SIMSCAPE MULTI BODY DEISGN SIMULATION FOR QUADRAPED BOT 3R

MINI PROJECT REPORT

Robot Dynamics and Control MTE4410

Submitted by

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ABSTRACT

This report presents the modeling and simulation of a quadruped robot performing trot gait locomotion using kinematic control strategies. Each leg of the robot is composed of three revolute joints—hip, knee, and ankle—assembled within the Simscape Multibody environment with defined mass and geometric properties. Joint actuation is achieved through sinusoidal motion profiles, with phase offsets applied to create a coordinated trot gait, wherein diagonal leg pairs move in synchronization. The robot's walking motion is generated purely through these prescribed joint trajectories. Simulation results validate the effectiveness of this approach in achieving stable, repeatable walking and turning motions, making it a suitable foundation for further exploration of gait patterns and legged locomotion control.

Keywords: Quadruped Robot, Trot Gait, Simscape Multibody, Sinusoidal Joint Control, Gait Simulation

LIST OF TABLES

LIST OF FIGURES

Contents

Chapter 1: Introduction

1.1 **Background and Context**

The field of legged robotics is inspired by biological systems that demonstrate remarkable capabilities in navigating diverse terrains. Quadruped robots mimic the four-legged walking of animals and offer improved stability compared to bipedal robots. Their ability to lift individual legs and maintain multiple contact points makes them suitable for challenging surfaces, such as rocky environments, stairs, and soft grounds. Legged robots are ideal for search and rescue, exploration, military applications, and operations in hazardous or remote areas.

With advancements in simulation tools like MATLAB and Simulink, it has become feasible to design, analyze, and validate complex robotic systems virtually before physical prototypes are built. Simscape Multibody offers a platform to model mechanical systems with realistic physics, allowing simulation of rigid bodies, joints, actuators, and constraints in a graphical environment. This project leverages these tools to create a full quadruped model and simulate its locomotion behaviors.

1.2 **Current Trends and Technological Relevance**

In recent years, robots like Boston Dynamics' Spot and MIT's Mini Cheetah have highlighted the potential of quadrupeds in real-world applications. These systems often use advanced hardware and control systems for mobility, perception, and planning. Simulating such systems helps us understand gait cycles, energy efficiency, terrain adaptability, and stability control without incurring the high costs of real-world experimentation. Our project aims to simulate a simpler but scalable model that captures the fundamental dynamics of such platforms.

1.3 **Motivation for the Project**

The primary motivation is to understand the kinematics and control aspects of quadruped motion using a minimal design approach. We chose a 3R joint structure for each leg to capture sufficient degrees of freedom while maintaining simplicity. Our goal was to enable walking behavior through joint actuation and test various control inputs and trajectory profiles for speed and directional control. By building this in Simscape

Multibody, we also aimed to gain experience in virtual prototyping and kinematics analysis.

1.4 Project Planning and Work Distribution

The project was structured into phases: initial modeling of a single leg, system integration for a complete quadruped, control input design, trajectory planning, kinematics analysis, and result evaluation. Each team member contributed to different segments of this workflow, ensuring a collaborative and modular approach.

Sl. No.	Student Name	Registration Number	Individual objective
1	Raj Vaingankar	220929152	Synopsis, Literature Review, Modelling of Bot
2	Aryan Pawar	220929076	Report, Modelling of Bot
3	Pranav P	220929062	PPT, Implementing Gait Controller

Chapter 2: Literature Review and Theoretical Background

The design and control of quadruped robots have evolved significantly over recent decades, with increasing interest due to their adaptability to complex terrains and versatility in various applications. A quadruped robot, inspired by the biological locomotion of animals, offers enhanced stability and mobility compared to wheeled or bipedal systems. This literature review explores historical developments, state-of-the-art technologies, and control strategies relevant to the simulation and design of quadruped robots, especially single-leg 3R systems as developed in this project.

Biswal and Mohanty (2021) present a comprehensive review of the development of quadruped walking robots, charting a timeline from early mechanical systems like the Chebyshev walker to advanced platforms such as Boston Dynamics' Spot. Their study identifies a key design trend: a move towards biologically inspired systems that emphasize dynamic balance, agility, and adaptability across uneven terrain. Robots such as MIT's Cheetah and IIT’s HyQ are examples where powerful actuators and lightweight structures have been combined with complex gait planning algorithms to achieve efficient locomotion. These developments underscore the importance of accurate simulation tools for prototyping and validation, especially when dealing with high degrees of freedom and nonlinear dynamics.

