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Quadruped Robot Modeling by Mirroring Bipedal Robot for Trot Gait Simulation

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Abstract

In order to explore the development of stable quadruped robots, a method is proposed using concepts that have proven efficient in the design of bipedal robots. The legs of a bipedal robot are mirrored, and the parameters are adjusted to suit a quadruped robot. Starting by generating a foot trajectory through the use of the Linear Inverted Pendulum Model, the generated positions are used to derive joint angles via inverse kinematics from the D-H parameters of the model. The process is simulated and tested, and the results of the simulation show a stable trot gait of a quadruped at low speed on a horizontal plane. It is observed from the simulation that the stability still has room for improvement.

Keywords: Quadruped, LIPM, Inverse Kinematics, Trajectory, Trot Gait.

1. Introduction

Legged robots have become a focus in robotics. Popular for their versatility. Legged mobile robots are designed to mimic the movements of animals found in nature, since these animals are highly skilled at navigating such complex terrain. There are various legged robot designs inspired by different creatures found in nature. Some of these mobile robots are two-legged, some four-legged, and others six-legged. The four-legged robots have long proven to offer the best mobility and stability, as well as being relatively easy to design and control, hence most of the research has been centered around them.

Modern research has focused on various aspects such as stability and versatility. It has also focused on applications in multiple fields of engineering, leading to the development of robots with precise and dynamic motion. These developments have now gone beyond prototypes found in laboratories; they are being applied in real-world domains. Fields such as agriculture, search and rescue, environmental monitoring, exploration, logistics, etc.[1]. The results of these advancements can be observed in some of the well-known quadruped robots.

We now have advanced robots like HYQ Bot, MIT's Cheetah, ETH Zurich's ANYmal, StarlETH etc[2-3]. With the advancements of four-legged robots come challenges [4-6]. Coming up with the best mechanical design for the robots, finding the most efficient control systems with which to run them, and incorporating the robots with more sensors and actuators for better versatility.

In this paper, a model of a quadruped robot is presented, mirroring two bipedal robot models through the use of MATLAB/Simulink.
The control methods are detailed and results of the simulation are displayed. The paper is structured in the following manner. Section 2 goes over the Kinematic model of the robot. Section 3 focuses on the generation of the foot trajectory, which is essential to the gait pattern. The simulation process is explained in Section 4. Section 5 contains the summary.

2. Kinematic Model

The robot model used is about 0.4m long, 0.2m wide, and 0.3m tall. This method starts with modeling a Bipedal robot and then duplicates the legs to obtain mirrored hind legs. The robot is designed to run based on an analytic solution as described in [7]. In this solution, the base of each leg is taken as the end effector, while the foot is taken as the base. This allows the hip, pitch, roll, and yaw to intersect at a point, since the joint angles are being solved in reverse. A transform matrix is given as the input of this inverse kinematics module, containing values for the orientation and position of the foot relative to the orientation and position of the body. The module used in this paper transforms base to foot using offset, then finds the inverse rotation to get foot to base, and lastly, it computes the analytic solution. In order to calculate the joint angles, a kinematic tree is set up, following the D-H method. Table 1 shows the D-H parameters used for the right leg, and Table 2 shows the parameters corresponding to the left leg. For simplicity and ease of control, a single right leg and left leg are designed and later duplicated to form a quadruped.

3. Generation of Foot Trajectory

The foot trajectories are acquired using Linear Inverted Pendulum Module (LIPM). This method generates a walking trajectory by simulating an LIPM, as explained by Kajita et al [8]. This module works to generate a body trajectory based on two assumptions. The first is that the walking pattern is symmetric, and the second is that there are no disturbances. The height of the robot when standing straight is taken into account (zRobot), as well as the height of the pendulum (zModel) and the swing height.

In order to generate a symmetric trajectory, initial conditions will start from a positive x position and move into a positive y direction. Here, we use a simple model to generate a trajectory as the robot stands straight and still. The trajectory comes from the natural dynamics of the inverted pendulum. All we are doing is selecting the next foothold and allowing the pendulum to show us the

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trajectory. The simulation of the LIPM has two phases. The first phase moves the robot's COM to a half-step position and plans smooth cubic trajectories for the body and swing foot, then updates simulation states to single support, and finally animates the first half step in the walking cycle. The second phase implements the main walking cycle, continuously generating alternating steps. Once the initial symmetric step has been defined, the same pattern is reused to create successive steps by mirroring the foothold and updating LIPM Equation

$$\ddot{x} = (g / z)\, x \Rightarrow x(t) = A \cosh(t/\tau) + B \sinh(t/\tau), \tau = sqrt(z/g) \quad (1)$$

