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ORIGINAL ARTICLE

Stability Control of Humanoid Biped Robot using PID Controllers

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ABSTRACT – As technology has advanced, the usage of robots has become a major worldwide issue, especially for robots that interact with people. Humanoid biped robots have the potential to function as people's helpers, capable of assisting society and replacing humans in various or dangerous tasks. However, despite advances in robotic stability control, robust control for a broad variety of applications remains a difficulty. The purpose of this research is to look at optimum control techniques for stability control in humanoid biped robots in order to obtain superior stability. To regulate the robot's stability, several control techniques such as Proportional-Integral-Derivative control, Proportional-Integral control, Proportional-Derivative control, and Linear Quadratic Regulator (LQR) are utilised. Before implementing these control techniques, the humanoid biped robot's open loop system is evaluated to determine its stability response. To investigate the system response of robot stability control, the MATLAB programme is used.

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INTRODUCTION

The research on humanoid biped robot legs is important because biped robots are widely used in industrial settings to handle risky tasks. In the event of an accident, injuries to humans can be minimized and safety levels can be maximized. Employers are particularly concerned with the stability control of robot legs to increase efficiency without human supervision. Additionally, studying biped robots allows for an understanding of how they can walk on a trajectory with stability control using different methods, and for the construction of biped robot legs in MATLAB simulations to obtain response feedback with completed algorithms [1], [2]. The authors chose this topic because it allows me to understand the working principles of biped robots by manipulating the stability of the robot base and analyzing error data in simulations, in order to provide solutions for future projects where real prototypes may be needed.

The purpose of this research is to design a biped humanoid robot with stability control by applying kinematic operations and developing various closed-loop control systems. This will enable the fulfillment of stability control in biped robots. Furthermore, this project will allow me to capitalize on my simulation skills by demonstrating the stability control of robots using different mathematical modeling techniques.

RELATED WORK

The proportional–integral–derivative (PID) feedback controller is a common type of feedback controller used in industrial control applications. It consists of a variable that is controlled depending on error, the difference between the set point, and is used to measure a certain plant. Each PID controller element represents a specific control action, and the error is utilised to change some process input to its target value [3].

A proportional integral controller (PI controller) is a form of feedback control system that combines the control actions of a proportional controller with an integral controller. The proportional controller adjusts the control output based on the error signal, which is the difference between the desired and actual values. It produces an output proportionate to the error signal. The integral controller adjusts the control output based on the accumulated mistake over time. It produces an output proportional to the error signal's integral over time.

The use of a PD type controller for controlling the hip and knee joints of a robot during operation is a common approach. In order to improve the accuracy of the control system, a predictive PD controller can be implemented to monitor the positions and angular momentum of both the right and left legs. This helps to prevent errors that may occur due to incorrect modeling. The Simulink tool can be utilized to implement the PD controller block. The control block receives two input signals, the reference signal and the actual joint position, and produces an output signal based on this information. The error signal is calculated by subtracting the reference signal from the actual joint position. The controller then uses this error signal to determine the appropriate output for adjusting the joint position.

LQR (Linear Quadratic Regulator) is a contemporary controller type. Using the state-space technique, it analyses and regulates such systems. Using the state space approach to manipulate a multi-output system is straightforward. Because the results of the PID Controller improve when there is a disturbance in the system, a LQR controller is necessary [4]. This control theory aims to run a dynamic system at the lowest cost achievable. The LQ issue is defined as a circumstance in which the system dynamics are represented by a set of linear differential equations and the cost is characterised by a

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quadratic function. LQR is also required for the stability control of biped robots, since PID can barely monitor feedback and cannot effectively regulate or manipulate the stability system.

