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Comparison Between Trot and Wave Gait Applied in Quadruped Robot

Feriyonika[1*)], Martin[2)] , Noor Cholis Basjaruddin[3)], and Salman AASAP[4)]

[1,2,3,4)] Department of Electrical Engineering, Politeknik Negeri Bandung, Indonesia
Corresponding Email: *) feriyonika@gmail.com

***Abstract* – A Quadruped robot is a type of robot that moves on four legs and has a structure like a four-legged animal. The quadruped robot tends to have poor movement patterns. This study investigates the best movement between Trot and Wave gait by comparing the speed performance, stopping distance accuracy, and the tilt of the robot body angle. To minimize the influence of the mechanical quality of the robot, this study used two robots based on the type of servo used (based on the SG90 [Robot 1] and MG995 servos [Robot 2]). In this study, the motion pattern based on Trot and Wave gait is realized using Inverse Kinematics and Polynomial trajectory on each leg. The verification experiment shows that the Wave gait has a smaller error for the orientation angle of the robot body and the target distance. For error angle orientation of the robot body, it shows a Wave gait of 4.41 degrees compared to 6.57 degrees on the Trot gait (Robot 1) and 3.7 degrees compared to 5.28 degrees (Robot 2). The distance measurement also shows that the Wave gait has a target distance error of 3.61 cm versus 5.13 cm for Trot gait (Robot 1) and 4.1 cm versus 5 cm for Robot 2. In another hand, the Trot gait is better in speed performance. It has a speed of 10.53 cm/s compared to 3.05 cm/s on the Wave gait (Robot 1) and 9.74 cm/s compared to 3.44 cm/s.**

***Keywords*: Inverse Kinematic, Quadruped Robot, Trot gait, Wave gait**

I. INTRODUCTION

A robot is one part of the field of Artificial Intelligence (AI), according to the Robot Institute Of America (1979), a robot is something that can be programmed and reprogrammed, by having a mechanical manipulator or mover designed to move goods, components or specialized tools with various flexible programs adapted to carry out a wide variety of tasks [1]. Robots are divided into 2 types, namely wheeled robots and legged robots. A legged robot is a robot that moves using its legs. The advantage of legged robots is that they can move on uneven terrain so that they can be used to perform more specific tasks [2]–[4]. One type of legged robot is a 4-legged robot (Quadruped). A quadruped robot is a type of robot that moves using four legs which are arranged by several servo motors as the driving force in each leg depending on the used Degree of Freedom (DOF). When compared with hexapod robots, quadruped robots have fewer servos (12 of 18) but have challenges in the balance of each movement which will ultimately affect the precision level of robot movement. Several researchers have studied the movement of each joint in a robot's legs [5]-[7]. In their research, the movement of the joint is derived based on a geometric mathematical model which is then applied to the robot's kinematic system. Current research around robot movement is leg-based power, e.g by using hydraulic [8]. In this research, energy consumption in each step of Trot gait was analyzed. For the gait pattern, research in [9] used a neural network to generate gait for Gecko Robot. The research result showed that robot can adapt its gait according to the environment faced by the robot.

In quadruped robots, Trot gait and Wave gait step patterns are commonly used and are easier to implement than other step patterns. Several studies have conducted trials on gait patterns realized in legged robots. In research [10], the Trot gait was used in conjunction with the Swing Leg gait to get a smoother robot movement when executing the path planning trajectory. The verification of the research method was carried out by simulation. Another study compared the effectiveness of gait patterns on hexapod and quadruped robots. This study discusses the effectiveness of various gait patterns on robot speed [11].

This study compares the performance of Trot and Wave gait patterns on the two different mechanical quadruped robots which disappear in other similar researches. The compared performances are the performance of speed, accuracy of stepping distance, and angle of inclination of the orientation of the robot body. The results of the research are intended to be a reference to determine the kind of gait which can be used.

II. METHODOLOGY

A. Inverse Kinematics

Inverse Kinematics is a kinematic analysis to get the angle of each servo based on the coordinates of the destination position in Cartesian space (x,y,z) at the end effector. The quadruped robot has 4 legs and each leg has an insect-like leg structure that consists of 3 joints and 3 bone parts, namely the coxa, femur, and tibia. The illustration of an insect-like leg structure in one robot leg is depicted in Figure 1.

