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Stabilization of Six-Legged Robot on Tilt Surface With 9 DOF IMU Based on Invers Kinematic

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ABSTRACT: *Robot is a tool which is developed very fast. There are several types of robots, one of them is six-legged robot. One of the problems of this robot is when the robot walks on the tilt surface. This would result the movement of the robot could be late and the center of gravity is not balanced. In this research, stabilization of six-legged robot walking on tilt surface using nine degree of freedom (DOF) inertial measurement unit (IMU) sensor based on invers kinematic is designed. The IMU sensor comprises a gyroscope, a magnetometer, and three-axis accelerometer. This sensor works as the input of the tilt degree and heading of the robot, therefore they can be processed in fuzzy-pid controller to balance the body of the robot on tilt surface. The results show that the robot will move forward when the x-axis translation inverse changed from its original position, move aside when the y-axis translational modified and move up and down if the translation to the z-axis was changed. From the testing of IMU get the total of RMSE pitch is 1,73%, roll =1,67% and yaw = 1,24%. In controller fuzzy-pid get the good respon is on the value Kp have k1=0,5, k2=1 , k3 = 3 , Ki have k1=0,5 , k2=0,5, k3=0,5 and Kd have k1=0,25 , k2=0,35 dan k3=0,45.*
Keywords -*Hexapod, IMU, Fuzzy-PID*

I. INTRODUCTION

Robot is one of familiar lessons in control and instrument's students. The development of robotic is so fast with so many new system which has founded. One of the types of robots is six-legged robot (hexapod). Hexapod moves with its legs which is designed to make the body of robot in balance. Legs are built from servo motor[1].

Some disadvantage of hexapod are if the robot find the tilt surface. In this area, robot's movement can cause negative effect on the center of gravity; causing imbalance in the robot. It can be disturbance on the servo motors which given the biggest load and so the servo motor can be broken faster than before[1].

Because of that, the control of the body of the robot needed to make the body of the hexapod still balance in one line to reduce error the center of gravity and so it can reduce the broken of servo motor. One solution to make stabilization of hexapod in tilt surface is with developing invers kinematic. This can give the movement of hexapod based on X, Y and Z coordinate[2].

Beside on kinematic's of movement, the sensor needs to give the reference of orientation degrees to compare with the orientaion degree in robot. The sensor are MPU 6050 and HMC 5883 these sensors built from accelerometer, gyroscope and magnetometer. The method of control is fuzzy-PID to give the value of SetPoint and make hexapod still balance in tilt surface.

II. METHOD

2.1 Fuzzy-PID Controller

In this experiment, stabilization of legged robot in tilt surface is made with fuzzy controller for tuning the parameter of PID. The value of membership function of fuzzy is given by the error of the orientations which tested before. This membership function can make the parameter of PID. The block diagram of system is show in figure 1 :

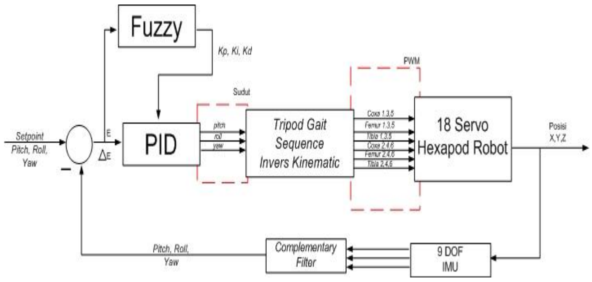


Figure 1. Blok diagramcontroller

The inputs of fuzzy are error and delta error as show in figure of membership function in figure 2 and figure 3.

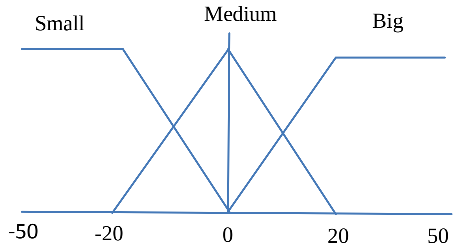


Figure 2.membership function with input is error.

