Implementation of Inverse Kinematics Method for Self-Moving on Hexapod Robot

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ABSTRACT
The development of robotics is overgrowing with the increasing number of robot competition activities in Indonesia. One of the divisions in the Indonesian robot competition is smart robots. One of the obstacles in the smart robot competition is the uneven playing field. The design of the legged robot system is an option to overcome these obstacles. The smart robot has six legs resembling insects, often called a hexapod robot. This study aimed to determine the results of implementing the inverse kinematics method on the balance of the hexapod robot when doing self-moving. This research starts by designing the mechanical system of the hexapod robot, designing the self-moving, and testing the balance of the self-moving on the hexapod robot with the inverse kinematics method. The design of the mechanical system includes the design of the robot body layout, the design of the robot legs, the sensor settings, and the servo motor movement settings. Designing the hexapod robot body's layout includes determining the number of legs on the robot body, as many as six robot legs. While in the design of the robot legs, each robot leg has 3 degrees of freedom. A servo motor drives each angle of degrees of freedom on each leg of the robot, so the number of servo motors needed is 18. Furthermore, the design of the self-moving system includes the analysis of the coordinate transformation of the robot body and legs. The last stage is to test the self-moving balance using the inverse kinematics method on the hexapod robot. The test is carried out by determining the initial angle on each servo motor of each robot leg, then moving the robot leg on the Y axis from 72 to 78.9 to obtain a change in angle with the same pattern at the initial angle. This shows that the inverse kinematics method is suitable for adjusting the balance of the hexapod robot when doing self-moving.

Keywords: robot, hexapod, inverse kinematics, self-moving, servo motor, degree of freedom

1. INTRODUCTION

The development of science in robotics is overgrowing today. Robots in various industries have begun to be widely used to assist human tasks, such as robots in industrial and manufacturing machines [1]. In addition, in Indonesia, robots have begun to develop for matches organized by the Ministry of Education, Culture, Research, and Technology, which include six divisions, namely ABU robots, smart rescue robots, wheeled soccer robots, humanoid soccer robots, dance robots, and thematic robots [2]. One of the robot contest divisions constantly changing is the smart robot. One of the obstacles in the smart robot competition is the uneven competition arena, so a legged smart robot system is designed [3]. A legged robot is a robot that can walk like an animal or a human [4]. A legged robot has multiple input and outputs systems, so the mechanical design, framework, and control system are often faced [5]. The design of the legged robot is inspired by insects, where the legs of insects have a complex structure so that they can walk on various types of terrain. The insect-like legged robot that is often used is a six-legged or often called a hexapod robot [6].

Some things that need to be considered when designing a hexapod robot are the mechanical design and control system [5]. One mechanical design that needs to be considered is the leg movement system on the robot. An actuator is needed to control the movement of the robot's legs. In this case, the joint motion of the legged robot uses a servo motor controlled through a servo controller. In making a servo controller, it is necessary to pay attention to several things, including the number of servo motors needed and the type of input used [7]. In addition to the mechanical system, another thing to consider is the control system. One system to control movement and guide direction is a sensor [8]. The sensor is an input to the agent that will bring the calculation results to the microcontroller [9]. This hexapod robot requires many sensors, so many agents are needed, so there needs to be an agent organization that can handle various calculations on this system [10]. One of the systems used to organize various agents in the hexapod robotic footwork system is forward kinematics and inverse kinematics [10] [11].

Previous research on the forward kinematics method has been applied in designing the hexapod robot movement system [12] and the landing gear drive system on the multi-copters robot [13]. While previous research related to the inverse kinematics method has been applied in the design of motion systems that have various degrees of freedom, including the Gough-Stewart parallel robot with 6 degrees of freedom used in nuclear reactors [14], welding and drilling robots that have 7 degrees of freedom [15], robotic arms for pick and place with 4 degrees of freedom [16], and various motion applications with various degrees of freedom systems.

Inverse kinematics analysis has been widely used to control motion with various degrees of freedom. One of the systems with movement that uses various degrees of freedom is the hexapod robot. The hexapod robot design was chosen with the hope that it can run well on various flat and uneven surfaces. In the movement of the hexapod robot, the critical thing to note is the balance when doing self-moving. Therefore, it is necessary to do a test related to the balance of the hexapod robot when doing self-moving using the inverse kinematics method. This is to get a dynamic balance when the robot's legs are moved, where each leg has an autonomous movement system.

