Quadruped Robot with Stabilization Algorithm on Uneven Floor using 6 DOF IMU based Inverse Kinematic

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Abstract—**Robotics technology is always growing very quickly. One type of the robot is 4 legged robot (Quadruped). The Problem from this robot is if quadruped find the uneven floor, the movement of robot can be late and the center of the gravity are not balance. This research makes a designed stabilization algorithm quadruped on uneven floor with 6 DOF IMU MPU 6050 based on invers kinematic. MPU 6050 sensor are consist of accelerometer and gyroscope. This sensor will give an input of tilting degree of the robot and then it can be processed in stabilization algorithm with proportional controller to balance the body of robot on uneven floor. Quadruped robot moves using inverse kinematics by following the coordinates given. The method of inverse kinematics will help to find the angle value of servo moves through the final coordinates. The test result shows that quadruped robot with stabilization algorithm can increase stability percentage of pitch angle equal to 75,58% and stability percentage of roll angle equal to 71,15%.**

Keywords—Quadruped, Stabilization Algorithm, Invers Kinematic

I. INTRODUCTION

Robots are familiar for students of electrical and Instrumentation Control concentration in particular. In line with the development of science and technology in all areas of rapid and dynamic change in the society especially in the developed countries as well as countries that are developing, the use of robots are indispensable. The development of Robotics is currently very rapid with a variety of the new system were found. One of the types of robots that has many-legged robots are four-legged robot (Quadruped). This robot moves based on kinematics of motion are applied on each foot compiled by servo motors [1].

Some of the shortcomings of the quadruped robot is when encountering an uneven floor surfaces, then the robot will tend to run unstable. In addition the instability will cause the point load body of quadruped robot will move and resulting imposition on one servo motor. This will cause the servo motor that is given the highest damage to load faster [2].

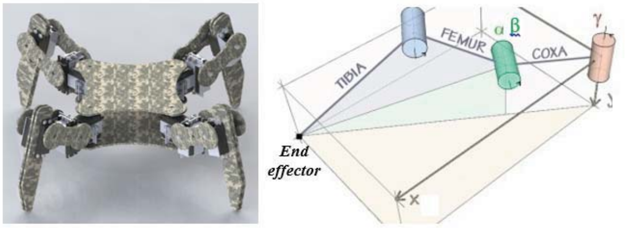
That is why we need a robot that can maintain its fix position on uneven floor, a robot that can stabilize its body . One way to make the center gravity of the robot remains stable is to develop an inverse kinematic. Inverse kinematic is a variety of robotic motion oriented robot distance. This will generate the movement kinematics based on translational angle X, Y, Z and rotation angle of Pitch, Roll, Yaw. This variables is the things that we will control [3].

Beside motion kinematics, it needs sensor that can produce the required data angle as a comparison and provide data setpoint that we want. One of the sensors is 6 DOF IMU MPU 6050 [4]. This is a combination of two sensor, Accelerometer and Gyroscope. The control method of Proportional is used to maintain the robot on the desired setpoint [5]. Then the results of the proportional control values is used on the Stabilization Algorithm to change the height of the legs of the robot. Thus it is expected that the robot can automatically adjust their feets to be able to pass through the uneven floor.

II. DESIGN AND METHOD

A. The Design Of The Hardware

The design of the mechanical specifications of quadruped robot are using 12 DoF (Degree of Freedom). Divided into four feet with each feet consist of 3 DoF as a driving force towards coordinates. This quadruped robot has specifications of 53.7 mm coxa link length (L0), 54.6 mm femur link length (L1), and 130 mm tibia link lenght (L2). From the above specifications, the robot can be illustrated as shown in Fig.1.



(a) (b)

Fig.1. Example robot quadruped, quadruped Robot (a), (b) the configuration of the coxa, femur, and the tibia.