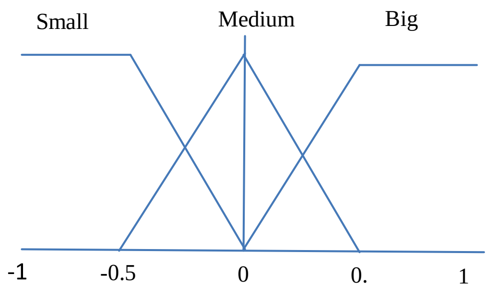


Figure 3. Membership function with input is delta error

The membership function then make in rule base of fuzzy for tuning Kp in PID as show in table 1:

Table 1 Rule based of fuzzyfor tuning Kp

ΔE \ E	Small	Medium	Big
Small	0.5	0.5	0.5
Medium	0.5	1	1
Big	0.5	1	3

Table 2 Rule based of fuzzy for tuning Ki

ΔE \ E	Small	Medium	Big
Small	0.5	0.5	0.5
Medium	0.5	0.5	0.5
Big	0.5	0.5	0.5

Table 3 Rule based of fuzzy fortuning Kd

ΔE \ E	Small	Medium	Big
Small	0.25	0.25	0.25
Medium	0.25	0.35	0.35
Big	0.25	0.35	0.45

The value of the rule based above is the single tone output which used in the PID controller as the parameter of controller.

2.2 Invers Kinematic

Invers Kinematic is defined how to get the position of legs with the calculation both of rotation every joint. This six legs robot uses invers kinematic with 3 degree of freedom. Degree of freedom is a configuration of mechanic system which measured how far the system can follow the track which is given in [2].

The representation graphic of legged robot in show in figure 4:

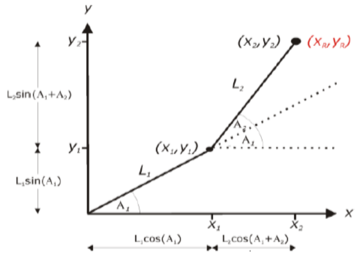


Figure 4. Graphic representation of legged robot

There are two methods to make the solution in invers kinematic, they are algebra solution and geometric solution. Both of them are same to solve the problem, but the authors just used one of the solutions that is algebra solution [2].

Which has known, that the calculation of forward kinematic is show in figure 4 above so get the formula in point x2 and y2 in formula (1) and (2) :

$x_2 = L_1 \cos(A_1) + L_2 \cos(A_1 + A_{2)}$ (1)

$y_2 = L_1 \sin(A_1) + L_2 \sin(A_1 + A_{2)}$ (2)

To get the output based on distance which needed, so the calculation to search the value of A1 and A2 as shown:

Quadratic of x and y on the formula (1) and (2) :

$[x_2]^2 = [L_1 \cos(A_1) + L_2 \cos(A_1 + A_2]^2$ (3)

${x_2}^2 = L_1^2 cos^2 (A_{1)} + 2L_1L_2 \cos(A_1)\cos(A_1 + A_2) + L_2^2 cos^2(A_1 + A_2)$ (4)

$[y_2]^2 = [L_1 \sin(A_1) + L_2 \sin(A_1 + A_{2)}]^{\;2}$ (5)

${y_2}^2 = L_1^2 sin^2 (A_{1)} + 2L_1L_2 \sin(A_1)\sin(A_1 + A_2) + L_2^2 sin^2(A_1 + A_2)$ (6)

Sum the x and y which has calculate in formula (4) and (6) :

$${x_2}^2 + {y_2}^2 = L_1^2[sin^2(A_1) + cos^2(A_1)] + L_2^2[sin^2(A_1 + A_2) + cos^2$$
$$+2L_1L_2\,[sin(A_1)\,sin(A_1 + A_2) + cos(A_1)\,cos(A_1 + A_2)]$$
(7)

As we know that:

$sin^2(\propto) + cos^2(\propto) = 1$ (8)