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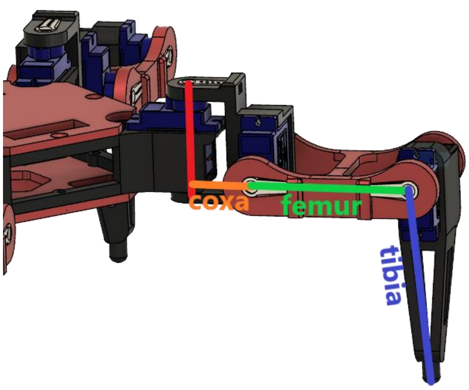


Figure 1. Robot Leg Structure

The angle of coxa, femur, and tibia is obtained by using geometric analysis. The coxa angle was analyzed by looking at the robot from the top point of view (X and Y planes) which is illustrated in Figure 2. While the analysis for the angle of the femur and tibia is done by looking at the robotic arm from the point of view of the X-Y and Z planes. The X-Y plane is the plane formed by the X and Y coordinates. The illustration of this plane is shown in Figure 3.

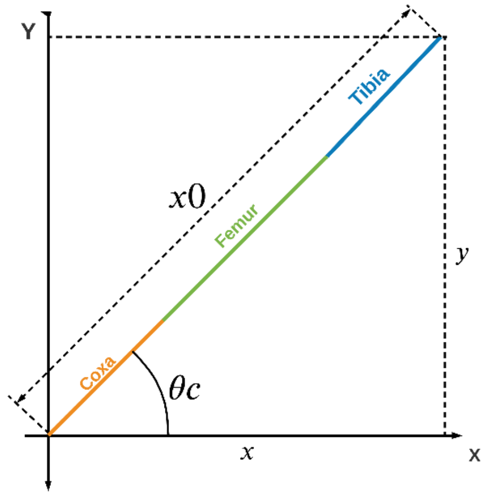
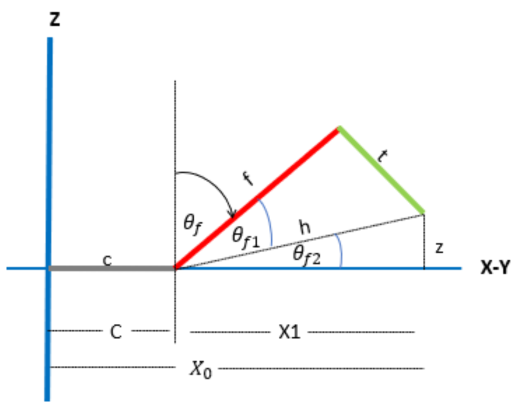
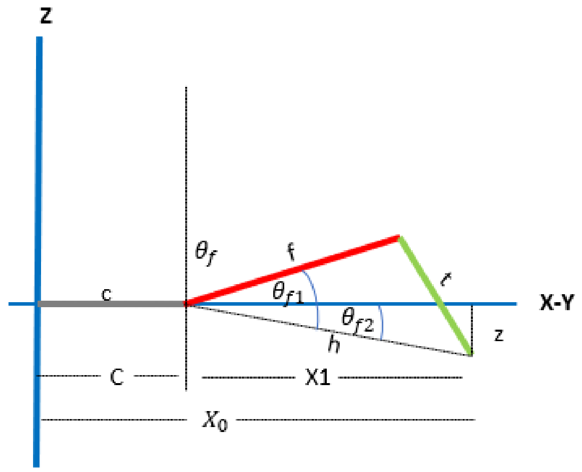


Figure 2. Joints Viewpoint from X and Y plane



(a)



(b)

Figure 3. Joint Viewpoint X-Y and Z plane to calculate femur angle: for Positive Z value (a), for Negative Z value (b)

Based on the desired endpoint value (X, Y, Z), the following procedures are the steps in determining the value of the coxa (θ_c), femur (θ_f), and tibia (θ_t) angles:

1. Find The Coxa Angle (θ_c)

To find the value of the coxa angle (θ_c) can be seen in Figure 2. The value of c is obtained by using equation (1). The value of θ_c for the left quadruped robot arm will adjust based on the location of the quadrant formed by the X and Y values.