This study aimed to determine the results of implementing the inverse kinematics method on the balance of the hexapod robot when doing self-moving. This research starts by designing a hexapod robot which includes self-moving design and self-moving balance testing on a hexapod robot with the inverse kinematics method. Self-moving design includes coordinate transformation and hexapod layout design. After the self-moving design, the robot body balance is tested when self-moving using the inverse kinematics method.

2. METHODS

In this study, the main focus is on how to design a hexapod robot that has a balance when doing self-moving. To make it easier to understand the research flow, this method section is divided into three parts: the design of a hexapod robotic mechanical system, the design of a self-moving system, and testing the robot's balance using the inverse kinematics method.

At the design stage of the hexapod robot mechanical system, things that need to be considered include the design of the robot body, the numbering of the legs on the robot body, and the design of the robot legs. The leg numbering on the robot body will make it easier when programming to determine the movement of each robot leg. In designing robotic legs, it is necessary to pay attention to the shape of the robot's leg movements so that it is known how many degrees of freedom are needed, where a servo motor drives each degree of freedom on the legs of the robot.

The next stage is to design a self-moving system. In designing a self-moving system, things that need to be considered are the coordinate transformation, sensor settings, and servo motor movement settings. To regulate the robot's movement, it is necessary to pay attention to the coordinate transformation because it is related to the width and length of the robot body. In the transformation settings, the coordinates are determined by the center point of the robot body, so the coordinates on the robot's legs adjust. This sensor setting serves to control the movement of the robot, mainly to avoid the movement of the robot crashing into a barrier or wall. In comparison, the regulation of servo motor movement is carried out based on the results of the coordinate transformation analysis on the legs of the robot.

The last stage is testing the balance of the robot movement with the implementation of the kinematic method. Two types of kinematic methods are used to control the robot's movement, inverse kinematics, and forward kinematics. Inverse kinematics is a way to determine the orientation and position of the end effector coordinates (X, Y, Z). The effector coordinate is the center point of the mass distribution which will be given the connecting angle and the connecting arm from the length of the robot arm (servo position). This equation is deterministic, so the servo angular position on each connecting arm is known [17]. Forward kinematics as opposed to inverse kinematics. Forward Kinematics is a method for determining the orientation and position of the end effector from the magnitude of the connecting angle and the connecting arm. The forward kinematics equation is obtained based on the number of degrees of freedom and the type of kinematic chain from the hexapod robot leg [18]. Forward kinematics is not used in this research method because a change in the angle of a servo motor on an effector will affect the whole movement. However, given a change in the coordinates, the whole set of effectors (servo) may have to move at a certain angle to reach the desired position. Using the kinematic method for both inverse and forward kinematics needs to know how many degrees of freedom the robot leg design is. The design of the mechanical system on this hexapod robot uses legs with 3 degrees of freedom. An illustration of the robot leg model with 3 degrees of freedom can be seen in Figure 1.

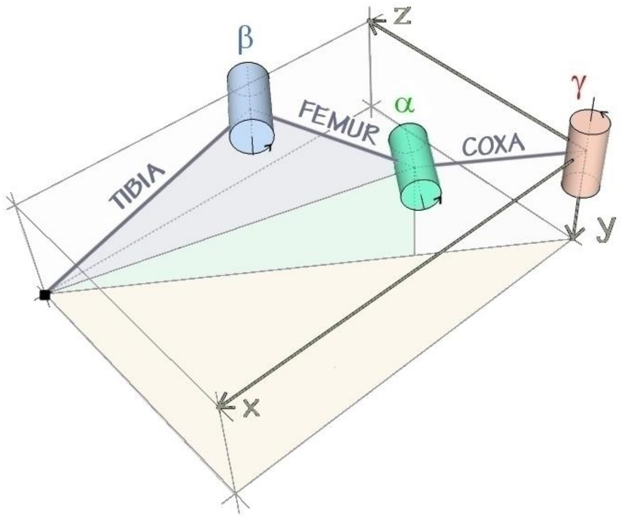


Figure 1. Robot leg model with 3 degrees of freedom [17]

