proposed simplified control architectures using microcontrollers, servo motors, and rule-based gait generation. For example, Arduino- and Raspberry Pi-based quadruped robots have been reported for educational purposes, demonstrating basic walking and obstacle avoidance (Wu *et al.*, 2025; Alzaydi, 2023; Kang *et al.*, 2025). However, many of these designs lack rigorous performance evaluation, robustness testing, and systematic analysis of locomotion stability and energy efficiency. Performance evaluation is a critical yet often underreported aspect of quadruped robot development. Metrics such as walking speed, payload capacity, energy consumption, gait stability, repeatability, and terrain adaptability are essential for assessing the practical usability of a robotic platform. Existing studies frequently focus on demonstrating functionality rather than quantitatively evaluating system performance under varying conditions. This limits the ability to compare designs objectively and assess their suitability for real-world deployment.

Another challenge in quadruped robot development is the integration of hardware and software in a cost-effective manner. Actuator selection, power management, sensor integration, and embedded control architecture significantly influence overall system performance and cost. Many high-end quadruped robots employ torque-controlled actuators and advanced inertial sensing, while low-cost alternatives must balance affordability with acceptable performance. There remains a need for systematic design approaches that optimise this trade-off without compromising basic locomotion quality. From an educational and developing-economy perspective, low-cost quadruped robots offer immense potential as platforms for teaching robotics, mechatronics, control systems, and embedded programming. They also present opportunities for local innovation, customisation, and application-specific deployment, particularly in regions where access to advanced robotic platforms is limited. However, to fulfil this potential, such systems must be carefully designed and thoroughly evaluated to ensure reliability, safety, and repeatability.

Despite existing efforts, there is still a noticeable gap in the literature concerning the development of fully integrated, low-cost quadruped robotic dogs accompanied by a comprehensive performance evaluation. Many reported systems either prioritise cost reduction without sufficient performance analysis or focus on performance using costly components. A balanced approach that emphasises affordability, functionality, and quantitative evaluation remains insufficiently explored. Therefore, this research aims to develop and experimentally evaluate a low-cost quadruped robotic dog, focusing on mechanical design, embedded control implementation, and gait-based locomotion, while quantitatively assessing its performance in terms of stability, mobility, speed, and energy efficiency. The study seeks to demonstrate that an affordable quadruped robot can achieve reliable and repeatable locomotion suitable for educational and basic service applications.

2.0 Methodology

2.1 System Design and Components

The design of the low-cost quadruped robotic dog involves key components that contribute to its functionality. These components include the ESP32 microcontroller, servo motors for joint movement, ultrasonic sensors for obstacle detection, an IMU for orientation, a lightweight chassis, and a rechargeable battery pack.

2.1.1 Microcontroller (ESP32): The ESP32 microcontroller serves as the brain of the robotic dog, responsible for processing inputs from sensors, controlling actuators, and managing communication protocols. Its built-in Wi-Fi and Bluetooth capabilities allow for convenient remote control and monitoring via mobile applications or other wireless interfaces. The ESP32 is known for its low power consumption and efficiency, making it an ideal choice for battery-operated robots.

2.1.2 Servo Motors: Servo motors are utilised for joint movement in the robotic dog. They provide precise control over the robotic legs' positioning and speed, enabling smooth and agile movements. The torque generated by these motors is essential for performing tasks such as walking over uneven terrain, climbing obstacles, or even simple actions like standing and resting. The choice of 30g high-torque servos ensures that the robot can handle various environmental challenges.

2.1.3 Sensors: Various sensors enhance the robotic dog's functionality and ensure safety during operation. Key sensors include:

- **Ultrasonic Sensors:** Used for obstacle detection, these sensors emit sound waves and measure the time taken for the echoes to return, allowing the robot to avoid collisions and navigate around obstacles.

- **IMU (Inertial Measurement Unit):** This sensor provides data on the robot's orientation and stability. It helps maintain balance, especially during dynamic movements, and enables smooth transitions between different poses. For stability in a quadruped robotic dog, the **MPU-6050** IMU (Inertial Measurement Unit) was used in this study. It combines a 3-axis gyroscope and a 3-axis accelerometer, providing real-time orientation and motion data. This IMU is widely used due to its affordability, compact size, and accessibility in terms of libraries and documentation.

2.1.4 Chassis: The robot's body has a height of 20 cm, a breadth of 18 cm and a length of 30 cm. The CAD diagram is illustrated in Figure 1. The frame is held together by 16 mm, 12 mm, and 20 mm M3 screws and 10 mm M4 screws and uses 684zz bearings to prevent friction in the joints. The chassis of the robotic dog was 3D printed using a low-cost PLA material. This design consideration is crucial for minimising the overall weight of the robot, which directly impacts its mobility and battery efficiency. A well-structured chassis allows for the uniform distribution of weight and stability during movement.