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

2. Find The Femur Angle (θ_f)

To find the value of the angle of the femur (θ_f) can be seen in Figure 3a. First, calculate the angles θ_{f1} and θ_{f2} with (2) – (4):

$$X_0 = \sqrt{x^2 + y^2} \tag{2}$$

$$X_1 = X_0 - C \tag{3}$$

$$h = \sqrt{X1^2 + z^2} \tag{4}$$

so that angles θ_{f1} and θ_{f2} can be found using the formulas in (5) and (6).

$$\theta_{f2} = \tan^{-1}\left(\frac{z}{x_1}\right) \tag{5}$$

$$\theta_{f1} = \cos^{-1}\left(\frac{f^2 + h^2 - t^2}{2.f.h}\right) \tag{6}$$

By knowing the value of the angle θ_{f1} and θ_{f2}, it can be seen the angle of the femur (θ_f) with (7).

$$\theta_f = 90 - (\theta_{f1} + \theta_{f2}) \tag{7}$$

At the position of the negative Z value (Figure 3b) equations (5) to (7) adjust to the Z value.

3. Find The Tibia Angle (θ_t)

Based on Figure The 4 angles of the tibia (θ_t) can be identified through (8) and (9).

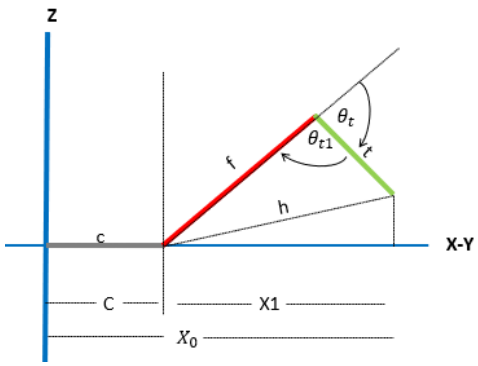


Figure 4. Tibia Angle

$$\theta_{t1} = \cos^{-1}\left(\frac{f^2+t^2-h^2}{2.f.t}\right) \quad (8)$$

$$\theta_t = 180 - \theta_{t1} \quad (9)$$

B. Step Trajectory

The trajectory design on the robot's legs aims to make the moving process from one end-point to another follow a certain track. In this study, the trajectory follows a parabolic shape as in equation (10). The parameter t is an iteration factor that increases from 0 to 1 over time, the smaller the value of t, the smoother the swing of the robot leg. The trajectory point generated by this polynomial equation is used as the path of the robot step [12]

$$P(t)_{x,y,z} = (1-t)^3 P1_{x,y,z} + 3t(1-t)^2 P2_{x,y,z} + 3t^3(1-t) P3_{x,y,z} + t^3 P4_{x,y,z} \quad (10)$$

$P(t)_{x,y,z}$ is the desired end-point in the t-th iteration. P_1, P_2, P_3, and P_4 are vector reference points. While t is an iteration factor that increases from 0 to 1 over time. If the equation is simplified then the formula becomes (11).

$$P(t) = AP_1 + BP_2 + CP_3 + DP_4 \quad (11)$$

The values of P_1, P_2, P_3, and P_4 can be substituted into the equation so that the end-point value of each iteration is obtained from the starting point (P_1) to the destination point (P_4). The value of each end-point is substitued into the Inverse Kinematics equation so that the angle of each servo is obtained. Figure 5 is an example of the iteration result from point P_1 (10,-30,-100) to point P_4 (10,30,-100).

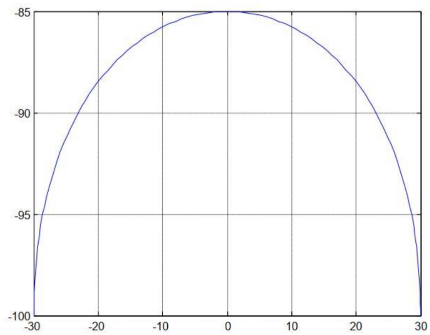


Figure 5. Trajectory Output of leg swing with 0.01 iteration (100 steps)

C. Walking Gait

Gait is a movement pattern that moves with a sequence of leg contact with the ground to produce good movement on the robot whereas the gait on this quadruped robot imitates the motion of animals. In this study, the types of gait patterns used in quadruped robots are Trot and Wave gait. The Trot and Wave gait patterns can be seen in Figure 6 where R1 is the right front leg, R2 is the right rear leg, L1 is the front left leg, and L2 is the left rear leg.