Simulations using tools like MATLAB Simscape Multibody, as adopted in this project, mirror this shift by enabling virtual prototyping of articulated legs and testing control strategies in realistic environments. The use of a 3R configuration (three revolute joints) per leg captures essential features of animal locomotion while maintaining manageable complexity. This aligns with earlier research, such as the TITAN series, which demonstrated the effectiveness of modular and symmetrical leg designs for terrain adaptability.

In terms of control, Meng et al. (2023) focus on gait stability using a combination of Model Predictive Control (MPC) and the Zero Moment Point (ZMP) method. These advanced techniques manage nonlinearity and ensure real-time balance during walking. The MPC method, by predicting future states and adjusting control inputs dynamically, offers robustness against disturbances and modeling inaccuracies. ZMP complements this by ensuring dynamic stability, particularly by keeping the robot's center of gravity projection within the support polygon during motion.

Integrating these control methods into a simulation framework provides valuable insights into the viability of walking gaits and the effect of different trajectories on robot stability. Such integration is particularly relevant for small-scale robots, where weight and energy efficiency are critical. The literature indicates that using inverse and forward dynamics, along with MPC and ZMP, facilitates the generation of biologically plausible and mechanically feasible walking behaviors.

In conclusion, this review highlights the evolution of quadruped robot designs and the shift towards dynamic and adaptive gait control strategies. The project’s focus on modeling a 3R leg structure and simulating trajectory-based control in Simscape aligns with contemporary research trends, serving as a foundational step towards more complex gait planning and real-world implementation.

Chapter 3: Problem Definition and Objectives

Designing quadruped robots for real-world applications poses multiple challenges: stability, accurate leg coordination, trajectory generation, and actuation control. These challenges become more manageable through simulations that replicate real-world physics.

The specific problems addressed in this mini project include:

- Developing a simplified yet functional 3R leg mechanism for a quadruped system.
- Ensuring that joint-level actuation can drive coordinated walking patterns.
- Implementing and testing inverse and forward kinematics to simulate realistic motion.
- Creating trajectory-based walking algorithms to control direction and speed.

Objectives

- Design a minimal 3R joint mechanism in Simscape Multibody for a robotic leg.
- Replicate and arrange four such legs to construct a quadruped bot.
- Develop joint actuation strategies using Simulink inputs.
- Generate walking gaits using trajectory profiles.
- Simulate motion in both forward and inverse kinematics scenarios.
- Validate walking through foot trajectory analysis and joint torque evaluation.

Chapter 4: Methodology

4.1 System Design and Modeling

The design began with defining a single robotic leg with three revolute joints—representing the hip, knee, and ankle. The links were modeled using Simscape blocks for rigid bodies with proper physical properties such as mass, inertia, and dimensions. Revolute joints were inserted between the links to allow rotational motion.

