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Design of 3 DOF hexapod leg movement using inverse kinematics: bridging gaps in multilegged robot kinematics literature

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Abstract
Designing the motion of a hexapod robot with 3 Degrees of Freedom (DOF) using the Inverse Kinematics method allows the robot to move by adjusting the angles of its leg joints according to the desired position and direction. This research involves the geometric and structural design of the hexapod robot and the development of an Inverse Kinematics algorithm to calculate the leg joint angles based on the target pose. The study uses the Inverse Kinematics method to design a hexapod robot for movement with 3 DOF. The testing results show an average Inverse Kinematics error of 1.56 mm on the X-axis, 0.88 mm on the Y-axis, and 0.78 mm on the Z-axis. During the forward and backward movement tests covering a distance of 100 cm, the average error was 2.58 cm and 12.38 cm, respectively. For the rotation tests, the average error was 3.6° for a 90° rotation to the right, 3° for a 90° rotation to the left, 13.2° for a 180° rotation to the right, and 3.8° for a 180° rotation to the left. The results indicate that the design of the 3DOF hexapod robot using the Inverse Kinematics method provides a sufficient level of accuracy in controlling movements along the X, Y, and Z axes. Despite some errors, the robot is capable of moving fairly accurately during forward, backward, and rotational movements.

Keywords:
3 DOF;
Hexapod Robot;
Inverse Kinematic;

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INTRODUCTION

Six-legged robots are renowned for their stability in maneuvering, granting them an advantage in walking on uneven terrains. The challenge in robot movement lies in achieving desired forward, backward, and rotation motions. Conventional methods for designing hexapod robot movements involve manually recording the movement patterns of each leg and using them as references during robot motion. Considering the flexibility and stability requirements of the hexapod bionic spider robot, the body of the spider-like robot is designed from a bionics perspective [1]. However, this conventional approach has limitations, as any changes to the movement patterns necessitate re-recording, thereby restricting the robot's motion to specific positions. Compared to wheeled and tracked robots, the motion mode of a multi-joint robot is more adaptable to the ground and less restrictive. However, its design is relatively more complex, and its control system algorithm is more intricate, posing a challenge for multi-legged robots [2, 3, 4].

The movement of robots with legs necessitates intricate and synchronized coordination of their leg joints [5]. Correcting leg movements involves intricate calculations and requires more time and energy than wheeled robots. Consequently, this can limit the speed of legged robots during rapid movements. The challenge in their movement lies in reaching the desired target point directly without significant changes in facing direction, similar to the motion of a wheeled vehicle [6]. The hexapod robot is a type of legged robot, with a drive system consisting of legs composed of several degrees of freedom (DOF), enabling movement in all directions without the need for additional maneuvers [7]. The recommended hexapod robot system is typically divided into three subsystems, which likely include the body structure of the spider robot, its sensors, and the control algorithm [8]. The design of robot mechanisms, based on various types of mechanisms, primarily determines several basic characteristics such as the degree of freedom (DOF), workspace, and so forth [9]. Focus on the design of 3 degrees of freedom (DOF) hexapod robot and utilize the Inverse Kinematics method, along with a geometric and trigonometric approach, which aims to calculate the angles required for the servo motors controlling the leg movements. Moreover, the foot placement and lifting of a leg in a walking robot change the total topology of the mechanism. Also, due to more number of driven joints, the control of a legged robot is much more complex than that of parallel robots [10].

The inverse kinematics method enables us to determine the joint angles necessary for the robot's end-effectors to reach specific positions within its workspace [11, 12, 13, 14]. The complex mathematical equations involved in inverse kinematic calculations can be effectively solved by employing a geometric and trigonometric approach. Due to the uniform movement of all six legs, the Hexapod robot can traverse abrupt terrain [15]. Legged robots, which rely on discrete support points to move, exhibit superior terrain adaptability compared to wheeled and crawler robots, and they are easier to control than hybrid robots [16]. The desired joint angles for the next step of the controller are calculated using the inverse kinematics of the hexapod [17]. This approach furnishes us with a systematic and accurate method for controlling the hexapod robot's movements, ensuring precise and efficient locomotion. Inverse kinematics involves transforming the end-effector position into the joint variable [18]. A geometric approach differs in that it decomposes the spatial geometry of a leg into several geometric problems on the plane [19]. Solving the position of each motion joint is called the inverse kinematics solution, which is the basis of robot motion planning and trajectory control [20].

