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Humanoid robot balance control system during backward walking using linear quadratic regulator

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ABSTRACT

Humanoid robots are designed to replicate human activities, including tasks in hazardous environments. However, maintaining balance during backward walking remains a significant challenge due to center of mass (CoM) shifts beyond the support polygon and limited knee joint motion. This study proposes a control strategy that integrates a linear quadratic regulator (LQR) with optimized walking patterns to enhance dynamic stability. The approach combines LQR-based control with CoM trajectory planning to ensure safe and stable backward walking. The methodology includes inverse kinematics for generating walking patterns and the use of Inertial Measurement Unit (IMU) sensors to estimate the CoM trajectory. LQR parameters were tuned through simulation to improve responsiveness to disturbances. Evaluation metrics focused on CoM deviation, rise time, settling time, and overshoot. Experimental results demonstrate that the proposed LQR system effectively maintains the CoM within 5% of the support polygon boundary. The system achieved rise times under one second and settling times below two seconds, while minimizing pitch and roll overshoots. Compared to proportional control, the proposed method significantly improves stability and reduces the risk of falling. This research advances control strategies for humanoid robots, contributing to improved mobility and operational safety. Moreover, it supports Sustainable Development Goal (SDG) 9 by promoting innovation in intelligent robotic systems that can assist in complex or high-risk environments.

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1. INTRODUCTION

Humanoid robots are designed to emulate human abilities, including walking, lifting, and performing tasks in complex environments [1]. They are increasingly utilized in a wide range of applications, such as supporting industrial automation, healthcare services, and assisting in daily human tasks [2]. These robots offer significant advantages due to their human-like structure, which allows them to navigate environments built for humans [3]. However, ensuring dynamic stability during maneuvers like backward walking remains a critical challenge [4]. Issues such as the shift of the center of mass (CoM) beyond the support polygon and the limited range of motion in knee joints lead to frequent instability, increasing the risk of falls and limiting their usability in real-world scenarios [5].

Although much research has explored humanoid robot locomotion, it has mainly focused on forward walking and static balance [6], [7]. Existing controllers such as proportional-integral-derivative (PID) [8], fuzzy logic [9], and other conventional approaches struggle with dynamic CoM adjustments required for backward walking, often lacking the precision and adaptability for maintaining stability during unpredictable movements [10], [11]. This highlights a need for control strategies tailored specifically for backward walking.

Simplified dynamic models like the linear inverted pendulum [12] offer a promising foundation due to their linearity and computational efficiency [13], though additional refinements are necessary to address the distinct biomechanics of backward motion [14]. Stability is largely determined by the Zero Moment Point (ZMP), derived from CoM projection [15], [16], and should remain within the support polygon formed by foot contact points [17], [18].

Backward walking is crucial in applications where space constraints or sudden environmental changes exist, such as in industrial or healthcare settings [19]. To improve performance in such scenarios, this study proposes a control framework combining linear quadratic regulator (LQR) with optimized walking patterns [20], [21]. LQR enables stable, rapid responses in MIMO systems [22], while inverse kinematics ensures effective CoM trajectory management.

The key contributions are i) development of an LQR-based control framework with optimized walking patterns for stable backward walking and ii) experimental validation showing superior performance compared to traditional control methods, thereby addressing critical gaps in humanoid robot balance control.

This paper is organized as follows: Section 2 reviews the problem statement and research preliminaries. Section 3 details the methodology, including system design, control strategy, and experimental setup. Section 4 presents the results and performance analysis, and Section 5 concludes with implications and directions for future research.

2. THE PROPOSED METHOD

This study addresses the underexplored problem of maintaining balance in humanoid robots during backward walking, a maneuver that is considerably more unstable than forward locomotion. The scientific question investigated is: Can the integration of optimized walking pattern generation and Linear Quadratic Regulator (LQR) control enhance stability in humanoid robots walking backward?