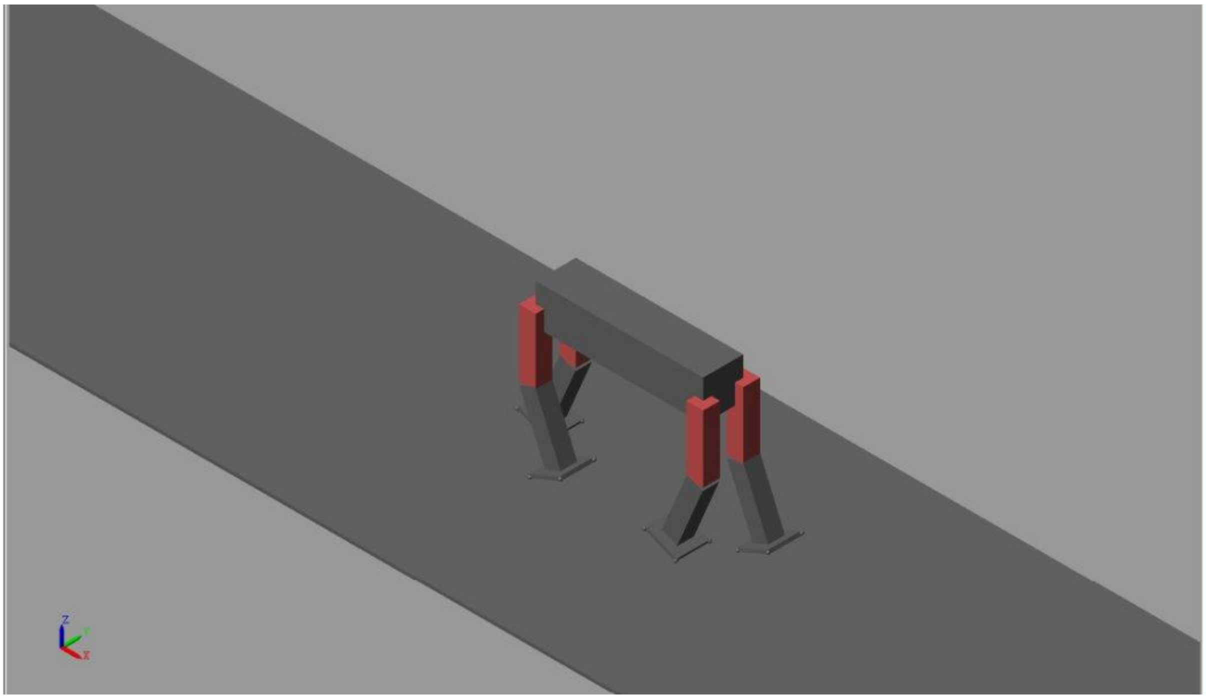


Figure1: Quadruped Bot

The leg structure was then cloned and arranged symmetrically to form a quadruped configuration with four legs placed at the corners of a rectangular chassis. Each leg was connected via revolute joints to the central body. All components were assembled in Simscape using 3D visualization tools to verify alignment and mobility.

To model the foot and ensure realistic contact with the ground, four **spherical geometries** were added at the corners of each foot. These spheres provided discrete, contactable surfaces that made foot-ground interaction more robust and physically accurate. Without these, contact was either inconsistent or unstable due to minimal or single-point geometry, especially when using flat or cornered foot shapes. The spheres act like soft, compliant toes that distribute contact forces more effectively across uneven terrain or during dynamic motion.

In addition, **Spatial Contact Force blocks** were integrated between each sphere and the ground. These blocks simulate the reaction forces when the foot touches the ground, including normal force and friction (both static and dynamic). This was essential to enable lifelike walking behavior using joint actuation and torque control, especially when the robot was simulated with floating dynamics and gravity.

These design features collectively contributed to a more stable, physically plausible walking motion and enabled support for dynamic gait modes such as trotting and jumping.

4.2 Joint Actuation and Control

Each joint was actuated using motion profiles from Simulink. These profiles were generated using mathematical functions (sine waves or time-based polynomials) to simulate walking cycles. Individual joints were provided separate control inputs, allowing synchronized motion across all legs.

Control inputs were carefully designed to alternate leg movements, maintain balance, and create repeatable gait cycles. Simulink's parameter tuning features were used to fine-tune speed, frequency, and phase offsets to optimize walking behavior. Trot gait was used to simulate bot's motion.

4.2.1 General equation of Sine function

Y(t) = Asin(2.pi.f.t + theta)

A → Amplitude of wave

F → frequency

t → Time period of stride

theta → phase shift

by changing these parameters, variation in motion could be achieved

4.2.2 Trot Motion in Quadruped Robot

The trot gait is one of the most stable and widely used gait patterns in quadruped locomotion. It is characterized by diagonal leg pairs moving in unison, providing both balance and forward motion.

How Trot Motion Works In a trot gait, the robot's legs move in diagonal pairs:

- Front Left (Leg 1) moves in sync with Rear Right (Leg 4)
- Front Right (Leg 2) moves in sync with Rear Left (Leg 3)

This ensures that at any given time, two diagonally opposite legs are in contact with the ground, while the other two swing forward. This configuration provides good dynamic stability and allows for a natural-looking walking pattern, especially when the robot is moving at moderate speeds.

To simulate this gait, each leg is assigned a time-dependent joint trajectory (typically for the hip and knee joints), using sinusoidal or trajectory-tracked control. The diagonal synchronization is achieved by applying phase shifts to the trajectory inputs for each leg.

Leg Number	Leg Name	Phase Shift (in rads)
1	Front Left	0
2	Front Right	Pi
3	Rear left	Pi
4	Rear Right	0

Table1: Phase Shift Table

Joint	**Phase1: Lift/Move Forward**	**Phase2: Land/ Push Back**
Hip pitch	Move leg forward (positive θ)	Move leg backward (negative θ)
Knee Pitch	Bend (negative θ)	Extend (toward 0°)
Ankle Pitch	Flex (positive θ)	Flatten/push (negative θ)