We can get the new formula from formula (7):

${x_2}^2 + {y_2}^2 = L_1^2 + L_2^2 + 2L_1L_2\,[\sin(A_1)\sin(A_1 + A_2) + \cos(A_1)\cos(A_1 + A_2)]$ (9)

Then we have the calculation:

$\frac{{x_2}^2+{y_2}^2-L_1^2-L_2^2}{2L_1L_2} = \sin(A_1)\sin(A_1 + A_2) + \cos(A_1)\cos(A_1 + A_{2)}$ (10)

$\cos(A_2) = \frac{{x_2}^2+{y_2}^2- L_1^2-L_2^2}{2L_1L_2}$ (11)

From formula (10) and formula (11) we can get the final formula of invers kinematic in formula (12) and formula (13):

$A_2 = cos^{-1}\left\{\frac{{x_2}^2+{y_2}^2- L_1^2-L_2^2}{2L_1L_2}\right\}$ (12)

$A_1 = cos^{-1}\left\{\frac{[L_1+L_2\cos(2)]\,x-[-L_2\sin(A_2)]\,y}{[L_1+L_2\cos(2)]^{\,2}+[-L_2\sin(A_2)]^{\,2}}\right\}$ (13)

A1 and A2 is the formula of Invers Kinematic in Femur and Tibia. The calculation of coxa is given by the simple calculation with used trigonometry theorem and show in figure 5:

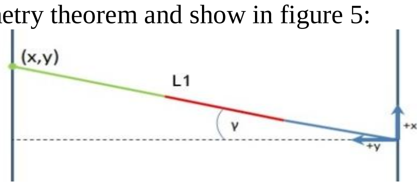


Figure 5. representationmovement of*coxa*

Figure 5is representation of coxa joint and we get the formula of A0 in formula (14)

A0 = Atan2 (X, Y)   (14)

2.3 MPU 6050*6 DoF IMU*

MPU 6050 is the transformation of 2 sensors that are accelerometer and gyroscope with I^2C communications. This sensor can detect the velocity in 3 axis (x, y, and z) and detect the angular velocity also in 3 axis. The configuration of pin in MPU 6050 show in figure 6:

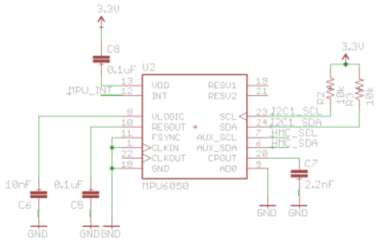


Figure 6. Razor *6 DoF IMU.*

2. 4 Sensor Magnetometer HMC5883

HMC 5883 is magnetic sensor which make in size of mount 3.0x3.0x0.9 mm 16-pin leadless chip carrier (LCC). HMC 5883 build with the resistive magnetic sensor with ADC 12-bit resolution to measure the magnetic of the earth [14].

Figure 7.HMC 5883

2.5 Complementary Filter

Two inputs from 3 sensors have different characteristic. To minimize the noise, the filter which can filter the low frequency and high frequency is needed. One of methods is used complementary filter. Complementary filter will filter out the low frequency if the sensor not so good in dynamic system, and will filtering the high frequency if the sensor not so good in static system. From low frequency and high frequency the method of complementary filter will compare both of that to one signal as show in figure 8.

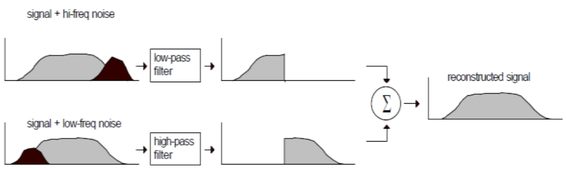


Figure8. Principle of Complementary filter.