Backward walking introduces specific challenges that are not present in forward motion. The CoM tends to shift beyond the support polygon due to the reversed direction of movement and limited actuation range in the knee joints, increasing the risk of instability and falls [23], [24].

To overcome these issues, the proposed method combines two key strategies.

a. Walking pattern optimization

A stable walking trajectory is generated using inverse kinematics. The pattern consists of four structured phases: shifting, lifting, stepping, and planting. These phases are carefully coordinated to ensure that the robot's CoM remains within the support polygon during each step. The pattern also accounts for the unique biomechanical constraints and motion timing associated with backward walking [25]–[27].

b. Linear quadratic regulator for dynamic balance

LQR is a model-based optimal control method that computes a gain matrix to minimize a quadratic cost function. This cost reflects the trade-off between state deviations (e.g., pitch and roll angle errors) and control efforts (e.g., ankle joint torque) [28], [29]. In our application, the LQR controller is designed based on a simplified state-space model that includes i) roll angle and angular velocity and ii) pitch angle and angular velocity. Using real-time feedback from IMU sensors, the LQR continuously adjusts the ankle joint torques to maintain CoM stability, especially during transitions between the swing and stance phases. This is critical for backward walking, where visual and proprioceptive feedback is less effective, and balance relies more heavily on control robustness.

By combining the optimized walking pattern and the LQR control, the humanoid robot can respond quickly to dynamic changes and disturbances while walking backward. The control system was tuned via simulation using a linear inverted pendulum model before deployment on the actual robot. The result is a system capable of maintaining balance without falling, even when the CoM momentarily approaches the boundary of the support polygon.

Compared to proportional control, the proposed method significantly improves stability. i) CoM deviation remains within 5% of the polygon boundary. ii) Rise time is below 1 second, and settling time is below 2 seconds. iii) No falls were observed during multi-step backward walking tests. These results provide evidence that the integrated LQR and trajectory optimization method is effective for maintaining robust balance during backward walking. This work contributes a novel solution to a less-studied aspect of humanoid locomotion, with implications for safe mobility in constrained or dynamic environments.

3. METHOD

The study uses a humanoid robot with 18 DoF (12 in legs, 6 in arms), focusing on leg behavior for backward walking, where maintaining balance is challenging due to CoM shifts. CoM is estimated using forward kinematics and IMU data. A Linear Quadratic Regulator (LQR) controls ankle torques based on pitch/roll deviations and angular velocities to keep CoM on track. Inverse kinematics guides foot trajectories. System performance criteria include: CoM within 5% of the support polygon, rise time ≤1s, settling time ≤2s, and pitch/roll overshoot < half foot length/width—ensuring stable and smooth walking.

3.1. Design of the backward walking pattern

A well-designed walking pattern is essential for humanoid robot locomotion [30]–[32]. It determines joint movements and appropriate control mechanisms. The backward walking pattern consists of four key phases, as shown in Figures 1 and 2.

a. Shifting Phase: The center of mass (CoM) shifts above the support leg to ensure stability.
b. Lifting Phase: The swing leg is lifted, requiring precise control to maintain balance.
c. Stepping Phase: The swing leg moves backward, followed by support leg adjustments for smooth motion.
d. Planting Phase: The swing leg is placed on the ground, and the CoM is readjusted to restore stability.

Figures 1 and 2 illustrate the walking pattern starting with the right and left foot, respectively. By progressing through these phases systematically, the robot maintains its CoM within the support polygon, reducing fall risk and enhancing stability during backward walking.

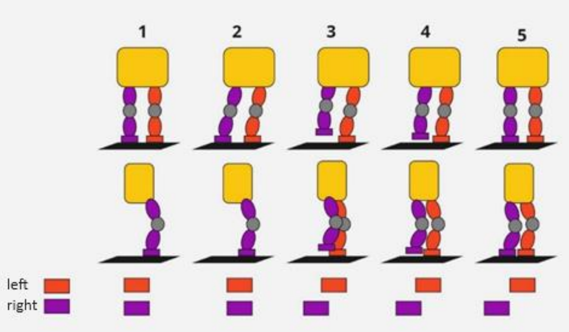

Figure 1. The design of the backward walking pattern starts with a step from the right foot.