Figure: Gait Patter for Each Leg

4.2.3 Program to execute motion

MATLAB Function

Four_leg_bot_wuth_spheres ▸ leg1 ▸ MATLAB Function

```
function [hip, knee, ankle] = fcn(t)
    % parameters
    f = 0.5; % frequency
    A_hip = 0.2;      % hip pitch amplitude (rad)
    A_knee = 0.4;     % knee pitch amplitude (rad)
    A_ankle = 0.15;   % ankle pitch amplitude (rad)

    phase_hip = 0;
    phase_knee = pi/2;
    phase_ankle = pi;

    % Joint angle as a function of time
    hip = A_hip * sin(2*pi*f*t + phase_hip);
    knee = -A_knee * sin(2*pi*f*t + phase_knee);
    ankle = A_ankle * sin(2*pi*f*t + phase_ankle);
end
```

Figure2: Program Implementation

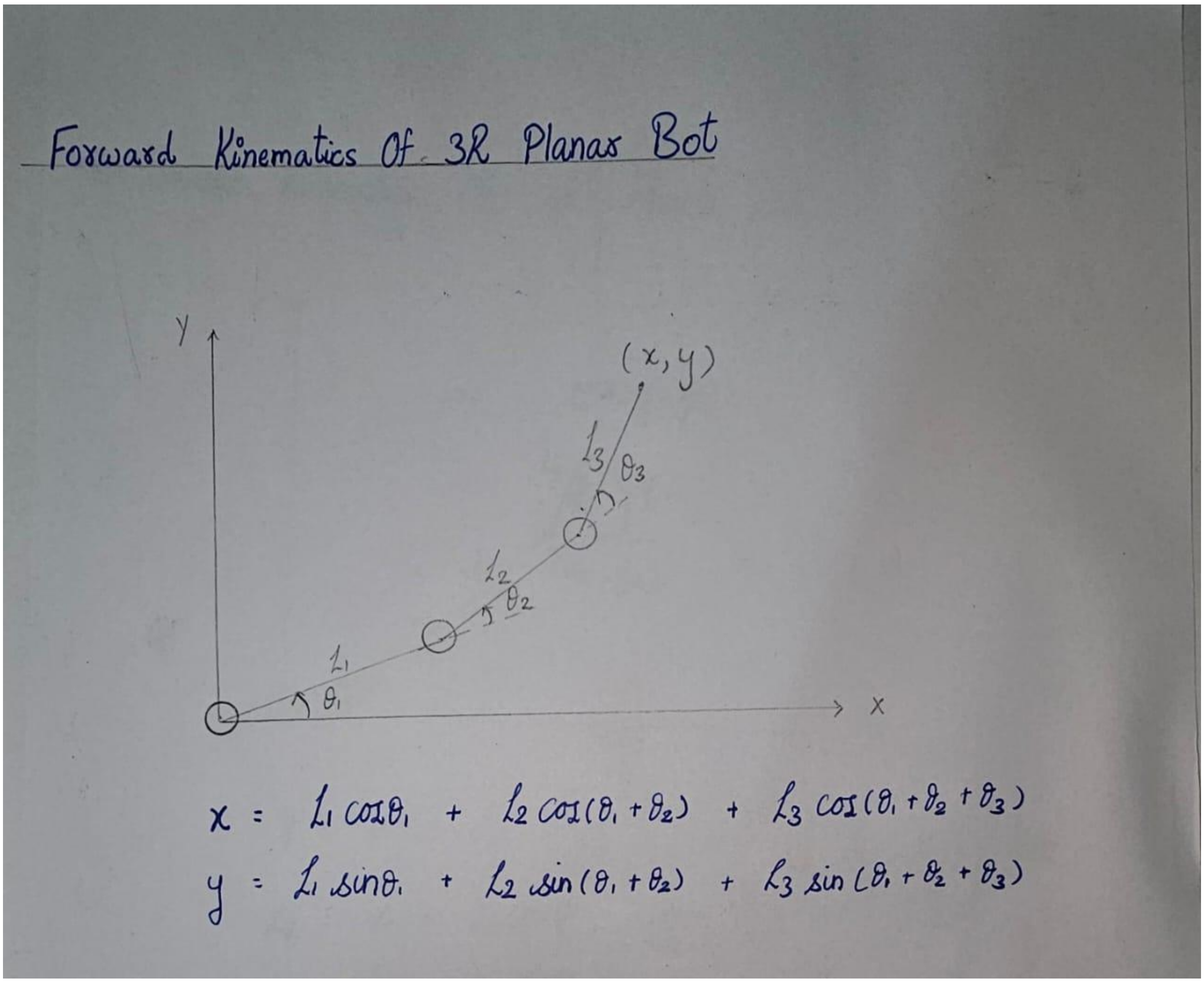
4.2.4 Directional Control via Amplitude Modulation

Turning behavior was implemented by modifying the amplitude of the sine wave trajectories provided to the hip joints. By increasing the amplitude on one side of the robot and decreasing it on the other, the stride length of the corresponding legs was altered. For example, a left turn was achieved by increasing the hip amplitude for the right-side legs and reducing it for the left-side legs. This created a net rotational torque about the robot's vertical axis, causing it to turn smoothly while maintaining a trot gait. This technique enabled controlled directional movement without interrupting the periodic nature of the gait cycle.

