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Design and Kinematic Analysis of a Quadruped Walking Robot Utilizing Chebyshev Mechanism for Enhanced Mobility

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Abstract:
This paper presents the design and development of a quadrupedal walking robot intended for effective mobility in complex and constrained environments. Unlike traditional wheeled systems, legged robots offer superior adaptability, making them suitable for applications in public safety, military operations, and rescue missions. The proposed system replicates animal-like motion using a single degree of freedom (1-DOF) leg mechanism, with each leg designed based on a Chebyshev linkage to convert rotational motion into a curved, linear stepping trajectory. The mechanism is actuated by a stepper motor operating at an angular velocity of 2.8 rad/sec, ensuring stable and controlled locomotion. A detailed kinematic analysis is conducted, and numerical simulations are performed to verify the mechanical design and evaluate the leg dynamic behavior. Results show that the maximum velocity at point B varies between –0.044 m/s and 0.15 m/s along the X-axis, and between –0.127 m/s and 0.092 m/s along the Y-axis, demonstrating the feasibility and effectiveness of the proposed walking mechanism.

Keywords:
Four legged robot, walking robot, Leg mechanism,Chebyshev mechanism, Four bar mechanism.

1 Introduction

Walking robot are the most wanted, important and interesting ones and their stability is the most crucial problem these days. Two main types of walking robot are presented: Static and Dynamic.Four legs walking robot maintains stability by ensuring that at least three legs support its body weight at all times. This design enhances reliability, as the robot remains upright even if all joints freeze instantaneously. While this approach prioritizes safety, it results in slow and inefficient locomotion.Dynamic walking is considered to be human or animal like, dynamic robots are faster, more maneuverable and dexterous.

1.1 Previous Research

Significant advancements have been made in the development of walking robots, particularly in the areas of gait generation, obstacle negotiation, and control strategies. Previous research has explored various approaches to enable stable and adaptable locomotion in quadruped robots, often focusing on sensor integration, movement planning, and mechanical design. The following works provide key insights that inform and support the development of the current design. The Guará robot is a notable example of earlier research in four-legged locomotion, using a gait matrix for straight paths and differential leg strokes for curved movement. It relied solely on foot contact sensors for obstacle detection and climbing, executing complex tasks through sequences of simple movements. This research demonstrated effective locomotion with minimal sensors and emphasized modular control strategies [1].

Hoover in 2010 developed small-scale hexapod robots using compliant mechanisms constructed by folding flat sheets with integrated flexure hinges and rigid links. This approach led to the creation of two robots: RoACH, a lightweight and steerable platform, and DynaRoACH, a faster and more energy-efficient successor. A compliance modeling framework was introduced to assess mechanical behavior, and experimental results showed that tuning leg stiffness significantly improved turning performance. These findings underscore the importance of considering full three-dimensional dynamics in the design of agile legged robots [2].

Another notable contribution to walking robot research is the development of the ROBOTURK SA-2which represents a unique approach to walking robot design, featuring an eight-legged, spider-inspired structure powered by a single actuator. The robot was first digitally modeled and animated to test gait stability before being built as a physical prototype. Its main contribution is an innovative motion mechanism that coordinates all legs using just one actuator, demonstrating a highly efficient and mechanically optimized solution for multi-legged locomotion[3].

To address the challenges of redundant joints in quadruped robots, a new Time-Pose control method was proposed, utilizing an enhanced extended Jacobian matrix for solving inverse kinematics. This method was adapted to handle arbitrary joint lengths, offering more flexibility in joint movement. Its key benefit is the generation of smooth, continuous joint paths. Applied to the trot gait on flat ground, both simulations and experiments confirmed the effectiveness and practicality of this inverse kinematics solution for quadruped locomotion[4].

The Cheetah-cub is a small, compliant quadruped robot designed for fast and stable trotting using spring-loaded, multi-segment legs by Spröwitz et al. in 2013. It operates with an open-loop controller and has demonstrated self-stabilizing behavior in both simulations and real-world tests, including step-down scenarios. Achieving speeds of up to 6.9 body lengths per second (Froude number 1.30), it stands out as one of the fastest quadrupeds under 30 kg. Its lightweight,low-cost, and safe design makes it a valuable platform for researching compliant leg mechanics and high-speed quadruped locomotion [5].

StarlETH is a medium-sized quadruped robot designed by Hutteret al. in 2014 to study efficient and dynamic locomotion using series elastic actuators for precise torque control and energy-efficient movement. With model-based control, it can perform a range of gaitsfrom slow walking to fast runningeven on rough terrain. The robot is equipped with onboard computing, batteries, and sensors, enabling autonomous operation. A real-time control and simulation environment supports its development, and experiments have demonstrated its robust and versatile performance in various locomotion tasks[6].

A lightweight quadruped robot weighing 1.71 kg was developed by Oak andNarwane in 2014, using a four-bar chain leg mechanism to achieve efficient locomotion. The study focused on the robot mechanical design, gait analysis, and fabrication, resulting in a system with eight degrees of freedom powered by servomotors. Locomotion on flat terrain was accomplished using symmetrical gaits, specificallytrot and pace, with movement generated by precisely controlling the angular positions of the servomotors. This research demonstrated a compact and mechanically simple design capable of executing basic walking patterns, contributing to the development of accessible and easily controllable quadruped robots [7].

A bio-inspired control architecture was developed to achieve bounding gait locomotion in quadruped robots by mimicking animal motor control systems. The controller includes three layers: a high-level planner (like the cerebellum), a mid-level system using central pattern generators to produce rhythmic motion, and a low-level PD controller to execute precise leg and spine movements. Tested on a virtual cheetah and the SQBotrobot with a spine joint, the controller effectively maintained stable bounding across different speeds. The results highlight its potential for improving the agility and control of real quadruped robots [8].

The HyQ2Max is an improved, hydraulically actuated quadruped robot developed from the earlier HyQ platform, with enhanced durability, power, and added self-righting ability. The study emphasizes optimizing the robot actuator system, which plays a critical role in overall performance such as speed, payload, and energy use. By simulating various motions like trotting, stair climbing, and push recovery, the researchers determined the joint requirements necessary for actuator and linkage design. This work provides both a robust quadruped capable of complex tasks and a detailed approach to hydraulic actuator selection for agile legged robots [9].

TITAN-XIII represents a significant advancement in sprawling-type quadruped robots, which are known for their high stability due to a large support polygon and low center of gravity. Unlike earlier sprawling designs that lagged in speed and efficiency compared to mammal-inspired robots, TITAN-XIII addresses these limitations through a right-angle wire-driven leg mechanism aimed at reducing weight and improving compactness. Experimental results demonstrated the robot's ability to walk at 1.38 m/s with a cost of transport (COT) of 1.76, placing its performance on par with more dynamic, mammalian quadruped models [10].

A novel hybrid leg mechanism based on a five-bar linkage was introduced to enhance legged robot mobility and load capacity. Each leg features three degrees of freedom, and both the forward and inverse kinematics were theoretically analyzed and solved using MATLAB. The robot adopts a diagonal gait, and simulations in ADAMS were conducted to evaluate foot and centroid displacement during motion. Built on a series-parallel configuration, the mechanism offers expanded movement range, improved load-bearing capability, and simplified control, making it highly adaptable for various walking patterns. This work provides a solid theoretical framework for future experimental development of versatile quadruped systems[11].

