The Development of Walking Pattern and Stabilization of Humanoid Soccer Robot DARDROID (DARWIN-ODROID)

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Abstract. One of the main problems on humanoid robot is motion, which is related to the stability of the robot when walking. This problem can be solved by using static walking and dynamic walking method, and the application of zero moment point and inverse kinematics supported by inertial measurement unit (IMU) with also the application of Kalman filter method and Proportional Derivative (PD) controller. The PD controller uses feedback from IMU to improve the servo position obtained from the calculation of zero moment point and inverse kinematics during the robot walking. This research would be done by comparing results from previous research and direct examination of a humanoid robot to get its stability margin and velocity. The result of humanoid robot stability margin is 5.367 mm in X-axis and 10.567 mm in Y-axis, and its minimum velocity 0.0524 m/s and maximum velocity 0.0633 m/s on grass with altitude 3 cm and minimum velocity 0.0933 m/s and maximum velocity 0.1048 m/s on grass with altitude 1.5 cm.

1. Introduction
There are problems and challenges that often arise on humanoid robot which are the design and control of the stability of walking movement of the humanoid robot, to prevent the robot from falling due to the instability, it’s required a control instruction from accurate calculations, which it’s get from an IMU.

Research on humanoid robot has been done in the University of Indonesia, but the research focus is only on the mechanical design of the bracket so there are some problems arise in the autobalance system due to the imprecise servo position on the bracket resulting obstructed of servo movement[1]. Due to this problem, further research is needed from the previous research to optimize joint trajectory control, balancing control, and motion planning[2].

In order for the robot to move properly, it takes a kind of cooperation between mechanical system, electrical, and artificial intelligence algorithm or program of robot with each system has its own role that supports the overall robot movement system[3][4]. The walking model of the humanoid robot can be divided into two main motion phases namely Single Support Phase (SSP), which only one foot is in contact with the ground to sustain the robot, and Double Support Phase (DSP), which both feet make contact with the ground[5][6][7]. This research will discuss about the zero moment point control using forward and inverse kinematics.
2. Theoretical Review and Research Methodology

2.1. Artificial Intelligence Motion Robot System

In order to design a capable artificial intelligence system in controlling the robot motion well, a method is needed to define the relation between each robot part as the basis of movement. This method is later referred to as Denavit-Hartenberg (DH) Parameters. This method can only be used if the right and left sides of the robot are symmetrical so that the equations in one part of the robot can be used in the symmetrical pair by mirroring the matrix $[\theta]$.

| $i$ | $\alpha_{i-1}$ (deg) | $a_{i-1}$ (mm) | $d_i$ | $\theta_i$ |
|-----|---------------------|----------------|-------|-----------|
| 1   | 0                   | 0              | 0     | $\theta_7 + 90^\circ$ |
| 2   | $90^\circ$          | 0              | 0     | $\theta_9 - 90^\circ$ |
| 3   | $-90^\circ$         | 0              | 0     | $\theta_{11}$ |
| 4   | 0                   | $L_{13}$       | 0     | $\theta_{13}$ |
| 5   | 0                   | $L_{15}$       | 0     | $\theta_{15}$ |
| 6   | $90^\circ$          | 0              | 0     | $\theta_{17} + 90^\circ$ |

By knowing the sixth parameter of DOF, DH parameter, and angle limitation on the right foot, so to get the DH parameter value and the angle limitation on the left leg only need to do the reflection matrix to the rotation axis [9].

Meanwhile, using the matrix equation on the right foot $fT$, calculating the angle values $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6$ can use partial geometry and partial algebra. Because of $fT$ and $gT$ are constant, so it can be simplified into:

$$ gT = [fT]^{-1} fT [fT]^{-1} $$  \hspace{1cm} (1)

2.2. Kalman Filter

In order to make the humanoid robot walks well and efficiently, the humanoid robot requires a system that calculates servo movement to keep the robot stable when switching from SSP to DSP and vice versa. One of the systems is Kalman filter method. Kalman filter method is a technique of mathematical calculation (algorithm) which provides an efficient calculation method in the process of estimating the validity of a data by minimizing the mean squared error (MSE)[10].

Kalman Filter is used to know the zero moment point (ZMP) and center of mass (CoM) on the robot when moving dynamically or statically. Kalman filter is used in a process that can be expressed in form of linear state equation as in the following equations.

$$ x_{k+1} = A_k x_k + B_k u_k + w_k $$  \hspace{1cm} (2)

The above equation can be observed with a measurement model that maps state $x$ to $y$ output as in the following equation.

$$ y_k = H_k x_k + v_k $$  \hspace{1cm} (3)

Process noise ($w$) and measurement noise ($v$) are not bound noise, they are mutually independent noise. The estimated state value $\hat{x}_k$ in the Kalman filter is determined from the posteriori estimate $\hat{x}_k$ and the difference between the actual measurement $\hat{y}_k$ and the estimated measurement $H_k x_k$ as in the following equation.

$$ \hat{x} = x_k + K_k (y_k - H \hat{x}_k) $$  \hspace{1cm} (4)

$$ \hat{x} = x_k + K_k (H_k x_k + v_k - H \hat{x}_k) $$  \hspace{1cm} (5)