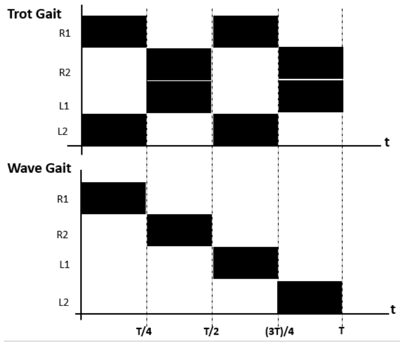


Figure 6. Time Diagram of Trot and Wave Gait

The Trot gait step pattern is a step pattern where the right front leg and left hind footstep together and the opposite footsteps and pushes. The Wave gait pattern is a step pattern where the steps are taken one by one in turn.

D. Quadruped Robot System Design

The Block diagram design for the Quadruped robot is shown in Figure 7.

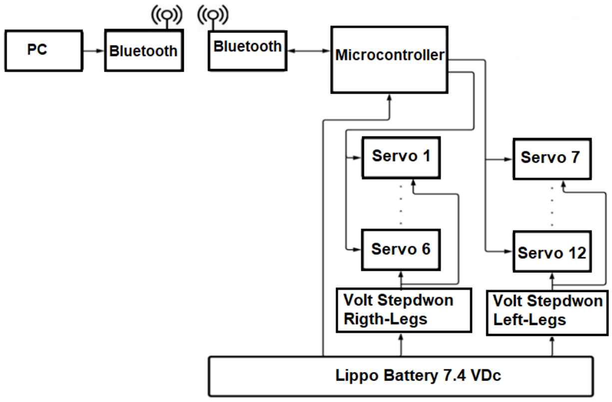


Figure 7. Block Diagram of Quadruped Robot

This system consists of input components, data processors, and actuators. The input component consists of Bluetooth which is embedded in the microcontroller. Bluetooth is used as an input receiver for the inverse kinematic testing process and the robot navigation process. The microcontroller is used to process the robot movement algorithm, namely Inverse Kinematics, and also interfaces with input components, and output components. In this study, the microcontroller no longer needs to use any drivers because this microcontroller has more than 12 PWM pins which are sufficient to control the quadruped servo simultaneously.

E. Robot Mechanical Design

This study uses two types of robots based on the type of servo used. The use of these two types of servo aims to minimize the influence of hardware on the analysis of performance consistency of the type of gait used. The mechanical design can be seen in Figure 8 and 9.

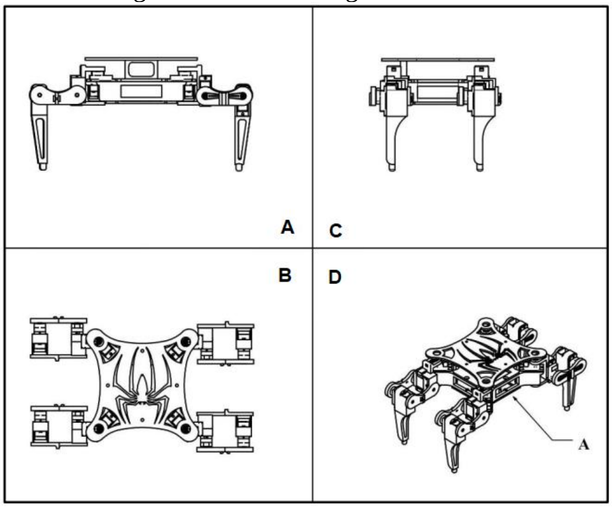


Figure 8. Quadruped Robot 1 Mechanical Design (Servo SG90): Front View (A), Top View (B), Left View (C), Isometric (D)