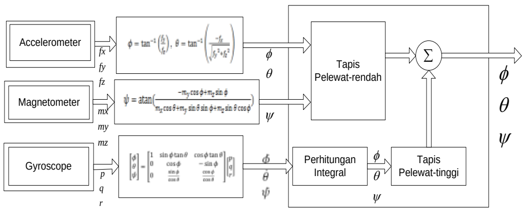


Figure9. Diagram of complementary filter

$$\phi = (K_{giroskop}) \times \left(\phi + \phi_{Giroskop} \times dt\right) + (K_{AkslMag}) \times (\phi_{AkslMag}) \quad (15)$$

2.6 Design of Hardware

The block diagram of all of system in stabilization hexapod is shown in figure 10. Figure 10 show about all hardware which used in this experiment:

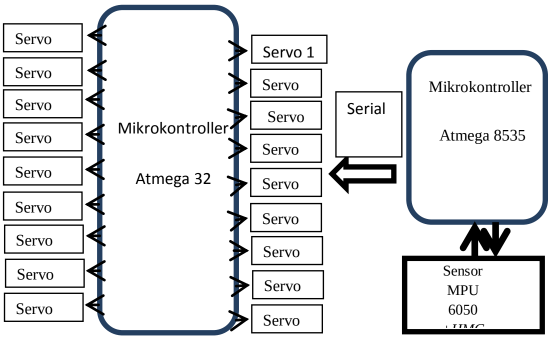


Figure 10. Diagram blok of hardware system

Figure 10 shows how the data from sensor will compute in the first microcontroller (ATMega8535) as master then will send to second microcontroller (ATMega32) as the value of orientation to make the robot's movement. Data from the first microcontroller also can send to computer to show in interface and it can be easy to analyze. The method of sending data from first microcontroller to second microcontroller or from microcontroller to computer is with serial communications (Tx/Rx).

2.9 Design of Software

The design of software is to realize the algorithm of stabilization hexapod with 9 DOF IMU. The design in this system is divided in two systems that are design of software in microcontroller and software in computer.

Software in microcontroller doing to get data, computer and sending the orientation of degree from sensors and also convert to position of body robot which the form is PWM servo motor. Software in microcontroller is used in C language and used integrated development environment (IDE) Codevision AVR. The design is about invers kinematic's program, for complementary filter and also design about fuzzy-PID in CV AVR.

The design of software in computer is made to analyze the data of sensor to be easily. The software is made with Microsoft Visual Studio 2013 in C# language. Design is about to receive serial data, compute data and showing the data from microcontroller to software.

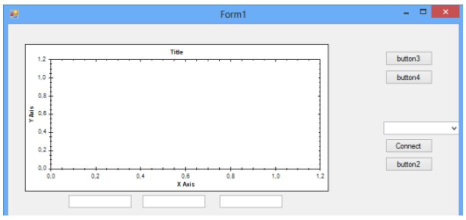


Figure 11. GUI of Software.

III. RESULT AND ANALYZE

3.1 Motor Servo Testing

Motor servo is test by change the position of body robot based on every coordinate (x, y, z) and compare with the first coordinate which has given in initial of robot. The result given by table 4:

Table 4.Value PWM Servo at initial position

Servo No	Nilai PWM
1	135
2	169
3	167
4	125
5	169
6	167
7	125
8	169

9	167
10	124
11	80
12	82
13	124
14	80
15	82
16	124
17	80
18	82

Tabel 5.Value PWM Servo if invers change base in X coordinate

Servo no	**Pengujian Posisi *body* Robot Terhadap Sumbu X**					
	15	**20**	**25**	**-15**	**-20**	**-25**
1	118	113	108	155	162	169
2	165	163	161	167	165	163
3	142	133	124	183	187	191
4	99	91	83	151	160	169
5	169	169	169	169	169	169
6	164	162	160	164	162	160
7	104	97	90	141	146	151
8	167	165	163	165	163	161
9	183	187	191	142	133	124
10	145	152	159	108	103	98
11	82	84	86	84	86	88
12	66	62	58	107	116	125
13	150	158	166	98	89	80
14	80	80	80	80	80	80
15	85	87	89	85	87	89
16	141	146	151	104	97	90
17	84	86	88	82	84	86
18	107	116	125	66	62	58