3. RESULTS AND DISCUSSION

3.1. Hexapod Robot Mechanical System Design

In designing the mechanical system of a robot, the primary consideration is the type of robot to be made and the function of the robot. In this study, the robot design to be designed is a hexapod robot or a robot with six legs. The first stage in designing a robotic mechanical system is designing the robot body, then designing the robot legs, setting sensors and servo motor movements, and finally designing self-moving movements.

a. Hexapod Robot Body Layout Design

The first hexapod robotic mechanical system is to design the layout of robotic bodies. The layout of this robot's body will be used as a standard for placing the robot's legs. Where each leg of the robot will move autonomously, it is necessary to regulate the movement of each leg. A leg number is given to the robot's body to make it easier to set up. The robot that will be made is hexagonal-shaped, so the number of robot legs is 6 feet with the exact distance between the sides of the legs. Details of the design of the robot body layout in question as shown in Figure 2.

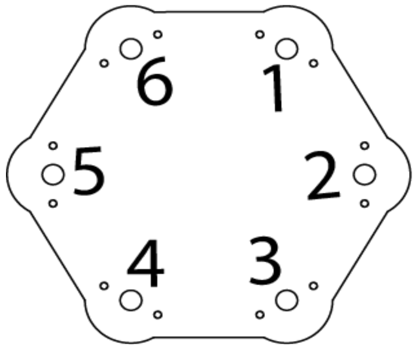


Figure 2. Numbering the legs on the hexapod robot body

b. Hexapod Robot Leg Design

After designing the layout of the hexapod robot body, the next step is to design the legs of the robot. The number of robot legs is 6, each of which can move autonomously. Each leg of the robot has 3 degrees of freedom, so three servo motors are installed. Therefore, to move all the legs on the hexapod robot, 18 servo motors are needed. Each servo motor has its angle value. The design of the hexapod robot leg can be seen in Figure 3.

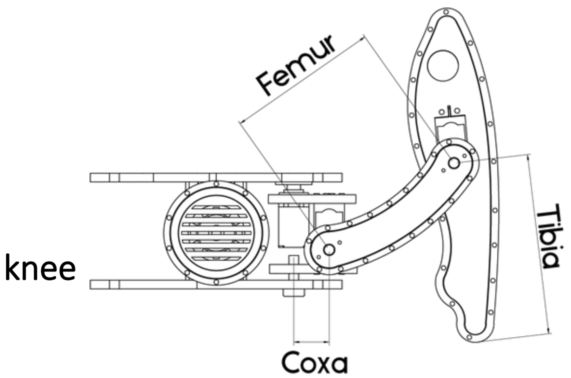


Figure 3. Design of hexapod robot legs

c. Servo Motor Sensor and Movement Settings

The next step is to adjust the need for the sender to help the hexapod robot move. The sensor used to guide the motion of the hexapod robot is an ultrasonic sensor. An ultrasonic sensor consists of a transmitter and a receiver with the working principle of wave reflection. The transmitter unit emits ultrasonic waves through the air medium. If the ultrasonic wave hits an object, then the wave will be reflected and received by the receiver unit on the sensor, thus producing an alternating voltage with the same frequency [19]. The working principle of the ultrasonic sensor can be seen in Figure 4; namely, the trigger or trigger is blocked by an object, and then it is reflected into an echo or echo [20]. Based on Figure 4, the distance between the sensor and the obstacle object can be an equation as in Equation (1).

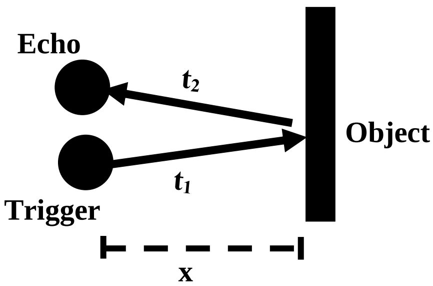


Figure 4. How the ultrasonic sensor works

$$x = \frac{vt}{2} \tag{1}$$

Information:
x = Distance (m)
v = Speed of wave propagation in air (m/s), which is 340 m/s at 25 ^{0}C and 330 m/s at 0 ^{0}C
t = Time (s)

After setting the sensor, the next step is to adjust the servo motor movement. To control the servo motor, pulse width modulation (PWM) is used by manipulating the width of the signal expressed by pulses in a period (duty cycle). This expression with pulses in a period is used to obtain different average voltages. The SG90 servo motor has a pulse width of 20 ms every period with a frequency of 50 Hz. To adjust the servo position to an angle of 0^o, the servo is given a pulse width of 1.5 ms. To adjust the servo motor's position to an angle of 90^o clockwise, a pulse width of 2 ms is given. To adjust the servo motor's position to an angle of 90^o counterclockwise, a pulse width of 1 ms is given.