To advance high-speed locomotion in quadruped robots, a single-leg platform was designed with a focus on lightweight construction and low inertia, mimicking the leg structure of quadruped animals using three joints. Recognizing the intense accelerations and loads experienced during rapid movement, the design carefully balances mass and structural strength, validated through finite element analysis. Drawing inspiration from animal locomotion, a foot-end trajectory for high-speed trot gait was developedmaintaining stable swing durations while adjusting stride frequency and contact time. The trajectory is divided into swing and stance phases, ensuring smooth transitions with minimal acceleration and continuous position, velocity, and acceleration profiles. This proposed trajectory was compared against a Bézier curve in terms of power consumptionand tested through simulations in Webots along with motion capture evaluations, confirming improved stability and tracking accuracy for high-speed trotting[12].

The fundamental considerations in designing a robotic leg include the ability to produce a foot trajectory that is nearly a straight line relative to the robot's body. Additionally, the leg should feature a mechanically simple design. When necessary, it should also incorporate the minimum number of degrees of freedom (DOFs) required to achieve the desired movement[13],[14].

In the 1850s, Chebyshev introduced a mechanism based on revolute joints that significantly simplified the development of walking systems. This mechanism made it possible for a robot's body to move horizontally by coordinating the motion of its legs and feet in a fixed pattern. As a result, many early walking automata were successfully built using Chebyshev's design principles [15].Chebyshev designed a four-legged walking machine with carefully selected proportions to ensure that only one leg moved at a time, replicating the slow walking pattern of animals like cows or horses. By adjusting the lengths of the mechanism's parts, the foot's path could closely mimic the natural trajectory of a human step[16].

1.2 Problem Statement

This work addresses the design and development of a four-legged walking robot intended to replicate the natural, efficient movement of quadrupedal animals using a Chebyshev linkage mechanism for each leg. By employing two motors, with each motor powering a pair of legs, the robot simplifies actuation while maintaining coordinated motion. The primary goal is to achieve stable and efficient walking performance, making the robot suitable for assisting in tasks suchas supply transportation and mission-oriented operations.

2 Methods

The quadruped robot is designed to emulate an alternating diagonal gait, a common locomotive strategy found in natural quadrupeds, which ensures high stability and efficient movement across varied terrains. The robot's motion sequence is driven by two synchronized stepper motors, each responsible for actuating a pair of legs through a Chebyshev linkage mechanism, enabling a repeatable and well-coordinated walking cycle. This design minimizes actuation complexity while maintaining functional adaptability.

The gait cycle of the quadruped robot is systematically divided into five coordinated phases to ensure stable and efficient locomotion. It begins with Phase 1, where the back-left and front-right legs are simultaneously lifted, while the front-left and back-right legs remain in contact with the ground to provide support and balance. In Phase 2, the elevated diagonal pair swings forward, propelling the body from positions (a) and (b) to (a′) and (b′), generating forward momentum while maintaining diagonal stability. Phase 3 follows with all four legs momentarily grounded, forming a stable support frame that resets the robot's posture and prepares it for the subsequent swing phase. Phase 4 involves lifting the opposite diagonal pair, front-left and back-rightwhile the previously lifted legs (now grounded) support the body. Finally, in Phase 5, the newly lifted legs swing forward, transitioning the robot from positions (c) and (d) to (c′) and (d′), thereby completing the cycle. This sequence repeats in a continuous loop, allowing for smooth, rhythmic walking. Throughout the cycle, at least two legs remain in ground contact, ensuring consistent static stability. The entire motion planning and transition strategy is graphically represented in the flowchart shown in Figure 1 inspired fromLiangin2012[17].

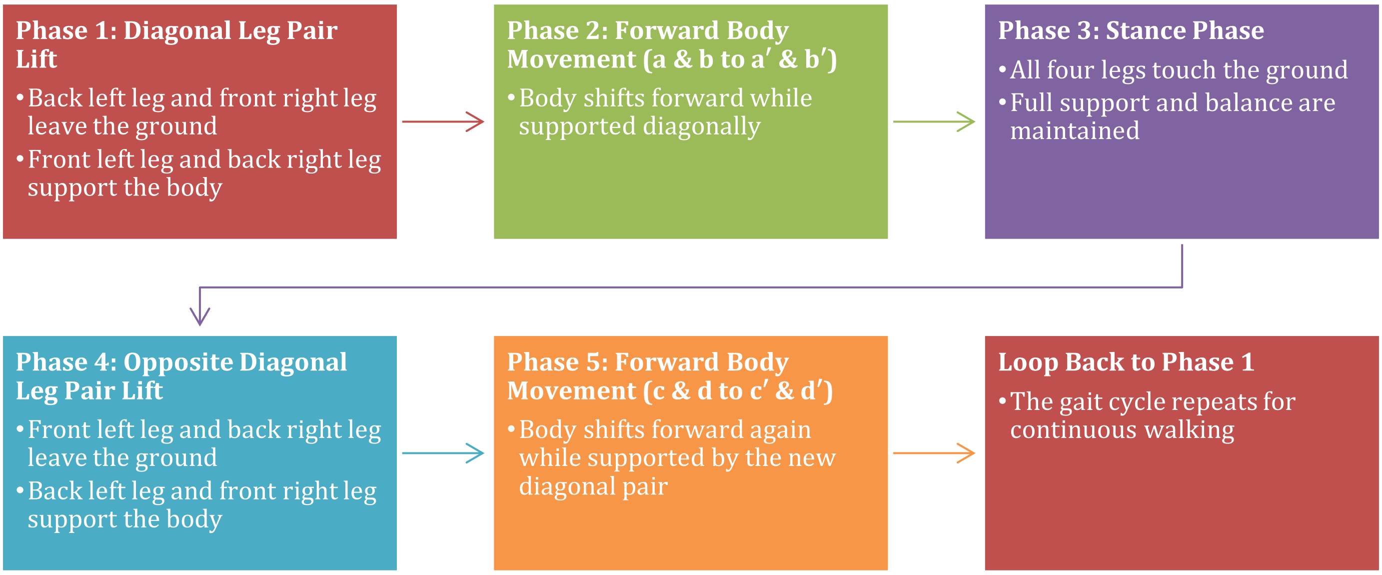
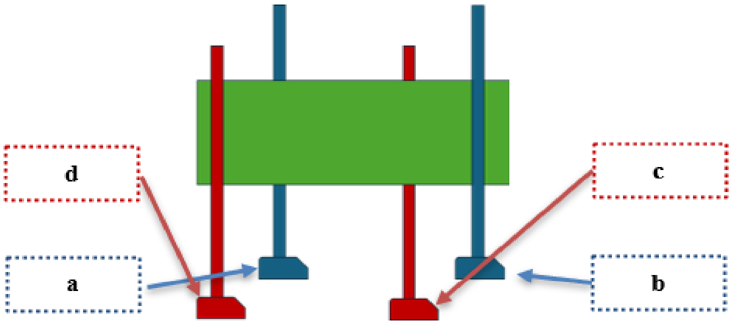


Figure 1: Gait cycle flowchart of the proposed quadruped robot.

