Balance Control of a Hexapod Robot Using Fuzzy Logic and Inverse Kinematics Algorithm with Real-Time IMU Sensor Measurement

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Robotic technology is a crucial pillar in modern civilization, especially in high-risk environments such as post-disaster evacuation scenarios. Hexapod legged robots are designed to navigate uneven terrains that are inaccessible to humans. Although hexapods offer superior mobility and flexibility, they face stability challenges when moving on inclined surfaces due to uneven load distribution, which can affect servo motor performance. To address this issue, this study implements a control system combining fuzzy logic and inverse kinematics to maintain body stability. An Inertial Measurement Unit (IMU) sensor is also integrated to detect the robot’s orientation angle in real-time, enabling adaptive posture correction. This research focuses on three main problems: first, how inverse kinematics can stabilize hexapod posture on sloped surfaces; second, how IMU sensors detect inclination and orientation; and third, how fuzzy logic control contributes to balance regulation. The methodology involves system design, experimental testing, and performance analysis based on the robot's body tilt measurements across various inclinations. The results show that the proposed system responds effectively to surface tilt, particularly in pitch angle correction and maintaining a neutral position. Inverse kinematics successfully calculates leg configurations to keep the body posture stable. The IMU sensor demonstrates high accuracy in angle detection, while fuzzy logic provides flexibility in decision-making for posture control. The integration of these three approaches proves effective in maintaining hexapod balance on inclined terrains, thus supporting their potential use in complex, unstable environments.

Keywords: Hexapod Robot, Inverse Kinematics, IMU Sensor, Fuzzy Logic, Robot Balance, Inclined Surface.

I. INTRODUCTION

Balance is a vital aspect in the movement of hexapod robots, especially when carrying loads such as glasses filled with water [1]. The stabilization system functions to keep the robot's body aligned and its legs moving in coordination, thereby preventing excessive shaking or tilting [2]. Without proper stability, the robot may lose its footing, veer off course, or make sudden movements that cause the water to spill [3]. Spilled water not only reflects a failure to maintain the load but also indicates that the mechanical system and motion algorithms are unable to adapt to dynamic conditions [4]. Therefore, stabilization is not merely a supporting function but the core of the hexapod robot's success in sensitive load-carrying scenarios [5].

Currently, many hexapod robot control systems still use conventional control approaches that require high-precision mathematical calculations and manual intervention to adjust movement and balance [6]. This approach is often less adaptive to real-time changes in terrain conditions, thereby reducing the efficiency and stability of the robot's movement [7]. Previous studies have developed inverse kinematics-based control systems to mathematically regulate leg position and orientation [8]. However, most of these systems have not integrated adaptive control mechanisms capable of adjusting movement based on real-time sensor input, especially in unstructured conditions [9].

Additionally, although sensor technologies such as IMUs (Inertial Measurement Units) have been widely used in navigation and stabilization systems [10], the integration of IMUs with adaptive control logic such as Fuzzy Logic Control has rarely been fully developed on hexapod platforms [11]. IMU-based systems are known to enhance robot movement stability, but many still rely on manual parameter tuning [12]. Some systems only use IMU for posture estimation without being followed by automatic motion correction through adaptive intelligent control [13].

This research presents a new innovation in hexapod robot control that not only utilizes inverse kinematics algorithms for leg motion control [14], but also combines them with a Fuzzy Logic Control system to adaptively adjust balance based on real-time IMU sensor readings [15]. This integration concept has proven to enhance the robot's performance in traversing uneven terrain, such as rocky or sloped surfaces [16]. Thus, the system can stabilize the robot's body position against changes in slope or external disturbances without requiring complex reprogramming [17].