MATERIAL & METHOD

In this section, the inverse kinematic and straight walking gait are presented. It shows how the movement of the hexapod is designed.

Inverse kinematic of hexapod

The robot is constructed using 6 units of 2 axes Dynamixel 2XL-430 servos and 6 units of 1 axes Dynamixel XL-430 servos. The servo driver utilized is OpenRB-150, chosen for its compatibility with the servos employed in the robot [21]. For the body material of the robot, acrylic is used, while the coxa, femur, and tibia are 3D printed using Polylactic Acid (PLA) material. They have the following length measurements: coxa = 25mm, femur = 50 mm, and tibia = 70 mm. The real model of this robot can be seen in Figure 1.

Inverse Kinematics used in this method enables the six-legged robot to move accurately and optimize its performance in navigating difficult terrains [22]. The Inverse Kinematics algorithm is implemented to calculate the leg joint angles based on the desired positions, enabling the robot to achieve the desired movements [11]. Testing is conducted to measure the accuracy of the robot's control over its movements along the X, Y, and Z axes, as well as to evaluate the average errors in forward, backward, and rotational movements. The test results provide insights into the robot's level of accuracy in executing these movements. By utilizing inverse kinematics, this research aims to enhance the movement capabilities of the hexapod robot in adapting to its environment and executing precise movements. Inverse kinematics calculation is done before implementing the control algorithm to the robot so that the robot can move faster [14]. The findings of this study are expected to contribute to the development of more efficient and flexible six-legged robots.

According to Figure 2, the coxa angle θ_c can be calculated as (1).

$$\theta_c = \tan^{-1}\left(\frac{y}{x}\right) \quad (1)$$

$$x_0 = \sqrt{x^2 + y^2} \quad (2)$$

Where x and y represent the given cartesian coordinate as a desired pose and since they are known, x_0 can also be calculated [23] by applying the Pythagorean theorem as (2). Moreover, the next step is to find the femur angle. Similar to the previous step, geometrical analysis is conducted according to the robot side view in Figure 3.

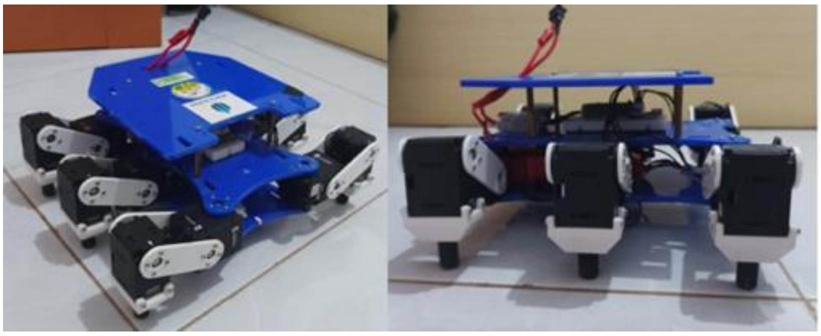

Figure 1. Real Hexapod

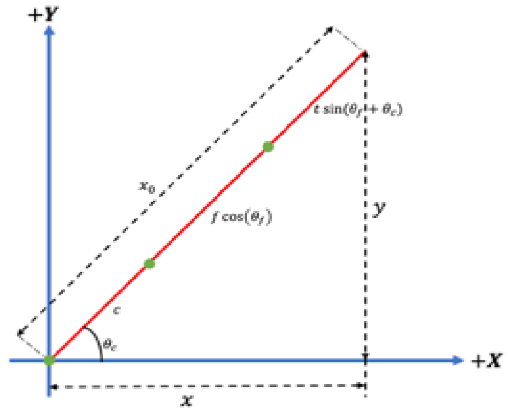

Figure 2. Robot Top View

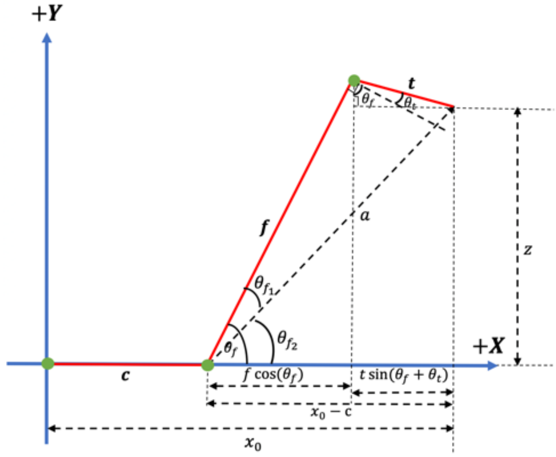

Figure 3. Robot Side View

As can be seen from Figure 3, the femur angle θ_f can be calculated as (3)

$$\theta_f = \theta_{f_1} + \theta_{f_2} \tag{3}$$

where θ_{f_1} and θ_{f_2} are calculated as (4) and (5), respectively.