The difference in value between $y_k$ actual measurement and estimated measurement is referred to as residual value. If the residual value is zero, then it indicates that the estimation result is the same as the measurement result. The value of $K_k$ is the gain factor on the Kalman filter [10].
2.3. PID Controller
Besides using the Kalman filter to filter the data used, a control system is also required to adjust the servo movement. A PID controller which is a control system that utilizes data feedback to maintain the stability of the system by continuously calculating the value of error as the difference between the desired setpoint value and the measured process variables, is used in the system [11]. PID controller will minimize the error value in any time with adjustment of control variable. The value of PID controller can be calculated using the following equation model:

\[ u(t) = P(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \]  

(6)

with \( u \) is the value of PID controller, \( K_p \) is the proportional gain, \( K_i \) is the integral gain, \( K_d \) is the derivative gain, \( e \) is the error of the setpoint minus the process variable, \( t \) is time, \( \tau \) is the integration variable from time zero to \( t \). PID controller model is required to keep the robot balance parameter value either static or dynamic [12] [11].

Then, to control the servo on the foot so that the CoM position does not exceed the robot zero moment point, an acceleration equation is used:

\[ \frac{d}{dt} \dot{x} = u_x \]  

(7)

By using the basic equation of ZMP [13]

\[ T_{zmp} = mg(x - p_x) - mx\dot{z}_c = 0 \]  

(8)

So, the equation of an optimal control with zero moment point can be expressed as follows

\[ J = \sum_{i=k}^{\infty} Q_e (p_d(i) - p(i))^2 + \Delta X^T Q_x \Delta X + R \Delta u(i)^2 \]  

(9)

\( Q_e \) is the multiplier of the ZMP error reference, \( Q_x \) is the error multiplier of the system condition and \( R \) is the input error multiplier. By following the law of the control system, it is obtained that

\[ u(k) - K_x \sum_{i=0}^{k} (p(i) - p_d(i)) - K_x X(k) = \sum_{i=k}^{N_L} G(i)p_d(k + i) \]  

(10)

\( K_x \) is gain error, \( K_x \) contains the gain of system condition and \( G(i) \) is a function variable that can show optimal preview gain for \( N_L \) preview steps [14].

3. Results and Discussion

3.1. Results of Walking Parameter Testing
This test is done with five parameters i.e. step forward, foot height, Y offset, Hip pitch offset and time period. The test is done by comparing the inverse kinematics calculation with the result that occurs when the robot is walking, the given parameters is foot height of 45 mm.

![Figure 1](image1.png)  
**Figure 1.** Testing on Height Right Foot Step on Grass 3 cm in This Research.

![Figure 2](image2.png)  
**Figure 2.** Testing on Height Right Footstep in Previous Research.
The test on the robot height footsteps in Fig. 1 uses a control chart with a range between UCL (Upper Control Limit) and LCL (Lower Control Limit) using 2 times the standard deviation of data. The data taken are the footsteps as much as 6 steps on grass with height 3 cm. In Figure 1, the result can be seen that there is a deviation of 0.00667 mm.

Figure 2 shows that there is a deviation of 0.49 mm. Even figure 1 and figure 2, That value are the average of 3 times the test on the position of the SSP, which the proper height of the foot is 45mm, but this is not so on the test. Therefore, it needs to be analyzed every angle and compare with the calculation of inverse kinematics angle.

3.2. Results of Robot Trajectory Testing
Trajectory is a pattern of a robot trace in the walking process. Trajectory testing is done to be able to know the mathematical calculation of robot velocity when walking.

\[ X(t) = (b + f) \left( \frac{t-t_{1}}{t_{2}-t_{1}} - \frac{1}{2\pi} \sin \left( 2\pi \frac{t-t_{1}}{t_{2}-t_{1}} \right) \right) - b \]

(11)

b is the initial footstep (m) and f is the final footstep (m), t is the time variable, t1 is the start time of the first step walking (s), t2 is the end time of the last step walking (s) and X is trajectory direction of the x axis.

In addition, the required trajectory support is the trajectory direction of y axis to know the pattern of y axis direction movement on the robot by using the following equation:

\[ Y(t) = \left( 2 - \left( \cos \left( 2\pi \frac{t-t_{1}}{t_{2}-t_{1}} \right) + 1 \right) \right) \frac{h}{2} \]

(12)

h is the height of the robot footstep when walking (m) [14]. From the above equations, the following graphs are obtained.

![Figure 3](image1.png) **Figure 3.** Trajectory of Robot Ankle Steps with 5 mm step size in This Research.

![Figure 4](image2.png) **Figure 4.** Trajectory of Robot Ankle Steps step size in Previous Research.

From this research, if testing the distance traveled is 3.5 m with a distance of 1 step is 0.03 m, it will require 117 steps. However, if a distance of 1 step is 0.01 m it will require 350 steps. From previous research, if testing the distance traveled is 0.8 m with a distance of 1 step is 0.012m, it will require 67 steps. So, to get the initial velocity of a robot requires a period of one phase walking, and in order to get the required acceleration, it takes the distance of step of the overall walk.