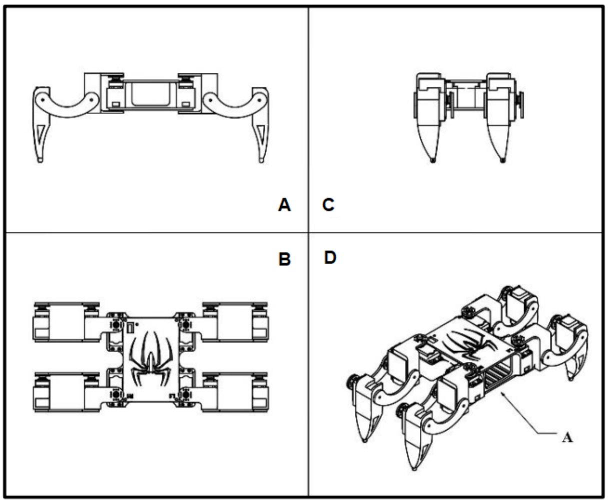
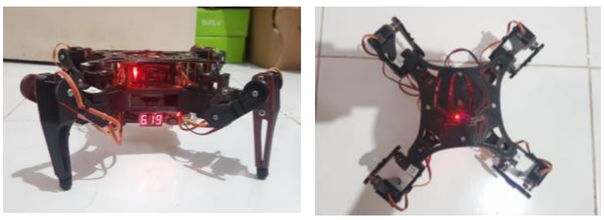


Figure 9. Quadruped Robot 2 Mechanical Design (Servo MG996R): Front View (A), Top View (B), Left View (C), Isometric (D)

III. RESULTS AND DISCUSSION

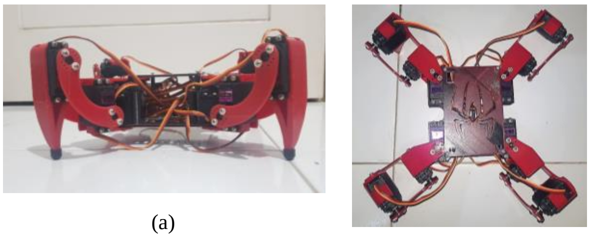
A. Realization of Robot Mechanic

The result of this mechanical design is the assembled robot frame. The results of the design are shown in Figure 10 and 11.



(a) (b)

Figure 10. Robot mechanic realization 1: Front view (a), Top view (b)

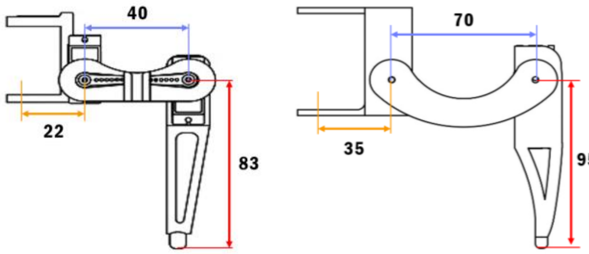


(a) (b)

Figure 11. Robot mechanic realization 2: Front view (a), Top view (b)

B. Inverse Kinematic for Each Leg

The first step in performing an inverse kinematic analysis is to determine the size of the coxa, femur, and tibia. The structure of the robot leg used is illustrated in Figure 12 with the description in Table 1.



(a) (b)

Figure 12. The structure and dimensions of the legs: Robot 1(a), Robot 2 (b)

Table 1. Length of Leg Structure of Robot 1 and Robot 2

	Robot Leg Length 1 (mm)	Robot Leg Length 2 (mm)
Coxa	22	70
Femur	40	35
Tibia	83	95

The arrangement of the axes of the coordinate plane of the robot is done to facilitate the programming of the robot. For the Inverse Kinematics method, the coordinate center is on the coxa axis of each leg. The coordinate plane applies to the right and left legs of the robot, so there are differences in the direction of motion on the X-axis of the left and right robotic legs. Figure 13 is an example of the coordinate plane of the right leg of the robot.

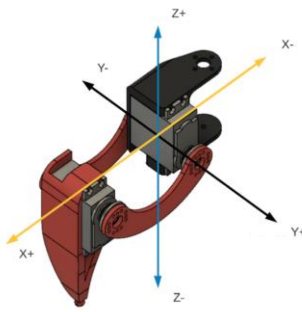


Figure 13. Coordinate field of robot's leg

In the Inverse Kinematics equation, the initial angle of the servo with the initial angle in the calculation is different, then normalization of the servo angle is carried out to adjust the position of 0 degrees between the calculation and the hardware used. Normalization of 0 degrees has a difference in the left and right feet due to the position of the servo motor components. The calculation of normalization of 0 degrees is described in Figure 14 to 15 and Table 2 to 3.