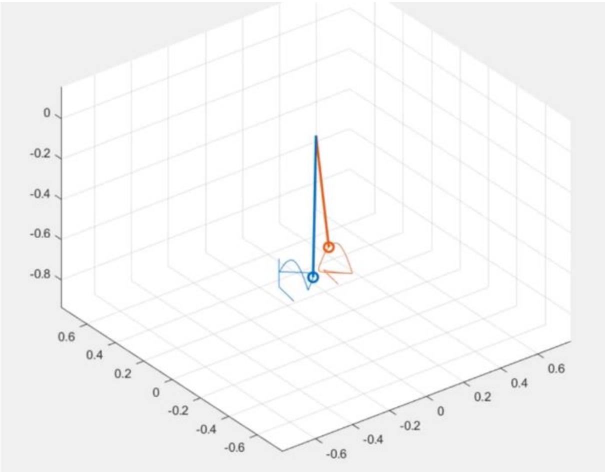

Fig. 1 Simulated walking trajectory

Table 1:D-H Parameters for right leg

a_i (m)	αi (rad)	d_i (m)	θ_i (rad)
L_1	0	$-L_2$	0
0	$-\pi/2$	0	0
0	$-\pi/2$	0	0
L_3	0	0	0
L_4	0	0	0
0	$\pi/2$	0	0
0	0	L_5	0

Table 2:D-H Parameters for left leg

a_i (m)	α_i (rad)	d_i (m)	θ_i (rad)
$-L_1$	0	$-L_2$	0
0	$-\pi/2$	0	0
0	$-\pi/2$	0	0
L_3	0	0	0
L_4	0	0	0
0	$\pi/2$	0	0
0	0	L_5	0

3.1 Inverse Kinematics Derivation (Analytic Solution)

Joint angles:

$$\theta_4 = atan2(\sqrt{(1 - cos^2\theta_4)}, cos\theta_4)$$
$$cos\theta_4 = ((p_x + L_5)^2 + p\_y^2 + p\_z^2 - L_3{}^2 - L_4{}^2) / (2\, L_3\, L_4)$$

$$\theta_5 = atan2(-p\_z, \sqrt{((p_x + L_5)^2 + p\_y^2)}) - atan2(L_3\, sin\theta_4, L_3\, cos\theta_4 + L_4)$$

$$\theta_6 = atan2(p\_y, -p_x - L_5)$$

$$\theta_2 = atan2(-\sqrt{(1 - (sin\theta_6\, a_1 + cos\theta_6\, a_2)^2)}, sin\theta_6\, a_1 + cos\theta_6\, a_2) + \pi/2$$

$$\theta_1 = atan2(-sin\theta_6\, s_1 - cos\theta_6\, s_2, -sin\theta_6\, n_1 - cos\theta_6\, n_2)$$

$$\theta_{345} = atan2(a_3, cos\theta_6\, a_1 - sin\theta_6\, a_2) - \pi \quad (2)$$
$$\theta_3 = \theta_{345} - \theta_4 - \theta_5$$

Joint vector:
$$\theta = [\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6]$$

θ_1 = Angle of hip yaw joint

θ_2= Angle of hip roll joint

θ_3= Angle of hip pitch joint

θ_4= Angle of knee pitch joint

θ_5= Angle of ankle pitch joint

θ_6 = Angle of ankle roll joint

4. Simulation

The simulation and testing of the robot model are conducted in the MATLAB Simulink environment.
The joint angles derived using inverse kinematics are fed to a robot joint controller. The controller sends each joint its required signal, thereby actuating it and starting the motion that allows the robot to follow the planned path. A motion joint sensor is connected to each joint, allowing us to measure the motion of the joint and compare it to the reference motion, which was given as the input. This measured signal is then fed back to the controller so that the joint motions can be corrected if any discrepancy is discovered, thereby creating a feedback loop. As can be seen in Fig.2.

A world plane is constructed using Simulink's multibody library. This gives the robot a virtual ground surface for simulated contact. The robot and the world plane are connected to a mechanism configuration block, which enables physical effects such as gravity. A 6-DOF joint is also connected to the robot, allowing for translational and rotational motion on all axes. Upon running the simulation, MATLAB's Scope feature allows us to view a graphical representation of the signals going in and out of our model, which helps us in testing that the model behaves in the expected manner.

