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Stabilizing Quadruped Robot Movement Using Fuzzy Logic Control for Yaw Angle Adjustment in Walking and Trotting Gait

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ABSTRACT

Balance is a fundamental aspect of quadruped robots that determines their movement success. Imbalanced movement can affect the robot's orientation, leading to potential deviations from the intended direction due to changes in the attitude angle. An unstable attitude angle can result in loss of control, complicating effective navigation. This loss of control may prevent the robot from maintaining its stability, increasing the risk of falling. This study designs a control system for a quadruped robot using fuzzy control system to manage the yaw angle while the robot walks forward using both walking and trotting gaits. The fuzzy control system outputs are used to adjust the hip joint angles of the robot's four legs, modifying the stride length of each leg accordingly. The quadruped robot was tested with both walking and trotting gaits moving forward for 30 seconds. The quadruped robot successfully maintained balance and stability in the z-axis (yaw) on a flat, obstacle-free surface using fuzzy control system. The fuzzy logic control effectively reduced positional distance fluctuations from the set point and enhanced the robot's ability to return to the set point after fluctuations, without producing excessive overshoot.

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1. INTRODUCTION

Legged robots offer advantages over wheeled and tracked robots, particularly due to their ability to reduce ground contact, allowing for faster movement and enhanced navigation across diverse terrains [1], [2]. Among legged robots, quadrupeds stand out for their ability to mimic animal walking patterns, resulting in efficient locomotion. These robots are inspired by biological systems, which naturally adjust posture for optimal movement [3], [4].

Quadruped robots strike a balance between mobility, stability, and load-carrying capacity, making them easier to control and maintain compared to bipedal or hexapod robots [5], [6]. Their design prioritizes fast movement, stability on various terrains, and the ability to perform high [7], [8]. Stability is crucial, as improper gait or disturbances can affect walking performance and cause deviations from intended paths due to unstable yaw angles, leading to navigation difficulties and the potential for falls [9], [10].

To ensure stability, effective gait use and stabilization control are necessary. This study explores stability analysis in quadruped robots using walking and trotting gaits, commonly employed on flat surfaces. Fuzzy logic-based gait planning is proposed to minimize attitude angle changes during movement.

Quadruped robot stability is influenced by both external factors, such as uneven terrain, and internal factors, such as servo condition and leg movement sequencing [11], [12]. Proper gait planning is essential to prevent instability, especially during trotting, where incorrect sequencing can lead to balance loss [13], [14].

Stabilization methods, including fuzzy logic control, are highly effective for quadruped robot navigation [15], [16], [17], [18]. Fuzzy logic, with its intuitive use of linguistic variables, has demonstrated superior performance compared to traditional PID control in achieving stable locomotion, particularly by addressing challenges related to instability and yaw angle deviation. This study enhances quadruped robot stability by integrating fuzzy logic control with gait planning for walking and trotting patterns, thereby improving the robot's ability to maintain its trajectory and adapt to real-time disturbances.

While advanced control methods, such as adaptive control or model predictive control (MPC), offer sophisticated solutions for dynamic systems, they often demand extensive computational resources and precise models of robot dynamics. This complexity can pose significant challenges in real-time applications, especially in unpredictable environments where quadruped robots are expected to operate [19]. In contrast, fuzzy logic control excels in handling imprecise inputs and offers an intuitive, flexible design that facilitates quicker adjustments to disturbances without requiring detailed modeling [20] [21]. This makes it particularly suited for applications involving frequent and abrupt changes in dynamics, such as navigating uneven terrains or adapting to unforeseen disturbances.

Advanced control methods often struggle to maintain stability under rapidly changing conditions due to their reliance on predefined models and parameters [22][23]. Fuzzy logic, on the other hand, adaptively adjusts its rules based on real-time feedback, ensuring effective stability management during trotting or walking gaits where disturbances are common [24]. Furthermore, traditional PID controllers, while widely used for their simplicity, face limitations in managing the nonlinearities and uncertainties inherent in legged locomotion. PID controllers alone may not provide the robustness required to handle complex gait patterns or external disturbances effectively [25][26].

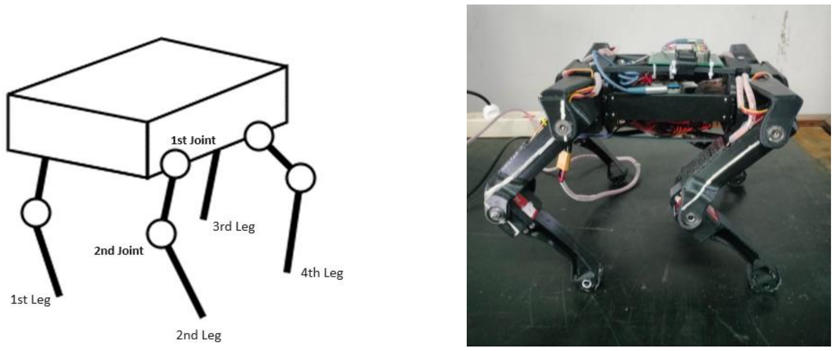
By integrating fuzzy logic with PID control, performance can be significantly improved [27], [28]. Fuzzy logic dynamically tunes PID parameters based on the robot's operational context, enhancing stability and responsiveness [29]. This hybrid approach leverages the adaptability and robustness of fuzzy logic alongside the precision of PID control, effectively addressing challenges posed by non-linear systems and real-world disturbances.

This paper is organized as follows: Section 2 outlines the problem statement, Section 3 describes the system design, Section 4 presents experimental results and performance analysis, and Section 5 concludes the paper.