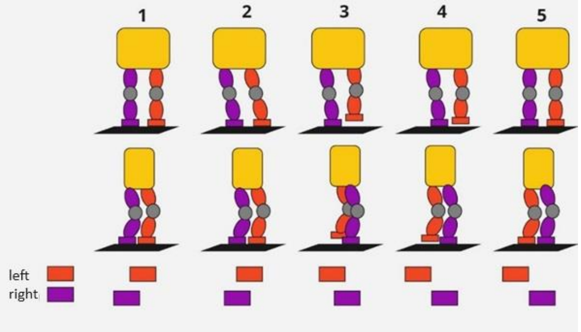

Figure 2. The design of the backward walking pattern starts with a step from the left foot.

3.2. Design of the backward walking algorithm

The walking algorithm aims to enable precise humanoid robot movement by integrating sensor setup, kinematics, walking pattern generation, and LQR control.

Footstep placement is guided by CoM and end-effector positions computed via forward and inverse kinematics. Forward kinematics, using Denavit-Hartenberg matrices, tracks CoM position and orientation, while inverse kinematics determines joint angles for desired foot positions, ensuring accurate motion and stability.

Figure 3 illustrates inverse kinematics projections on the robot's leg from both side in Figure 3(a) and front views in Figure 3(b). Inverse kinematics is used to determine the joint angles based on the final position of the end-effector [33]. To calculate the inverse kinematics of a humanoid robot's leg, trigonometric calculations are required. Equations (1) to (5) are the projected calculation for the inverse kinematics of a humanoid robot's leg as shown in Figure 3. Based on Figure 3, the angles to be determined are the hip angles of the robot (θ_1 and θ_4), the knee angle (θ_2), and the ankle angles (θ_3 and θ_5).

To find θ_1, it can be derived from (5).

$$Z_2 = Z - L_1 - L_4 \tag{1}$$

$$L_a = \sqrt{Z_2^2 + X^2} \tag{2}$$

$$\theta_j = \cos^{-1}\left(\frac{L_2^2 + L_a^2 - L_3^2}{2\, L_1\, L_2}\right) \tag{3}$$

$$\theta_k = \cos^{-1}\left(\frac{z_2}{L_a}\right) \tag{4}$$

$$\theta_1 = \theta_j + \theta_k \tag{5}$$

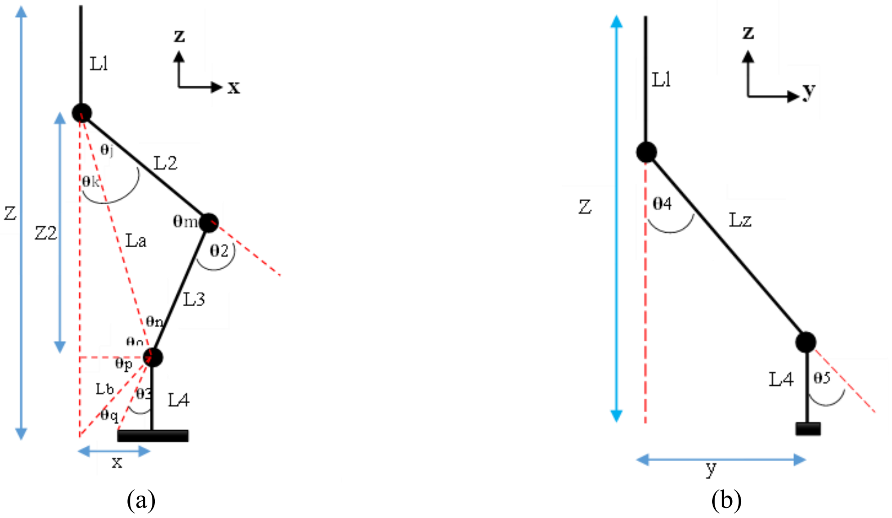

Figure 3. Projections of inverse kinematics on the humanoid robot's leg: (a) side view of the robot and (b) front view of the robot.