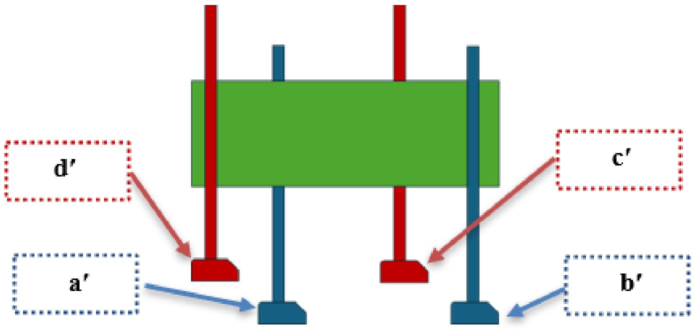
The robot features a quadrupedal architecture comprising four legs, two stepper motors, and integrated linear bearings. Each stepper motor drives one lateral pair of legs through a belt-and-gear transmission system linked to the Chebyshev mechanism. The symmetric arrangement of the legs guarantees diagonal coordination and synchronized actuation, a key requirement for maintaining consistent gait patterns as shown in Figure 2.

Linear bearings are utilized to guide leg movement along predetermined paths, reducing mechanical deviation and frictional loss. This not only improves the smoothness and precision of leg motion but also enhances the robot's gait robustness, particularly over uneven or constrained surfaces. The coordinated motion of all four legs, as demonstrated in the simulation and CAD models, confirms the feasibility and reliability of the proposed mechanical design.

This architecture, combining mechanical simplicity with gait efficiency, enables the robot to achieve stable, low-cost, and efficient locomotion, making it a suitable candidate for field applications such as rescue missions, military reconnaissance, and autonomous navigation in hazardous environments.



a) Phase 1



b) Phase 4

Figure 2: Sequential motion of the four-legged robot during gait cycle.

2.1 Mathematical Model

This paper will focus on the analysis and design of a leg utilizing a Chebyshev mechanismas illustrated in Figure 3. The foot point of the simplified Chebyshev mechanism traces an ovoid path, consisting of both a straight-line segment and a curved segment.

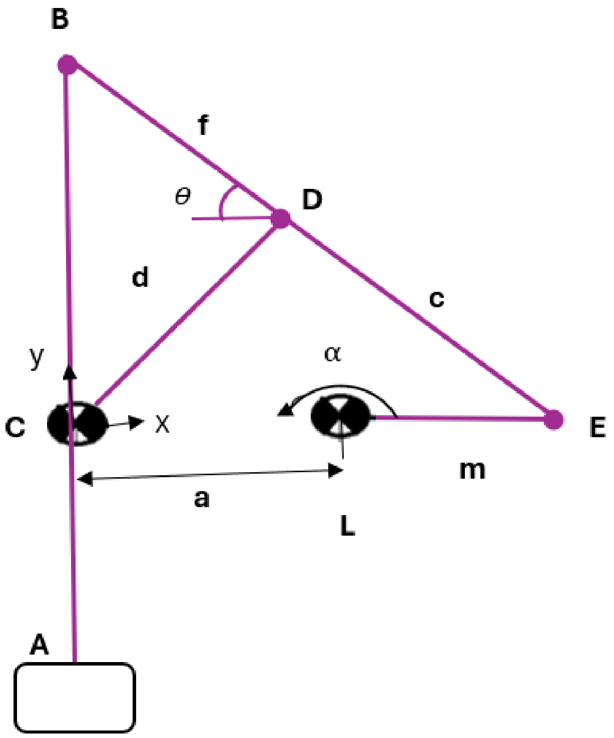


Figure 3: Kinematic diagram of (1-DOF) legmechanism based on Chebyshev linkage.

Table 1summarizes the key geometric parameters used in the design of the 1-DOF leg mechanism based on the Chebyshev linkage. The proportions of four bar Chebyshev’s straight line mechanismare(c=f=d=2.5*m) and (a=2*m), where m is the crank link [18]. The values are presented in centimeters and correspond to the critical dimensions required for accurate modeling and fabrication of the leg structure. The parameters c, f, and d are set equal to 10 cm, representing consistent link lengths that form part of the triangular configuration in the linkage. Dimension a, measured as 8 cm, defines the length of the crank arm (LE), which converts rotational motion into the desired foot trajectory. The parameter m, with a value of 4 cm, denotes the offset distance essential for generating the curved path of the foot during the swing phase. Vertical and horizontal distances from point A to point

C are represented by K (35 cm) and H (0.87 cm), respectively. Finally, BA is set to 50 cm and represents the linear distance from the base point B to the foot contact point A, which is critical for maintaining the stride length and ensuring ground clearance during the walking cycle. These dimensions were selected to optimize the leg's motion trajectory and contribute to the overall stability and efficiency of the robot's locomotion.

Table 1: Geometric design parameters of the 1-DOF Chebyshev leg mechanism (all dimensions in cm).

Design Parameters	Value (cm)
c=f=d	10
a	8
m	4
H	0.87
K	35
BA	50

2.2 Kinematic Analysis for Chebyshev Mechanism

A kinematic analysis was conducted to assess and simulate the performance and operation of the leg mechanism. A fixed reference frame (CXY) was established at point (C), as illustrated in Figure 3. The position of point (B) relative to the (CXY) coordinate system can be determined as a function of the input crank angle (α)and the kinematic parameters of the Chebyshev mechanism (LEBDC), expressed in the following form[17],[19]

$$X_B = -a + m\,cos(\alpha) + (c+f)cos(\theta) \quad (1)$$

$$Y_B = m\,sin(\alpha) + (c+f)sin(\theta) \quad (2)$$

$$B = cos(\alpha) - (a/m) \quad (3)$$

$$D = (a/c) * cos(\alpha) - (\frac{(a^2 + m^2 - c^2 + d^2)}{(2mc)}) \quad (4)$$

$$\theta = 2\,tan^{-1}\frac{sin(\alpha) - (sin^2(\alpha) + B^2 - D^2)^{-0.5}}{(B+D)} \quad (5)$$

As illustrated inFigure 3, the position of Point (A) relative to the (BXY) reference frame can be determined as a function of the input crank angle (α)and the kinematic parameters of the Chebyshev mechanism. This relationship can be expressed in the following form.

$$X_B = -(a+H) + mcos(\alpha) + (c+f)cos(\theta) \quad (6)$$

$$Y_B = msin(\alpha) + (c+f)sin(\theta) + 2K + BA \quad (7)$$

Where

- K: vertical distance from point A to C
- H: horizontal distance from point A to C

The velocity of point B can be evaluated as

$$\dot{X_B} = -m\dot{\alpha}\,\sin(\alpha) - \dot{\theta}\,(c+f)\sin(\Theta) \quad (8)$$

$$\dot{Y_B} = m\dot{\alpha}\cos(\alpha) + \dot{\theta}(c+f)\cos(\Theta) \quad (9)$$

Where

$$\dot{\theta} = 2\cos2(\Theta)\dot{\alpha}\left[\frac{\left(\cos(\alpha) - \left(\cos(\alpha)\sin(\alpha) - \sin(\alpha) + \left(\frac{a}{c}\right)\sin(\alpha)\right)(\sin^2(\alpha) + B^2 - D^2)^{-0.5}\right)(B+D)}{(B+D)^2} - \frac{(\dot{B} + \dot{D})(\sin(\alpha) - (\sin^2(\alpha) + B^2 - D^2)^{-0.5})}{(B+D)^2}\right] \quad (10)$$

The input crank angular velocity (ω) is maintained at a constant value of 2.8 rad/s during the operation.