$$t^2 = a^2 + f^2 - 2af\cos(\theta_{f_1})$$
$$\theta_{f_1} = \cos^{-1}\left(\frac{a^2 + f^2 - t^2}{2af}\right) \tag{4}$$

$$\theta_{f_2} = \tan^{-1}\left(\frac{z}{(x_0 - c)}\right) \tag{5}$$

However, a is unknown. For this reason, before calculating θ_{f_1}, a should be calculated. It can be done by applying the Pythagorean theorem based on z and $x_0 - c$ as shown in (6).

$$a = \sqrt{(x_0 - c)^2 + z^2} \tag{6}$$

Once the angle of the femur and coxa are known, the next step is to find the tibia angle. It is done sequentially by calculating (7) and (8).

$$a^2 = f^2 + t^2 - 2ft\cos(90 + \theta_t) \tag{7}$$

$$\theta_t = \cos^{-1}\left(\frac{f^2 + t^2 - a^2}{2ft}\right) - 90$$

In θ_t, the law of cosines is also applied. However, with the condition that a obtained must not exceed the sum of the femur length and tibia length, as exceeding this value would mean that the length has exceeded the physical length of the robot's femur with the tibia [23]. When (1), (3) and (7) are found and calculated, the inverse kinematic design is complete.

Walking Gait

The adaptation of the gaits pattern is basic and important for the hexapod robot to move stably and efficiently, which depends on the servos of the robot's legs, and also the body structure of the robot [24]. Robot gait refers to the way that a robot moves its legs regularly in the process of motion. When a robot is walking, its legs support the weight of the body and make it move in the walking direction [25]. A regularly organized gait to produce a forward or walking motion. A proper gait is essential in optimizing the efficiency and stability of the robot's movement while walking. In the Inverse Kinematics method, the forward or walking motion of the robot is regulated by calculating the angles of the leg joints based on the desired position and orientation. Figure 4 shows the relation between the angle of rotation and the displacement of a leg tip.

To achieve the movements, the servos at the leg joints are set such that the legs of the robot take turns walking in a synchronized and coordinated manner. This movement pattern is regularly arranged and synchronized to create efficient and stable forward motion. The method used to control the walking gait of the robot in this study is the tripod gait. The tripod gait is a common and widely used walking pattern for hexapod robots. Three-legged gait three legs in the support state, one leg in the swing motion [26]. This alternating movement between the two sets of legs provides stability and efficient locomotion.

During the tripod gait, the three moving legs are referred to as the "supporting tripod," shown in Figure 5A. while the stationary legs are the "swinging tripod." shown in Figure 5B. The supporting tripod provides stability to the robot by forming a stable triangular base, while the swinging tripod allows the robot to advance smoothly. The tripod gait is known for its simplicity and stability, making it suitable for various terrains and environments.

By using the tripod gait in combination with the inverse Kinematics method, the robot can achieve coordinated and stable walking motions, enabling it to navigate through uneven surfaces and obstacles effectively.