2. PROBLEM STATEMENT AND PRELIMENARIES

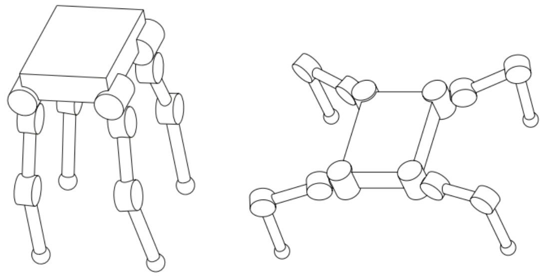
Quadruped robots, inspired by four-legged animals, are designed to navigate various terrains and excel in load carrying, making them suitable for applications such as search and rescue, military operations, and environmental exploration [30]. Their mobility, a critical factor in determining functionality, can be enhanced by increasing the Degrees of Freedom (DOF), which represent the robot's joints. However, this also increases design complexity [31]. An illustration of the joints and links in a quadruped robot's leg is shown in Figure 1.

Quadruped robots are generally classified into two types based on leg configuration: sprawling and mammal types. Sprawling-type robots, with their wide-legged stance, offer a lower center of gravity (CoG) and greater stability, while mammal-type robots, with upright legs, offer higher speed and reduced actuator torque requirements, making them more efficient and agile [32], [33]. The differences between sprawling-type and mammal-type quadruped robots are shown in Figure 2.



(a) (b)

Figure 1. A quadruped robot (a) Joints and links in the robot's leg (b) actual quadruped



(a) (b)

Figure 2. Differences in the shape of quadruped robots: (a) mammal-type, (b) sprawling-type

In this study, a mammal-type quadruped robot with three degrees of freedom in each leg—hip, thigh, and knee joints—was used [34]. The goal is to improve the robot's balance and forward movement along the z-axis through the implementation of a fuzzy logic control system. This control system is designed to maintain consistent movement in the desired direction, particularly under real-time disturbances, which can affect the robot's trajectory and performance.

The experiment involved two gait patterns: walking, where three legs are in the support phase and one in the transfer phase, and trotting, where two legs are in the support phase and two in the transfer phase [35], [36]. Gait planning with inverse kinematics was utilized to move the legs, calculating the joint angles for each servo. A fuzzy logic controller regulated the robot's yaw angle, based on input from an IMU sensor, adjusting the actuator angles to maintain stability and improve locomotion. The positional adjustments were computed using the Pythagorean theorem, ensuring the robot stayed on its intended path.

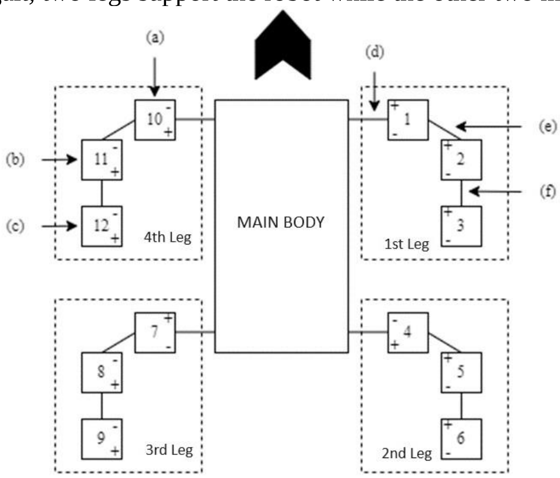
Mechanical variability in servos, such as differences in maximum torque or response time between servos, can affect the robot's motion stability. In this study, fuzzy logic control helps mitigate the effects of this variability by dynamically adjusting servo angles based on real-time data from the IMU sensor. However, mitigation measures such as initial calibration before development or servos with more consistent specifications can be implemented to address variability further.

3. SYSTEM DESIGN

3.1. Walking Design

This study employs a quadruped robot with a mammal-type leg configuration, where each leg has 3 Degrees of Freedom (DoF), represented by three servos per leg. The coxa servo controls the roll angle, while the femur and tibia servos control the pitch angles. In total, the robot has 12 DoF, requiring 12 servos to operate its four legs (see Figure 3). The arrangement of the servos varies, resulting in different rotation directions. Specifically, servos 1, 2, 3, 5, 6, and 7 increase their angle values when moving forward, while servos 4, 8, 9, 10, 11, and 12 decrease their angle values when moved forward.

Gait in quadruped robots refers to the pattern of leg movements during walking or running. The choice of gait depends on the robot's speed, terrain, and objective, with gait algorithms determining how many legs provide support during each step. There are two primary gait algorithms: tripod and dualpod. In the tripod gait, three legs support the robot during the support phase while one leg moves in the transfer phase. In the dualpod gait, two legs support the robot while the other two move.



where
(a) Hip servo
(b) Thigh servo
(c) Knee servo
(d) Coxa segment
(e) Femur segment
(f) Tibia segment

Figure 3. Configuration of the quadruped robot's legs

Based on speed, quadruped gaits are classified as walk, amble, pace, trot, canter, and gallop. Walk and canter fall under the tripod gait category, where three legs support the robot. Amble, pace, trot, and gallop belong to the dualpod gait category, where two legs serve as support. Selecting the appropriate gait is critical to ensure efficient and stable movement according to the robot's operational requirements.

This study focuses on two gaits: the walking gait and the trotting gait. In the walking gait, the robot's legs move one at a time, while in the trotting gait, diagonal legs move simultaneously. The walking pattern is designed using gait planning, which involves determining the sequence of leg movements, swing timing, and support phases to enhance stability. Proper gait planning ensures accurate timing for each leg during the support and transfer phases, which is crucial for maintaining stability. Table 1 and Table 2 provide timing diagrams for the walking and trotting gaits, while Figure 4 and Figure 5 show top views of the respective gait diagrams.