MODELLING OF BIPED ROBOT

Modelling of 2 Legs and Body

In this research, the robot's leg is constructed by two part which are hip and knee. Modelling of robot's hip and knee is to design based on stability control to ensure the robot can walk like a normal human. There are some criteria of making a walking robot. The understanding of human walking is the first criteria must be concerned. This basic human behaviour continues to be one of the more challenging study problems in multi-body systems and robots. Figure 1 portrays human walking as a periodic process divided into two parts, referred to as a gait cycle. The first phase is the swing phase, also known as the single support phase, while the second phase is the double support phase The hip height is the height at which the robot begins to stand. A stance leg is one that makes contact with the ground. Otherwise, it is known as a swing leg. It is also important to note the transitions between the single support and double support stages. The moment of lift off, which occurs immediately at the start of the single support, is when the foot is just moving the body forward until the point where the leg loses touch with the ground [5].

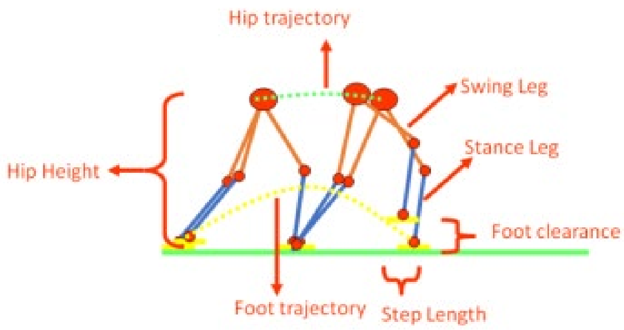

Figure 1. Human Gait Cycle and Parameter

The illustration diagram show in Figure 2 is to define the coordinates frame of the Humanoid Biped robot leg for each joint through D-H conventions. The red arrows represent x-axis, green arrows indicate y-axis and blue arrows denote z-axis. Assuming that each joint only possesses a single degree of freedom, it is possible to describe the action of each joint using a single real number. For example, the angle of rotation in the case of a revolute joint, or the displacement in the case of a prismatic joint, can be used to describe the action of the joint. The purpose of forward kinematic analysis is to establish the cumulative effect of joint variables for the whole system. Besides, work on developing a set of standards also provide a systematic procedure for carrying out the system.

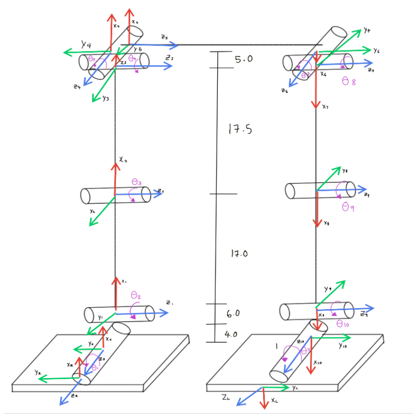

Figure 2. Coordinates frames of Biped Humanoid Robot for each leg joint

TABLE OF STRUCTURAL KINEMATIC PARAMETER

As the coordinate frame of humanoid biped robot through D-H convention is derived, then a structural kinematic parameter table is required to construct in purpose to calculate the transformation matrix. a_i is referred to as the link length, while d_i is referred to as the offset. α_i indicates the link offset. θ_i is the joint angle that must be computed in order to place a link accurately. At least one set of joint angles that meet a particular posture in standard walking condition.

Table 1. Kinematic Parameter Table

Link i	a_i(cm)	$\alpha_i(\angle)$	$\theta_i(\angle)$	d_i(cm)
1	10.0	90	θ_1	0
2	17.0	0	θ_2	0
3	17.5	0	θ_3	0
4	5.0	-90	θ_4	0
5	0	90	θ_5	0
6	5.0	-90	θ_6	0
7	17.5	0	θ_7	0
8	17.0	0	θ_8	0
9	10.0	90	θ_9	0
10	0	0	θ_{10}	0

ANALYSIS CONTROL SYSTEM BASED ON MATHEMATICAL MODELLING

The different control method is applied onto the hip and knee of robot to analyse the response of position control system in MATLAB simulation. The calculation of mathematical modelling is required to discover that the features with some strategies and understanding of the system modelled.