3 Mechanical System Design

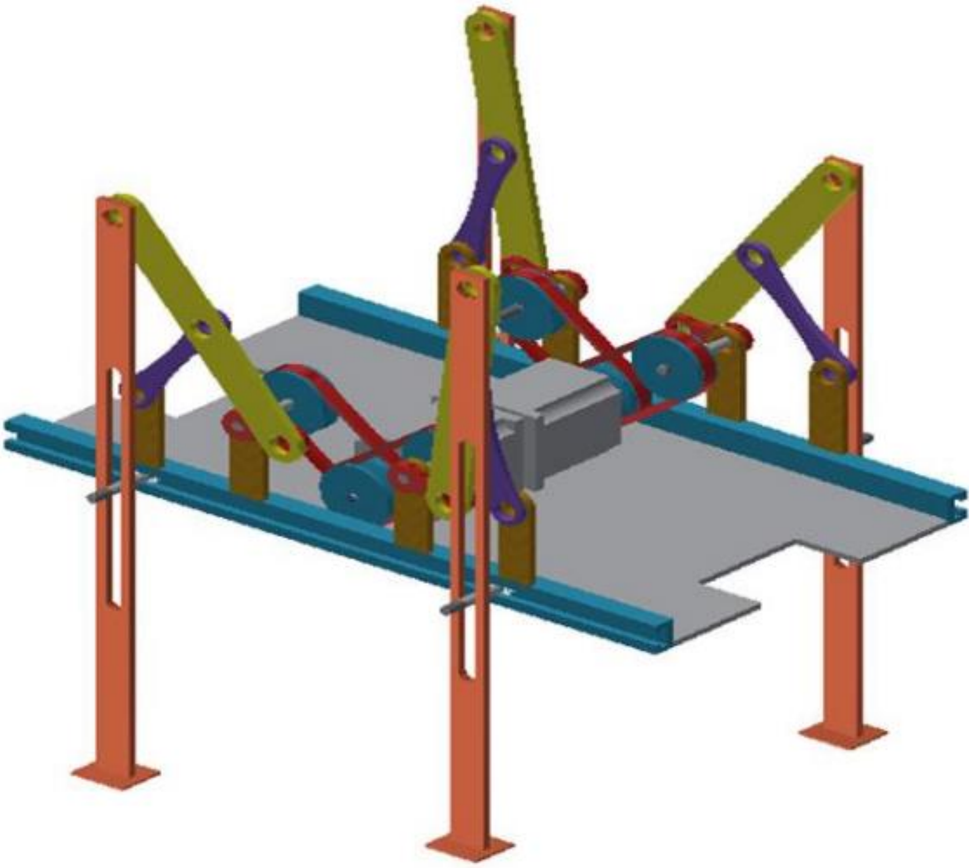


Figure 4: Initial mechanical design of the quadruped walking robot.

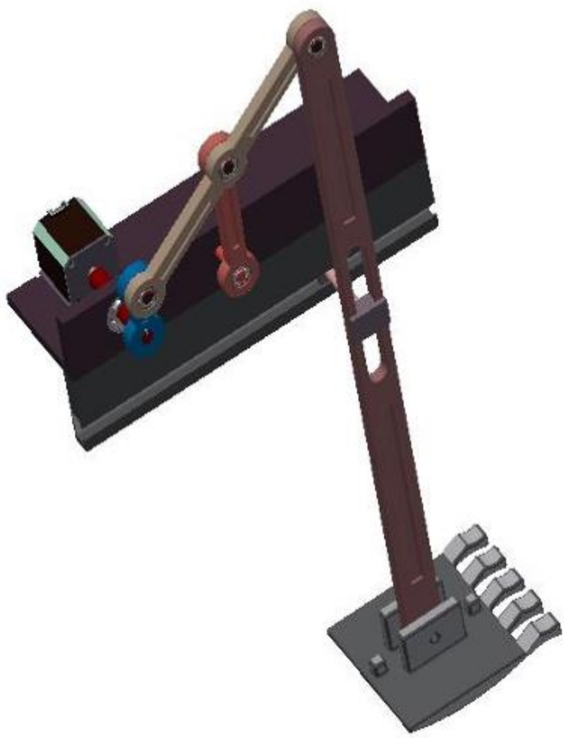
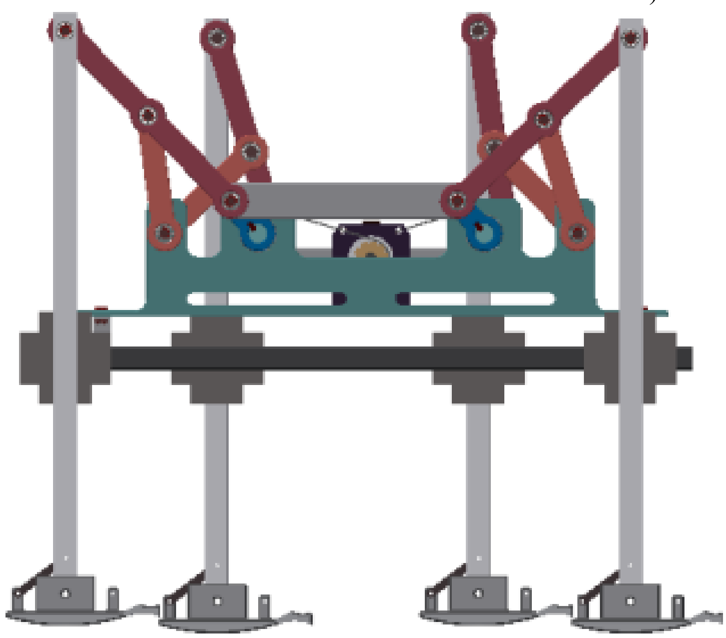
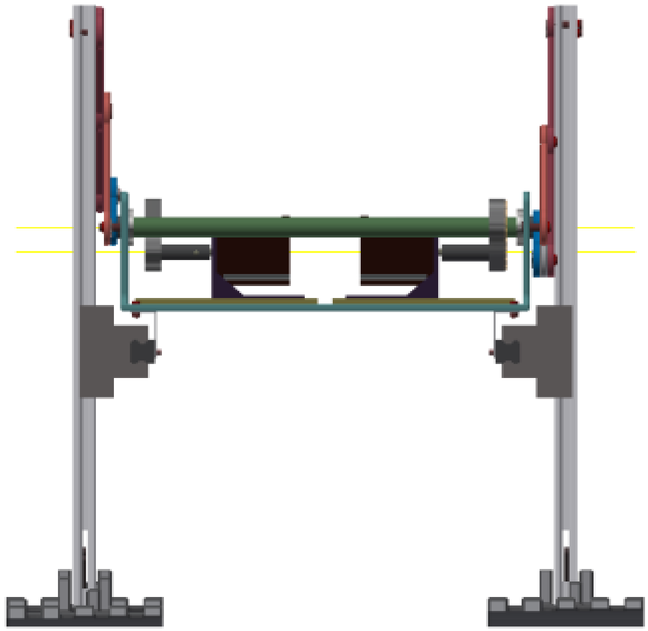


Figure 5: Mechanical design of (1-DOF) leg mechanism.