To find θ_2, it can be derived from (7).

$$\theta_m = \cos^{-1}\left(\frac{L_2^2 + L_3^2 - L_a^2}{2\,L_2\,L_3}\right) \tag{6}$$

$$\theta_2 = 180° - \theta_m \tag{7}$$

The pitch angle at the ankle forms the angle θ3, which is obtained using (12).

$$L_b = \sqrt{x^2 + L_4^2} \tag{8}$$

$$\theta_o = \cos^{-1}\left(\frac{x}{L_a}\right) \tag{9}$$

$$\theta_p = \sin^{-1}\left(\frac{L_4}{L_b}\right) \tag{10}$$

$$\theta_q = 180° - \theta_n - \theta_o - \theta_p \tag{11}$$

$$\theta_3 = 90° - \theta_p - \theta_q \tag{12}$$

To find θ_4, it is derived from (14).

$$L_z = L_a \tag{13}$$

$$\theta_4 = \sin^{-1}\left(\frac{y}{L_z}\right) \tag{14}$$

To find θ_5, it is derived from (16).

$$\theta_a = \cos^{-1}\left(\frac{y}{L_z}\right) \tag{15}$$

$$\theta_5 = 180° - 90° - \theta_a \tag{16}$$

After the foot contacts the ground and becomes the support leg, the double support phase begins. To maintain balance, the IMU sensor is configured and calibrated to function optimally. Forward kinematics uses servo angle feedback to calculate the robot's center of mass (CoM) position. Combined with IMU sensor data, it helps determine the robot's tilt and ensures the CoM remains within the support polygon to prevent falls. Meanwhile, inverse kinematics is applied to implement the walking pattern and coordinate CoM shifts during backward walking.

3.3. Design of the backward walking balance control system

This study focuses on the development of a control system aimed at reducing the robot's body imbalance and achieving low error values. In this research, states are used as the fundamental reference for control parameters. These four states form the basis for controlling the robot and minimizing the difference between the desired position and the robot's actual position: roll angle (ϕ), pitch angle (θ), roll angular velocity ($\dot{\phi}$), and pitch angular velocity ($\dot{\theta}$).

$$\underbrace{\begin{bmatrix}\dot{\theta}\\ \ddot{\theta}\\ \dot{\phi}\\ \ddot{\phi}\end{bmatrix}}_{\dot{\mathbf{x}}} = \underbrace{\begin{bmatrix}0 & 1 & 0 & 0\\ \frac{mgl}{I_{xx}} & 0 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & \frac{mgl}{I_{yy}} & 0\end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{bmatrix}\theta\\ \dot{\theta}\\ \phi\\ \dot{\phi}\end{bmatrix}}_{\mathbf{x}} + \underbrace{\begin{bmatrix}0 & 0\\ \frac{1}{I_{xx}} & 0\\ 0 & 0\\ 0 & \frac{1}{I_{yy}}\end{bmatrix}}_{\mathbf{B}} \underbrace{\begin{bmatrix}u_1\\ u_2\end{bmatrix}}_{\mathbf{u}},\ \underbrace{\begin{bmatrix}y_1\\ y_2\end{bmatrix}}_{\mathbf{y}} = \underbrace{\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}}_{\mathbf{C}} \underbrace{\begin{bmatrix}\theta\\ \dot{\theta}\\ \phi\\ \dot{\phi}\end{bmatrix}}_{\mathbf{x}} + \underbrace{\begin{bmatrix}0 & 0\\ 0 & 0\end{bmatrix}}_{\mathbf{D}} \underbrace{\begin{bmatrix}u_1\\ u_2\end{bmatrix}}_{\mathbf{u}} \tag{17}$$

where
θ = Pitch angle
$\dot{\theta}$ = Pitch angular velocity
$\ddot{\theta}$ = Pitch angular acceleration
ϕ = Roll angle
$\dot{\phi}$ = Roll angular velocity
$\ddot{\phi}$ = Roll angular acceleration
u_1 = Pitch action
u_2 = Roll action
I_{xx} = Moment of inertia on the x-axis
I_{yy} = Moment of inertia on the y-axis
g = Gravitational force of the Earth
y_1 = Pitch output
y_2 = Roll output
M = Total mass of the robot
l = Distance from the center of mass to the foot sole