Forward Kinematics

Denavit-Hartenberg Convention

The Denavit and Hartenberg (D–H) convention, which was established by Jacques Denavit and Richard S. Hartenberg, is a well-known convention for creating the reference frame in robotics applications. The Denavit Hartenberg (DH) protocol is a well-known method for assigning coordinate frames to the various links of a robotic leg. By reducing complexity from kinematic analysis and allowing us to develop equations of motion using kinetic and potential energy, the DH method ensures that the position and orientation of each frame can be defined using just four variables [3]. The convention is often used for mathematical modelling of industrial robot manipulators, and the D-convention is employed to provide a coordinate frame to each joint.

Transformation matrix for links is shown in Equation 1.

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

Transformation matrix of Biped robot leg

This approach comprises the calculation of one leg with three degrees of freedom for a humanoid biped robot in right-standing position. This is achievable because it is believed that the modelling parameters for the left and right robot legs are identical. This assumption is since the geometry, mass distribution, and actuator characteristics of the left and right legs of a humanoid biped robot are often symmetrical.

By calculating just one leg with three degrees of freedom, the complexity of the model is minimised, allowing for more efficient analysis and simulation. Without the extra complexity of modelling the complete robot, this method allows for a more concentrated investigation of the individual leg and its dynamics. Notably, this technique may not be applicable in all situations, and it is vital to test the symmetry of the robot's left and right legs; if the robot has asymmetrical legs, the findings of the research may not be correct. In addition, even if the legs are symmetrical, the research will only give insight into the dynamics and control of one leg, and it does not account for the interactions between the legs, which might impair the robot's overall stability and performance. The approach entails calculating one leg with three degrees of freedom for a right-standing humanoid biped robot, as it is expected that the modelling parameters for the left and right robot legs are identical. This method permits a more concentrated investigation of the individual leg and its dynamics, but it has limits, and it is required to verify the similarity of the legs and their interactions. The transformation matrices of biped robot leg are shown below.

$$\boldsymbol{A_0^1} = \begin{bmatrix} \cos\theta_1 & 0 & sin\theta_1 & 10.0cos\theta_1 \\ sin\theta_1 & 0 & -\sin\theta_1 & 10.0sin\theta_1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$A_1^2 = \begin{bmatrix} \cos\theta_2 & -sin\theta_2 & 0 & 17.0cos\theta_2 \\ sin\theta_2 & cos\theta_2 & 0 & 17.0sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$A_2^3 = \begin{bmatrix} \cos\theta_3 & -sin\theta_3 & 0 & 17.5cos\theta_1 \\ sin\theta_3 & cos\theta_3 & 0 & 17.5sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$A_3^4 = \begin{bmatrix} \cos\theta_4 & 0 & -sin\theta_4 & 5.0cos\theta_4 \\ sin\theta_4 & 0 & \sin\theta_4 & 5.0sin\theta_4 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

$$A_0^2 = A_0^1 \times A_1^2$$

$$A_0^2 = \begin{bmatrix} \cos\theta_1 & 0 & sin\theta_1 & 10.0cos\theta_1 \\ sin\theta_1 & 0 & -\sin\theta_1 & 10.0sin\theta_1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos\theta_2 & -sin\theta_2 & 0 & 17.0cos\theta_2 \\ sin\theta_2 & cos\theta_2 & 0 & 17.0sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} a & \mathrm{b} & c & \mathrm{d} \\ e & f & \mathrm{g} & \mathrm{h} \\ \mathrm{i} & j & k & \mathrm{l} \\ \mathrm{m} & \mathrm{n} & \mathrm{o} & \mathrm{p} \end{bmatrix} \quad (6)$$

$$A_2^4 = A_2^3 \times A_3^4$$

$$= \begin{bmatrix} \cos\theta_3 & -sin\theta_3 & 0 & 17.5cos\theta_1 \\ sin\theta_3 & cos\theta_3 & 0 & 17.5sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos\theta_4 & 0 & -sin\theta_4 & 5.0cos\theta_4 \\ sin\theta_4 & 0 & \sin\theta_4 & 5.0sin\theta_4 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} a_1 & b_1 & c_1 & d_1 \\ e_1 & f_1 & g_1 & h_1 \\ i_1 & j_1 & k_1 & l_1 \\ m_1 & n_1 & o_1 & p_1 \end{bmatrix} \quad (7)$$