As illustrated inFigure 4, the initial design of the robot and inFigure 6, the CAD design using Inventor version 19, features four legs constructed from simple linkages capable of performing the motion characteristic of a Chebyshev mechanism, which includes both a straight-line segment and an elliptical segment. The robot is actuated by two motors, supported by a basic power transmission system comprising gears and belts to effectively transfer motion from the motors to the legs.

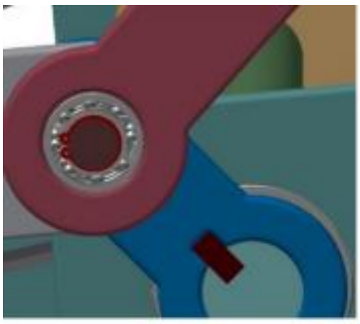
a) Isometric

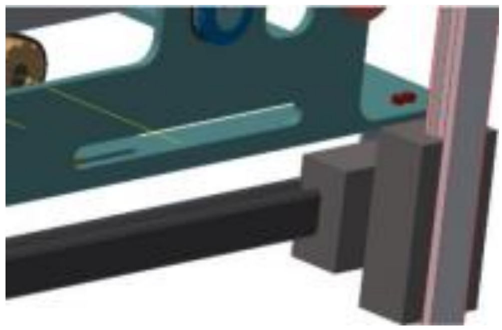




b) Elevation c)Side

Figure 6: CAD model of the four-legged walking robot.





(a) Crank link (b) Power transmission (c) Linear bearing

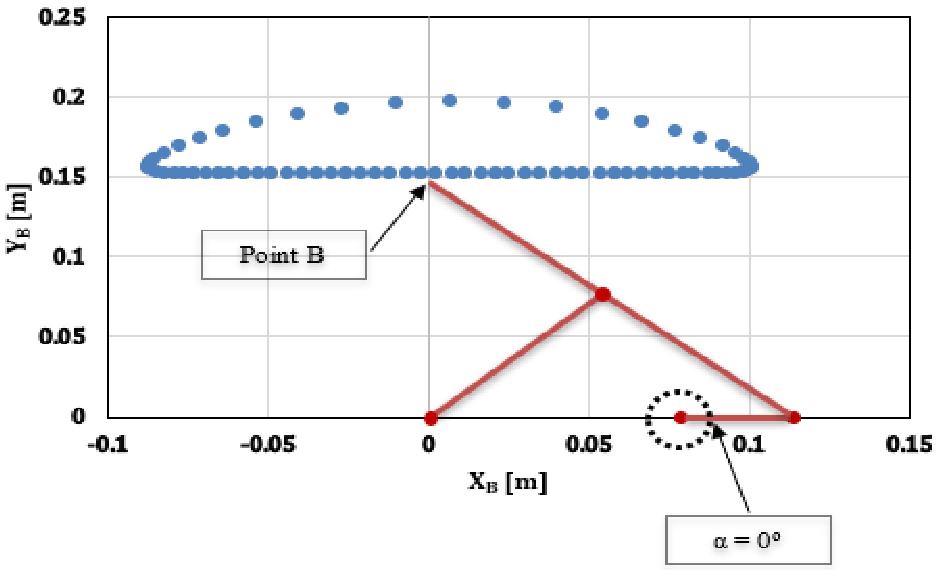
Figure 7: Key components of the four-legged robot CAD assembly.

Actuators are essential for any robot, as they convert input signals into mechanical motion to control movement. In this project, stepper motors were selected as the actuators. These motors transform electrical pulses into precise, incremental movements. The direction of rotation depends on the pulse sequence, the speed on the pulse frequency, and the rotation angle on the total number of pulses applied.Stepper motor (NEMA 23) has been selected.Stepper motors are ideal for this project due to their ability to provide precise and repeatable motion control without the need for feedback systems. Their proportional response to input pulses allows accurate positioning and smooth control over a wide range of speeds. Additionally, they offer full torque at standstill, excellent reliability due to the absence of brushes, and simple, cost-effective open-loop controlmaking them highly suitable for robotic applications like the one presented in this design[20].

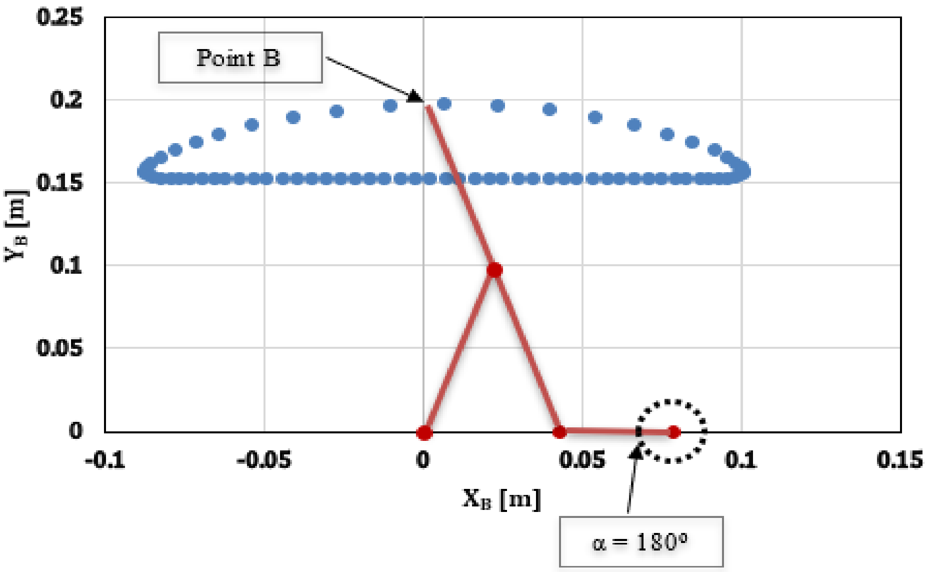
As illustrated in Figure 7 , the main components of four-legged robot. Compound belt drive has been chosen for power transmission as shown inFigure 7 (b). The small gear is connected directly to the motor, So the torque of the small gear is equal to the torque of the stepper motor.Angular velocity of the stepper motor equals 2.8 rad/s.Linear bearings is used as shown in Figure 7 (c) to provide smooth, precise, and controlled linear motion of the leg by guiding a moving part along a fixed path, while minimizing friction and wear.

4 Results and Discussion

Figure 8 illustrates the trajectory of Point B, which is attached to the Chebyshev leg mechanism. The blue dotted curve represents the path traced by Point B during the rotation of the crank, showcasing a distinctive ovoid trajectory composed of a nearly straight segment (the lower part) and a curved segment (the upper arc). This path is characterized by the Chebyshev mechanism and is particularly beneficial for walking robots, as the straight portion simulates foot contact with the ground, enhancing stability and efficiency during locomotion.The trajectory shown is obtained from the kinematic analysis using the mathematical equations (1) through (5) that describe the motion of the mechanism.The crank angle at the initial position is indicated as α = 0°, representing the starting configuration of the leg cycle, while the crank angle at the final position is marked as α = 180°, denoting the end of the leg cycle. These positions highlight the full range of motion of the crank during one complete walking step.



(a) α = 0°



(b) α = 180°

Figure 8: Simulated trajectory of point B based on kinematic analysis (a) at α = 0° (b) α = 180°

Figure 9 illustrates the trajectories of Points (A) and (B) of the Chebyshev leg mechanism throughout a complete crank rotation. The red and blue curves represent the paths traced by Points (A) and (B), respectively, as functions of the input crank angle (α). The linkage structure depicts the configuration of the leg at a specific instance, highlighting the motion transmission from the crank to the end effector. The crank angle (α) is indicated for reference. This analysis demonstrates the mechanism ability to generate two distinctsymmetric foot trajectories,one for the upper limb motion and one for the lower contact pathproviding insight into the walking cycle of the quadruped robot.