In table 5 is shown the change of PWM servo based of the body in X coordinate. We can look if PWM change big from the initial position, the PWM servo no.1 is also bigger. It is because the change about X coordinate will change the value of coxa and femur in system of robot because the movement is translation head and backward

3.2 Pitch, Roll dan Yaw Testing

The method of analyze is to get the data every 50ms sampling rate. If we have the data of sensor so we calculate the Root Mean Square of error every degree (pitch, roll and yaw) then we can conclude that the sensor is good to make in the system of stabilization or no.

Result can be look at table 6, table 7 and table 8

Table 6 pitch data

NO	Degree						
	0	10	15	20	-10	-15	-20
1	-0.89	10.63	15.17	20.23	-10.60	-15.75	-20.19
2	-0.55	10.49	15.23	20.25	-10.15	-15.52	-20.15
3	-0.89	10.31	15.35	20.37	-10.09	-15.62	-19.68
4	-0.75	10.42	15.34	20.44	-10.17	-15.47	-18.93
5	-0.79	10.73	14.90	20.43	-10.18	-15.89	-18.95
RMSE (%)	**0.43**	**0.28**	**0.11**	**0.19**	**0.13**	**0.36**	**0.23**

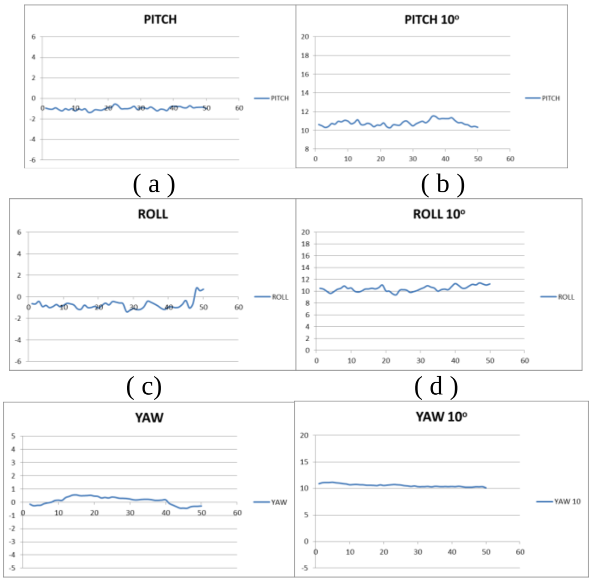
Tabel 7 roll data

NO	Degree						
	0	10	15	20	-10	-15	-20
1	-0.63	10.51	14.25	20.54	-10.85	-15.49	-20.17
2	-0.66	10.37	14.78	21.03	-10.86	-15.51	-20.23
3	-0.42	9.99	15.38	20.50	-10.44	-15.85	-20.12
4	-0.90	9.64	15.23	20.56	-10.77	-15.94	-19.69
5	-0.79	9.94	14.25	20.43	-10.85	-15.23	-19.74
RMSE (%)	**0.37**	**0.05**	**0.12**	**0.34**	**0.41**	**0.33**	**0.05**

Tabel 8 yaw data

NO	Degree						
	0	10	15	20	-10	-15	-20
1	-0.15	10.76	15.06	20.32	-10.71	-15.41	-20.17
2	0.13	10.71	15.01	20.28	-10.64	-15.47	-20.14
3	0.14	10.61	15.04	20.33	-10.54	-15.52	-20.02
4	0.35	10.54	15.34	20.24	-10.43	-15.45	-20.01
5	0.44	10.77	15.40	19.92	-10.29	-15.34	-19.97
RMSE (%)	**0.10**	**0.37**	**0.09**	**0.12**	**0.29**	**0.24**	**0.03**

From table 6, table 7 and table 8 we know that the total of RMSE of pitch is 1,73%, roll is 1,67% and yaw 1,24%.