3.2. Self-Moving System Design

The second stage in designing a hexapod robot is to design a self-moving system. The principle of movement of the hexapod robot is that when the robot's body is moved, it will continue to coordinate the movement of its legs. Therefore, the movement of the robot body will change the angle of each servo on all robot legs simultaneously. In general, there are three types of robot movement: roll, pick, and yaw. If the robot moves to the right, the center of the robot body moves from the red color to the blue dot, as shown in Figure 5. The movement of the coordinates of the legs will move to the right the same as the distance from the center of the robot.

The displacement of the robot body will not change position in absolute terms from the position of the robot legs, but the position of the robot legs will be relative to the center point of the robot body. To facilitate the analysis, the position of the robot's legs needs to be converted into a value. The change in the position of the robot's legs is analyzed by calculating the coordinate transformation. The inverse kinematics procedure calculates the last coordinate value of the robot leg. Furthermore, the results of these calculations are described in the program or microcontroller code to provide the angle value on the servo motor.

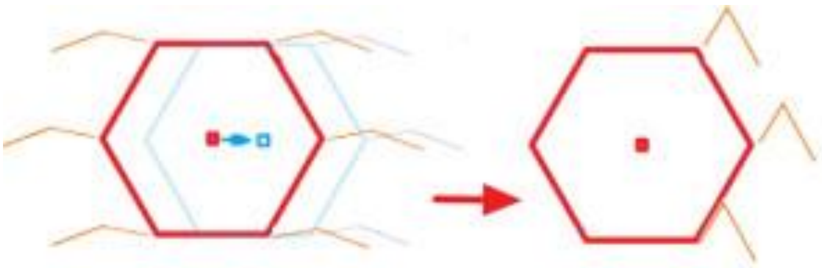


Figure 5. Illustration of the movement of the hexapod robot [17]

Frame coordinates must refer to the hexapod robot body design, as shown in Figure 2. In comparison, the hexapod robot leg design refers to the design shown in Figure 3. So that the determination of the center point of the robot body is very dependent on the dimensions of the robot. Therefore, the robot's dimensions greatly determine each movement's value during the implementation of inverse kinematics. Based on these considerations, the configuration of the center point of the hexapod robot body can be seen as shown in Figure 6, where the center point of the X, Y, and Z coordinates is the diagonal of each side of the hexapod robot frame.

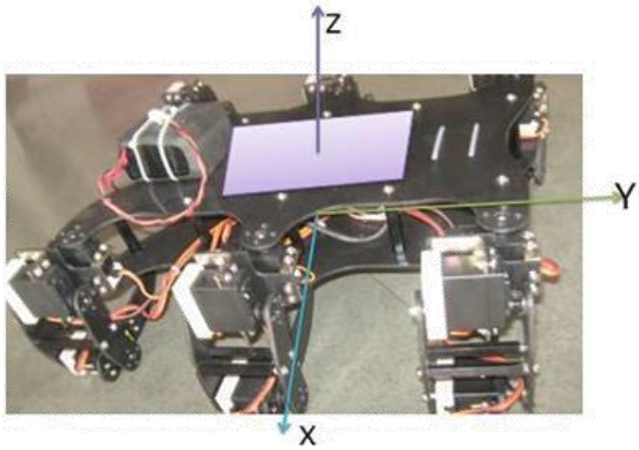


Figure 6. Configuration of the center point of the hexapod robot *body*

Based on Figure 6, each leg is in a different frame on the robot body. Where the front frame is facing each other with the forelegs. So to get a precise value of the robot's movement on the X axis and Y axis or the displacement of the coordinates from X_0,Z_0 to X_1,Z_1, it is necessary to make an equation according to the angle. Therefore, to find a solution from the inverse kinematics method, it is necessary to simplify the system by converting the 3D image in Figure 6 into a 2D image, as in Figure 7. Meanwhile, to find the parameter value of the arm on the robot's leg, it can be seen the movement of the coxa line, namely on the X and Y axes, so that the angle parameter value can be determined by the equations α (alpha), β (beta), and γ (gamma). The following parameter to look for is the knee parameter value (γ). These parameters are required to move the femoral line and the joint parameters to move the tibia. The robot leg model with 3 degrees of freedom is drawn in 2D, as shown in Figure 8. After being seen in the form of a 2D image, the knee parameters (γ) can be calculated using Equations (2) and (3).