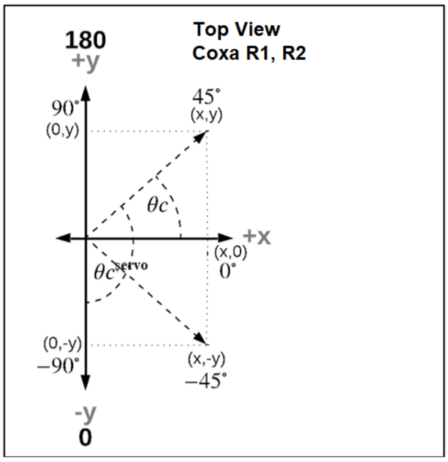


Figure 14. Servo Normalization of Right Side of Coxa

Table 2. Right Side Servo Coxa Normalization

θc	θc^{servo}	Coordinate
-90	0	(0, -y)
-45	45	(x, -y)
0	90	(x, 0)
45	135	(x, y)
90	180	(0, y)

From Figure 14 and Table 2 in order that the calculation results with the hardware on the right side of the coxa match, then it is obtained from (12).

$$\theta c^{servo} = 90 + \theta c \tag{12}$$

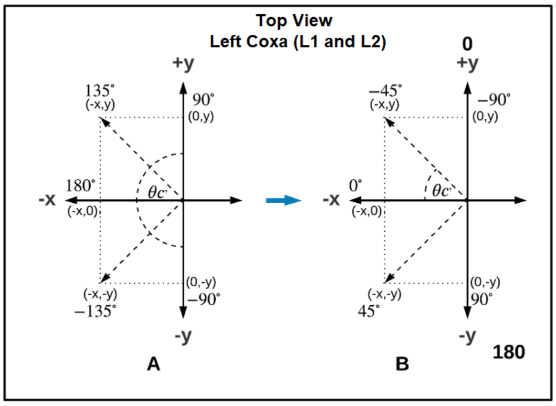


Figure 15. Left side Servo Coxa Normalization

Table 3. Left side Servo Coxa Normalization

$\theta c1$	θc	θc^{servo}	Coordinate
90	-90	0	(0, -y)
135	-45	45	(-x, -y)
180	0	90	(-x, 0)
-135	45	135	(-x, -y)
-90	90	180	(0, y)

Where $\theta c1$ = the value of the resulting angle from the program, θc = the value of the calculated angle, and θc^{servo} = servo angle.

In the normalization process, the left coxa servo produces data as shown in Figure 15 part A, but in the equation to produce data as in part B, it needs to be adjusted first in the following way:

If $\theta c1 > 0$, then, $\theta c = \theta c1 - 180$

If $\theta c1 < 0$, then, $\theta c = \theta c1 + 180$

After the value is appropriate, the servo normalization process is carried out using a linear regression equation to obtain equation (13).

$$\theta c^{servo} = \theta c + 90 \tag{13}$$

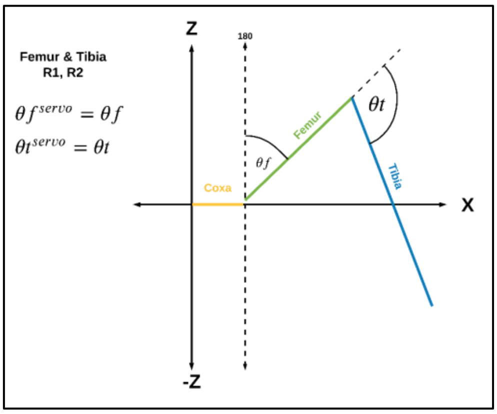


Figure 16. Right Servo Normalization For Femur and Tibia

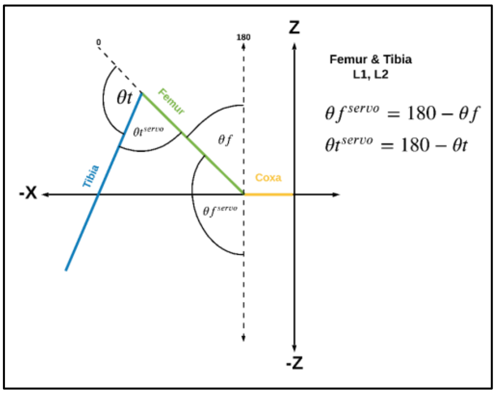


Figure 17. Left Servo Normalization For Femur and Tibia

Based on the explanation of the image above, it can be concluded that the normalization of 0 degrees servo is in Table 4.