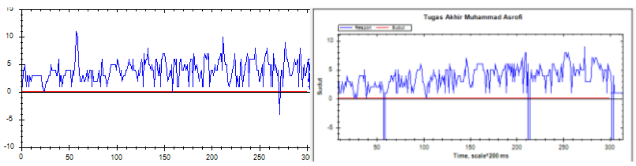


(a) (b) (c) (d) (e) (f)

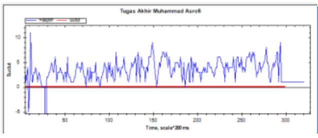
Figure 12. Graphic of Degree (a) *pitch* 0°, (b) *pitch* 10°, (c) *roll* 0°, (d) *roll* 10°, (e) *yaw*0°, (f) *yaw* 10°

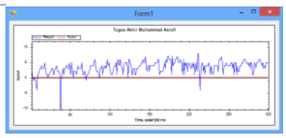
3.3Testing with disturb pitch to up

The first experiment with change the single tone output of fuzzy and get the result in figure 13:

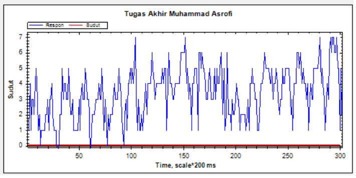


(a) (b)





(c) (d)



(e)

Figure 13. Testing with disturb of pitch up and with the variation of single tone output fuzzy.

the result show that the good response is 4^{th} experiment. The experiment is used with Kp has k1=0,5, k2=1 and k3=3. Parameter Ki is k1=0,5, k2=0,5 and k3=0,5. The Kd is k1=0,25, k2=0,35 and k3=0,45.

3.4The Heading Testing

The heading of robot is test to make the robot can walk to one line. The result is show by figure 14:

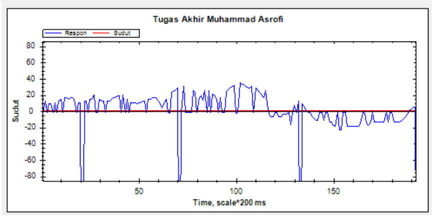


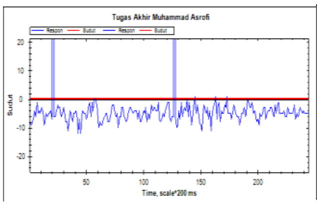
Figure14. Response the heading of robot.

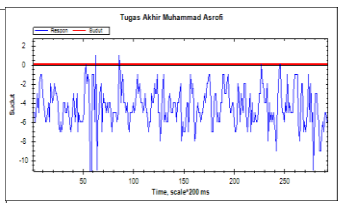
The result show that the robot can walk to one line in one heading. Position of body in track show by figure 15 :

Figure 15. The final position robot in track.

3.5Testing in all of track

In all of track is made by 2 variation of tilt that are 5^{o} and 7^{o}. Robot was walking from starting point with no degree of tilt and finish in tilt to down. The result is show by figure 16:





(a) (b)

Figure16. Graphic of Robot (a) First Tilt 5^{o}(b)First Tilt 7^{o}

The result is good in 5^{o} but in 7^{o} that are so many isolation of respond. It is because the distance in 7^{o} has offset with the maximum movement of robot. In 7^{o} the offset of distance in maximum point and minimum point is 4 cm and the maximum of movement robot to move up is just 2.5.

IV. CONCLUSION

Based on the experiment we conclude that if the invers kinematic is change based on X coordinate the body of robot move to backward and forward translation. If the change in Y coordinate, the body will move in beside starting point, and if change in Z coordinate the body will move in up and down translational. The single tone output of fuzzy which very good in this experiment is 4^{th} variation that are Kp with value k1=0,5 k2=1 and k3=3, the parameter of Ki is k1=0,5, k2=0,5 and k3=0,5. The Kd is have k1=0,25, k2=0,35 and k3=0,45. The disturbance up and down or with change the heading is not so change the responds. The respond sill can follow the SetPoint of degree which has given before.

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