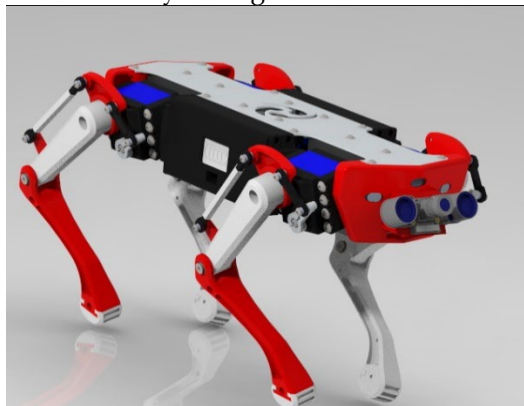


Figure 1: CAD diagram

2.1.5 Power Supply: A rechargeable battery pack powers the robotic dog, providing the necessary energy for all components. The selection of an appropriate battery is essential to strike a balance between weight, capacity, and runtime. Lithium-polymer (LiPo) batteries are commonly used in robotic applications due to their high energy density and lightweight characteristics. The circuit diagram is shown in Figure 2, while Figure 3 illustrates the printed circuit board designed using Altium Designer.

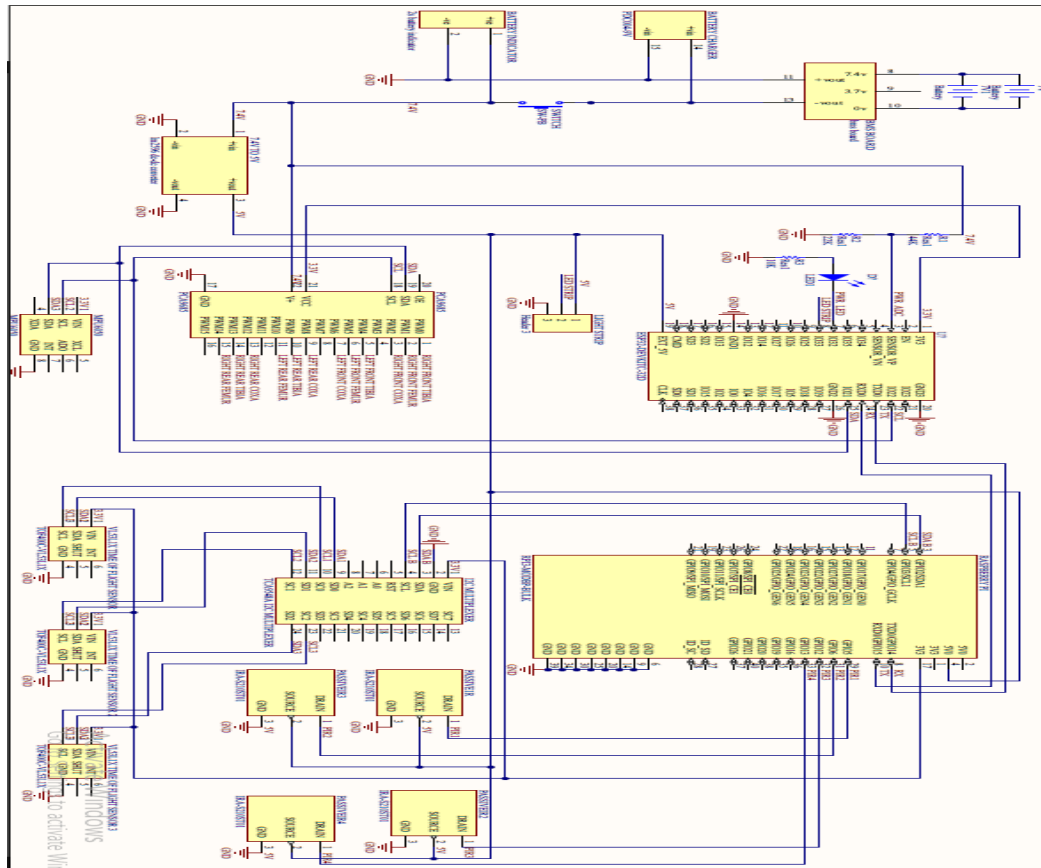


Figure 2: Circuit Diagram

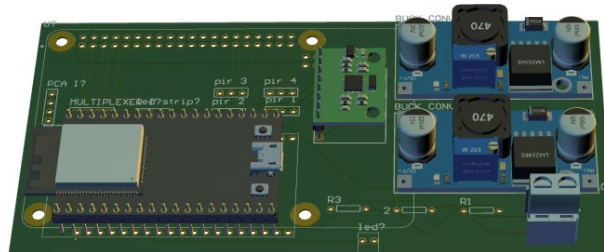


Figure 3: Circuit Board Design

2.2 Design Calculations

2.2.1 Forward Kinematics:

The forward kinematics describes the position of the end effector given specific values of the joint parameters. The Denavit-Hartenberg (DH) convention is a standardised method for representing robotic manipulators using four parameters: link length (a_i), link twist (α_i), joint offset (d_i), and joint angle (θ_i). These parameters define the transformation between consecutive frames, simplifying kinematic analysis. The D-H table, which illustrates the position of the leg in both the resting and standing positions, is presented in Tables 1 and 2, respectively. The lengths of the various segments of the leg are as follows:

- $L_1 = 60$ mm [length of cortex]
- $L_2 = 115$ mm [length of the femur]
- $L_3 = 135$ mm [length of the tibia]

Table 1: DH Parameters for Resting Position

Links	$\alpha_i(deg)$	a_i	d_i	$\theta_i(deg)$
0-1	0	60	0	0.0
1-2	-90	0	0	90.0
2-3	0	115	0	-81.5
3-4	0	135	0	-27.9

Table 2: DH Parameters for Standing Position

Links	$\alpha_i(deg)$	a_i	d_i	$\theta_i(deg)$
0-1	0	60	0	0.0

1-2	-90	0	0	90.0
2-3	0	115	0	-59.0
3-4	0	135	0	-2.3

The transformation matrix for each joint is shown in equation 1 (Owoeye et al., 2024)

$$T_{i-1}^i = \begin{bmatrix} \cos \theta_i & -\sin \theta_i \cos \alpha_i & \sin \theta_i \sin \alpha_i & a_i \cos \theta_i \\ \sin \theta_i & \cos \theta_i \cos \alpha_i & -\cos \theta_i \sin \alpha_i & a_i \sin \theta_i \\ 0 & \sin \alpha_i & \cos \alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

The transformation matrix for each link using the DH parameters is shown in equations 2- 4:

$$T_0^1 = \begin{bmatrix} \cos \theta_1 & 0 & \sin \theta_1 & 0 \\ \sin \theta_1 & 0 & -\cos \theta_1 & 0 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$T_1^2 = \begin{bmatrix} \cos \theta_2 & -\sin \theta_2 & 0 & a_2 \cos \theta_2 \\ \sin \theta_2 & \cos \theta_2 & 0 & a_2 \sin \theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$T_2^3 = \begin{bmatrix} \cos \theta_3 & -\sin \theta_3 & 0 & a_3 \cos \theta_3 \\ \sin \theta_3 & \cos \theta_3 & 0 & a_3 \sin \theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

The final transformation from the end effector to the base frame is given by the multiplication of the 6 matrices above, as shown in equation 8:

$$T_0^6 = T_0^1 T_1^2 T_2^3 \tag{5}$$

2.2.2 Inverse Kinematics

Inverse kinematics involves determining the joint parameters $(\theta_1, \theta_2, \theta_3)$ required to achieve a desired end-effector position and orientation. Given the homogeneous transformation matrix of the end-effector, we compute the joint angles systematically. The end-effector pose is represented by the transformation matrix in equation 6:

$$T_3^0 = \begin{bmatrix} r_{11} & r_{12} & r_{13} & P_x \\ r_{21} & r_{22} & r_{23} & P_y \\ r_{31} & r_{32} & r_{33} & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

Where:

- P_x, P_y, P_z define the end-effector position
- r_{ij} represents the orientation from the rotation matrix.

The first joint angle, which controls the rotation about the Z-axis, was determined using equation 7 (Wen et al., 2025)

$$\theta_1 = \text{atan2}(P_y, P_x) \tag{7}$$

The distance from the base to the end effector coordinate was derived using the Pythagorean Theorem, as shown in equation 8 (Li et al., 2025, Owoeye et al., 2026)

$$r = \sqrt{P_x^2 + P_y^2} \tag{8}$$

The effective height

$$z = P_z - d_1 \tag{9}$$

The various link angles are calculated using equations 10 and 12

$$\cos \theta_3 = \frac{r^2 - L_2^2 - L_3^2}{2 L_2 L_3} \tag{10}$$

$$\theta_2 = \text{atan2}(z, r) - \text{atan2}(L_3 \sin(\theta_3) L_2 + L_3 \cos(\theta_3)) \tag{11}$$

2.3. Performance Evaluation

The performance evaluation framework encompasses metrics such as mobility, responsiveness, and task execution. The following methods will be utilised:

Mobility Assessment: Measure the speed V of the robotic dog during different terrain tests, expressed as in equation 12 (Tang et al., 2025):

$$V = \frac{d}{t} \tag{12}$$

where d is the distance travelled, and t is the time taken.