Thus, the use of hexapod robots resembling multi-legged organisms in nature is highly relevant for implementation in various tasks requiring high stability on uneven terrain [18]. The six-legged structure has been proven to provide more even load distribution and better resistance to loss of balance compared to two- or four-legged robots [19] As the need for intelligent robotic systems capable of operating autonomously increases, the development of adaptive and responsive control systems to environmental dynamics becomes a critical aspect in supporting the performance and reliability of robotic systems in various application conditions [20].

II. METHODS

A. Definition of Methods

This research is classified as Research and Development (R&D), which aims to design, develop, and test the effectiveness of a real-time sensor-based hexapod robot balance control system. The main objective of this research is to create a control system product capable of automatically stabilizing the robot's body position when experiencing changes in tilt angle, using the Fuzzy Logic Control approach [21] and Inverse Kinematic algorithm [22] [23]. This method was chosen because it is effective in producing a product while also testing its functionality and performance [24].

The development model used in this research includes the stages of analysis, design, and implementation. This model has been widely applied in the development of technology-based systems because it ensures that the final product truly meets user needs and is suitable for the application environment [25].

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B. Research Stages

1. Analysis

This stage is carried out to identify problems in maintaining the balance of the hexapod robot, especially when the robot is walking on uneven or sloping terrain, or experiencing external forces. From literature studies and field observations, it is known that traditional control systems such as pure PID are not yet capable of adaptively anticipating changes in body position. Therefore, integration between IMU sensors and fuzzy logic systems is required to detect changes in the roll and pitch angles of the robot's body and automatically correct its posture [26] [27].

2. Design

In the manufacture of mechanical systems, 3 mm thick acrylic material is used because it is lighter and reasonably strong, thereby reducing the load on the robot. For electronic systems, several components are assembled into a single system [28].

a. Sistem elektronik

It consists of a series of electronic components, including ESP32, GY-521, OLED, PCA9685, servo, step down, battery, and switch, as shown in Figure 1.

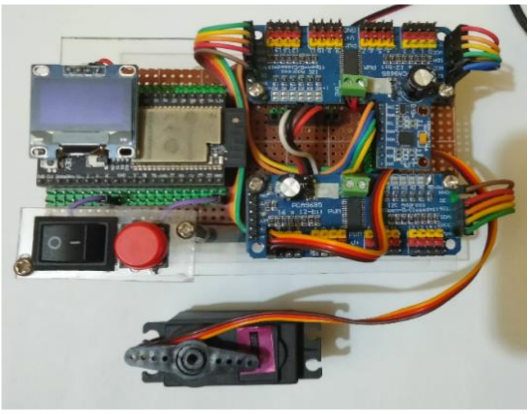

Figure 1. Components used

b. Sistem mekanik

It has several parts that are combined into a single unit, with a body frame that is cm long and cm wide. The shape of the robot's body can be seen in Figure 2.

Figure 2. Body frame shape

Next, there is a leg shape that has three parts consisting of the coxa, femur, and tibia with different lengths, such as the coxa measuring 15 mm, the femur measuring 75 mm, and the tibia measuring 120 mm, as shown in Figure 3..

Figure 3. Robot leg design

After all parts are combined and assembled into a system, the result will be as shown in Figure 4.

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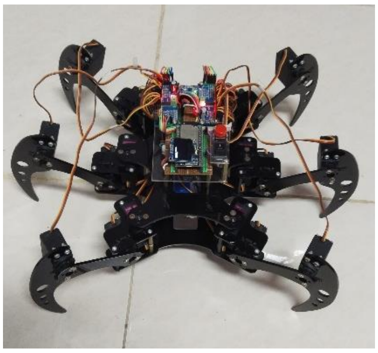

Figure 4. Appearance of the hexapod robot

3. Implementation

System testing was conducted directly on the hexapod robot unit with disturbance scenarios such as: ±15° inclined plane, lateral thrust, and surface changes. The system was tested in static (stationary) mode. The IMU sensor reads position changes and activates real-time posture compensation [29]. If the pitch or roll exceeds the 5° threshold, the fuzzy system adjusts the leg angles to return to a balanced position, as shown in Figure 5.