Moment of inertia refers to an object's tendency to maintain its position against rotational motion. In this study, only movements on the x and y axes are controlled, so the moment of inertia on the z-axis is ignored. To obtain the moment of inertia values for the robot parts, robot design can be used in Autodesk Inventor software. Subsequently, (18) can be used to calculate the moment of inertia on the x and y axes of the robot.

$$I_{xx} = \sum_{j=1}^{n}\left(I_{G_{xx_j}} + m_j\left(y_j^2 + z_j^2\right)\right), \qquad I_{yy} = \sum_{j=1}^{n}\left(I_{G_{yy_j}} + m_j\left(x_j^2 + z_j^2\right)\right) \tag{18}$$

In (18), $I_{G_{xx_j}}$ dan $I_{G_{yy_j}}$ are the moments of inertia on the x and y axes located at the center of mass of each robot part; x_j and y_j are the distances from the center of mass of each robot component to the foot support point on the x and y axes, respectively, and m_j is the mass of each robot component.

Simulations play a vital role in robot control system development by minimizing risks before real-world implementation. Direct testing without simulation may lead to system damage due to unmeasurable errors and lack of control over real-time behavior. Therefore, simulation is essential for validating the control system design.

In this study, the LQR control system is simulated using Python, where **Q** and **R** matrices are varied to determine the optimal gain **K** [34], [35]. This gain is applied to a two-dimensional linear inverted pendulum model. The optimal gain **K** is then implemented in the actual robot to ensure accurate and stable walking control. The block diagram of the proposed control system is shown in Figure 4.

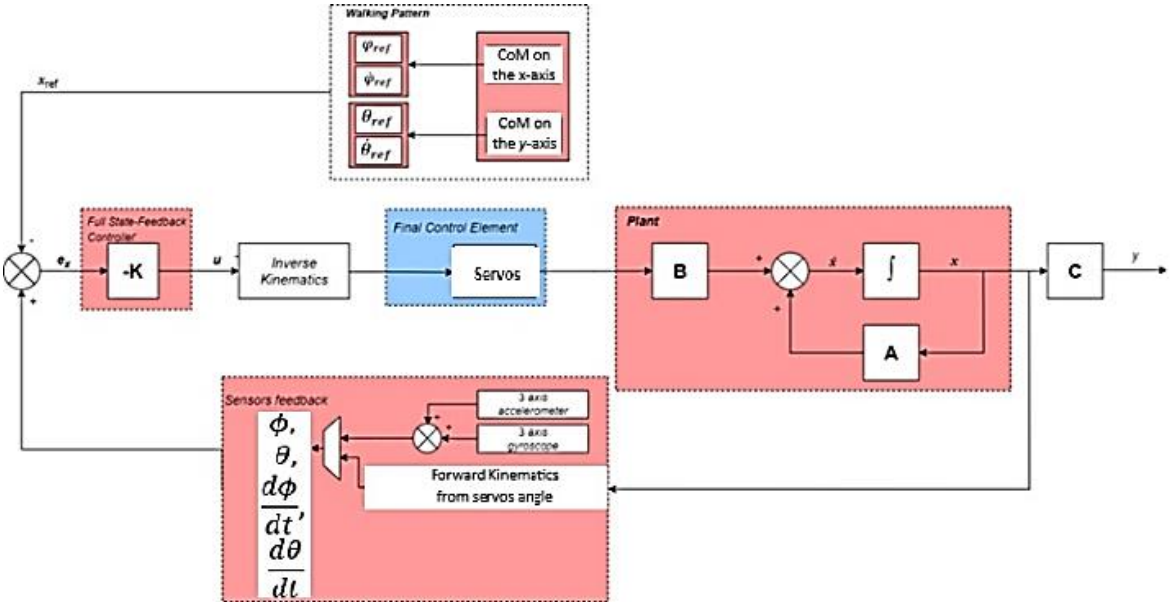

Figure 4. The block diagram of the control system.