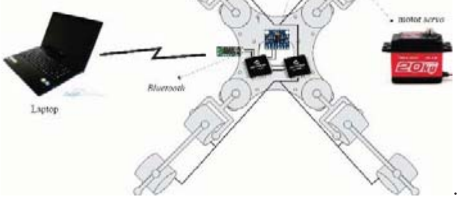


Fig.2. Block diagram input of quadruped robot output

Design of input output hardware of the quadruped robot are shown in Fig.2. Quadruped robots have IMU 6050 sensor for reading the slope of the body, a bluetooth as a serial communications with the laptop, and 12 motors as servo robot actuator.

B. MPU6050 IMU Sensor

MPU 6050 Sensor is a combination of two kinds of sensors wich are accelerometer and gyroscope , produced by invensense with I2C communications interface. MPU-6050 combines accelerometer and gyroscope in one board. This sensor can detect acceleration in 3 axis (x, y, and z) and the angular velocity in 3 axis (x, y, and z) [6].

Fig.3. The physical shape of the sensor MPU6050.

It needs a filter in order to gain a good data acquisition on 6050 MPU IMU. It is a complementer filter that is used in this design and are represented in Fig.4, it shown that there are two entries, one of which has a high frequency noise and the others have low noise frequency. Entries that have a high noise frequencies are filtered down by low-pass filters, while the inputthat has low noise frequency are filtered with high-pass filter. The results of this reconstruction of this two signals, each of which has filtered are the variables that you want to read without any noise that was previously associated with the sensor [2].

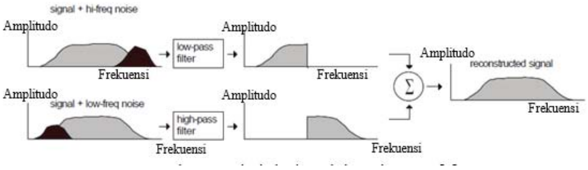


Fig.4. The Working Principle of complementary filters.

Exponential smoothing is a method that can be used to create a row of data in a sequence of time becomes smoother. The refined data is typically data that has noise or random data. A sequencial time domain data is represented by x_t While the data that was refined was represented s_t with t is a sequence of time. The calculation of the Exponential smoothing can be expressed as equation (2) [2].

$$s_0 = x_0 \tag{1}$$

$$s_t = (1-\alpha)x_t + \alpha s_{t-1},\ t > 0 \tag{2}$$

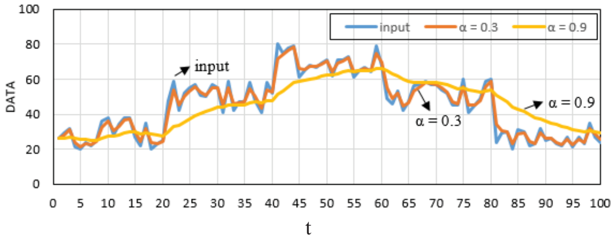


Fig.5. Influence of exponential smoothing filters.

C. Inverse Kinematic

To facilitate users in moving the end-effector of robot arms to certain positions, the inverse kinematic motion method is required. This method uses the input position coordinates in the forms of X, Y, and Z. The output from the inverse kinematic is the angle that formed at the joint. In Fig.6 and Fig.7 the quadruped robot has 3 joint on each of his legs. The angle is formed by each joint , i.e. the angle of coxa (A0), the angle of femur (A1), the angle of the tibia (A2). And then the value of those angles are converted into the value of PWM to move the servo.

Inverse kinematic Functions that are designed requires input of the coordinates X, Y, and Z. X value represent of forward and backward movements of the robot. Y value represent rightward and leftward movements of the robot. Z value represent upward and downward movements of the robot.