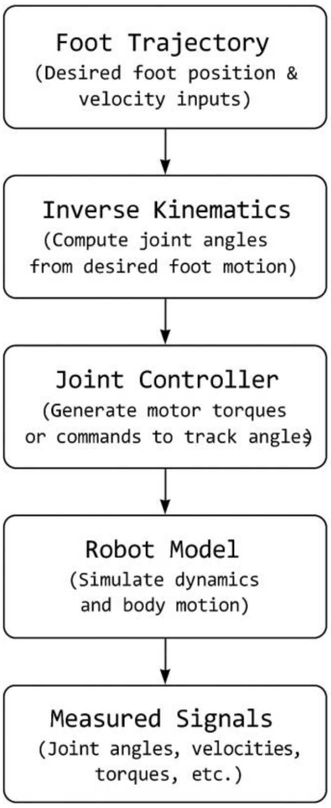

Fig.2: Flowchart

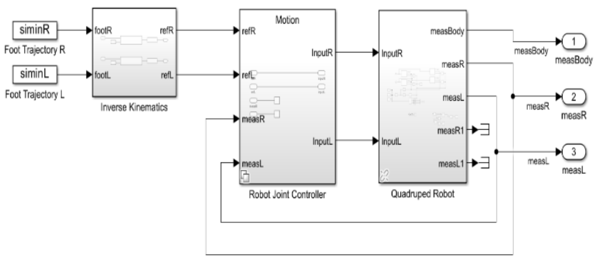

Fig.3: Simulink block of Model

4.1 Testing and Results

As stated in the previous section, the scope feature has been used in the testing phase to ensure the desired signals are being registered. Fig.6 shows a graphical

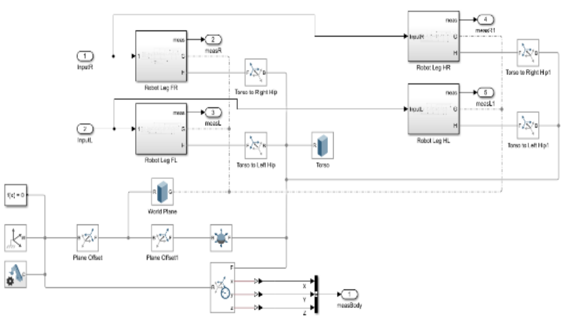

Fig.4: Simulink block of quadruped

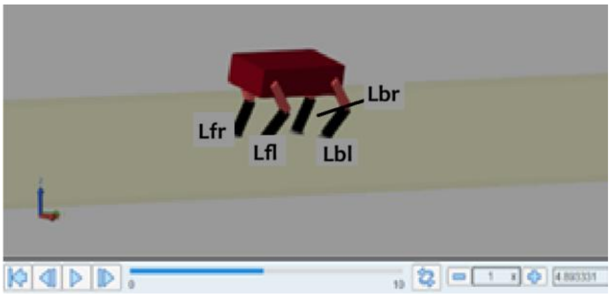

Fig.5: Isometric View of Quadruped Robot in Mechanics Explorer

representation of the robot's position on all 3 axes during the simulation, relative to the world frame. We can observe from the graph that the robot starts at a higher point along the z-axis before going down. It then slowly oscillates from one height to another. This indicates the robot starting from a standing position before bending its knees to begin the gait. The gait then continues steadily for the duration of the simulation. The x-axis shows a slight back-and-forth motion from left to right. This is indicative of the slight wobble seen in the simulation; we can therefore assume the stability is not perfect. Finally, the y-axis shows the robot steadily moving forward, represented by a continuously rising curve, though the step trajectory causes it to oscillate slightly.

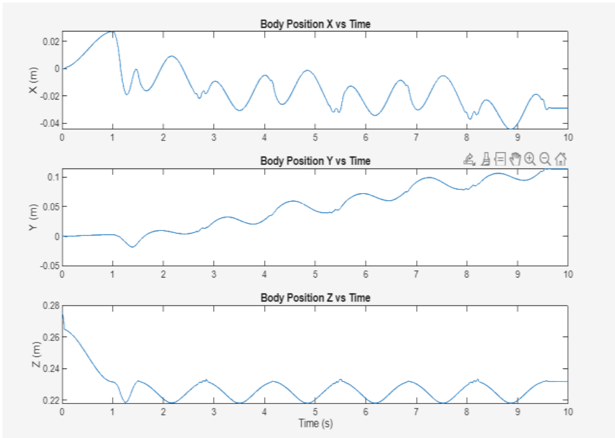

Fig.6: Robot coordinates during Simulation

Fig.7 shows a graphical representation of the generated foot trajectories. The back right foot mirrors the front left, and the back left mirrors the front right. We can observe from the graph that the peak of one pair always coincides with the trough of the other. This tells us that whenever one pair of feet is swinging the other remains on the ground.

In Fig.8, we can see the foot trajectory of an unstable gait. Although the pairs of feet also have coinciding peaks and troughs, the swing height is higher, which distorts the gait of the robot and renders it unstable.