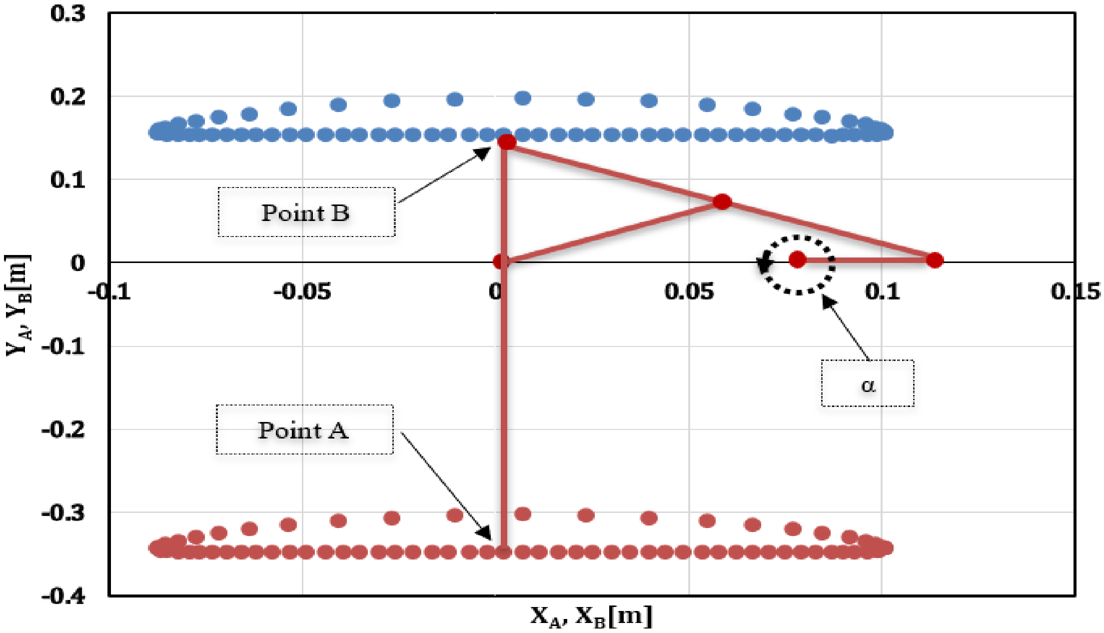


Figure 9: Comparative trajectories of points A and Bresulting from kinematic analysis.

The Figure 10 illustrates the velocity of point B (X_B) along the X-axis as a function of the input angle α (in degrees) during a full rotation cycle from equation (8). The velocity reaches a peak of approximately 0.15 m/s around α = 30°, corresponding to the mid-support phase where the leg moves most rapidly forward. Following this, the velocity decreases steadily, becoming negative between approximately α = 120° and 230°, indicating a backward motion or sliding during the double-support phase. The second velocity peak (~0.10 m/s) occurs near α = 270°, showing a secondary forward motion before the leg transitions again. These fluctuations confirm the cyclic nature of the stepping mechanism and highlight distinct swing and support phases. The zero crossings represent key transition points between forward and backward motion of the leg.

The Figure 11 shows the Y-axis velocity of point B as a function of the input angle (α) during one complete rotation cycle from equation (9). The velocity fluctuates between approximately –0.127 m/s and 0.092 m/s, reflecting the vertical motion of the leg during different phases of the gait cycle. Positive velocity values correspond to the upward movement of the leg during the swing phase, while negative values indicate downward motion during the support or landing phase. The maximum upward velocity typically occurs as the leg begins the swing phase (around α = 20°), and the maximum downward velocity is observed near the end of the swing or beginning of support (around α = 300°–330°), indicating foot contact. These oscillations are consistent with a periodic stepping pattern and are essential for maintaining continuous walking motion and balance.

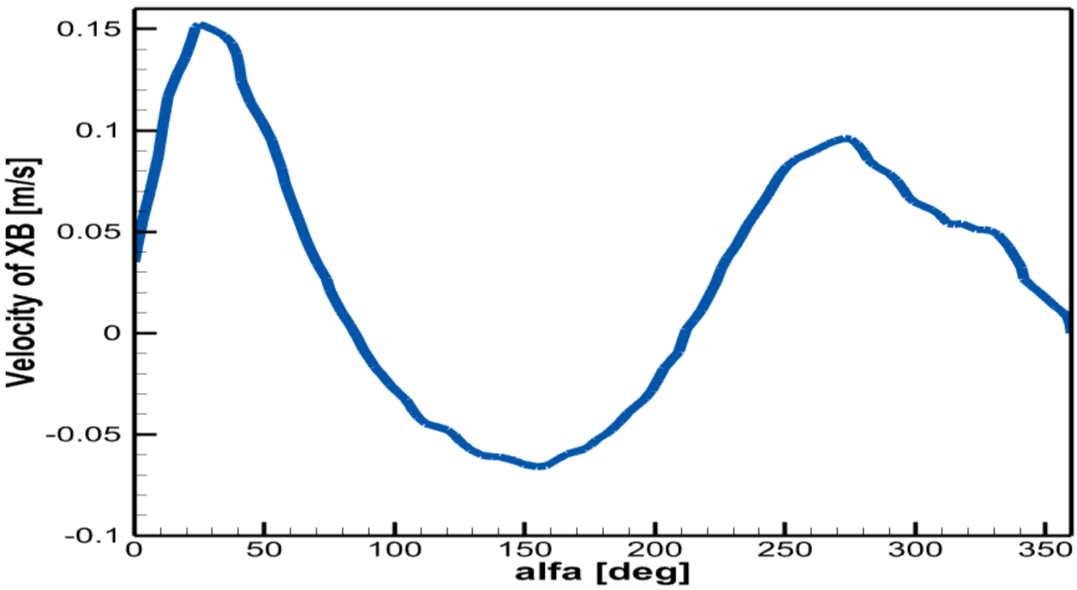


Figure 10:Simulatedvelocity profile of point B along the X-axis.