4.3 Trajectory Planning

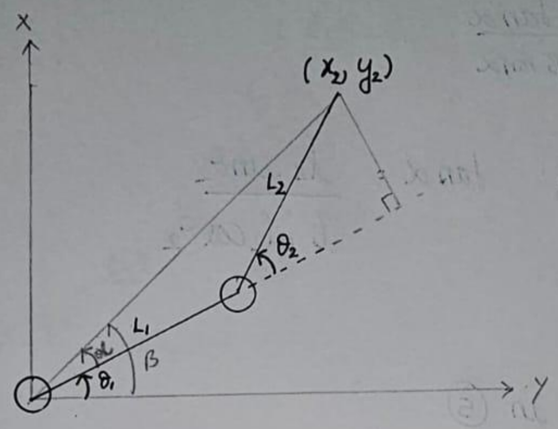
Foot trajectories were generated using predefined path equations, and inverse kinematics was used to calculate joint angles for foot placement. Forward kinematics verified the resulting foot positions. These trajectories ensured the robot moved in a controlled manner with direction modulation.

Forward Kinematics of 3R Planar Bot:



Inverse Kinematics of 3R Planar Bot:

1. 2R Planar bot



Forward Kinematics :

$$x = l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) \quad \text{— } ①$$

$$y = l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) \quad \text{— } ②$$

Inverse Kinematics :

$$x = \cos\theta_1 (l_1 + l_2 \cos\theta_2) - \sin\theta_1 (l_2 \sin\theta_2) \text{ from } ① \quad \text{— } ③$$

$$y = \sin\theta_1 (l_1 + l_2 \cos\theta_2) + \cos\theta_1 (l_2 \sin\theta_2) \text{ from } ② \quad \text{— } ④$$

$$③^2 + ④^2 \Rightarrow \quad x^2 + y^2 = l_1^2 + l_2^2 + 2 l_1 l_2 \cos\theta_2$$

$$\theta_2 = \cos^{-1}\left[\frac{x^2 + y^2 - l_1^2 - l_2^2}{2 l_1 l_2}\right] \quad \text{— } ⑧$$

$$\theta_1 = \beta - \alpha$$

$$\tan\theta_1 = \tan(\beta - \alpha)$$

$$\tan\theta_1 = \frac{\tan\beta - \tan\alpha}{1 + \tan\beta \tan\alpha} \quad \text{— (5)}$$

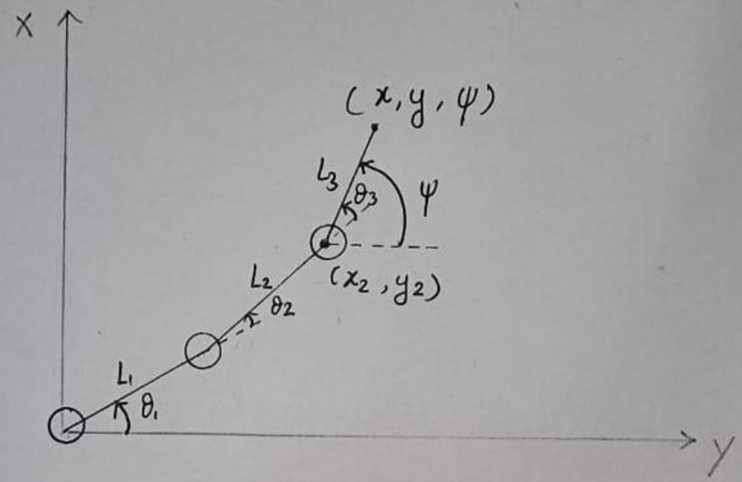
$$\tan\beta = \frac{y}{x} \quad \text{— (6)} \qquad \& \qquad \tan\alpha = \frac{l_2 \sin\theta_2}{l_1 + l_2 \cos\theta_2} \quad \text{— (7)}$$

Sub (6) & (7) in (5)