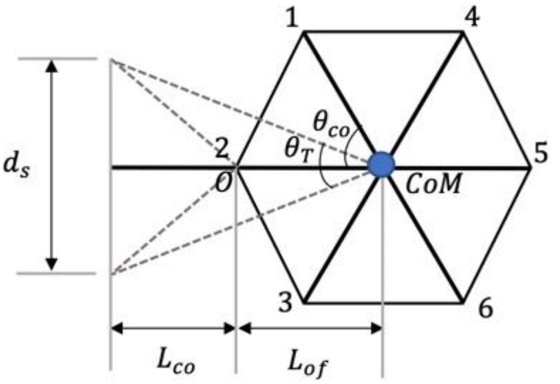

Figure 4 The relation of angle of rotation and the displacement of a leg tip

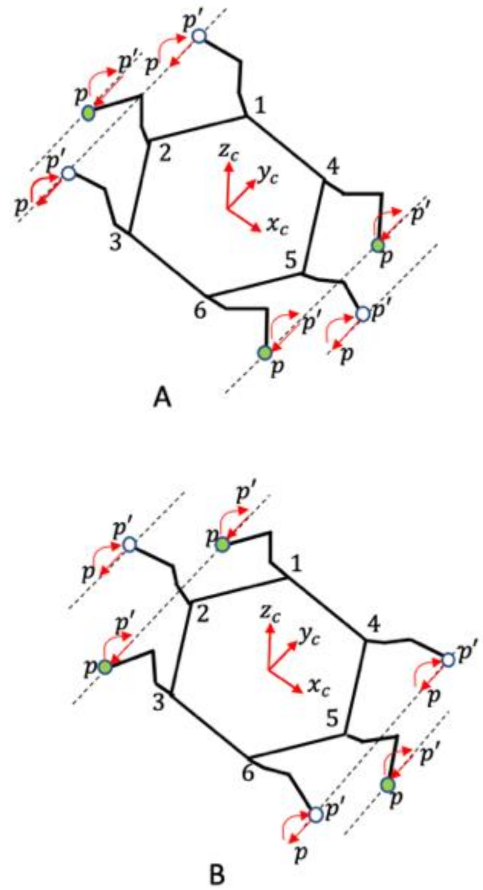

Figure 5. Tripod Gait

Each leg of the robot has a structure similar to that of a telescopic parallelogram mechanism with folding capability, which is beneficial to the gait planning and real-time control of the robot [27]. Among existing multi-legged walking platforms, six-legged robots have an exclusive status as six legs is the smallest number of legs to offer a two-stride statically stable gait [28][29].

RESULTS AND DISCUSSION

Data used to examine the inverse kinematic is obtained based on x, y, z in the desired cartesian coordinate plane as can be seen in Table 1. There is a difference between the degree angle of the left and right legs of the robot due to adjustments in the hardware. For example, for coxa, the 0° degree starts from 90° because it cannot do a counterclockwise rotation or 360° degree to 0°.

Error Inverse Kinematics

Errors can happen if the kinematic model of the robot is not completely accurate or does not describe the actual movement with enough precision. Physical obstacles and friction, during the movement of the robot, there are many physical obstacles and friction that can affect the actual movement. This can cause differences between the expected movement based on Inverse Kinematics calculations and the movement that occurs.

For testing the movement guided by inverse kinematics, several targets of pose for the end-effector robot are defined. These targets are presented in Table 2. According to these targets, the test is conducted and the results are represented as shown in Table 3. Referring to Table 3, the absolute error can be presented in Table 4.

Table 1. Testing Inverse Kinematics

Phase	x	y	z	θc	θf	θt
Right Leg						
Advancing	75	10	-46	82.40°	151.7°	67.15°
Touch down	75	10	-60	82.40°	168.5°	79.85°
Swing	75	-10	-60	97.59°	168.5°	79.85°
Lift-off	75	-10	-46	97.59°	151.7°	67.15°
Left Leg						
Phase	**x**	**y**	**z**	θc	θf	θt
Advancing	75	10	-46	97.59°	151.7°	112.8°
Touch down	75	10	-60	97.59°	168.5°	100.2°
Swing	75	-10	-60	82.40°	168.5°	100.2°
Lift-off	75	-10	-46	82.40°	151.7°	112.8°

Table 2. Target Defined for Initially Testing Inverse Kinematic for 3 DoF Hexapod

Test	End-effector Pose		
	X-axes (mm)	Y-axes (mm)	Z-axes (mm)
1st	75	10	-45
2nd	70	15	-50
3rd	60	20	-55
4th	65	20	-60
5th	80	25	-65
6th	90	10	-60
7th	60	20	-55
8th	80	15	-50
9th	70	15	-45

Table 3. The Results for testing inverse kinematic for single leg movement reaching The Pose Target

Test	End-effector Pose		
	X-axes (mm)	Y-axes (mm)	Z-axes (mm)
1st	74	9	-45
2nd	69	15	-49
3rd	57	19	-55
4th	63	18	-58
5th	77	24	-64
6th	89	10	-60
7th	60	19	-55
8th	78	18	-49
9th	69	20	-44

Table 4. The error given the incorrect pose of the end-effector robot based on the target

Test	Absolute Error for End-effector Pose		
	X-axes (mm)	Y-axes (mm)	Z-axes (mm)
1st	1	1	0
2nd	1	0	1
3rd	3	1	0
4th	2	2	2
5th	3	1	1
6th	1	0	0
7th	0	1	0
8th	2	2	1
9th	1	0	1
Average	1.56	0.88	0.78

The unexacted movement of the robot is caused by environmental influences such as uneven surfaces, slippery surfaces, and other influences. This can lead to differences between the desired movement and that which occurs in the field.