4. RESULTS AND DISCUSSION

The study evaluated the robot's backward walking stability by testing its walking algorithm and control system. IMU sensors and forward kinematics were used to track CoM, while inverse kinematics ensured correct joint movement. Mechanical limitations affected stability during leg lifting and stepping phases. Without LQR, the robot frequently fell. With LQR, tuned using a linear inverted pendulum model, ankle adjustments improved pitch/roll control, maintaining balance and keeping the CoM within a safe range.

4.1. Backward walking robot using proportional control method

The testing begins with the robot in an upright position, feet parallel. It then performs backward steps following the designed pattern: the left footsteps first, supported by the right foot, followed by the right foot stepping back while the left supports. This sequence continues for six steps, each phase lasting 2 seconds.

The motion pattern includes a double support phase, where the robot balances before shifting its CoM. Tests were conducted to determine the optimal duration for this phase to enhance stability before stepping.Initially, proportional control was used without stabilizing mechanisms. The robot failed to complete the backward walking task without falling, as the CoM exceeded the support polygon boundaries. CoM data on the x- and y-axes was analyzed to assess stability. As shown in Figure 5, several CoM positions during the first step fell outside the support polygon, though the robot remained upright. In the second step, the robot-maintained stability. However, in the third step, the CoM dropped to zero, indicating a fall and sensor shutdown. This test highlights the importance of CoM monitoring and control for maintaining balance during backward walking.

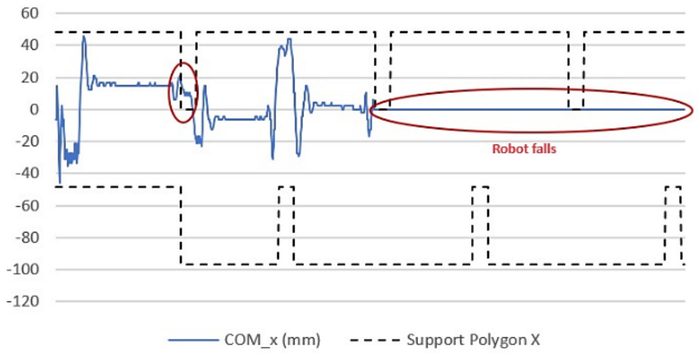

Figure 5. Backward walking test on the x-axis using proportional control

Next is the backward walking test on the y-axis using proportional control that is shown in Figure 6. In this figure, the lower bound of the support polygon represents the right side of the robot's body, while the upper bound represents the left side. Based on the test result graph, there are still CoM position points on the y-axis that fall outside the support polygon area.

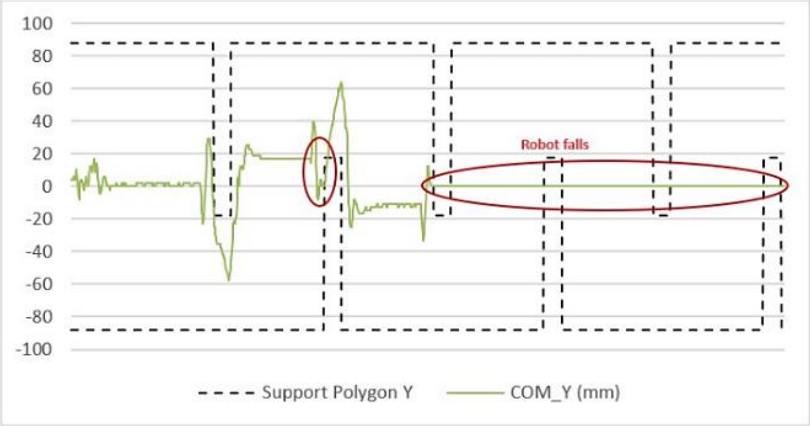

Figure 6. Backward walking test on the y-axis using proportional control

As seen in Figure 5 dan Figure 6, the balance and stability of the robot while walking backward are inadequate, making it prone to falling. This condition is due to the current use of a conventional proportional control system, which is not rigid and optimal enough to maintain the stability of the humanoid robot when walking backward. The potential for falling is higher when walking backward because the primary support on the foot sole is only at the heel.