Table 1. Walking Gait Timing Diagram

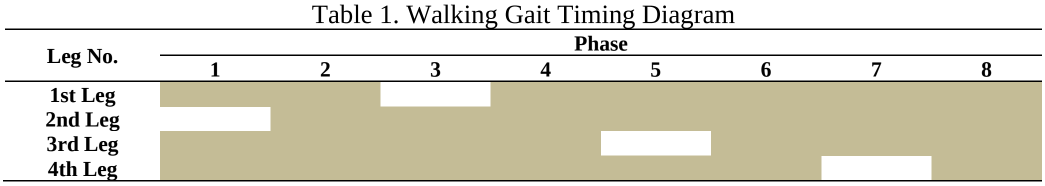
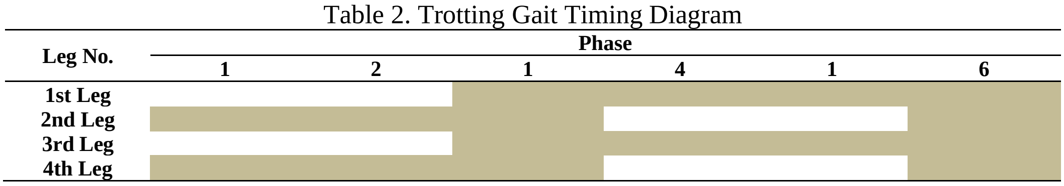


Table 2. Trotting Gait Timing Diagram



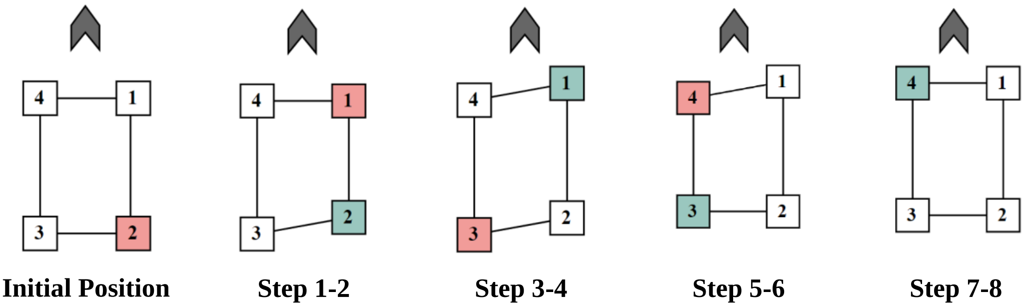
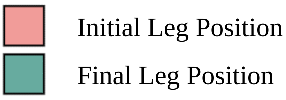


Figure 4. Walking Gait Diagram (Top View of the Robot)

where

- 1 — 1st leg (Right Front Leg)
- 2 — 2nd leg (Right Rear Leg)
- 3 — 3rd leg (Left Rear Leg)
- 4 — 4th leg (Left Front Leg)



Based on Figure 4, the red boxes represent the initial leg positions, while the green boxes represent the final leg positions. The sequence of the robot's steps using the walking gait is as follows:

1. The robot stands in the initial position.
2. The right rear leg, represented by the number 2, steps forward.
3. The right front leg, represented by the number 1, steps forward.
4. The left rear leg, represented by the number 3, steps forward.
5. The left front leg, represented by the number 4, steps forward.

Based on Figure 5, the red boxes represent the initial leg positions, while the green boxes represent the final leg positions. The sequence of the robot's steps using the troting gait is as follows:

1. The robot stands in the initial position.

2. The right front leg, represented by the number 1, and the left rear leg, represented by the number 3, step forward.
3. The left front leg, represented by the number 4, and the right rear leg, represented by the number 2, step forward.

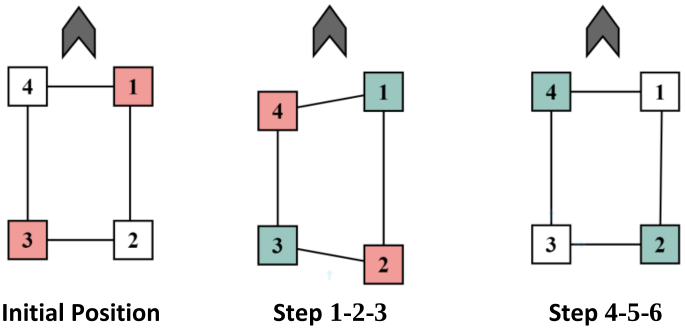


Figure 5. Trotting gait Diagram (Top View)

3.2. Mechanical Model

The quadruped robot consists of joints and links that mechanically connect them. There are several types of joints, but the most used are prismatic joints and revolute joints [37], [38]. Prismatic joints allow for translational movement of the link, while revolute joints allow rotational movement of the link along the joint axis.

Inverse Kinematics (IK) is used to calculate the joint angles of the robot based on the position and orientation of the end-effector [39]. The IK applied to the robot uses trigonometric equations based on the geometric shape of the robot's legs. Through IK calculations, several outputs are obtained, including the hip servo angle (α), thigh servo angle (θ), and knee servo angle (φ). Figure 6 shows the front view projection of the robot's leg.

The angle α is obtained by viewing the robot's leg from the x and z axes, as shown in Figure 6. Several trigonometric equations can then be derived as shown in equations (1), (2), and (3).

$$\alpha = 180° - \beta - \gamma \quad (1)$$

$$\gamma = tan^{-1}\left(\frac{x}{z}\right) \quad (2)$$

$$\beta = tan^{-1}\left(\frac{A}{B}\right) \quad (3)$$

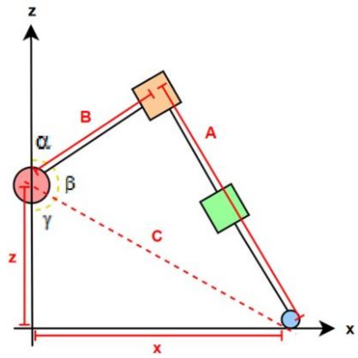


Figure 6. Front View Projection of the Robot's Leg

where
x = Input leg position on the x-axis
z = Input leg position on the z- axis
A = Variable representing the length of the femur and tibia viewed from the front
B = Constant representing the length of the coxa
C = Variable representing the hypotenuse of the triangle formed by line A, line B, and the x and z axes
α = Variable representing the angle between the coxa and the z-axis (hip servo angle)
β = Variable representing the angle between the coxa and line C
γ = Variable representing the angle between line C and the z-axis

From these equations, equations (4), (5), and (6) can be obtained using the right triangle equations.