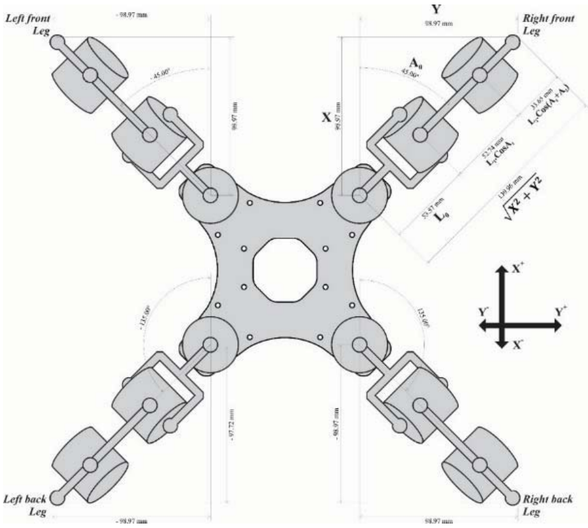


Fig.6. Quadruped Robot (top view).

Discussion of the formula that resulting angle of inverse kinematic functions will be explained in the section on the right front leg. At first, we placed the value of the coordinates X, Y, and Z. To get all three angles on joint, it use the approach of algebra and geometry. The first calculation is to find the value of coxa angle (A0), i.e. use the arcus tangent from equation (3).

$$A_0 = tan^{-1}(\frac{Y}{X}) \tag{3}$$

To find the angle of femur (A1) and the angle of the tibia (A2), It is explained by Fig.7 showing the quadruped robot from the side.

Next, find the value of the resultant quantity of X and Y by the equation (4)

$$\overrightarrow{XY} = \sqrt{X^2+Y^2} \tag{4}$$

Due to the influence of the mechanic that can’t make an angle of coxa (A0) and angle of femur (A1) into a single point, then the calculations refer to the offset or in Fig.7 L0. L0 is the distance from the coxa joint to the femur joint in perpendicular.

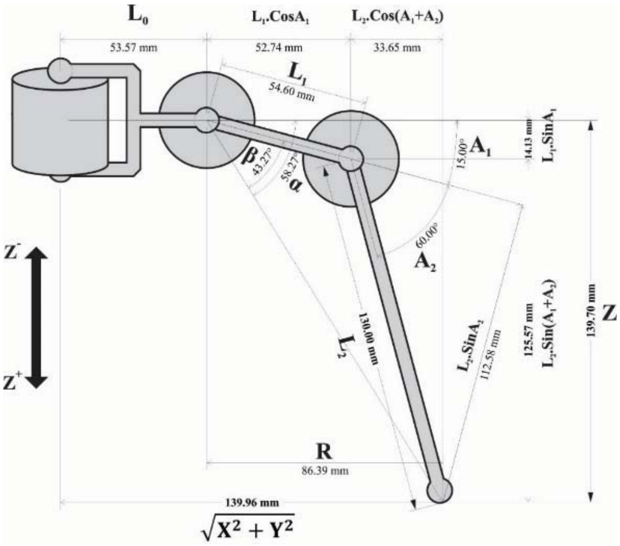


Fig.7. Robot quadruped (side view).

In the next calculation it is R, which is $\overrightarrow{XY}$ reduced by L0, as in equation (5)

$$R = \sqrt{X^2 + Y^2} - L_0 \tag{5}$$

Note that there are similarities in the Forward Kinematic with the image above 2.1 retrieved value for the point R and Z as follows:

$$R = L_1 \cos(A_1) + L_2 \cos(A_1 + A_2) \tag{6}$$
$$Z = L_1 \sin(A_1) + L_2 \sin(A_1 + A_2) \tag{7}$$

To get the output based on the desired distance, the calculation will be looking for the value of A1 and A2 with quadrating R and Z on the equation (6) and (7) [7].

$$[R]^2 = [L_1 \cos\ (A_1) + L_2 \cos(A_1 + A_2)]^2 \tag{8}$$

$$\begin{aligned} R^2 \ &= L_1^2 \cos^2 (A_1) \\ &\quad + 2L_1L_2 \cos(A_1) \cos(A_1 + A_2) \\ &\quad\ + L_2^2 \cos^2(A_1 + A_2) \end{aligned} \tag{9}$$
$$[Z]^2 = [L_1 \sin(A_1) + L_2 \sin(A_1 + A_2)]^2 \tag{10}$$

$$\begin{aligned} Z^2 \ &= L_1^2 \sin^2 (A_1) \\ &\quad + 2L_1L_2 \sin(A_1) \sin(A_1 + A_2) \\ &\quad\ + L_2^2 \sin^2(A_1 + A_2) \end{aligned} \tag{11}$$