4.2 Backward walking robot using LQR control method

The next test uses the LQR method. Inverse kinematics is used to plan the end-effector's path, while LQR ensures the actuators, particularly the ankle servos, follow that path precisely and efficiently. The optimal gain **K** is determined by tuning the **Q** matrix and observing how closely the robot's CoM follows the reference trajectory. Smaller deviations indicate better system response.

Test results are shown in Figure 7 (x-axis) and Figure 8 (y-axis). The robot successfully performed backward walking without falling—unlike in the proportional control test—since no CoM value dropped to zero. On the x-axis, some CoM points in the fourth step exceed the support polygon, but the robot regains balance through passive control. On the y-axis, all CoM positions remain within bounds. Overall, applying LQR leads to a clear improvement in balance and stability during backward walking.

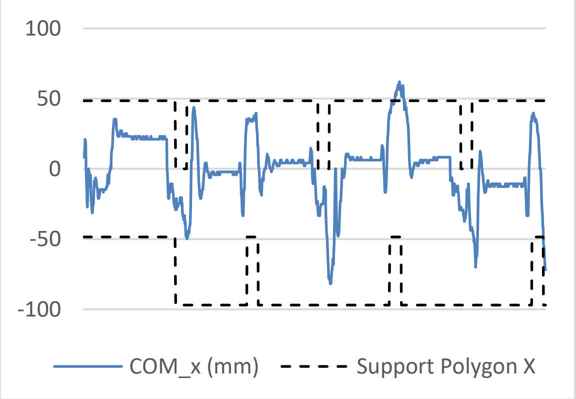

Figure 7. Backward walking test graph on the x-axis using LQR

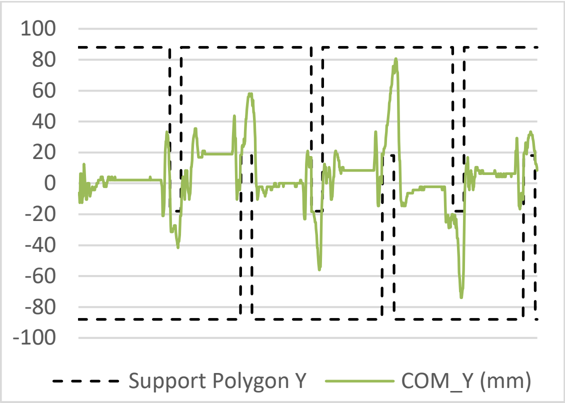

Figure 8. Backward walking test graph on the y-axis using LQR

5. CONCLUSION

This study successfully demonstrates that the humanoid robot can walk backward while maintaining balance and stability along both the x-axis (roll) and y-axis (pitch) using a linear quadratic regulator (LQR) control system. The robot was able to maintain its stability despite occasional deviations of the center of mass (CoM) from the support polygon area, attributed to the passive control provided by the robot's structure. The application of LQR control has been shown to significantly improve the robot's stability during backward walking, confirming the effectiveness of this approach in enhancing robotic balance and movement. This research contributes to the field of robotics by providing a reliable control method for maintaining stability in humanoid robots during complex movements.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Muhammad Auzan		✓	✓			✓	✓			✓			✓	
Jazi Eko Istiyanto					✓		✓			✓		✓	✓	
Oskar Natan	✓			✓		✓		✓		✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis

I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting

Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support this review paper is available from the references cited in the manuscript.

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