Table 4. Normalization Equation for 0-degree Angle

Normalization of 0 degree	Left (L1,L2)	Right Angle (R1,R2)
Femur's angle at servo position (θf^s)	$\theta f^s = 180 - \theta f$	$\theta f^s = \theta f$
Tibia's angle at servo position (θt^s)	$\theta t^s = 180 - \theta t$	$\theta t^s = \theta t$

C. *Inverse Kinematic Test*

Inverse Kinematics robot testing is carried out on each leg. There are 12 test points tested, where each leg represents the test on the X, Y, and Z coordinate axes. This test is carried out on a tool in the form of a base measuring 1189 x 841 mm which has been given measurement lines. The shape of the Inverse Kinematics measurement board can be seen in Figure 18.

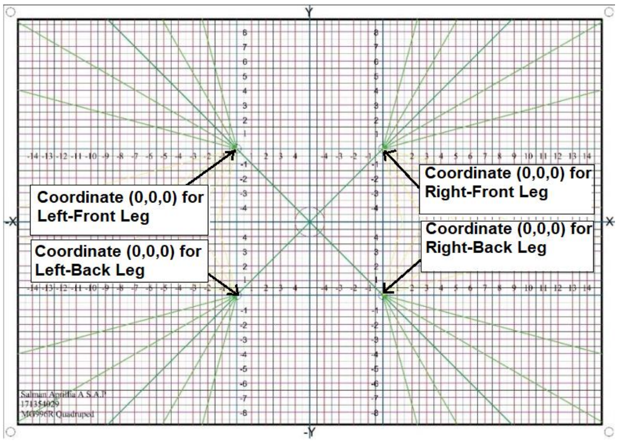


Figure 18. Inverse Kinematics Test Board

The robot will be placed on a pedestal board and instructed to perform the Inverse Kinematics function, then the leg end results are measured on the measurement board. The positioning of the robot must be precise so that the measurement results become more accurate. The complete Inverse Kinematics test results on the robot can be seen in the measurement data in Tables 5 and 6.

Table 5. Robot Leg Inverse Kinematic Testing 1

Leg	Error Average (mm)		
	X Angle	Y Angle	Z Angle
L1	3.33	3.00	4.33
L2	3.67	3.33	3.17
R1	2.67	2.17	2.50
R2	2.50	2.67	3.17
Average	**3.04**	**2.79**	**3.29**

Table 6. Robot Leg Inverse Kinematic Testing 2

Leg	Error Average (mm)		
	X Angle	Y Angle	Z Angle
L1	2.50	1.33	4.17
L2	1.83	2.67	2.83
R1	1.83	1.83	3.67
R2	0.83	2.17	2.83
Average	**1.75**	**2.00**	**3.38**

D. Walking Gait Test

The test is carried out by dividing into 4 movements, namely forward, backward, right sliding, and left sliding. The test is carried out on a gait test measuring board. The measurement process is carried out by first placing the robot on the test board, then measuring and recording the starting point where the robot stands. After that, it is programmed according to a predetermined distance, then the robot and stopwatch are run. When the robot stops, record the speed, distance, and angle of inclination of the robot by seeing where the robot stops. This test was carried out 3 times. In measuring the tilt angle, the orientation of the robot body is illustrated as shown in Figure 19.