Sum R and Z then squared it in equation (9) and (11):

$$\begin{aligned} R^2 + Z^2 = L_1^2\ &[\sin^2(A_1) + \cos^2(A_1)] \\ &+ L_2^2[\sin^2(A_1 + A_2) + \cos^2(A_1 + A_2)] \\ &\quad + 2L_1L_2\ [\sin(A_1) \sin(A_1 + A_2) + \\ &\qquad + \cos(A_1) \cos(A_1 + A_2)] \end{aligned} \tag{12}$$

Where as we know that:

$$\sin^2(\propto) + \cos^2(\propto) = 1 \tag{13}$$

A simpler equation Obtained from equation (12) :

$$\begin{aligned} R^2 + Z^2 = L_1^2 + L_2^2 + 2L_1L_2\ &[\sin(A_1) \sin(A_1 + A_2) \\ &+ \cos(A_1) \cos(A_1 + A_2)] \end{aligned} \tag{14}$$

Retrieved the equation as the simplification of inverse kinematic formula as follows:

$$\begin{aligned} \frac{R^2+Z^2-L_1^2-L_2^2}{2L_1L_2} = \ &\sin(A_1) \sin(A_1 + A_2) \\ &+ \cos(A_1) \cos(A_1 + A_2) \end{aligned} \tag{15}$$

Further calculations were obtained:

$$\cos(A_2) = \frac{R^2+Z^2-L_1^2-L_2^2}{2L_1L_2} \tag{16}$$

From equation (16) yields the equation end to the corner of the tibia (A2) of the following :

$$A_2 = \cos^{-1} \left\{ \frac{R^2+Z^2-L_1^2-L_2^2}{2L_1L_2} \right\} \tag{17}$$

Then see Fig.8 back, by observing the alpha angle (α) and gamma angle (β), yielding the equation as follows:

$$\alpha = A_2 + \beta \tag{18}$$

where the alpha angle (α) can be calculated from the following equation:

$$\alpha = \tan^{-1} \frac{Z}{R} \tag{19}$$

and gamma angle (β) can be calculated from the following equation:

$$\beta = \tan^{-1} \frac{(L_2 \sin A_2)}{(L_1)+(L_2 \cos A_2)} \tag{20}$$

From equation (18) , (19) , and (20) are resulting final equation for the angle of femur (A1):

$$A_1 = (\tan^{-1} \frac{Z}{R}) - (\tan^{-1} \frac{(L_2 \sin A_2)}{(L_1)+(L_2 \cos A_2)}) \tag{21}$$

D. Stabilization Algorithm Quadruped Robot

This quadruped robot uses stabilization algorithm, that contain algorithms and a Proportional controller . The value of Proportional parameters are obtained from trial and error from data sensor that has been tested on some experiments. In General, the block diagram of the process control robot quadruped is shown by Fig.8.

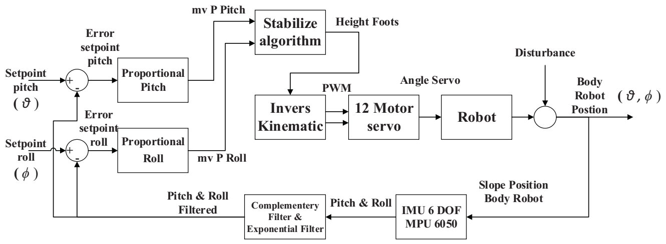


Fig.8. Block Diagram of the quadruped robot controllers

Stabilizing the quadruped body need a stabilization algorithm. Before designing the program, it needed a flowchart to make it easier to program the robot. Flowchart Stabilization Algorithm can be seen in Fig.9.