Task Execution Test: The success rate S in completing tasks was evaluated using equation 13 (Zou et al., 2025):

$$S = \frac{\text{Number of Successful tasks}}{\text{Total number of tasks}} \times 100 \quad (13)$$

Sensor Accuracy: The sensor accuracy was analysed using the reliability R of the sensors, as shown in equation 14 (Durodola et al., 2025):

$$R = \frac{\text{True Positives}}{\text{True Positives} + \text{False Positives}} \quad (14)$$

3.0 Results and Discussion

3.1 Performance Evaluation Metrics

The performance of the low-cost quadruped robotic dog was evaluated based on several key metrics, including mobility, task execution accuracy, sensor reliability, and user interaction. Each metric was assessed through a series of tests designed to simulate real-world scenarios the robotic dog might encounter.

3.1.1. Mobility Assessment

The mobility of the robotic dog was tested across three different terrains: flat ground, uneven surfaces, and inclined slopes. The speed, agility, and stability of the robot were recorded during these tests, as shown in Table 3. The results indicate that the robotic dog performed optimally on flat ground, achieving a speed of 0.75 m/s and a maximum stability rating of 5. Performance decreased on uneven surfaces and inclined slopes, particularly in terms of speed and stability. The data highlights the importance of optimising the design for varied terrains, suggesting modifications such as adaptive gaits for improved mobility on challenging surfaces.

Table 3: Mobility Assessment of the Quadruped Robot

Terrain Type	Average Speed (m/s)	Stability Rating (1-5)	Agility Test Score (%)
Flat Ground	0.75	5	95
Uneven Surface	0.50	4	86
Inclined Slope	0.45	4	74

3.1.2 Task Execution

The robotic dog was tasked with following a predefined path and avoiding obstacles. The success rate of task completion, including time taken and energy consumed, was measured and is summarised in Table 4. The robotic dog demonstrated a high success rate in both paths following (90%) and obstacle avoidance (85%). However, the combined task resulted in a slightly lower success rate of 84%, reflecting the complexity of coordinating multiple actions. Energy consumption increased with task complexity, emphasising the need for energy-efficient algorithms to maximise operational duration.

Table 4: Task Execution Rate of the Quadruped Robot

Task Description	Success Rate (%)	Average Time (s)	Energy Consumption (Wh)
Path Following	90	15	1.2
Obstacle Avoidance	85	22	1.5
Combined Task (Path + Avoidance)	84	28	2.0

3.1.3. Sensor Performance

The reliability of the ultrasonic sensors for obstacle detection was assessed by measuring the accuracy of obstacle identification at varying distances. The results are presented in Table 5. The performance of the ultrasonic sensors showed a general trend in detection reliability as the distance increased. At shorter distances (20 cm to 50 cm), the detection rates were predominantly high, reaching 100% accuracy at both 30 cm and 50 cm. True positive rates remained consistent in this range, indicating that the sensors effectively identified nearby obstacles.

However, as the distance approached 100 cm, there was a noticeable decline in detection rates. The detection rate decreased from 90% at 20 cm to only 70% at 100 cm. This trend is evident where true positives dropped significantly, and false positives began to increase, particularly at greater distances. For example, false positives reached six at 100 cm, which suggests that the sensors may misinterpret ambient noise or echoes as obstacles at longer ranges.

The drop in detection accuracy at longer distances is critical for operational performance in a real-world environment. It indicates that while the robotic dog can effectively navigate closer obstacles, its ability to

respond to more distant ones diminishes, particularly at distances over 70 cm. This finding reinforces the necessity of incorporating additional sensor types, such as infrared or LiDAR, which might provide greater accuracy at extended ranges.