3.3. Results of Robot Balance Testing
In testing the robot stability, the measurement is using a stability margin on the robot. The measurement of stability margin value is done in walking mode. By using Zero Moment Point method, the value of (Xcom, Ycom, Zcom) obtained are (-10, 7, 26.5) cm. The value of Xzmp and Yzmp occur during the initial position of the robot, so there is no effect due to acceleration and velocity of work.
However, when at a stage where acceleration in different condition resulting the spread of ZMP points as in the following graph:

**Figure 5.** The Robot Stability when walking, on X axis in This Research.

**Figure 6.** The Robot Stability when walking in Previous Research.

From Figure 5, we can see the zmp points when the robot is moving its feet without stepping forward which means it is in the support polygon, indicating that the robot is still in a stable state. But from Figure 6, we can see the zmp points. They have been reduction because it has unstable transition Single Support Phase (SSP) into Double Support Phase (DSP) and otherwise.

**Figure 7.** The Distribution Points of Center of Mass at Walking Time in This Research.

**Figure 8.** The Distribution Points of Center of Mass at Walking Time in Previous Research.

**Figure 9.** The Distribution of ZMP points at walking time in This Research.

**Figure 10.** The Distribution of ZMP points at walking time in Previous Research.

Figure 7 and figure 9 shows that the ZMP points are in the front of the robot feet. This is because the position of walking tends to be humpback, by purpose when the robot is in a condition move
moment inertia at the top of the robot body is at ZMP point and com robot when it is going nowhere. It can still be categorized as safe because ZMP is still on support of polygon robot. Therefore, it is necessary to view the distribution of ZMP during Single Support Phase (SSP) and Double Support Phase (DSP) separately. However, in figure 8 and 10 shows that the robot have been unsteady because the ZMP points have been unstable condition between Single Support Phase (SSP) into Double Support Phase (DSP) and otherwise. Sometimes, the distribution of ZMP during SSP and DSP isn’t on support of polygon robot.

3.4. Results of Robot Velocity Testing
The Robot Velocity Testing is done with 2 velocity approaches which are the maximum velocity and the minimum velocity with certain distance, and 2 big steps that are maximal and minimal. For the velocity of the robot can be stated by the following equation:

\[ V = 2 \frac{b}{T} \]  \hspace{1cm} (13)

V is the velocity of Robot (m/s), b is the footstep size (m) and T is the period of the robot foot step (s) [4]. From the testing of walk parameter, it is known that the robot walking period is 0.6s, with minimum distance of 0.005m and maximum distance of 0.015m, so it is obtained that the minimum velocity is 0.01667 m/s and the maximum velocity is 0.05m/s.

![Figure 11. The Graph of Maximum Velocity of the Robot on 3 cm Grass in This Research.](image)

![Figure 12. The Graph of Velocity of The Robot in Previous Research.](image)

Figure 11 and 12 above represent the velocity graphs on the distance travelled. If at the previous research maximum velocity calculation of 8.11 cm/s and in this research maximum velocity of 0.05m/s, then in this test obtained the average maximum velocity is 3.809cm/s from previous research, while the average maximum velocity is 0.0633m/s from this research. If it is analyzed further, this can happen due to an increase in velocity, thus we can know the acceleration that occurs with the following equation [14]:

\[ a = \frac{V(t) T - 2b}{T^2} \]  \hspace{1cm} (14)

From the equation and results of this test, it is obtained the maximum acceleration average is -5.51x10-5m/s² from previous research and the maximum acceleration average is 0.000995m/s² from this research. This is because at a short distance the robot still has a considerable momentum of velocity due to the start of the walking phase.

4. Conclusions
In this research shown, the average robot stability is 10mm by using auto-balance system from IMU and Kalman filter method and least square data acquisition with maximal error margin of 16%. The average robot stability can be 10mm cause the designed Robot Stability. The designed Robot Stability has average stability margin of 5.367 mm on the X axis and 10.567 mm on the Y axis during walking. For the sensor of robot, the authors use gyro as the feedback servo balance control, with Kp, Ki and Kd Knee values of 0.3, 0.0 and 0.1, Kp, Ki and Kd ankle pitch values of 0.9, 0.0 and 0.1, Kp, Ki and
Kd hip roll value of 0.5, 0.0 and 0.1 and Kp, Ki and Kd ankle roll value of 1, 0.0 and 0.1. Whereas, in the previous research did not use Gyro as its balance control and robot DARWIN-OP only use Kp on balance. The result from the gyro as sensor stability and designed Robot stability, the authors have got the minimum average of the robot velocity is 0.0524 m/s on 3 cm grass. Moreover, the maximum average of the robot velocity is 0.0633 m/s on 3 cm grass. Meanwhile, in the previous research is 8.11 cm/s. The average minimum acceleration of the robot is -1.206x10^-5 m/s^2 on 3 cm grass. Next, the average maximum acceleration of the robot is 0.000995 m/s^2 on 3 cm grass. Meanwhile, the previous research amounted to 0.551 cm/s^2.

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