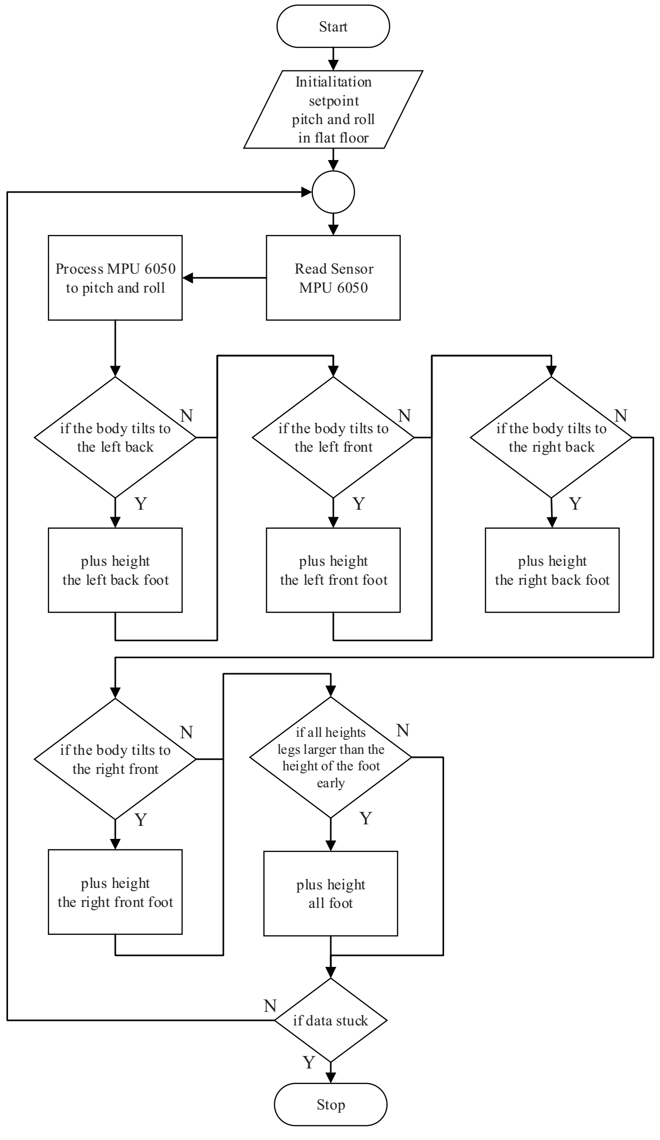


Fig.9. Image Stabilization Algorithm Flowchart Quadruped Robot

On The Fig. 9. it can be seen that the quadruped robot will stabilizing the body by elevating each robot's legs one by one. It has been designed so that the quadruped robot can customize on the trajectory of the uneven floor.

III. TESTING AND RESULT

A. Testing Parameter values of Stabilization Algorithm

This test is by changing the value of Kp that are vary by using try and error and then see the system response. Quadruped robot is placed on the position of the roll value -10 °. The best result is with value of Kp = 0.035. as it can see in Fig.10.

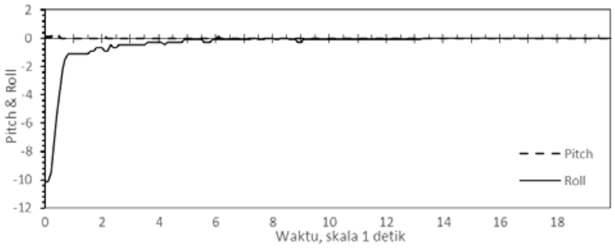


Fig.10. The test Graph parameter values stabilization algorithm with kp = 0.035

Fig.10. indicates that the quadruped robot is quick enough in stabilizing body in 5 minutes to achieve steady state.

B. Maximum Angle Testing Stabilization Algorithm

This test is done by putting the quadruped robot on the extreme roll angle. As it can be seen in Fig.11.