$$A_0^4 = A_0^2 \times A_2^4$$

$$= \begin{bmatrix} a & \mathrm{b} & c & \mathrm{d} \\ e & f & \mathrm{g} & \mathrm{h} \\ \mathrm{i} & j & k & \mathrm{l} \\ \mathrm{m} & \mathrm{n} & \mathrm{o} & \mathrm{p} \end{bmatrix} \times \begin{bmatrix} a_1 & b_1 & c_1 & d_1 \\ e_1 & f_1 & g_1 & h_1 \\ i_1 & j_1 & k_1 & l_1 \\ m_1 & n_1 & o_1 & p_1 \end{bmatrix}$$

$$= \begin{bmatrix} a_2 & b_2 & c_2 & d_2 \\ e_2 & f_2 & g_2 & h_2 \\ i_2 & j_2 & k_2 & l_2 \\ m_2 & n_2 & o_2 & p_2 \end{bmatrix} \quad (8)$$

Inverse Kinematic

In order to get the inverse kinematic equations, the biped robot may be decoupled and considered as two three-link planar manipulators rather than a single 6 degree of freedom manipulator [6]. This can tell which of the two is the stance or swing leg by decoupling the system. Because the global coordinate frame is allocated to the stance leg, the unknown joint angles for this leg must be obtained before the joint angles for the swing leg. We also assume that the hip and foot orientations for both the stance and swing legs are perpendicular to the ground. This assumption establishes a link between hip, knee, and ankle specifically $\theta_{hip} + \theta_{knee} + \theta_{ankle} = 0$. The hip and ankle roll joint angles of the two legs are equated to zero to realise the biped's movement exclusively along the sagittal plane. From what we have been discussed above, the inverse kinematic equation is referred to the gait cycle of human walking. Each foot makes one ground contact (stance phase) and remains on the ground for about 60–62% of the whole gait cycle. Consequently, the phase of the gait cycle when the foot is raised off the ground (swing phase) accounts for around 38–40%. In contrast to sprinting, when both feet never simultaneously touch the ground, walking has two double contact moments. 10% of the walking stance phase is devoted with both feet planted on the ground.

Stance Leg Equation

The stance phase accounts for around sixty percent of the gait cycle. When the foot is in touch with the ground and the leg is bearing weight. This phase starts when the foot makes its first contact with the ground and ends when the ipsilateral foot departs the ground. The equations is show as below:

$$
\begin{aligned}
& k_1 = s \\
& k_1 = h - l_1 - l_4 \\
& \theta_{knee} = -cos^{-1}\left(\frac{k_1^2 + k_1^2 - l_2^2 - l_3^2}{2 l_2 l_3}\right) \\
& \theta_{ankle} = -tan^{-1}\left(\frac{k_1(l_3 cos\theta_{knee} + l_2) - k_2 l_3 sin\theta_{knee}}{k_2(l_3 cos\theta_{knee} + l_2) + k_1 l_3 sin\theta_{knee}}\right) \\
& \theta_{hip} = -\theta_{knee} - \theta_{ankle}
\end{aligned} \tag{9}
$$

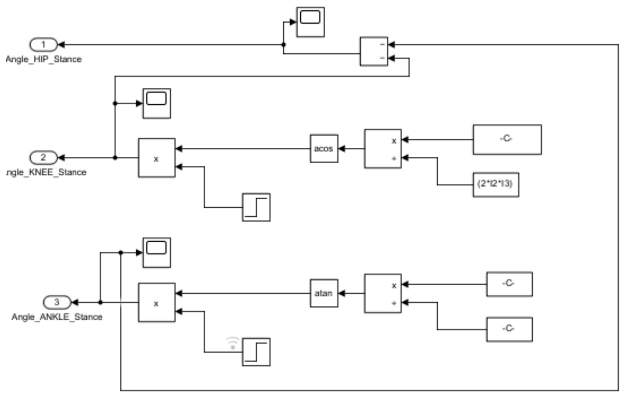

Figure 3. Inverse Kinematic Equation of Stance Leg

Swing Leg Equation

When the foot initially leaves the ground, the swing phase of gait starts and finishes when the same foot strikes the ground again. The swing phase contributes for forty percent of the gait cycle. The following equation are calculated as follows:

$$
\begin{aligned}
& k_1 = -s \\
& k_1 = h - l_6 - l_9 \\
& \theta_{knee} = -cos^{-1}\left(\frac{k_1^2 + k_1^2 - l_7^2 - l_8^2}{2 l_7 l_8}\right) \\
& \theta_{hip} = -tan^{-1}\left(\frac{k_1(l_8 cos\theta_{knee} + l_7) - k_2 l_8 sin\theta_{knee}}{k_2(l_8 cos\theta_{knee} + l_7) + k_1 l_8 sin\theta_{knee}}\right) \\
& \theta_{ankle} = -\theta_{knee} - \theta_{hip}
\end{aligned} \tag{10}
$$

CONTROL ALGORITHM

A control algorithm is a mathematical-logical action specification for the work that a controller is intended to do. Control algorithms are a logical series of separate execution stages that are specified individually. It is possible to include a control algorithm into the software of a computer so that it may be used in actual applications. In order to carry out an operation, a particular input will first be provided with a specific output. In feedback control, the output of the system is continually monitored and compared to a desired setpoint. This discrepancy, known as the error, is used to change the system's inputs in order to lower the error and bring the output closer to the setpoint. This control method is sometimes referred to as closed-loop control. In feedforward control, the algorithm predicts the impact of the system's inputs and changes them appropriately to reach the intended output.

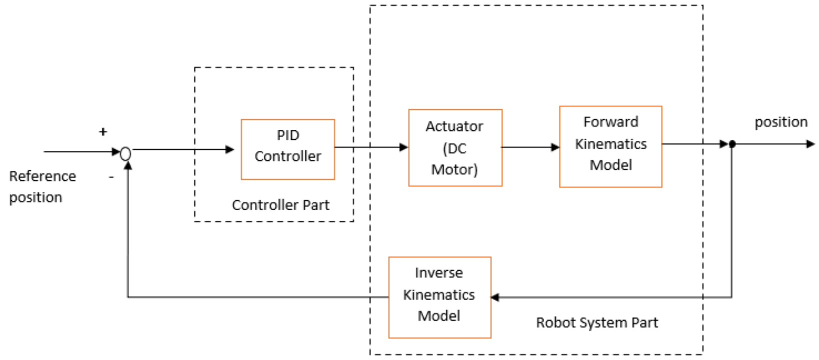

Figure 4. The concept of control system for robotic joint display

OPEN LOOP SYSTEM ANALYSIS

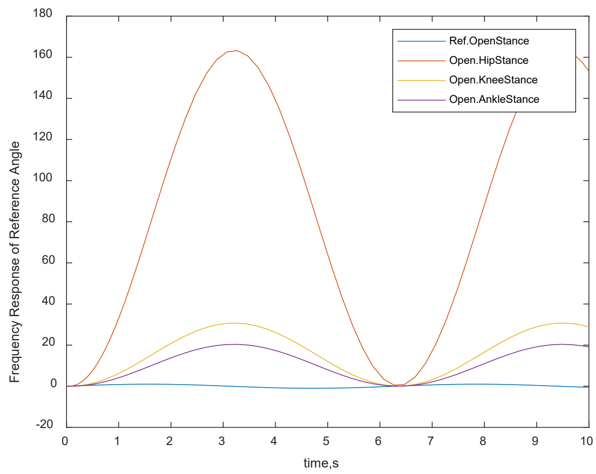

Figure 5. Response of Open Loop for Stance Leg

The diagram above illustrates the problem with using an open-loop system without a controller for the hip joint. Without feedback, the joint may overshoot its intended range of motion and become unstable. This is why a controller is necessary to ensure stability and control. Similarly, the response of the knee joint in the stance leg can be irregular and inaccurate in an open-loop system. Without measuring the output and adjusting the inputs accordingly, the system may deviate from its intended trajectory, which is unacceptable for a robot leg that needs to maintain stability and performance. Additionally, using an open-loop system for the ankle joint in the stance leg can also result in instability. Fluctuations in the system's parameters may cause significant changes in performance, making it difficult to predict the system's behavior. Additionally, the system is not able to compensate for external disturbances [7].