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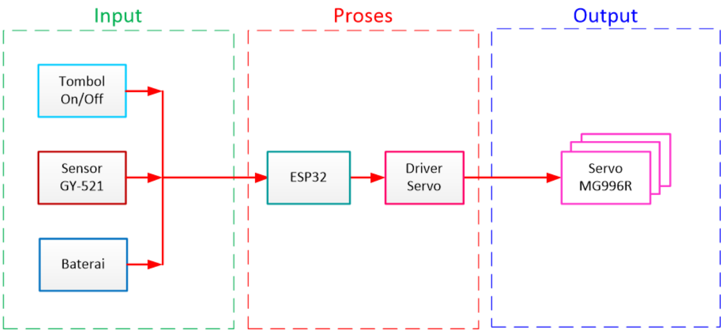

Figure 5. System block diagram

III. RESULT AND DISCUSSION

A. Results

The results of the study show that the developed hexapod robot balance control system is capable of maintaining the stability of the robot's body orientation under various surface inclination conditions. This system integrates fuzzy logic-based control and inverse kinematics algorithms with real-time measurements using IMU sensors. The IMU sensors accurately detect changes in orientation angles, which are then processed by fuzzy logic to generate control signals to the servos. The inverse kinematics algorithm then calculates the robot's leg positions to keep the body in a stable position. Test results show that the system can adaptively and gradually respond to changes in inclination and maintain the robot's stability at various inclination levels, thereby demonstrating the effectiveness of the control approach used in this study [30] [31].

Robot leg testing was conducted to evaluate the system's ability to precisely control the position and movement of the legs based on inverse kinematic algorithm calculations. The main objective of this test was to ensure that each robot leg could move according to the specified target coordinates and support the overall stability of the robot body. The testing was conducted under various surface inclination conditions to assess the system's adaptability to changes in body orientation. By utilizing angle inputs from the IMU sensor and signal processing via fuzzy logic, the robot legs are expected to adjust their positions responsively to maintain the robot's balance both during movement and in static conditions [32] [33].

Table 1. Table of Servo Motor Testing on Robot Legs

Leg section	**Right front foot servo angle (°)**
Coxa	45
Femur	30
Tibia	60

Table 1 shows the results of testing the servo motor angle on one of the robot's legs, namely the front right leg. This testing was conducted to ensure that each joint—the coxa, femur, and tibia—can achieve the specified angles with precision based on inverse kinematic algorithm calculations. The test results indicate that the servo in the coxa section can move at a 45° angle, the femur servo at a 30° angle, and the tibia servo reaches a 60° angle. These three angles indicate that the robot leg can perform articulation movements according to the input parameters, which is crucial for supporting the robot's stability and flexibility in responding to changes in terrain. The consistency in achieving these angles also demonstrates that the actuators and control system operate synchronously in executing the leg position commands [34] [35] [36].