$$A = \sqrt{C^2 - B^2} \tag{4}$$

$$C^2 = z^2 + x^2 \tag{5}$$

$$A = \sqrt{z^2 + x^2 - B^2} \tag{6}$$

The result from equation (6) and the value of B are substituted into equation (3) to obtain equation (7).

$$\beta = tan^{-1}\left(\frac{\sqrt{z^2+x^2-B^2}}{B}\right) \tag{7}$$

The angle α is obtained by substituting the results from equation (7) and the value of γ into equation (1) to obtain equation (8).

$$\alpha = 180° - tan^{-1}\left(\frac{\sqrt{z^2+x^2-B^2}}{B}\right) - tan^{-1}\left(\frac{x}{z}\right) \tag{8}$$

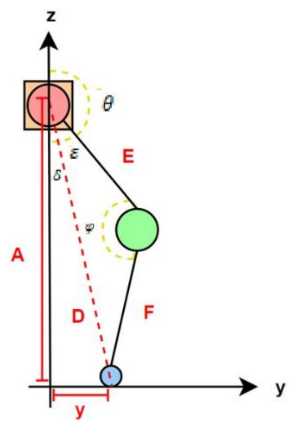


Figure 7. Side View Projection of the Robot's Leg

where
y = Input leg position on the y-axis
A = Variable representing the length of the femur and tibia viewed from the front
D = Variable representing the hypotenuse of the triangle formed by line A and y
E = Constant representing the length of the femur
F = Constant representing the length of the tibia
θ = Variable representing the angle between the femur and the z-axis (thigh servo angle)
ε = Variable representing the angle between the femur and line D
δ = Variable representing the angle between line D and the z-axis
φ = Variable representing the angle between the femur and tibia (knee servo angle)

The next step is calculating the angle φ by viewing the robot's leg from the y and z axes, as shown in Figure 7. The angle φ is obtained by viewing the robot's leg from the y and z axes, as shown in Figure 7. Using the cosine equation, equation (9) can be derived.

$$\varphi = cos^{-1}\left(\frac{E^2+F^2-D^2}{2EF}\right) \tag{9}$$

Based on Figure 7, line D represents the hypotenuse of the triangle, so the value of D can be obtained as shown in equation (10).

$$D^2 = A^2 + y^2 \tag{10}$$

The result from equation (10) is substituted into equation (9) to obtain equation (11).

$$\varphi = cos^{-1}\left(\frac{E^2+F^2-(A^2+y^2)}{2EF}\right) \tag{11}$$

Based on Figure 7, several trigonometric equations can be derived, as shown in equations (12), (13), and (14).

$$\theta = 180° - \delta - \varepsilon \tag{12}$$

$$\delta = tan^{-1}\left(\frac{-y}{A}\right) \quad (13)$$

$$\varepsilon = cos^{-1}\left(\frac{E^2+D^2-F^2}{2ED}\right) \quad (14)$$

The angle θ is obtained by substituting the results from equations (13) and (14) into equation (12) to obtain equation (15).

$$\theta = 180° - tan^{-1}\left(\frac{-y}{A}\right) - cos^{-1}\left(\frac{E^2+D^2-F^2}{2ED}\right) \quad (15)$$

3.3. Calculation of the Robot's Position Distance from the Set Point

When the robot moves away from the set point, the distance of the robot's position from the set point can be obtained based on the changes in the yaw values. These values are processed to determine the error between the desired value and the obtained value. The error in question represents the distance between the robot's position and the set point position, which is represented by the point 0 or the value 0 from the IMU. An illustration of the measurement is shown in Figure 8.

The change in each cycle during the robot's movement testing (s) is calculated using the formula shown in equation (16).

$$s \ = \tan(\varphi) \times L \quad (16)$$

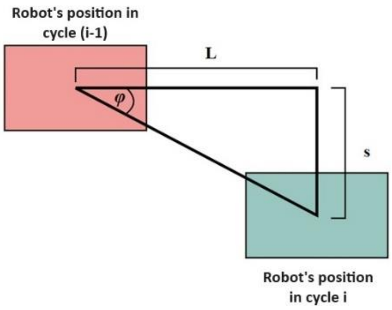


Figure 8. Illustration of the robot's distance change from the set point

The calculation method involves measuring the yaw angle (φ) in each cycle of the robot's movement and the step length (L) in centimeters. Data on the robot's step length and the change in yaw angle is required to obtain the distance of the robot's position from the set point. Based on the measurement results, the total error in the robot's movement over 30 seconds can be determined. The total error is obtained by summing the distances of the robot's position from the set point in each cycle, and the resulting value is used as the total error in the robot's movement.

3.4. Control Design

The control system employed in this study utilizes fuzzy logic to balance the robot's movement along the z-axis. The system begins by positioning the robot at its initial starting point. As the robot moves forward, the yaw angle, which is crucial for determining the robot's balance, is monitored. The system continuously reads the changes in the yaw angle, with the data obtained from the IMU sensor. This data is used to balance the robot's movement by minimizing the positional error between the robot's current position and the set point, applying necessary adjustments when the robot deviates from the set point.

The fuzzy control system is designed with yaw as the input variable, derived from the IMU sensor readings during each movement cycle of the robot. The yaw value serves as the basis for determining the adjustment needed in the servo angles for each required action. The servo angle adjustments are made according to pre-established fuzzy rules. By employing fuzzy logic, the system can adaptively adjust the servo angles in response to the robot's movement.

Three linguistic variables are used to describe the yaw input set: YN (Yaw Negative), YNR (Yaw Normal), and YP (Yaw Positive). Within the yaw input set, there is a set point value, a lower limit, and an upper limit. The set point value is the initial value obtained when the IMU is initialized. The lower limit represents the boundary for YN, and the upper limit represents the boundary for YP. If the yaw value received is outside these boundaries, the system will not operate. The design of the yaw input set is illustrated in Figure 9.