CLOSED LOOP SYSTEM ANALYSIS

This is an overview of the sinewave response of ankle joint on swing and stance leg. The root mean square (RMS) is implemented in order to compare the sinewave response of the controllers with the desired reference response.

Ankle joint of Swing Leg

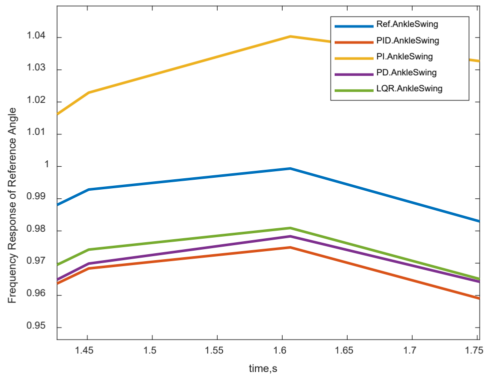

Figure 6. Magnify of Sinewave Response of Ankle joint of Swing Leg

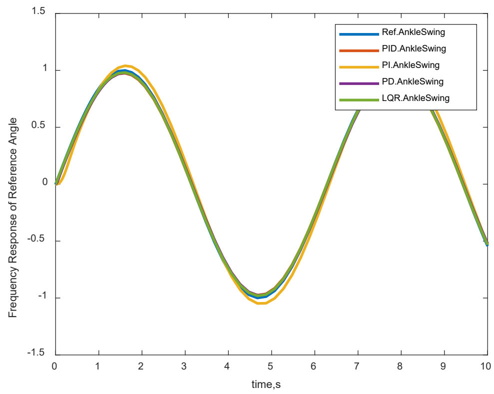

Figure 7. Sinewave Response of Ankle joint of Swing Leg

Based on the sinewave response above, the LQR controller proves to be an effective option for the ankle joint of the swing leg as it not only achieves a higher RMS value of 99.26% compared to the PID controller's 99.08%, but it also has the ability to control the rate change of the motor position, the motor position, and the current of the motor. This means that LQR can handle changes in the system more effectively and maintain stability in the ankle joint of the swing leg, which is crucial for the smooth and efficient movement of the robot. Furthermore, LQR's lower deviation in RMS value is essential for keeping the robot upright and steady. Consequently, LQR is the optimal choice for stability control of the ankle joint of the swing leg.

Table 2. Root Mean Square of Ankle joint of Swing Leg

Control Method	Root Mean Square,RMS
Proportional-Integral-Derivatives	0.534 (99.08%)
Proportional-Integral	0.505 (98.34%)
Proportional-Derivatives	0.538 (98.89%)
Linear Quadratic Regulator	0.540 (99.26%)

Ankle joint of Stance Leg

The LQR controller was found to have the lowest deviation in RMS value, at 98.52%, when applied to the ankle joint of the stance leg. This is significant because the stability of the ankle joint of the stance leg is a crucial factor in the overall stability and balance of the robot. The ankle joint of the stance leg bears the majority of the robot's weight and any deviation or instability in this joint can greatly affect the robot's ability to move and walk efficiently. The LQR controller's ability to achieve a lower deviation in RMS value on the ankle joint of the stance leg therefore it is highly recommended for apply to this joint. Despite that, PID controller achieve near RMS value than LQR, it is not recommended for use on the ankle joint of the stance leg as it does not provide the same level of stability and balance as the LQR controller.