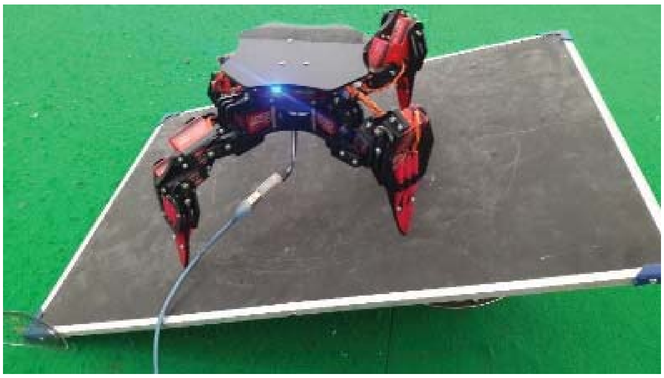


Fig.11. Maximum angular stabilization Testing algorithm

First testing is with roll angle of 33°. The results can be seen in graph below.

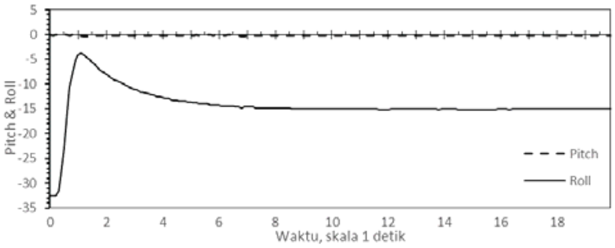


Fig.12. Maximum angular stabilization testing Graph algorithm with an angle of 33 °

Fig.12 indicates that the quadruped robot can't stabilize the body with roll angle of 33 ° and experiencing a dip in roll angle of 15 °. Next testing is with roll angle of 17°. The results can be seen in graph below.

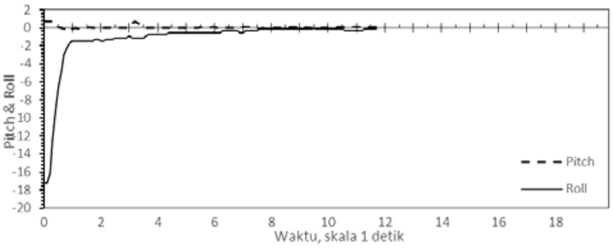


Fig.13. Maximum angular stabilization testing Graph algorithm with an angle of 17 °

Fig.13 indicates that the quadruped robot can stabilize the body with roll angle of 17 ° and do not experience a dip in roll angle.

C. *Testing Of Gait Quadruped Robot On Uneven Floor Without A Controller*

After done testing the gait without the controller then the terminology a graph of pitch and roll can be seen in Fig.14.

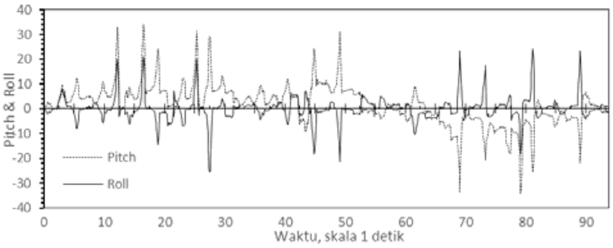


Fig.14. Gait test without Graph controller

Can be seen in Fig.14 graph that in 94 seconds the robot has made it through the uneven floor. However the stability of quadruped robots when walking on uneven floor without the controller is absolutely not a good thing because it has undergone a large slope value of pitch and roll angle to 33.9° and 25.3° respectively.

D. *Testing Of Gait Quadruped Robot On Uneven Floor With Stabilization Algorithm*

Can be seen in Fig.15 which is testing the quadruped robot with stabilization algorithm on while passing through the uneven floor. In the picture it looks clear that the position of the body of the quadruped robot remains stable despite the different floor heights (uneven floor).