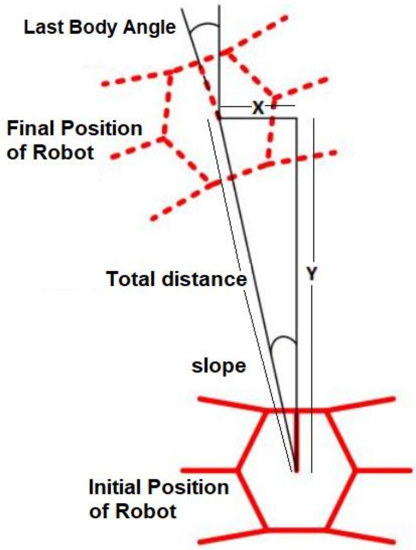


Figure 19. Step Pattern Measurement Process (gait)

After getting the X distance data, the total distance from the robot body is obtained by using (14).

$$\text{Total Length} = \sqrt{Length\ X^2 + Length\ Y^2} \tag{14}$$

Then to get the data on the tilt angle of the movement it is used (15).

$$tilt\ angle = tan^{-1}\left(\frac{Length\ X}{Length\ Y}\right) \tag{15}$$

The test results on distance, angle, and speed targets are described in the following subsections.

1. *Testing against mileage targets*

Tables 7 and 8 are the results of measurements of the direction movement with varying target distances (15cm, 30cm, 45cm, 60cm, and 75cm). Based on testing on two types of robots and four types of movement directions, it is known that the Wave gait motion pattern has a smaller error difference (3.61cm compared to 5.13 cm).

Table 7. Robot Distance Error Comparison 1

Movement	Error (cm)	
	Trot gait	*Wave gait*
Forward	5.97	3.84
Backward	5.26	4.66
Right	4.54	2.93
Left	4.79	3.03
Average	**5.13**	**3.61**

Table 8. Robot Distance Error Comparison 2

Movement	Error (cm)	
	Trot gait	*Wave gait*
Forward	5.6	4.6
Backward	5.0	4.3
Right	4.7	3.8
Left	4.7	3.7
Average	**5.0**	**4.1**

2. Testing the robot orientation angle at the end-point

Table 9 and 10 are the results of testing the orientation angles of the two robots at the end of the end-point. Based on Table 9, in Robot 1 testing, it is known that the angle error with Wave gait is smaller than Trot Gait (4.41 versus 6.57). The same thing happened to Robot 2 (3.7 versus 5.28).

Table 9. Robot Orientation Angle Change Comparison 1

Movement	Error (°)	
	Trot gait	***Wave gait***
Forward	6.8	4.09
Backward	7.42	5.03
Right	5.95	4.15
Left	6.11	4.39
Average	**6.57**	**4.41**

Table 10. Robot Orientation Angle Change Comparison 2

Movement	Error (°)	
	Trot gait	***Wave gait***
Forward	4.61	3.20
Backward	5.62	4.23
Right	5.65	3.55
Left	5.27	3.84
Average	**5.28**	**3.70**

3. Speed average test

The next comparison is the movement speed of the two robots based on the gait pattern used. Based on Table 11, the average movement speed of Robot 1 with Trot Gait is faster than Wave Gait (10.53 cm/second versus 3.05 cm/second). The same thing happened to Robot 2 (8.89 cm/second versus 3.44 cm/second).

Table 11. Speed Comparison on Robot 1

Movement	Speed (cm/s)	
	Trot gait	***Wave gait***
Forward	13.22	3.35
Backward	10.34	3.28
Right	9.26	2.88
Left	9.32	2.72
Average	**10.53**	**3.05**

Table 12. Speed Comparison on Robot 2

Movement	Speed (cm/s)	
	Trot gait	***Wave gait***
Forward	10.38	4.54
Backward	9.95	4.25
Right	9.74	2.49
Left	8.89	2.51
Average	**9.74**	**3.44**

IV. CONCLUSION

This study investigates the performance of Trot and Wave gait on two quadruped robots. In this research, each compared robot has a different servo which disappears in other similar research. Based on the verification experiment, it can be concluded that the accuracy of the distance and angle of the robot body shows the Wave gait step pattern is better than the Trot gait. For error angle orientation of the robot body, it shows a Wave gait of 4.41 degrees compared to 6.57 degrees on the Trot gait (Robot 1) and 3.7 degrees compared to 5.28 degrees (Robot 2). The distance measurement also shows that the Wave gait has a target distance error of 3.61 cm versus 5.13 cm for Trot gait (Robot 1) and 4.1 cm versus 5 cm for Robot 2. In another hand, the Trot gait is better in speed performance. It has a speed of 10.53 cm/s compared to 3.05 cm/s on the Wave gait (Robot 1) and 9.74 cm/s compared to 3.44 cm/s.

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