In fuzzy logic systems, rules (fuzzy rules) are the core of the decision-making process. These rules represent the logical relationship between inputs and outputs based on the desired knowledge or behavior of the system. In this designed fuzzy system, the Mamdani approach is used with 25 fuzzy rules formulated to reflect the relationship between two input variables, Roll and Pitch, and one output variable, Correction. Each rule consists of a combination of linguistic values on the input, which will produce a specific correction response. The structure of these rules allows the system to make decisions flexibly in uncertain or ambiguous conditions [37] [38] [39].

```
function fis = kemiringan_fis_manual()
    fis = mamfis('Name', 'kemiringan_fis');

    % Input 1: Roll
    fis = addInput(fis, [-25 25], 'Name', 'Roll');
    fis = addMF(fis, 'Roll', 'trimf', [-25 -25 -12.5], 'Name', 'SangatKiri');
    fis = addMF(fis, 'Roll', 'trimf', [-25 -12.5 0], 'Name', 'Kiri');
    fis = addMF(fis, 'Roll', 'trimf', [-12.5 0 12.5], 'Name', 'Tegak');
    fis = addMF(fis, 'Roll', 'trimf', [0 12.5 25], 'Name', 'Kanan');
    fis = addMF(fis, 'Roll', 'trimf', [12.5 25 25], 'Name', 'SangatKanan');

    % Input 2: Pitch
    fis = addInput(fis, [-25 25], 'Name', 'Pitch');
    fis = addMF(fis, 'Pitch', 'trimf', [-25 -25 -12.5], 'Name', 'SangatKiri');
    fis = addMF(fis, 'Pitch', 'trimf', [-25 -12.5 0], 'Name', 'Kiri');
    fis = addMF(fis, 'Pitch', 'trimf', [-12.5 0 12.5], 'Name', 'Tegak');
    fis = addMF(fis, 'Pitch', 'trimf', [0 12.5 25], 'Name', 'Kanan');
    fis = addMF(fis, 'Pitch', 'trimf', [12.5 25 25], 'Name', 'SangatKanan');

    % Output: Koreksi
    fis = addOutput(fis, [-25 25], 'Name', 'Koreksi');
    fis = addMF(fis, 'Koreksi', 'trimf', [-25 -25 -15], 'Name', 'NegatifBesar');
    fis = addMF(fis, 'Koreksi', 'trimf', [-20 -15 -5], 'Name', 'NegatifSedang');
    fis = addMF(fis, 'Koreksi', 'trimf', [-10 0 10], 'Name', 'Netral');
    fis = addMF(fis, 'Koreksi', 'trimf', [5 15 20], 'Name', 'PositifSedang');
    fis = addMF(fis, 'Koreksi', 'trimf', [15 25 25], 'Name', 'PositifBesar');
```

```
    % Aturan fuzzy (25 rules)
    ruleList = [...
        1 1 5 1 1;
        1 2 4 1 1;
        1 3 4 1 1;
        1 4 3 1 1;
        1 5 3 1 1;
        2 1 4 1 1;
        2 2 4 1 1;
        2 3 3 1 1;
        2 4 3 1 1;
        2 5 2 1 1;
        3 1 4 1 1;
        3 2 3 1 1;
        3 3 3 1 1;
        3 4 2 1 1;
        3 5 1 1 1;
        4 1 3 1 1;
        4 2 3 1 1;
        4 3 2 1 1;
        4 4 2 1 1;
        4 5 1 1 1;
        5 1 3 1 1;
        5 2 2 1 1;
        5 3 1 1 1;
        5 4 1 1 1;
        5 5 1 1 1];

    fis = addRule(fis, ruleList);
end
```

Figure 6. Fuzzy in pseudocode form

B. Discussion

The roll angle on the robot body is measured to determine how well the robot control system is able to follow specific body angle commands with the help of IMU sensors. The test was conducted on nine.

Table 2. Testing the robot body at roll angles

NO	Position testing on the roll angle robot body								
	−25°	-20°	−15°	-10°	0°	10°	15°	20°	25°
1.	18°	15°	−12°	−8°	0°	5°	8°	11°	16°
2.	−19°	−14°	−11°	−9°	0°	6°	7°	10°	15°
3.	−17°	−16	−13°	−6°	0°	8°	12°	16°	17°
4.	−5°	−14°	−9°	−5°	0°	7°	10°	14°	14°
5.	−14°	−13°	−12°	−7°	0°	5°	13°	15°	18°