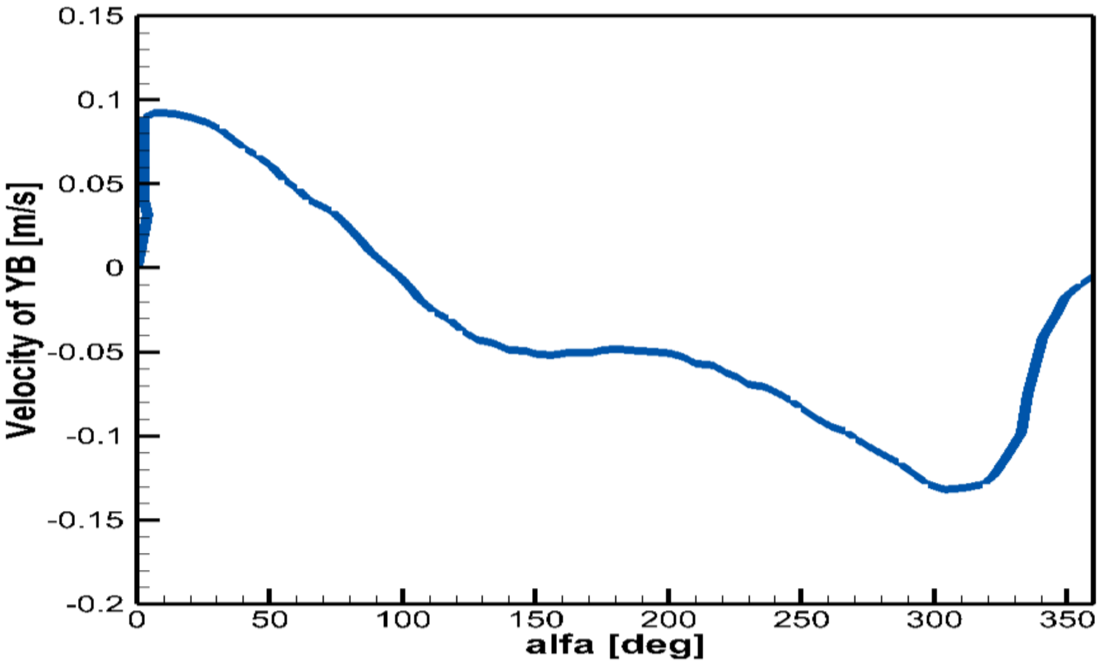


Figure 11:Simulatedvelocity profile of point B along the Y-axis.

These results are obtained from a one degree-of-freedom (1-DOF) leg mechanism driven by a single motor as illustrated in Figure 5 and the actual design for one leg in Figure 12. The actual trajectory of point B for a single leg mechanism is depicted in Figure 14, demonstrating highly satisfactory performance in the movement of the mechanism. As illustrated in Figure 13, the actual design for the four legs.

Figure 12:Constructed model (1-DOF) leg mechanism.

Figure 13:Fully assembled four-legged roboticmechanism.

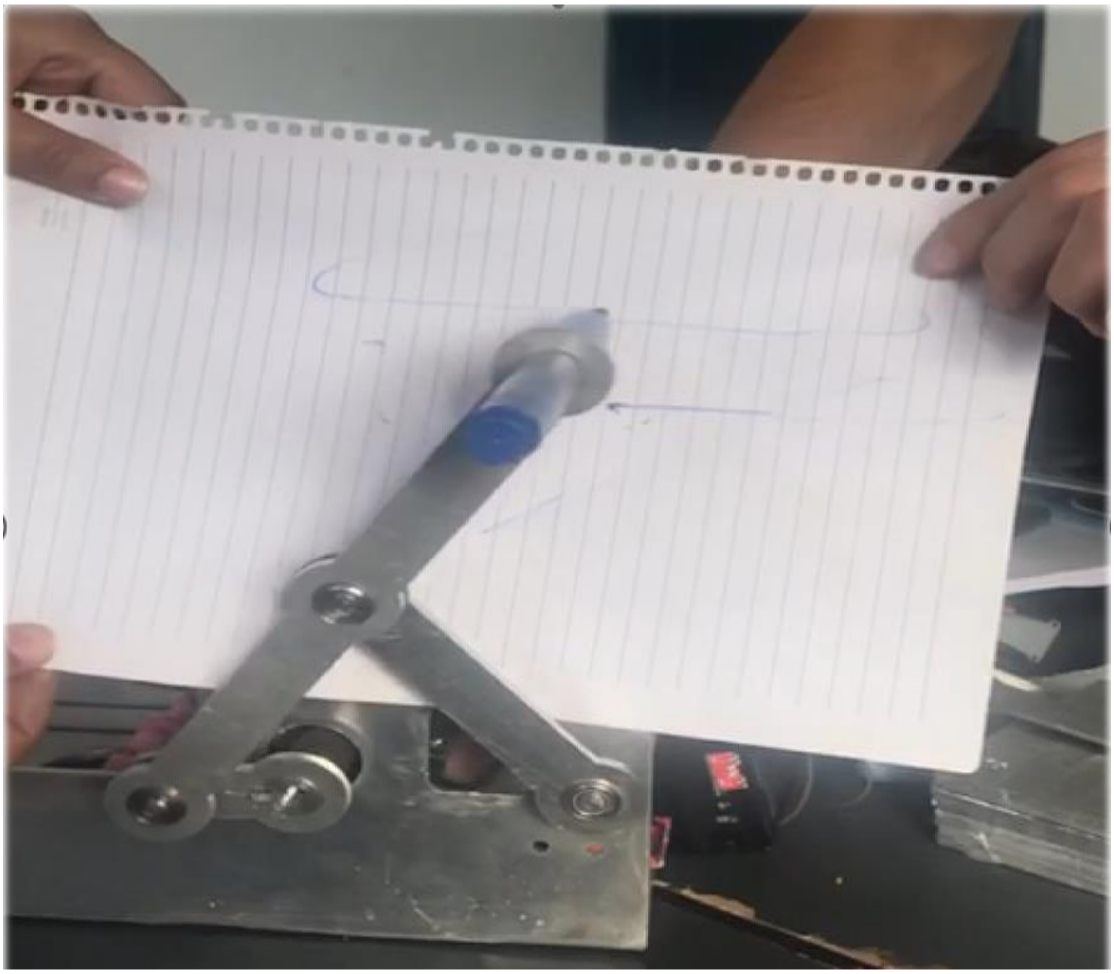


Figure 14: Experimentally observed trajectory of point B for a single leg mechanism.

Conclusions

This study introduces a novel four-legged walking robot inspired by quadrupedal locomotion, designed to emulate animal-like movement using a combination of straight-line and elliptical trajectories. The implementation of a 1-DOF Chebyshev linkage mechanism for each leg enables the transformation of simple rotary motion into an efficient and stable walking gait. Through detailed kinematic modeling and numerical simulation, the mechanical viability of the design has been validated, confirming its capacity to generate realistic foot trajectories that support smooth and repeatable locomotion.

The robot is specifically tailored for operations in hazardous or constrained environments, including search and rescue missions, military reconnaissance, and public safety surveillance. The use of dual motors and a symmetrical leg configuration ensures effective gait coordination while maintaining mechanical simplicity, making the design cost-effective and energy-efficient.

The key value of this work lies in the mechanical simplification of quadruped locomotion without sacrificing gait stability or adaptability. The use of a Chebyshev mechanism offers a low-complexity solution for generating effective foot trajectories, while linear bearings enhance motion smoothness and reduce mechanical wear. Additionally, the modular design allows for scalability and integration into various robotic platforms, extending the robot's application potential beyond exploration to assistive medical devices, such as artificial limbs.

Despite its promising capabilities, the current prototype exhibits certain limitations. The robot is constrained by a limited degree of freedom, which may reduce its maneuverability on uneven or highly dynamic terrain. Moreover, the system lacks feedback control, relying solely on open-loop actuation, which could hinder precise motion correction in real-time applications. The robot's payload capacity and battery autonomy also remain limited, impacting its deployment duration in field operations.

Future enhancements will focus on equipping the robot with renewable energy solutions, specifically integrating solar panels, to provide a sustainable power source for long-duration missions. Additionally, the incorporation of artificial intelligence (AI) and computer vision algorithms will be explored to enable autonomous navigation, obstacle avoidance, and target recognition. Real-time data from onboard sensors and cameras will feed into a decision-making framework, enabling the robot to adapt to complex and dynamic environments without human intervention. Furthermore, the mechanical design may be evolved to support adaptive gaits, improved terrain compliance, and feedback-controlled actuation for more robust performance in challenging real-world scenarios.