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

$$\theta_1 = \tan^{-1}\left[\frac{y(l_1 + l_2\cos\theta_2) - x l_2 \sin\theta_2}{x(l_1 + l_2\cos\theta_2) + y l_2 \sin\theta_2}\right] \quad \text{— (9)}$$

Inverse Kinematics Of 3R Planar Bot



$\psi = \theta_1 + \theta_2 + \theta_3$ (end effector orientation) — (10)

$x_2 = x - l_3 \cos\psi$

$y_2 = y - l_3 \sin\psi$

from eq^n (8) : $\theta_2 = \cos^{-1}\left[\dfrac{x_2^2 + y_2^2 - l_1^2 - l_2^2}{2 l_1 l_2}\right]$

from eq^n (9) : $\theta_1 = \tan^{-1}\left[\dfrac{y(l_1 + l_2\cos\theta_2) - x l_2 \sin\theta_2}{x(l_1 + l_2\cos\theta_2) + y l_2 \sin\theta_2}\right]$

from eq^n (10) : $\theta_3 = \psi - (\theta_1 + \theta_2)$

4.4 Tools and Platforms

- **Simscape Multibody** for mechanical system modeling
- **Simulink** for control input generation and trajectory management
- **MATLAB scripts** for kinematic analysis and data visualization

Chapter 5: Results and Conclusion

5.1 Results and Discussion

- The project successfully simulated a 3R single leg in Simscape with realistic joint motion.
- The quadruped structure showed good stability and coordination when actuated with proper input signals.
- Walking behavior was achieved through careful synchronization of joint motion across legs.
- Trajectory planning enabled the robot to follow predefined paths with smooth foot transitions.
- Forward and inverse kinematics simulations confirmed the physical validity of the design.