To represent the adjustment set, three linguistic variables are used: PN (Negative Adjustment), PNR (Normal Adjustment), and PP (Positive Adjustment). The adjustment set includes a set point, lower and upper limits for PNR, and lower and upper limits for PP. The set point represents the value when no adjustment is required. The upper and lower limits of PNR define the range within which the thigh servo angle adjustments are considered normal. The lower limit of PN and the upper limit of PP represent the boundary for the thigh servo's movement. The design of the adjustment set is illustrated in Figure 10.

A fuzzy inference system (FIS) was then designed using fuzzy rules based on the Mamdani method [40]. The Mamdani method operates on a basic rule structure: if X = A, then Y = B. The rules used in this system are as follows:

1. If "yaw" = "negative", then "adjustment" = "positive".
2. If "yaw" = "normal", then "adjustment" = "normal".
3. If "yaw" = "positive", then "adjustment" = "negative".

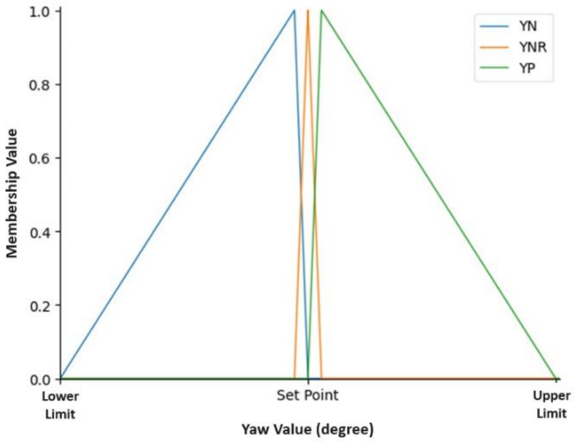


Figure 9. Design of the Fuzzy Yaw Set

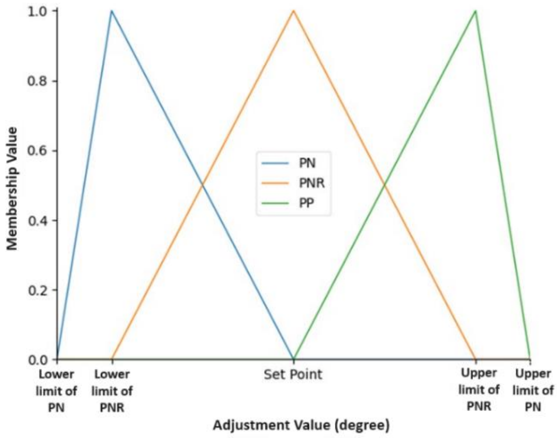


Figure 10. Design of the Fuzzy Adjustment Set

Once the fuzzy rules are established, a defuzzification process is carried out to produce the appropriate adjustment value for the thigh servo, ensuring that the robot maintains stable movement. The fuzzy control block diagram is shown in Figure 11 [41].

The adjustment values obtained are aligned with the gait configuration and the servo rotation direction. For instance, if the robot veers to the left, the left-side legs (Legs 3 and 4) receive an adjustment value to increase their forward step size, while the right-side legs (Legs 1 and 2) receive an adjustment value to increase their backward step size. Conversely, if the robot veers to the right, the right-side legs require a larger forward step adjustment, and the left-side legs require a larger backward step adjustment.

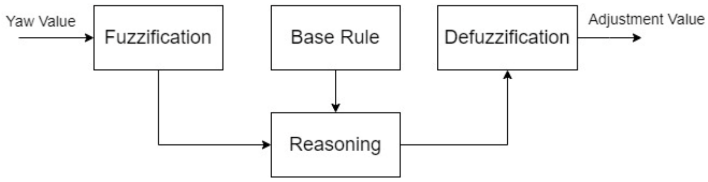


Figure 11. Fuzzy Control Block Diagram

Table 3. List of Angle Adjustment Values for Trotting gait

		Thigh Base Servo			
		1	**2**	**3**	**4**
Phase	**1**	0	0	0	0
	2	Y	X	X	Y
	3	Y	X	X	Y
	4	0	0	0	0
	5	X	Y	Y	X
	6	X	Y	Y	X

Table 4 Adjustment Values for Walking Gait Angles

		Thigh Base Servo			
		1	**2**	**3**	**4**
Phase	**1**	X	Y	Y	X
	2	X	Y	Y	X
	3	Y	0	Y	0
	4	Y	0	Y	0
	5	Y	X	X	Y
	6	Y	X	X	Y
	7	0	X	0	X
	8	0	X	0	X

In the trotting gait, there are six phases in one movement cycle. The phases where adjustments are applied are indicated by 'X' and 'Y' in Table 3. In the walking gait, a complete movement cycle consists of eight phases, with phases 1 and 4 serving as support phases for all four legs, requiring no adjustments. However, phases 2, 3, 5, and 6 are transfer phases that necessitate adjustments to maintain stability. In these phases, adjustments are made to the thigh servo angles to correct any tilting during movement.

Table 4 illustrates the phases where adjustments are necessary. The 'X' indicates adjustments for when the robot tilts to the left, while 'Y' marks adjustments for when it tilts to the right. Phases with no required adjustments are indicated by '0'. This systematic approach ensures that the robot remains stable throughout the gait cycle, particularly during the transfer phases where balance is most vulnerable.

When the robot veers to the right, adjustments are needed in phases 1, 2, 3, 4, 5, and 6. For leftward tilting, adjustments are required in phases 1, 2, 5, 6, 7, and 8. The design allows the robot to dynamically correct any deviations in real-time, ensuring balanced movement throughout its operation. The fuzzy control system plays a crucial role in managing the nonlinearities and uncertainties of quadruped locomotion, enabling the robot to adaptively sustain its stability.

4. RESULTS AND DISCUSSION

4.1. Control System Simulation

The robot's forward movement stabilization relies on yaw readings from the IMU sensor [42]. Fuzzy logic is applied to maintain a stable yaw value, ensuring balanced forward movement. The yaw value serves as the input variable, while the output variables are the adjustment values applied to each thigh base servo to correct the robot's trajectory.