Testing of the roll angle on the robot body was conducted to determine how well the robot control system is able to follow specific body angle commands with the help of IMU sensors. The testing was conducted on nine target angles, ranging from -25° to 25°. From five tests for each angle, data was obtained showing the actual response of the robot to the command. In general, the roll angle measurement results show that there is a deviation between the target angle and the actual angle. At negative angles (e.g., -25°, -20°, and -15°), the values read from the IMU sensor are still far above the target values on average. For example, at a target angle of -25°, the average measurement only reached around -13.4°. This indicates that the system has difficulty achieving extreme negative roll angles, which could be caused by mechanical limitations or the controller's inability to maintain body stability as negative tilt increases. Meanwhile, at positive angles, the system performed better. Between 10° and 25°, the difference between the target and actual values is relatively small. For example, at a target angle of 20°, the average obtained is 13.2°, and at 25°, the average is 16°. This indicates that the system is more responsive to roll commands in the positive direction than in the negative direction. Causes may include the robot's weight distribution design, actuator efficiency, or imbalance in shear forces between the legs. Additionally, at the neutral angle (0°), the system shows excellent results with the average measurement precisely at 0°, indicating that the IMU and posture control systems have high precision in the upright position. This is an indicator that sensor calibration is functioning well under conditions without tilt angles [40] [41] [42]. The choice of actuator is, therefore, essential for minimizing deviations from target angles, particularly under duress, such as at negative tilt angles.

Table 3. Testing the robot body at the pitch angle

NO	Position testing on the roll angle robot body								
	−25°	−20°	−15°	−10°	0°	10°	15°	20°	25°
1.	−19°	−14°	−11°	−8°	0°	9°	13°	16°	19°
2.	−19,2°	−14,4°	−11,2°	−8,5°	0°	9,5°	14°	15°	20°
3.	−18,9°	−15,1	−10,8°	−7°	0°	8°	12°	16°	15°
4.	−19,1°	−14,9°	−10,11°	−7,5°	0°	7°	10°	14°	16°
5.	−18,5°	−14,2°	−12,5	−8,1°	0°	9°	11°	13°	18°

In the pitch angle test, a similar approach was taken, namely testing the performance of the robot's posture control against nine target pitch angles from -25° to 25°. An IMU sensor was used to read the actual angle achieved by the robot's body in each position.

From the data obtained, it was found that the system also experienced a decrease in accuracy at negative angles, although not as severe as in the roll test. For example, at the target angle of -25°, the average measurement result was -19.14°. In other words, despite the deviation, the system was still able to approach the target angle better than roll. This indicates that the system's response to negative pitch is more stable and better controlled. At positive pitch angles, the system's performance appears to be even better. For example, at target angles of 10° to 25°, the actual results were close to the target, with a deviation of only about 1.5°–3°. The average result for the 25° target is 17.6°, which is quite close to the target, though not yet perfect. This more stable performance may indicate that pitch movements are easier to control by the mechanical system and controller, likely because the pitch direction aligns with the robot's longitudinal axis, which tends to be more stable than the transverse axis (roll). As with the roll test, at 0°, the system recorded an actual value of 0°, indicating that the system is in optimal condition for the neutral position. This serves as evidence that the IMU sensor system has been properly calibrated in a horizontal condition [40] [41] [42].

IV. CONCLUSION

Based on the results of testing and analysis that have been conducted, it can be concluded that the robot stability control system using inverse kinematics algorithms, IMU sensors, and fuzzy logic shows good performance in adjusting the robot's body orientation to surface inclinations. The inverse kinematics algorithm has proven effective in calculating and adjusting the position of the robot's legs to keep the body stable, even with small deviations in negative angles, especially in the roll direction. This demonstrates the system's ability to adaptively maintain the robot's body stability on uneven terrain.

The IMU sensor provides sufficiently accurate orientation angle readings, especially in neutral and positive pitch positions, with deviations still within the system's control tolerance limits. Meanwhile, the application of fuzzy logic in the control system enables smooth and flexible decision-making based on the slope data received from the sensor. The system's response to changes in tilt angle, especially when commands are given gradually between -25° and 25°, demonstrates that fuzzy logic can maintain the robot's orientation in a stable and adaptive manner. Overall, the integration of these three components forms an effective and responsive robot balancing system.

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