5.2 Visual outputs

Joint Angles

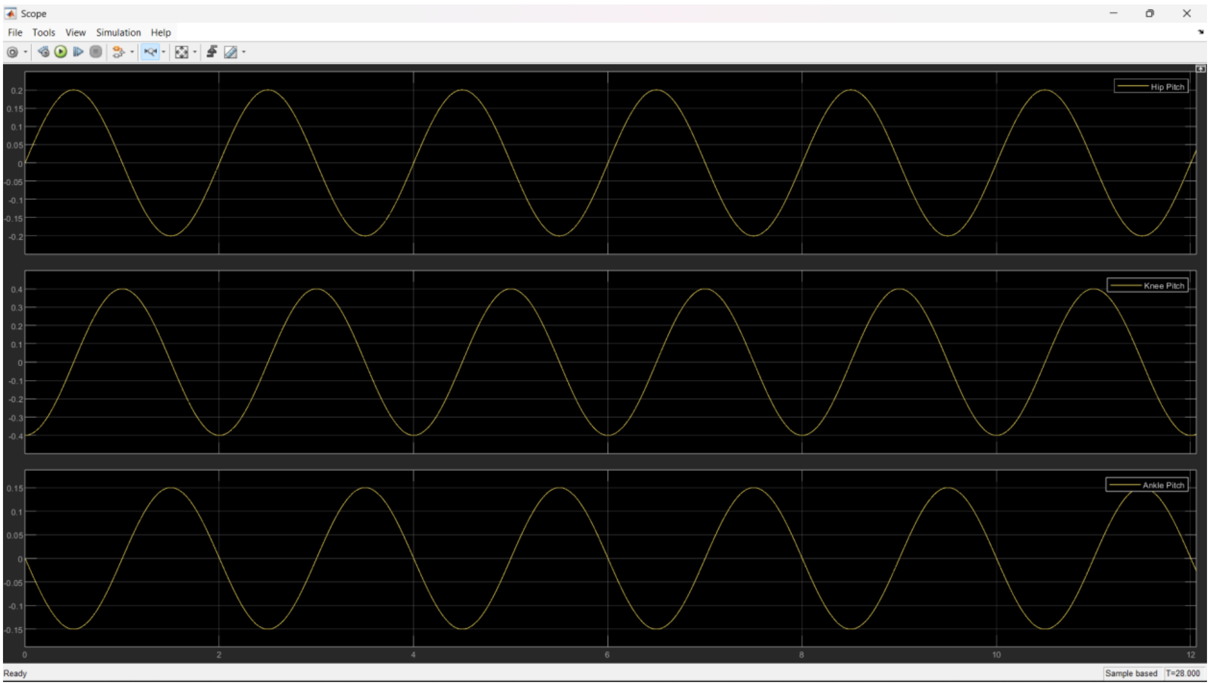


Figure3: Joint Angles of Leg1

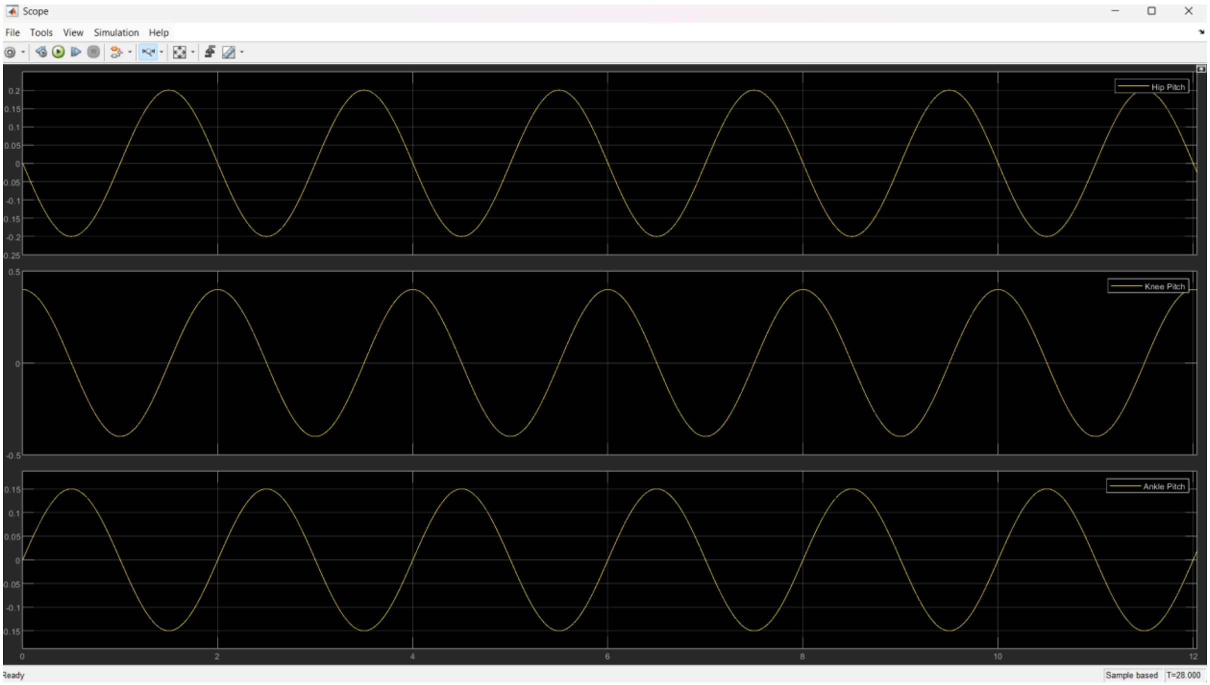


Figure4: Joint Angles of Leg2

The joint angle trajectories for the hip and knee joints exhibited periodic sinusoidal behavior consistent with the designed trot gait. Diagonally opposite legs moved out of phase by approximately π radians, confirming proper implementation of the gait phase table.

The hip joints oscillated within ±0.2 radians, while the knee joints ranged between –0.6 to +0.6 radians. This produced a realistic step height and stride length, facilitating forward locomotion without overextending joint limits.