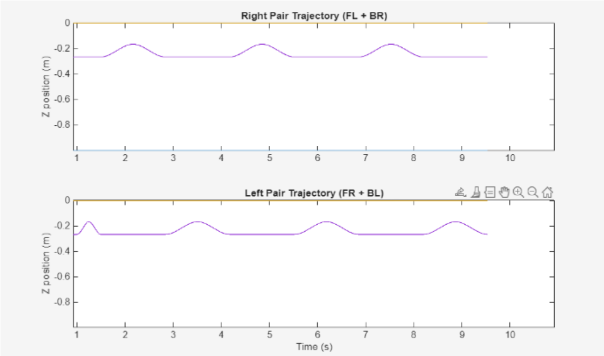

Fig.7: Z position of foot vs time (stable)

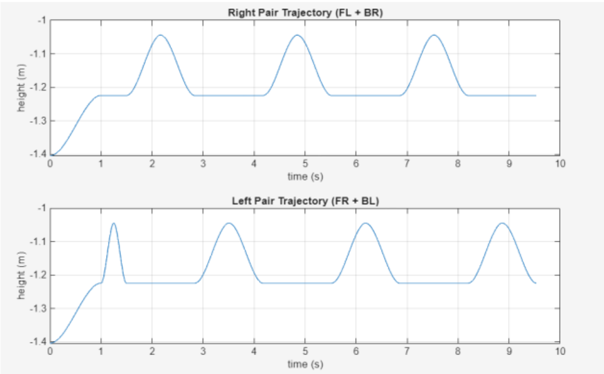

Fig.8: Z position of foot vs time (unstable)

Fig.9 shows a 3D view of the stable trajectory observed in Fig.7. This allows for better visualization as we are able to see not just the z position but also the x and y positions, giving us a better picture of the motion. Similarly, Fig.10 displays the 3-D view of the unstable trajectory observed in Fig.8.

5. Summary

This paper presents a method for actuating quadruped robots with a focus on the trot gait. The simulation results show that the foot positions obtained using LIPM were sufficient to generate a trot gait based on inverse kinematics, and the joint angles being measured by the sensors are consistent with the input signals. Thereby ensuring we have a feedback control system that keeps the robot on track. It was, however, observed that the stability of the robot can be improved.

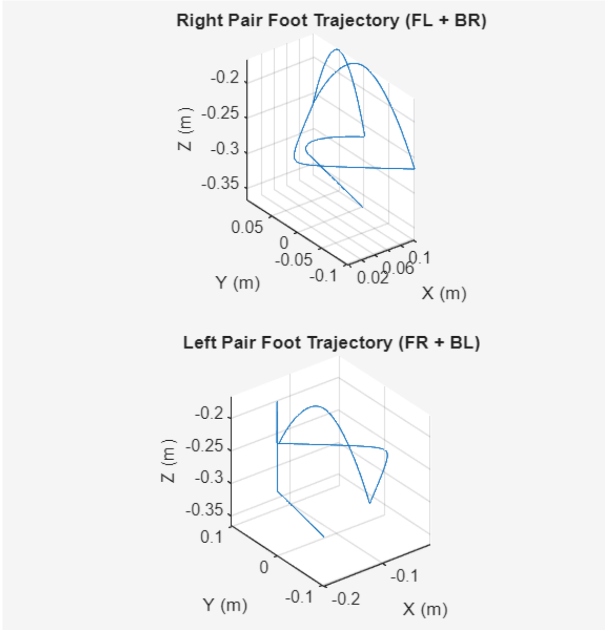

Fig.9: 3-D foot trajectory(stable)

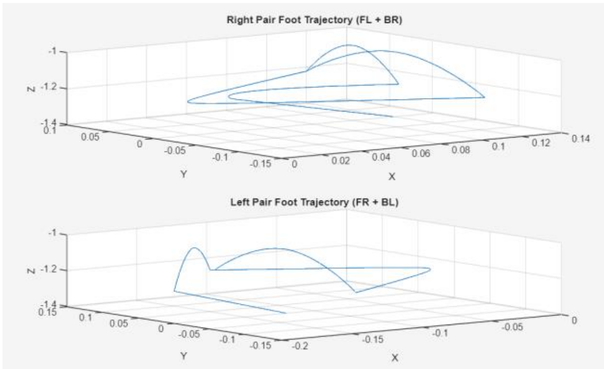

Fig.10: 3-D foot trajectory(unstable)

Leg	0 – 0.25T	0.25 – 0.5T	0.5 – 0.75T	0.75 – T
F-L	Swing	–	–	Swing
B-L	–	Swing	–	–
F-R	–	Swing	–	–
B-R	Swing	–	–	Swing

Fig.11: Gait sequence Diagram of Quadruped

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Nomenclature

Symbol	Meaning	Unit
a_i	Link Length	(m)
αi	Link Twist	(rad)
d_i	Link Offset	(m)
θ	Joint Angle	(rad)