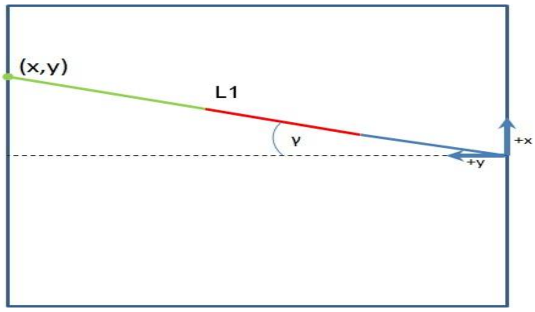


Figure 7. Gamma angle configuration (γ)

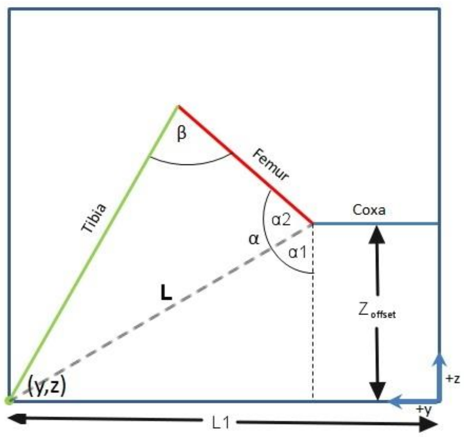


Figure 8. Knee parameters in 2D drawing

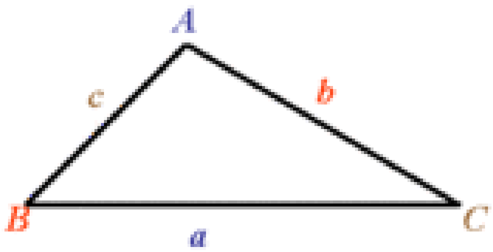
$$\frac{x}{y} = tan(\gamma) \tag{2}$$

$$\gamma = tan^{-1}\left(\frac{x}{y}\right) \tag{3}$$

Based on Figure 8, after the value is known from Equation (3), the value of the other two angles can be known. To get the angle α, it must be divided into angle α_1 and angle α_2. Meanwhile, to obtain the value of α_1, one must first find the value of L with Equations (4) and (5). Meanwhile, the cosine rule is needed to get the value of α_1 and the value of β, as shown in Figure 9.

$$L = \sqrt[2]{Z_{offset}^2 + (L_1 - coxa)^2} \tag{4}$$

$$\alpha_1 = \cos^{-1}\left(\frac{Z_{offset}}{L}\right) \tag{5}$$



$$a^2 = b^2 + c^2 - 2bc\ \cos A \qquad \cos A = \frac{b^2 + c^2 - a^2}{2bc}$$

$$b^2 = a^2 + c^2 - 2ac\ \cos B \qquad \cos B = \frac{a^2 + c^2 - b^2}{2ac}$$

$$c^2 = b^2 + a^2 - 2ab \cos C \qquad \cos C = \frac{a^2 + b^2 - c^2}{2ab}$$

Figure 9. Cosine rule

Based on the cosine rule in Figure 9, we get three sides of the triangle. Based on the illustration of the triangle's three sides, the value of α_2 can be calculated by Equations (6) and (7). Furthermore, the magnitude of α can be calculated by Equations (8) and (9). Furthermore, the magnitude of β can be known by calculations as in Equations (10) and (11).

$$Tibia^2 = Femur^2 + L^2 - 2(Femur)(L)cos(\alpha_2) \tag{6}$$

$$\alpha_2 = \cos^{-1}\frac{Tibia^2 - Femur^2 - L^2}{-2(Femur)(L)} \tag{7}$$

$$\alpha = \alpha_1 + \alpha_2 \tag{8}$$

$$\alpha = \cos^{-1}\frac{Z_{offset}}{L} + \cos^{-1}\frac{Tibia^2 - Femur^2 - L^2}{-2(Femur)(L)} \tag{9}$$