Position of Torso

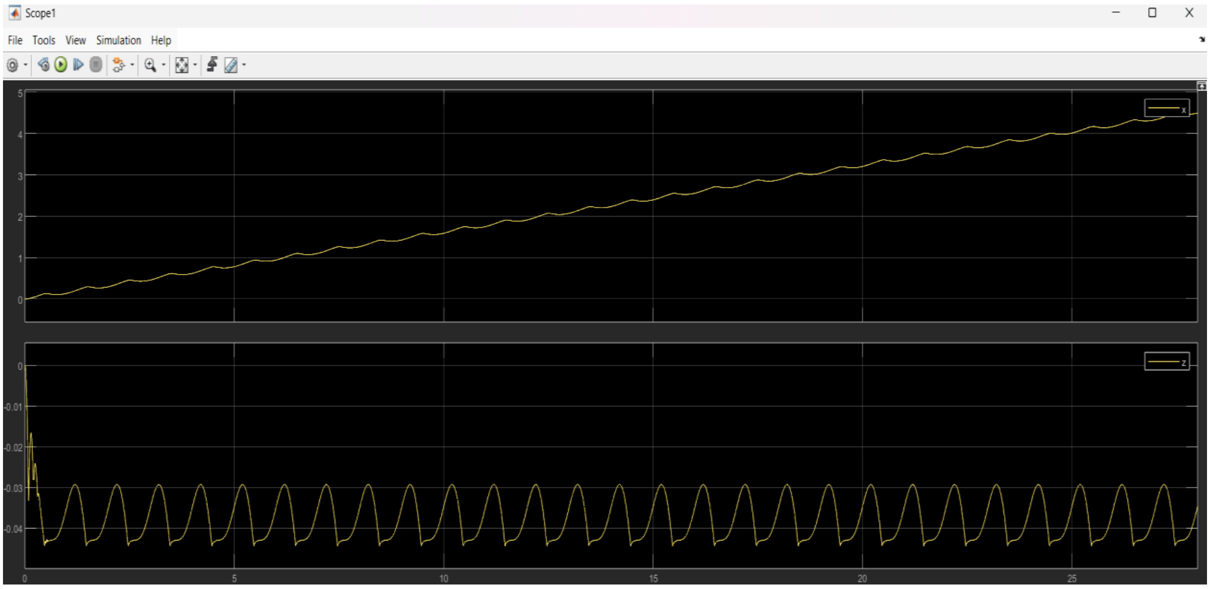


Figure5: Position of COM of the Torso

The torso x-position increased linearly over time, demonstrating successful forward propulsion. Vertical fluctuations in z-position were minimal (within ±1.5 cm), indicating stable support and effective foot-ground interaction.

5.3 Conclusions

The quadruped robot modeled in this mini project successfully demonstrates the capabilities of MATLAB Simscape for simulating complex legged robots. Through a modular 3R leg design, we built a complete walking quadruped capable of trajectory-based motion. The implementation of control strategies for joint actuation, combined with forward and inverse kinematics analysis, provides a strong foundation for further work in gait optimization, terrain adaptation, and real-world implementation.

This simulation not only validated our design approach but also emphasized the importance of virtual prototyping in modern robotics. The project opens pathways to advanced topics like sensory feedback integration, adaptive gait control, and machine learning-based motion planning in robotic locomotion systems.

Individual Contribution:

Raj Vaingankar (Reg. No. 220929152)

- Conducted an extensive literature review covering historical developments and modern control strategies in quadruped robotics.
- Developed the initial concept and modeling of the single leg 3R mechanism in Simscape Multibody.
- Assembled and integrated the full quadruped configuration from individual leg modules.

Aryan Pawar (Reg. No. 220929076)

- Authored and formatted the complete project report, ensuring clarity and coherence in documentation.
- Assisted in system-level modeling and visualization in Simscape, including physical properties assignment.
- Handled trajectory planning section: analyzed foot placement paths using inverse kinematics and validated results with forward kinematics.
- Verified simulation stability and contributed to result analysis and conclusions.

Pranav P (Reg. No. 220929062)

- Implemented the control system for gait generation using sinusoidal inputs and phase offset logic in Simulink.
- Programmed and simulated trot gait with amplitude modulation for directional control.
- Developed and tested the Simulink code to manage joint actuation cycles for synchronized motion.
- Prepared presentation slides summarizing methodology, results, and prospects.

6. REFERENCES

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7. Linear control theory and control law partitioning

Linear Control Theory

Linear control theory deals with systems that can be modeled using linear differential equations. The key assumptions are linearity and time-invariance. It uses classical methods (like PID, root locus, Bode plots) and state-space methods.

Example 1:

DC Motor Speed Control
Using a PID controller to regulate the speed of a DC motor, where the plant transfer function is linearized around a nominal operating point.

Example 2:

Cruise Control System in Cars
Designing a controller to maintain a constant vehicle speed despite road slope changes. The car dynamics are linearized, and a lead-lag or PID controller is applied.

Control Law Partitioning

Control Law Partitioning is a methodology used in complex systems (especially in aerospace and robotics) to divide the control law into different modules (e.g., inner loop for fast dynamics, outer loop for slower dynamics). This improves stability, robustness, and modularity.

Example 1:

Aircraft Flight Control
The inner loop controls attitude (pitch, roll, yaw), and the outer loop handles navigation (altitude, velocity, trajectory).

Example 2:

Quadruped Robot Leg Control
An inner loop controls joint torques, while the outer loop handles trajectory tracking or gait planning.

Linear Control Theory	Control Law Partitioning
A theoretical framework for designing controllers assuming linear systems.	A modular design strategy to separate control tasks based on dynamics or function.
Focuses on Stability and performance of linear systems using mathematical tools.	Focuses on Managing complexity by breaking down control tasks in multi-layered systems.