Linguistic variables YN (Negative Yaw), YNR (Normal Yaw), and YP (Positive Yaw) are used to model the yaw changes based on IMU sensor data. Positive yaw indicates the robot is veering left, while negative yaw indicates it is veering right. A yaw value within ±3˚ is considered normal (YNR), signifying stable, straight movement. YN represents yaw values between -55˚ and -3˚, and YP represents yaw values between 3˚ and 55˚. The 55˚ limit is set based on the maximum error observed without fuzzy logic control, ensuring the system effectively responds to positional changes.

For output adjustments, the categories PN (Negative Adjustment), PNR (Normal Adjustment), and PP (Positive Adjustment) are used. PNR corresponds to femur angle adjustments within ±10˚, which is the normal range for straight and stable movement. PN and PP represent the maximum adjustment values required to maintain stability. Failure to adjust these values properly can result in imbalance or falls during movement.

The yaw and adjustment sets are designed using triangular membership functions, with the defuzzification process converting fuzzy outputs into specific angle adjustments for each thigh base servo. Figures 9 and 10 illustrate the fuzzy sets, and Table 5 outlines the membership functions.

Table 5. Membership Function Parameter Values

	Sets	Membership	Parameter
Input	YN (Negative Yaw)	Triangle	-55, -3, 0
	YNR (Normal Yaw)	Triangle	-3, 0, 3
	YP (Positive Yaw)	Triangle	0, 3, 55
Output	PN (Negative Adjustment)	Triangle	-13, -10, 0
	PNR (Normal Adjustment)	Triangle	-10, 0, 10
	PP (Positive Adjustment)	Triangle	0, 10, 13

4.2. Stability Testing of Walking Gait

The stability testing of the walking gait aims to assess the robot's tilt direction while moving using the walking gait. The testing process begins with the robot standing in an initial position, where the feet are aligned with the thigh base servo position. The robot then moves forward using the walking gait without any balance control system. As the robot walks, the IMU sensor reads changes in the yaw angle at the end of each cycle. Based on the yaw angle, the change in the robot's distance from the set point can be calculated for each cycle using the equation provided in equation (16).

The total error in the distance change from the set point during the walking gait can be obtained by summing the distance values of the robot's position from the set point in each cycle. In this test, a total error of ± 53.28 cm was recorded. The robot's movement range is then determined through empirical observation. Each robot requires a specific range to move stably, and this range differs between robots. The determination of the robot's movement range was based on its movement using fuzzy control system. From the experiments conducted, a movement range of ± 1 cm was established for the robot. The speed of movement adjustment varies between robots depending on the servo torque. The stronger the servo torque, the faster the robot can adjust its movement. In this study, a range of ± 1 cm was used, based on the servo torque of the robot used in the research.

The robot's imbalance relative to the z-axis is attributed to both internal and external factors. Internal factors may include varying servo torques, where a servo with lower torque might cause insufficient foot thrust during stance phases. External factors may involve attached cables that disrupt the robot's balance. This imbalance leads to inconsistent changes in distance from the set point, resulting in instability in the robot's movement.

The results of the stability testing of the walking gait without fuzzy control system demonstrate that movement without balance control results in greater fluctuations in distance from the set point, and the robot is unable to return to the set point effectively. The robot continues to move away from the set point even in the final cycle, remaining outside the designated movement range. This indicates that balance control is necessary to reduce fluctuations in distance from the set point and to enhance the robot's stability relative to the z-axis.

Subsequently, a fuzzy control system was implemented to address these issues. The testing process begins with the robot standing in the initial position, where the feet are aligned with the thigh base servo position. The robot then moves forward using the walking gait with stability control. During movement, the IMU sensor reads the yaw angle changes at the end of each cycle. The yaw angle continues to change according to the robot's position in each movement cycle. Based on the yaw angle obtained in this test, the robot's distance from the set point in each cycle can be calculated using the equation provided in equation (16).

The total error in the distance change from the set point during the walking gait without fuzzy control system can be obtained by summing the distance values of the robot's position from the set point in each cycle. In this test, a total error of ± 3.83 cm was recorded. The robot's movement range was determined through empirical observation. Each robot requires a specific range to move stably, and this range differs between robots. The determination of the robot's movement range was based on its movement using fuzzy control system. From the experiments conducted, a movement range of ± 1 cm was established for the robot. The speed of movement adjustment varies between robots depending on the servo torque. The stronger the servo torque, the faster the robot can adjust its movement. In this study, a range of ± 1 cm was used, based on the servo torque of the robot used in the research. Although there are minor fluctuations, the pattern of distance change from the set point appears relatively consistent, with no drastic changes from one cycle to the next. The robot manages to keep the average distance from the set point close to the set point, demonstrating the effectiveness of fuzzy control system in maintaining stability. Comparative stability testing using the walking gait with and without fuzzy control system shows significant differences in the robot's movement stability. Figure 12shows the comparative graph of the distance change from the set point using the walking gait with and without fuzzy control system.

Based on Figure 12, it is evident that movement with the fuzzy control system exhibits smaller and more stable fluctuations around 0 compared to movement without the fuzzy control system. Without the fuzzy control system, the movement shows a significant increase in distance from the set point up to the 11th cycle, after which it decreases but remains significantly above the set point. In contrast, with the fuzzy control system, the distance from the set point remains stable around 0, with minimal fluctuations.