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$$L^2 = Tibia^2 + Femur^2 - 2(Tibia)(Femur)\cos(\beta) \tag{10}$$

$$\beta = \cos^{-1}\frac{L^2 - Tibia^2 - Femur^2}{-2(Tibia)(Femur)} \tag{11}$$

3.3. Inverse Kinematics Method Testing

a. Initial Positioning

In making movements on the hexapod robot, several things must be considered, namely the characteristics of the angular movement on each part of the robot leg. Each part of the robot leg has a different characteristic of angular movement. This happens because the design on each leg of the robot moves autonomously. Each leg of the robot has 3 degrees of freedom, so it is necessary to analyze every change in angle at each degree of freedom. Each degree of freedom needs to be regulated by the servo motor movement. As a test material, the position at the starting point of the corner on each servo motor on the six legs is conditioned as in Table 1.

Table 1. Servo angle at the starting point

Initial Feet Position						
Leg Number	**1**	**2**	**3**	**4**	**5**	**6**
Feet Pos X (wrt coxa)	23.5	47.0	23.5	-23.5	-47.0	-23.5
Feet Pos Y (wrt coxa)	72.0	72.0	72.0	72.0	72.0	72.0
Feet Pos Z (wrt coxa)	40.7	0.0	-40.7	-40.7	0.0	40.7

Table 1 shows that angles X and Z legs number 1 have the opposite position from angles X and Z legs number 4. While the Y angles on legs number 1 to 6 have the same value. This is because when the robot is standing, the primary shrinkage that supports the center point of the robot body is the Y angle so that every X and Z angle in the diagonal direction is where the robot's legs are. This applies to all legs, namely, leg number 1 and leg number 4, leg number 2 and number 5, and leg number 3 and number 6 will have opposite values. Details of the position can be seen in Figure 1 regarding the numbering of the legs on the robot body.

b. Change of Position by Implementing Inverse Kinematics Method

After determining the initial position of each angle on the servo motor that represents the motion system on the robot's legs, the next step is to test the balance of movement by implementing the inverse kinematics method. The value of each servo motor's angle is calculated by calculating the starting position and end point, and the fiber is calculated step by step until it gets a precision value. To find out how to test the implementation of the inverse kinematics method, try moving one of the robot's legs at an angle of Y of 78.9 degrees, then the other legs will automatically follow. Changes in the robot's legs using the inverse kinematics method can be seen in Figure 10, while the cross-sectional view can be seen in Figure 11.

The final position of each angle on the servo motor of each leg of the robot can be seen in Table 2, where there is a change in value when viewed from the values in Table 1. This happens because there is a movement in one of the robot's legs on the Y axis of 78.9 degrees. However, the change in the value in Table 2 will not change the previous pattern as in Table 1. This shows that the movement of the hexapod robot runs in a balanced manner. Therefore, inverse kinematics is suitable for use in hexapod robot motion modes.

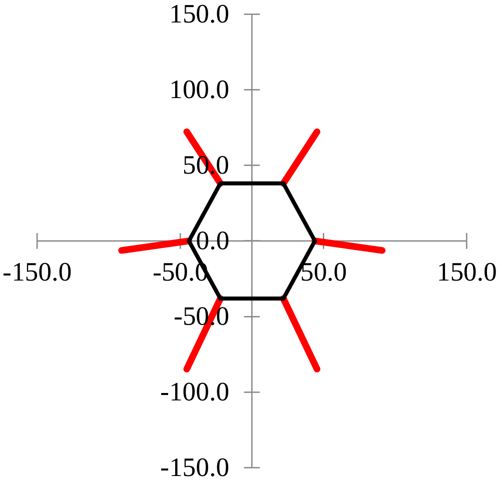
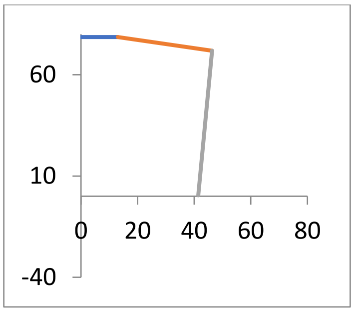
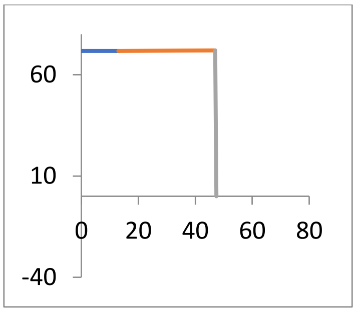