Forward and Backward Movements

The result test was performed with the robot moving 100 cm away. After various tests, it was found that there will always be a change in motion. Because inverse kinematics does not include friction, dynamic calculations, and the weight of the robot.

In testing the forward movement as shown in Table 5, it only experienced a slight deviation from its direction. From several tests, the robot always shifted to the right because the x-axis error result was greater on the right leg.

Table 5. Forward movement 100 cm from the initial pose

Test	Rear leg slide (cm)	Side leg slides (cm)	Distance Reached (cm)	Absolute Error (cm)
1st	3.1	3.5	97.2	2.8
2nd	4.2	5	98	2
3rd	3.9	4.5	97.7	2.7
4th	3.1	4	96.4	2.5
5th	4.2	4.5	97.1	2.9
Average	3.7	4.3	97.28	2.58

Table 6. Backward movement 100 cm from the initial pose

Test	Rear leg slides (cm)	Side leg slides (cm)	Distance Reached (cm)	Absolute Error (cm)
1st	6.6	3.2	96.9	3.1
2nd	6.4	5.1	96.3	3.7
3rd	7.1	4.2	97.2	2.8
4th	6.8	4.0	97.5	2.5
5th	7.5	4.3	96.7	3.4
Average	6.88	4.4	96.92	3.1

In backward movement testing in Table 6, it is quite far off from its direction. From several tests, the robot always shifts to the left because the x-axis error result is greater on the right leg.

Rotation Left and Right Movements

To test the rotation here, two tests were carried out, namely at 90 degrees and 180 degrees. From the data in Table 7, the robot does not always arrive at the desired degree it could be due to the moment of inertia and also does not consider environmental factors. The rotation test is also conducted in counterclockwise Rotation of 180° as shown in Table 8.

In testing the left rotation movement, there was a slight displacement of the body. From several tests, it always did not rotate completely by 90° and also 180°, always less than the average listed in Table 9 and Table 10. From the data in Table 9, the robot does not always arrive at the desired degree it could be due to the moment of inertia and also does not consider environmental factors. Inverse kinematics error also applies.

Table 7. Counterclockwise Rotation of 90°

Test	Body Displacement	Angle Error
1st	0.7	2°
2nd	1.1	3°
3rd	1	3.5°
4th	0.9	3.5°
5th	1.3	3°
Average	1	3°

Table 8. Counterclockwise Rotation of 180°

Test	Body Displacement	Angle Error
1st	2.6	2°
2nd	2.4	3°
3rd	2.5	6°
4th	2.4	4°
5th	2.2	4°
Average	2.42	3.8°

Table 9. Clockwise Rotation of 90°

Test	Body Displacement	Angle Error
1st	1.3	2°
2nd	1.2	1°
3rd	1.1	2°
4th	1.3	9°
5th	1.6	4°
Average	1.3	3.6°

Table 10. Clockwise Rotation of 180°

Test	Body Displacement	Angle Error
1st	2.9	16°
2nd	2.6	11°
3rd	2.8	14°
4th	2.7	12°
5th	2.7	13°
Average	2.74	13.2

In testing the right rotation movement, the body experienced a slight displacement. From several tests, it always did not really rotate as much as 90°, and also 180° is always less than based on the averages listed in Table 7 and Table 8. But especially during the 180° experiment, it was always more or less than the other averages to achieve it.

CONCLUSION

In this study, the movement of a 3 DoF hexapod robot is designed based on the inverse kinematic and tripod gait. Regarding the result of testing the correctness of reaching the target of the pose, the error on average for the end-effector robot is able to reach 1.56 mm of the X-axis, 0.88 mm of the Y-axis, and 0.78 mm of the Z-axis. Moreover, the results of testing the forward movement of the robot show an error average of 2.58 cm, and the backward movement of the robot shows an error average of 12.38 cm. For the body when forward shifts to the left an average of 4.3 cm and backward an average of 16.12 cm. Moreover, the test results of the 90° right rotation movement of the robot show an average percentage error of 3.6° and the left rotation movement of 3°. The 180° rotation movement of the right robot shows an average percentage error of 13.2° and the left rotation movement of 3.8°. According to these results, it can be concluded that the inverse kinematic guides the hexapod to move effectively.

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