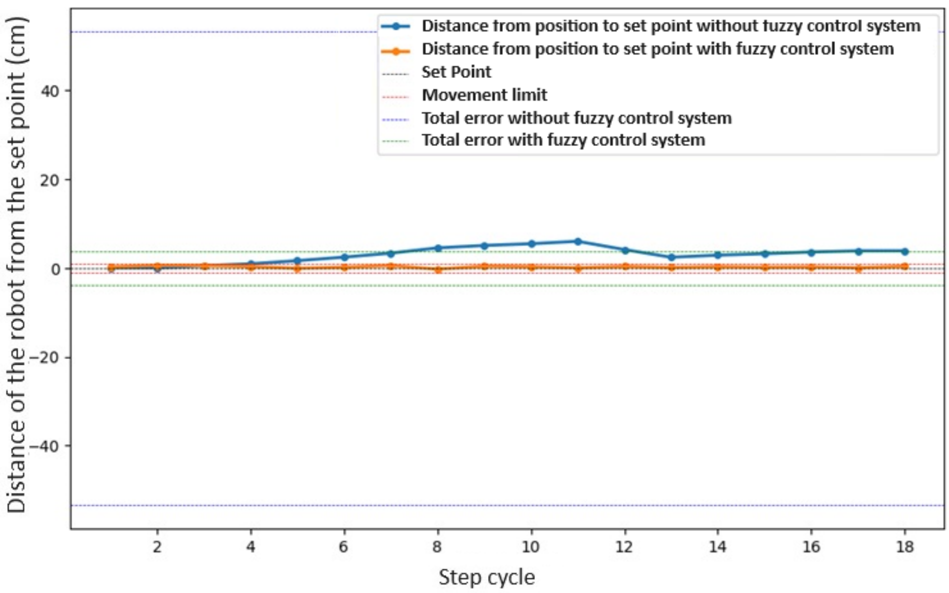


Figure 12. Comparative graph of the robot's distance change from the set point using walking gait with and without fuzzy control system.

Furthermore, without fuzzy control, the system experiences an overshoot of approximately 597% of the 1 cm tolerance (exceeding 5 cm), clearly surpassing the allowable limits. On the other hand, with the fuzzy control system, the highest overshoot is only about 54% of the 1 cm tolerance (approximately 0.5 cm), remaining well within the acceptable range. This demonstrates that the robot's movement using the walking gait with the fuzzy control system is more balanced and stable compared to its movement without the fuzzy control system.

With fuzzy control system, the issue of instability in the robot's movement relative to the z-axis can be addressed by dynamically adjusting the servo angle to compensate for differences in servo torque and external disturbances. Fuzzy control system provides real-time flexibility and adjustments, enabling the robot to maintain better balance and stability in its movement.

Although fuzzy control system improves stability, there is still a small error in the robot's distance from the set point. This error is caused by the mechanical variability of each servo. When the robot moves, a foot consisting of a servo with less torque than the others may cause the foot to be unable to push the robot's body firmly during stance phases. This prevents the robot from immediately returning to the desired position, even if the adjustment value is appropriate.

4.3. Stability Testing of Trotting Gait

Like the previous tests, the stability testing of the trotting gait aimed to assess the robot's directional tilt while moving using the trotting gait. The testing process began with the robot standing in an initial position, where the feet were aligned with the thigh base servo position. The robot then moved forward using the trotting gait without any balance control system. As the robot walked, the IMU sensor recorded changes in the yaw angle after each cycle. The yaw angle continued to change in accordance with the robot's position during each movement cycle. Based on the yaw angle, the change in the robot's distance from the set point for each cycle was calculated using the equation provided in equation (16).

The total error in the distance change from the set point during the trotting gait was determined by summing the distance values of the robot's position from the set point across each cycle. In this test, a total error of ± 17.47 cm was recorded. The robot's movement range was then empirically determined through direct observation. Each robot requires a specific range to move stably, which varies depending on the robot. The movement range was established based on the robot's behavior using fuzzy control. From the experiments, the robot's movement range was found to be within ± 1 cm. The speed of movement adjustment varies among robots based on the torque of the leg servos. The greater the servo torque, the faster the robot can adjust its movement. In this study, a range of ± 1 cm was used, based on the servo torque of the robot used in the research.

The robot's imbalance relative to the z-axis can be attributed to both internal and external factors. Internal factors may include varying servo torques, where servos with lower torque might result in insufficient thrust during stance phases, leading to a gradual decrease in the distance from the set point. External factors, such as attached cables, may disrupt the robot's balance. This imbalance causes inconsistent changes in the distance from the set point, resulting in instability in the robot's movement.

To address these issues, a fuzzy control system was implemented. The testing began with the robot in the initial position, where the feet were aligned with the thigh base servo position. The robot then moved forward using the trotting gait with stability control. As the robot moved, the IMU sensor recorded changes in the yaw angle after each movement cycle. The yaw angle continued to change in accordance with the robot's position during each cycle. Based on the yaw angle obtained in this test, the change in the robot's distance from the set point in each cycle was calculated.

The total error in the distance change from the set point during the trotting gait was determined by summing the distance values of the robot's position from the set point across each cycle. In this test, a total error of ± 0.34 cm was recorded. The robot's movement range was then empirically determined through direct observation. Each robot requires a specific range to move stably, which varies depending on the robot. The movement range was established based on the robot's behavior using fuzzy control. From the experiments, the robot's movement range was found to be within ± 1 cm. The speed of movement adjustment varies among robots based on the torque of the leg servos. The greater the servo torque, the faster the robot can adjust its movement. In this study, a range of ± 1 cm was used, based on the servo torque of the robot used in the research. A comparison of stability tests using the trotting gait with and without fuzzy control shows significant differences in the robot's movement stability. Figure 13 shows the comparative graph of the robot's distance change from the set point using the trotting gait with and without fuzzy control.

Based on Figure 13, it is evident that movement with fuzzy control exhibits smaller and more stable fluctuations compared to movement without fuzzy control. Without fuzzy control, the robot's deviation from the set point increases significantly and passes the allowable tolerance. Besides that, it shows no tendency to return to the set point. The robot experiences an overshoot of approximately 238% of the 1 cm tolerance (exceeding 2 cm), surpassing the allowable limits. On the other hand, with fuzzy control, the highest overshoot is only about 29% of the 1 cm tolerance (approximately 0.3 cm), which remains within the permitted range. This result demonstrates that the robot's movement using the trotting gait with fuzzy control is more stable and balanced than without fuzzy control. The stability test results on the trotting gait with fuzzy control show that the robot can correct and maintain stable movement around the set point. With fuzzy control, the problem of instability of the robot's movement relative to the z-axis (yaw) can be overcome by dynamically adjusting the servo angle to compensate for differences in servo torque and external disturbances. Fuzzy control provides flexibility and real-time adjustment, allowing the robot to maintain better balance and movement stability, even in challenging conditions.