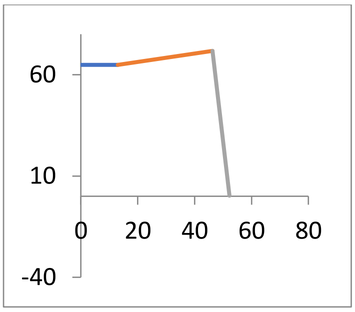
Figure 2. Robot leg movement in inverse kinematics implementation



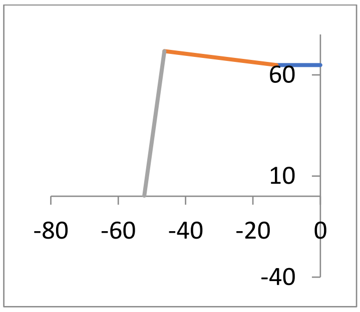
a. Change the angle of leg number 1



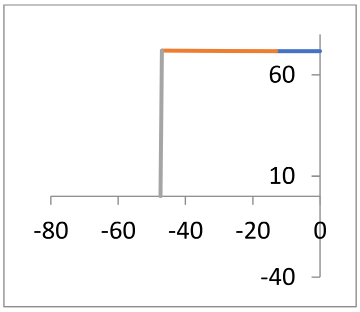
b. Change the angle of leg number 2



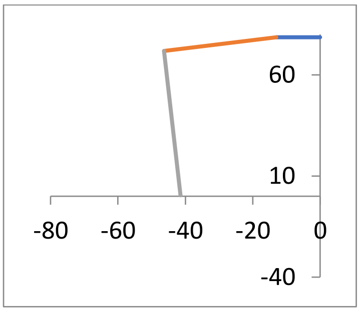
c. Change the angle of leg number 3



d. Change the angle of leg number 4



e. Change the angle of leg number 5



f. Change the angle of leg number 6

Figure 3. Display of servo motor angle changes with inverse kinematics method

Table 2. Change of servo motor angle with inverse kinematics method

Initial Feet Position						
Leg Number	**1**	**2**	**3**	**4**	**5**	**6**
Feet Pos X (wrt coxa)	45.5	91.0	45.5	-45.5	-91.0	-45.5
Feet Pos Y (wrt coxa)	78.9	72.0	65.1	65.1	72.0	78.9
Feet Pos Z (wrt coxa)	78.8	0.0	-78.8	-78.8	0.0	78.8

4. CONCLUSION

Based on the results of research ranging from mechanical system design, and self-moving design, to self-moving balance testing using the inverse kinematics method, it can be concluded that:

1. At the mechanical system design stage, things that need to be considered include the layout design of the robot body, the design of the robot legs, the sensor settings, and the servo motor movement settings. Designing the hexapod robot body's layout includes determining the number of legs on the robot body, as many as six robot legs. While in the design of the robot legs, each robot leg has three angles of freedom. A servo motor drives each angle of degrees of freedom on each leg of the robot, so the number of servo motors needed is 18.
2. At the design stage of the self-moving system, the things that must be considered are the Coordinate transformation analysis of the robot body and robot legs. To make it easier to analyze, the image of the legs is made in 2D so that every angle on the movement of the robot's legs can be calculated.
3. The last stage is testing the self-moving balance with the inverse kinematics method on the hexapod robot. The test is carried out by determining the initial angle on each servo motor of each robot leg, then moving the robot leg on the Y axis from an angle of 72 to 78.9 to obtain a change in angle with the same pattern at the initial angle.
4. Based on the results of the self-moving balance test on the hexapod robot, it can be said that the inverse kinematics method is suitable for adjusting the balance of the hexapod robot when doing self-moving. This is evidenced by the pattern of the final position of each corner being the same as the pattern of the position at the beginning.

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