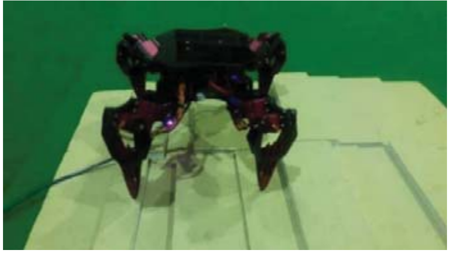


Fig.15. Robot quadruped gait Testing with stabilization algorithm

The testing was performed in five times. The first test with a variation of 5 cm step. second Test with variations of 6 cm step. the third Test with a variation of 7 cm step. the fourth Test is with a load of 0.5 Kg. Fifth Test with 1 Kg load variations. This quadruped robot testing is placed on the path of 70 cm uneven floor.

After done testing first gait stabilization algorithm with variations of 5 cm step, then the result a graph of pitch and roll can be seen on Fig.16.

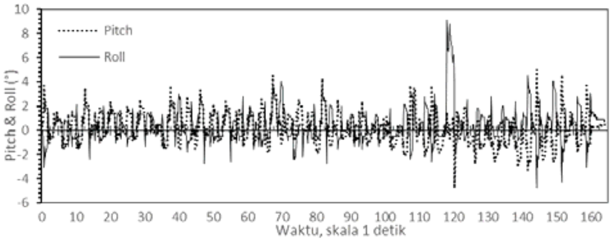


Fig.16. Gait test Charts with stabilization algorithm variation 5 cm step.

The chart shows that in 160 second, quadruped robot has crossed the uneven floor. The testing time that required to pass through the uneven floor with stabilization algorithm is indeed longer than testing without the controller, since stabilization algorithm takes several seconds to perform algorithms. The results of the stability of quadruped robot when walking on uneven floor with stabilization algorithm is very different from testing gait without a controller. It is because the quadruped robot when walking on uneven floor needs time for stabilization algorithm each time walking one by one. From the results of the test, the slope angle of the pitch and roll are 8.8° and 4.8° respectively.

After done testing the second gait stabilization algorithm with variations of 6 cm step, then the result a graph of pitch and roll like Fig.17.

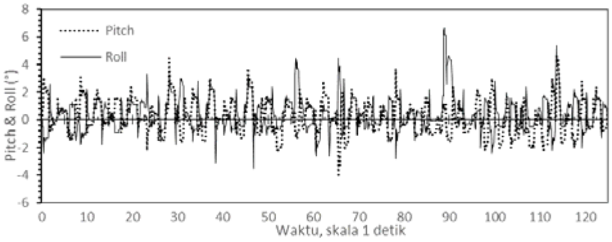


Fig.17. Gait test Charts with stabilization algorithm variation 6 cm step.

Can be seen in Fig.17, the graph shows that in 125 minutes quadruped robot has crossed the uneven floor. From the results of the test, the slope angle of pitch and roll are 6.5° and 4.1° respectively.

After done testing third gait stabilization algorithm with variations of the step 7 cm, then the result a graph of pitch and roll like Fig.18.

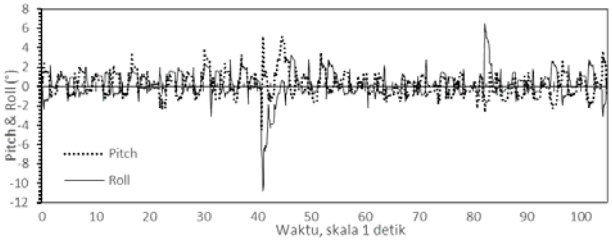


Fig.18. Gait test Charts with stabilization algorithm variation measures 7 cm.

Can be seen in Fig.18, the graph shows that in 105 seconds quadruped robot has crossed the uneven floor. From the results of the test, the slope angle of pitch and roll are 6.5° and 10.8° respectively.

After done testing all four gait stabilization algorithm with variations in load of 0.5 Kg, then the terminology a graph of pitch and roll like Fig.19.