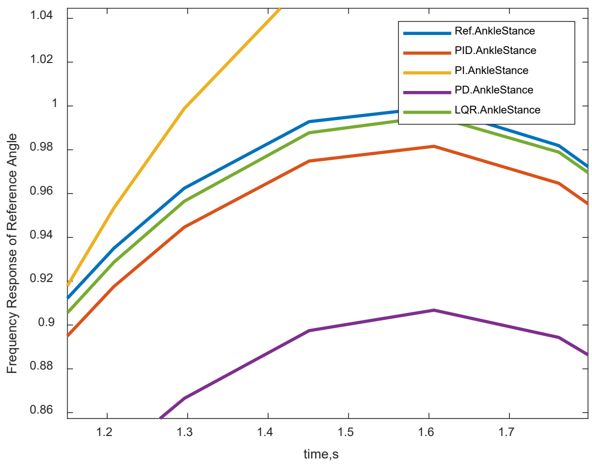

Figure 8. Magnify of Sinewave response of Ankle Joint of Stance Leg

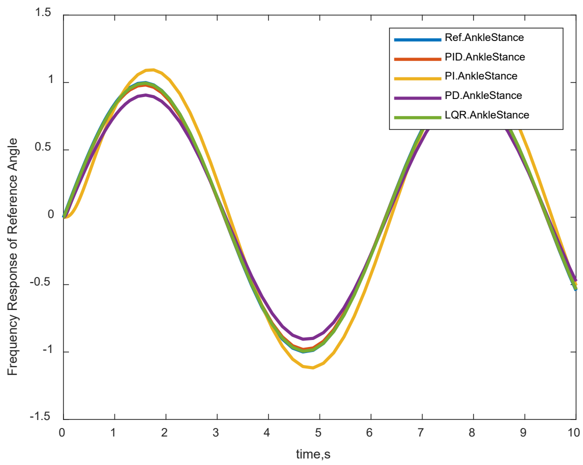

Figure 9. Sinewave response of Ankle Joint of Stance Leg

Control Method	Root Mean Square,RMS
Proportional-Integral-Derivatives	0.533 (97.97%)
Proportional-Integral	0.503 (93.01%)
Proportional-Derivatives	0.522 (95.96%)
Linear Quadratic Regulator	0.536 (98.52%)

EXPERIMENTAL RESULTS

Based on the findings of the characterization, it can be said that LQR is a better approach for providing the required angle of each joint in order to increase accuracy and create a strong, stability control for the humanoid biped robot leg. Through the MATLAB simulation, the sinewave responses were analysed, and the characteristics of each joint on the stance leg and swing leg were collected. The implementation controller's goal is to make the control method as stable as possible while also determining if it is feasible to achieve the target angle. MATLAB is user-friendly because it can be easy to adjust sinewave responses to reduce steady-state error, The LQR control approach is more effective at ensuring stability control. because it is compatible with three feedback gains, which are defined as the rate change of motor position, motor position, and current. The sinewave response is mathematically modelled and tuned to imitate a stability control system.

CONCLUSION

Based on the results of various controllers, including PID, PI, PD, and LQR, were effectively implemented and evaluated on the stability control of a humanoid biped robot leg. The controllers demonstrated different levels of success in reaching the desired reference angles for the various joints such as the hip, knee, and ankle. The PI controller were able to achieve the desired reference angles but with some level of steady state error or underdamping. On the other hand, the PD controller was able to reach the desired reference angle with minimal steady-state error and a small amount of critical damping at the start. The PID is performed well in term of stability control of biped robot but this controller has its limitation as it also able to control the output based on the error between the desired and actual position of the robot, as well as the rate of change of the error (derivative term) and the accumulated error over time (integral term) while LQR controllers consider system dynamics and optimise control inputs to minimise a cost function that incorporates the difference between the desired and actual states of the robot as well as the control inputs itself.. Consequently, LQR controller demonstrated successful performance by reaching the desired reference angle with minimal deviation from the target, specifically in the absence of overshoot. It is important to note that the controller's gain values were fine-tuned in order to achieve the desired level of damping and reach the reference angle. In general, the LQR controllers was able to achieve stable.

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