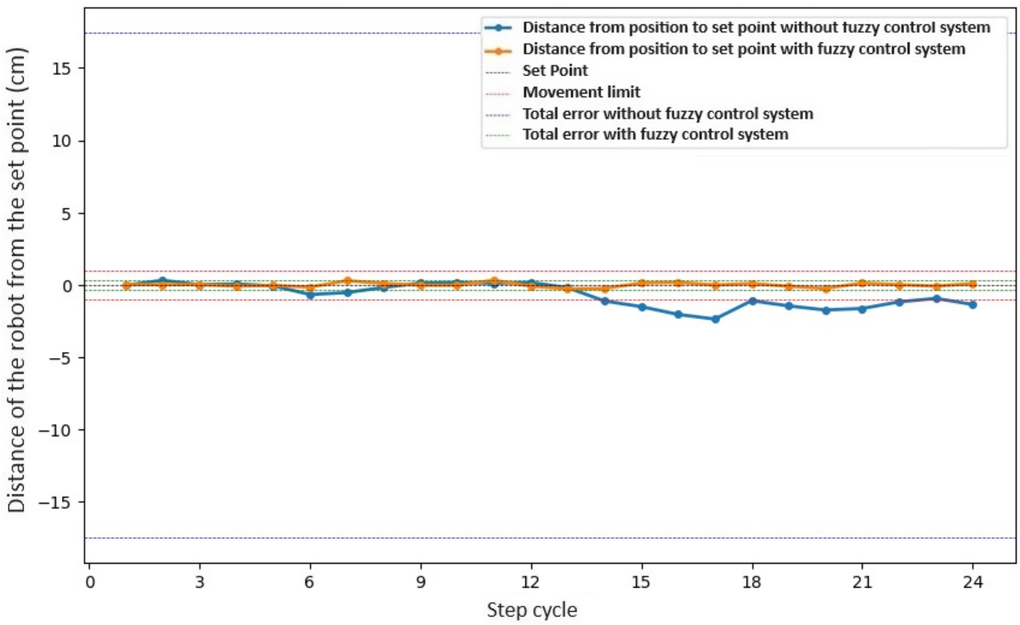


Figure 13. Comparative graph of the robot's distance change from the set point using trotting gait with and without fuzzy control system.

This study supports the use of quadruped robots for goods distribution in industry through the application of fuzzy logic control, which has been proven effective in maintaining the stability of robot movement. The control system developed focuses on managing the yaw angle, which is critical in maintaining balance while the robot moves. In goods distribution, this stability is very important to ensure that the goods carried remain safe and do not roll over or fall due to external disturbances or internal dynamics. In addition, fuzzy logic control can overcome position fluctuations by self-tuning and keep the robot on track even if there is a disturbance while the robot is moving. With these advantages, a four-legged robot equipped with fuzzy logic control can be a solution for distributing goods stably in industrial environments, especially on flat terrain. The findings in this study can be developed, especially the application of four-legged robots in goods distribution scenarios, which support operational efficiency.

Although fuzzy control improves stability, small errors in the robot's distance from the set point still occur. These errors are due to the mechanical variability of each servo. When the robot moves, a foot consisting of a servo with less torque than the others may cause the foot to be unable to push the robot's body firmly during stance phases. This prevents the robot from immediately returning to the desired position, even if the adjustment value is appropriate.

5. CONCLUSION

This study explored the stabilization of quadruped robots using fuzzy logic control, focusing on two common gaits: walking and trotting. The research demonstrated that stability is crucial for effective quadruped robot locomotion, particularly in maintaining a consistent trajectory and compensating for internal and external disturbances. Through a series of stability tests, it was observed that without any balance control system, the robot's movement exhibited significant deviations from the set point, leading to instability, especially in the yaw angle. This instability was more pronounced in the trotting gait, where the robot consistently moved away from the set point, indicating the need for a robust control mechanism.

The implementation of a fuzzy control system proved effective in addressing these issues. By dynamically adjusting the servo angles based on real-time yaw angle readings, the fuzzy control system enabled the robot to maintain a more stable trajectory. The comparison between movements with and without fuzzy control clearly showed that the fuzzy control system significantly reduced the total error in both gaits, keeping the robot within the designated movement range and closer to the set point. Despite the improvements, the study also highlighted the presence of small errors in the robot's position, attributed to mechanical variability in the servos. These findings suggest that while fuzzy logic control greatly enhances stability, further refinement in servo performance or additional control strategies may be necessary to achieve even greater precision.

In conclusion, this study shows that the quadruped robot walking control system using fuzzy logic is quite effective in improving the stability of the four-legged robot, especially in managing the complexity of walking and running movements. The results of this study show the importance of advanced control systems in developing more robust and adaptive four-legged robots to explore various types of terrain with greater understanding and efficiency. Further research will extend these findings to address real-world challenges, such as uneven terrain, slopes, and more complex external disturbances, including dynamic loads and sudden environmental changes. In addition, testing the robot in a real industrial environment and developing a control algorithm that can adapt in real-time will be a priority. The goal is to improve the robot's adaptability, robustness, and ability to meet the needs of various applications, especially the distribution of goods on rough terrain.

Additionally, further research is planned to evaluate the impact of servo variability on motion stability in more complex scenarios, such as dynamic loads and uneven terrains. Exploration of the use of more sophisticated actuators with more stable torques will also be carried out to reduce mechanical variability. In addition, alternative control algorithms, such as adaptive control or machine learning, are planned to overcome the limitations of current servos. Adding additional sensors, such as LiDAR or IMU with higher accuracy, will be a priority to improve the robot's ability to monitor and adjust motion in real-time. These steps will be the focus of further development to improve the robot's stability and performance in various complex environmental conditions.

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