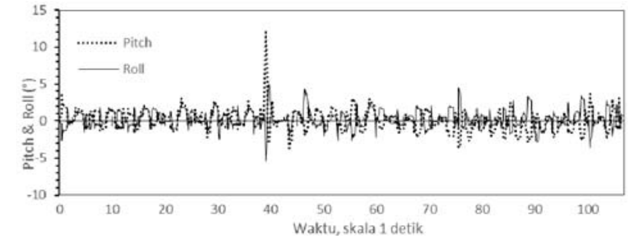


Fig.19. Gait test Charts with stabilization algorithm variations of load of 0.5 Kg.

Can be seen in Fig.19, the graph shows that in 105 seconds quadruped robot has crossed the uneven floor. From the results of the test, the slope angle of pitch and roll are 12.3° and 5.4° respectively.

After done testing all five gait stabilization algorithm with variations in load of 1 Kg, then the terminology a graph of pitch and roll like Fig.20.

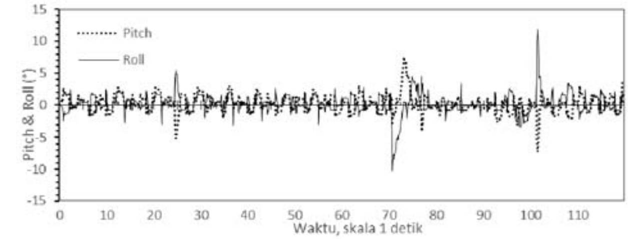


Fig.20. Gait test Charts with stabilization algorithm variations of load of 1 Kg.

Can be seen in Fig.20, the graph shows that in 115 seconds quadruped robot has crossed the uneven floor. From the results of the test, the pitch and roll angle are 7.3° and 11.4° respectively.

Due to the legs of the quadruped robot which already rests on the uneven floor, but skidded because of the leg rests on the surface of the floor surface with different elevations, the quadruped robot stabilization algorithm is longer and it causes the maximum angle of slope is bigger. Then from the fifth test results can be summarized in table 1.

TABLE 1. Gait Testing with stabilization algorithm.

No	**Variation**	**Time**	**Biggest pitch angle error (°)**	**Biggest roll angle error (°)**
1	Step 5 cm	160	8,8	4,8
2	Step 6 cm	125	6,5	4,1
3	Step 7 cm	105	6,5	10,8
4	Load 0.5 Kg	105	12,3	5,4
5	Load 1 Kg	115	7,3	11,4
Average		122	8,28	7,3

After five times of testing in quadruped robot with stabilization algorithm on uneven floor then we obtained time in 122 seconds for 70 cm distance. Produces biggest error of pitch angle in 8.28 ° and generates biggest error of angle roll in 7.3 °. Compared to the testing of gait without the controller and the one that use stabilization algorithm can be seen in table 2.

TABLE 2. Comparison testing of gait without controllers and gait with stabilization algorithm.

No	***Gait***	**Time**	**Biggest pitch angle error (°)**	**Biggest roll angle error (°)**
1	Gait without controllers	94	33,9	25,3
2	Gait with stabilization algorithm	122	8,28	7,3
Deviation		-28	25,62	18
Percentage (%)		-29,8	75,58	71,15

With the using of stabilization algorithm, it can decrease the travel time up to 29.8%, but with the design of the stabilization algorithm it can increase the stability of pitch angle up to 75.58% and roll angle up to 71.15%.

IV. CONCLUSION

The main Results of this research has managed to get the conclusion that quadruped robot using stabilization algorithm can improve the stability of pitch angle up to 75.58% and angle stability roll up to 71.15%. On testing gait quadruped robot using stabilization algorithm produces an average slope pitch angle up to 8.28° and an average slope roll angleup to 7.3°. On testing gait robot quadruped without the controller generates a slope pitch angle of 33.9° and slope tilt angle up to 25.3°. On the results of testing the gait of quadruped robot using stabilization algorithm will reduce the travel time of 29.8% than without a controller. On the results of testing quadruped robot with stabilization algorithm in a stationary condition and tilt angle of 10° brings a best result value of Kp in 0.035. On the results of testing quadruped robot with stabilization algorithm in a stationary condition can respond to a maximum slope angle of 17° with the body remains flat.

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