In conclusion, the proposed quadruped robot represents a significant step toward accessible, efficient, and application-ready walking robotic platforms. With further development, it holds the potential to contribute meaningfully to various sectors including disaster response, surveillance, environmental monitoring, and assistive robotics.

List of Abbreviations

Abbreviation	Definition
DOF	Degree of Freedom
CAD	Computer-Aided Design
K	Vertical distance from point A to point C
H	Horizontal distance from point A to point C
X-axis	Horizontal Direction of Motion
Y-axis	Vertical Direction of Motion

Declarations

▪ Availability of data and materials

The authors confirm that no datasets were generated or analyzed during the current study. All results presented are derived from original design, simulation, and modeling work.

▪ Competing interests

The authors declare that they have no competing interests that could have influenced the outcomes of this study.

▪ Funding

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▪ Authors' contributions

All authors made substantial contributions to the conception, design, implementation, and documentation of this study.Toka A. Abdo led the mechanical design, CAD modeling, and simulation analysis of the quadruped walking robot.Ahmed M. Hanafi was responsible for the system integration, gait coordination logic, and control system implementation.Nourhan A. Abbass contributed to kinematic modeling, numerical analysis, and manuscript drafting.Yousri M. Diab provided expertise in dynamic analysis and supported the refinement of the mathematical models and technical content.**Dr. Abdelrady O. Elnady** served as the academic supervisor for this project. He provided invaluable guidance throughout all stages of the work, from conceptualization to validation. His technical insights and mentorship were instrumental to the success of this research. **The authors wish to dedicate this work to his memory following his recent passing.**All authors reviewed and approved the final version of the manuscript.

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References

[1] A. B. Filho, P. F. S. Amaral, and B. G. M. Pinto, 2010,*A four legged walking robot with obstacle overcoming capabilities*, in *3rd International Conference on Human System Interaction*, pp. 374–379. doi: 10.1109/HSI.2010.5514543.

[2] A. M. Hoover, 2010,*Design of Minimally Actuated Legged Milli-Robots Using Compliant Mechanisms and Folding*,

CALIFORNIA, BERKELEY.

[3] S. Soyguder and H. Alli, 2011,*Motion mechanism concept and morphology of a single actuator tetrapod walking spider robot: the ROBOTURK SA-2 Robot*, *Ind. Robot An Int. J.*, vol. **38**, no. 4, pp. 361–371, doi: 10.1108/01439911111132058.

[4] C. Runbin, C. Yangzheng, L. Lin, W. Jian, and M. H. Xu, 2013,*Inverse kinematics of a new quadruped robot control method*, *Int. J. Adv. Robot. Syst.*, vol. **10**, doi: 10.5772/55299.

[5] A. Spröwitz, A. Tuleu, M. Vespignani, M. Ajallooeian, E. Badri, and A. J. Ijspeert, 2013,*Towards dynamic trot gait locomotion: Design, control, and experiments with Cheetah-cub, a compliant quadruped robot*, *Int. J. Rob. Res.*, vol. **32**, no. 8, pp. 932–950, doi: 10.1177/0278364913489205.

[6] M. Hutter, C. Gehring, M. A. Höpflinger, M. Blösch, and R. Siegwart, 2014,*Toward combining speed, efficiency, versatility, and robustness in an autonomous quadruped*, *IEEE Trans. Robot.*, vol. **30**, no. 6, pp. 1427–1440, doi: 10.1109/TRO.2014.2360493.

[7] S. Oak and V. Narwane, 2014,*Design, Analysis and Fabrication of Quadruped Robot with Four bar Chain Leg Mechanism*, *Int. J. Innov. Sci. Eng. Technol.*, vol. **1**, no. 6, pp. 340–345.

[8] C. Wang, T. Zhang, X. Wei, Y. Long, and S. Wang, 2017,*Bio-inspired control strategy study for the quadruped robot with a segmented spine*, *Ind. Robot An Int. J.*, vol. **44**, pp. 85–93, doi: 10.1108/IR-05-2016-0149.

[9] C. Semini, V. Barasuol, J. Goldsmith, M. Frigerio, M. Focchi, Y. Gao, and D. G. Caldwell, 2017,*Design of the Hydraulically Actuated, Torque-Controlled Quadruped Robot HyQ2Max*, *IEEE/ASME Trans. Mechatronics*, vol. **22**, no. 2, pp. 635–646, doi: 10.1109/TMECH.2016.2616284.

[10] S. Kitano, S. Hirose, A. Horigome, and G. Endo, 2016,*TITAN-XIII: sprawling-type quadruped robot with ability of fast and energy-efficient walking*, *ROBOMECH J.*, vol. **3**, no. 1, pp. 1–17, doi: 10.1186/s40648-016-0047-1.

[11] R. C. Liu, G. Y. Ma, Y. Chen, S. Han, and J. Gao, 2018,*Four-legged robot design and gait planning*, *J. Phys. Conf. Ser.*, vol. **1087**, no. 6, doi: 10.1088/1742-6596/1087/6/062047.

[12] X. Zeng, S. Zhang, H. Zhang, X. Li, H. Zhou, and Y. Fu, 2019,*Leg trajectory planning for quadruped robots with high-speed trot*, *Appl. Sci.*, vol. **9**, no. 7, doi: 10.3390/app9071508.

[13] C. Tavolieri, E. Ottaviano, M. Ceccarelli, and A. Di Rienzo, 2007,*Analysis and Design of a 1-DOF Leg for Walking Machines*, *Mediterr. Conf. Control Autom.*, pp. 1–6.

[14] S. M. Song, J. K. Lee, and K. J. Waldron, 1987,*Motion study of two- and three-dimensional pantograph mechanisms*, *Mech. Mach. Theory*, vol. **22**, no. 4, pp. 321–331, doi: 10.1016/0094-114X(87)90021-8.

[15] M. Raibert, 1986*Legged Robots That Balance*.

[16] F. PFEIFFER and T. ZIELINSKA, Eds., 2004*Walking: Biological and Technological Aspects*. New York: Springer-Verlag Wien.

[17] C. Liang, M. Ceccarelli, and Y. Takeda, 2012,*Operation analysis of a Chebyshev-Pantograph leg mechanism for a single DOF biped robot*, vol. **7**, no. 4, pp. 357–370, doi: 10.1007/s11465-012-0340-5.

[18] S. Çiklaçandir and Ö. K. Cura, 2017,*Design a Robot Insect Inspired by the Camouflage Characteristics of the Leaf Insect*, no. December, pp. 7–09, [Online]. Available: https://www.researchgate.net/publication/322696344

[19] E. Ottaviano, M. Ceccarelli, and C. Tavolieri, 2005,*Kinematic and Dynamic Analyses of a Pantograph-Leg for a biped walking machine*, *Climbing Walk. Robot.*, pp. 561–568.

[20] H. Xinda, ,*An Introduction to Stepper Motors*, *University of Arizona*. [Online]. Available: https://wp.optics.arizona.edu/optomech/wp-content/uploads/sites/53/2016/10/Tutorial_Xinda-Hu.pdf