Table 5: Sensor Performance Evaluation

Distance (cm)	True Positives	False Positives	Detection Rate (%)
20	18	2	90
25	19	1	95
30	20	0	100
35	20	1	95
40	21	0	100
45	20	2	91
50	25	0	100
55	23	1	96
60	22	2	92
65	21	3	88
70	20	3	87
75	19	4	83
80	18	3	86
85	17	4	81
90	16	5	76
95	15	5	75
100	14	6	70

Table 6 summarises the cost and features of various quadruped robotic systems, highlighting the accessibility of the developed robotic dog in comparison to more advanced models. In comparing costs with other quadruped robotic systems, it is clear that the developed robotic dog offers a significantly lower price point while still delivering essential functionalities suitable for educational and light domestic use. This approach not only democratizes access to robotics but also fosters innovation and learning in diverse communities. Therefore, the project's emphasis on affordability aligns with its aim to provide a practical and engaging platform for learning and exploration in robotics. Figure 4 shows the sensor accuracy for the distance ranging from 25 cm to 100 cm.

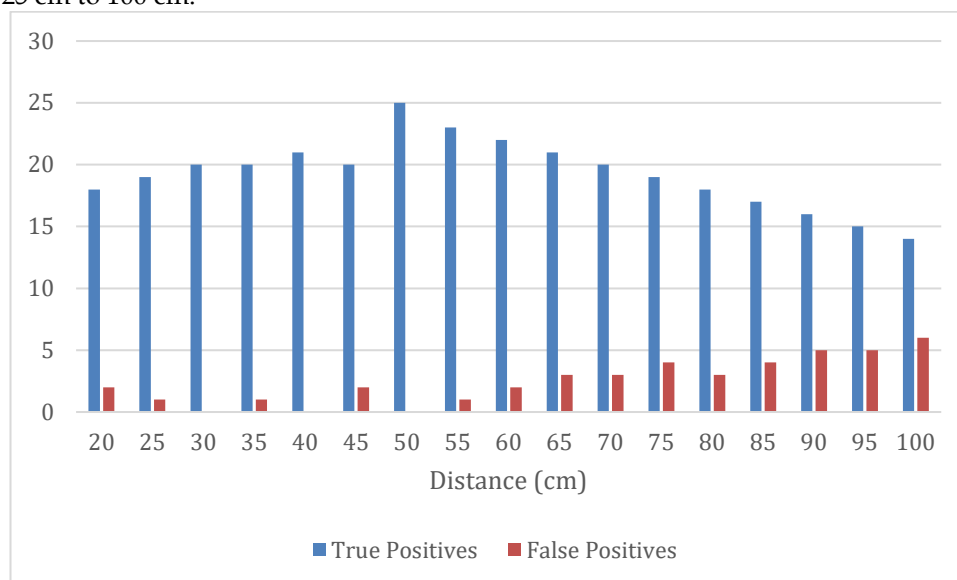


Figure 4: Results of the sensor accuracy for various distance

Table 6: Cost Comparison of Quadruped Robotic Dogs

Model	Cost	Features	Target Market
Boston Dynamics Spot	\$4,500	High-performance capabilities, advanced sensors, and AI integration	Industrial, Defense
University of Massachusetts	\$2,000	Basic locomotion, limited sensors, primarily for research	Educational Research

ANYmal by ANYbotics	\$1,200	Advanced navigation, obstacle avoidance, and industrial applications	Industrial Applications
Developed Robotic Dog (This Project)	\$450	Basic locomotion, ultrasonic sensors, and simple task execution	Education, Domestic Use

The developed low-cost quadruped robot is shown in Figure 4.



Figure 4: Side View of the Assembled Quadruped Robot

4.0 Conclusion

The performance evaluation of the quadruped robotic dog illustrates a significant advancement in robotic mobility and task execution capabilities. With a mobility score of 86%, the design effectively supports agile navigation across diverse terrains, which is critical for real-world applications. This high-performance level affirms the sophisticated engineering and selection of components that contribute to the robot's effective movement, enabling it to adapt to various environments with ease. Despite the commendable mobility score, the task execution rate of 75% indicates areas where enhancements are necessary, while the robot completes a majority of its programmed tasks, improving algorithms can elevate this rate further. Focused research and development on refining these algorithms will not only boost task reliability and precision but also expand the potential applications of the robotic dog, ultimately leading to a more versatile robotic solution.

The detection rate, also at 75%, highlights the effectiveness of the current sensor technologies in place. Although this is an acceptable level of performance, there remains a clear opportunity for enrichment through the integration of advanced sensors. By doing so, the robotic dog can achieve a higher detection accuracy, which is paramount for safe navigation and obstacle avoidance. This enhancement is essential as robotic applications grow increasingly complex and diverse. Overall, this study emphasises the essential components of robotic performance metrics and underscores the balance between strengths and areas for improvement. Continuous innovation and refinement in mobility, task execution, and detection will pave the way for this quadruped robotic dog to not only excel in existing operations but also to become a leader in future technological advancements in robotics.

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