Dynamic balancing humanoid robot using complementary filter to optimized pid controller

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Abstract. Balance control on humanoid robots is one of the means to create harmonic motion in a robot movement system to make it more stable and can reduce the frequency of robot crashes. To control the position of the robot, it can use force/torque-based sensors or moment-based sensors inertia. The moment inertia sensor is a sensor that reads the initial angle changes to the linear angle of the body sensor framework. The accuracy of sensors in balancing robots with a system looking for set-point values will never be separated from the process of refining data processing, one of which is a sensor value (complementary) and continuous control (PID) filter that is very efficient in controlling feedback effects. The optimal PID value for balancing in stationary conditions is Kp = 0.60, Ki = 0.07, Kd = 0.90, but in a running condition there is no need for a steady state PID value, because when the conditions are needed it requires a fast gain response to obtain tuning while walking is Kp = 1.20, Ki = 0.09, Kd = 1.50.

1. Introduction
Balancing is one of the most important and fundamental functionalities for bipedal robots. Contact between feet and soil has an important role in the exchange of strength and moments between robots and land, especially because bipedal robots do not have a fixed base. The strength of this contact and when needed to control the motion of the robot. On the other hand, if the robot cannot maintain balance with the current contact status, one foot must be placed in a different place to prevent the robot from falling down. In this paper, we focus on the problem of maintaining the stability of the robot in an upright position or in a moving condition. Most balancing algorithms control contact strength and moments to be in friction contact conditions and Zero Moment Points (ZMP) (Vukobratovic and Borovac 2004). To apply this algorithm to a robot-controlled position, Inverse Kinematics (IK) is used to find out what combined angle will be ordered to reach the specified Center Of Mass (COM) position of the robot, and body posture. [5] propose a real-time joint path modification method to control ZMP for balance. Kajita et Al [1], applying balance by controlling the torque of the ankle joint using a servo motor.

In a previous research journal, filtering sensors are very useful in determining the equilibrium point of a robot to its environmental conditions [3]. The more difficult the field of trajectory that the robot traverses, the more the vibration response effect will increase. If the level of the effect of the disturbance caused by the track or motion of the robot, all control processes will also be disrupted because of the high overshoot of the raw sensor value [9].
2. Basic Theory

2.1. Imu Sensor

GY-521 MPU-6050 Module is a core module MPU-6050 which is a 6 axis Motion Processing Unit with the addition of a voltage regulator and several other complementary components that make this module ready to use with a supply voltage of 3-5VDC. This module has an I2C interface that can be connected directly to the MCU that has an I2C facility.

![Image 1. Imu Sensor](image)

Spesification Imu sensor (Figure 1) :
- Base on Chip MPU-6050
- Power supply range 3-5V
- Gyroscope range + 250 500 1000 2000 ° / s
- Acceleration range: ± 2 ± 4 ± 8 ± 16 g
- Communication standard I2C
- Chip built-in 16 bit AD converter, 16 bits data output
- Space between pin header 2.54 mm
- Modul dimension 20.3mm x 15.6mm.

2.2. Complementer Filters

Broadly speaking, this filter is divided into two filter functions, namely high-pass filter and low-pass filter. Simply put, first-order integrator x=u, assume that both measurements x and u characteristics are suitable, so that they are formed:

\[
y_x = L(s)x + \mu_x, \quad y_u = u + \mu_u + b(t)
\]  

(2.1)

Where \( L(s) \) is the function of the low-pass filter, and is noise and \( b(t) \) is deterministic perturbation which is dominated by low-frequency. The two measurements \( y_x \) and \( y_u \) can be linked and then estimated \( \hat{x} \) precisely \( x \) by:

\[
\hat{x} = F_1(s)y_x + F_2(s)\frac{y_u}{s}
\]

(2.2)

Where the transfer function \( F_1 \) is a low-pass filter and \( F_2 \) is the high-pass filter shown in the image below. If \( F_1 + F_2 = 1 \) so the filter from \( \hat{x} = F_1(s)y_x + F_2(s)\frac{y_u}{s} \) wis called a complementary filter (fig 2).

![Image 2. complementary filter](image)

The results of mathematical calculations from complementary filters are as follows

\[
\theta_k = a \ast (\theta k - 1 + \theta_{gyro} \ast \delta t) + (1 - a) \ast \theta_{accel}
\]

(2.3)
2.3. PID

The proportional controller plus an integral controller plus a differential controller (PID) is a controller whose controller action has proportional, integral and differential properties to error signals. The block diagram of a proportional controller plus integral plus differential is as follows [8]:

\[ E(s) \rightarrow K_p \left( 1 + \frac{1}{\tau_i s} + \tau_d s \right) \rightarrow U(s) \] (2.4)

The PID output described from the block diagram system above, as is the algorithm of PID are as follows:

\[ PID = K_p e(t) + K_i \int e(t)dt + K_d e(t) \] (2.5)

From the formula equation above \((K_p + K_i + K_d)\) can be translated into a numerical value, so as to facilitate mathematical conversion into the form of an algorithm.

2.3.1. Proportional constant

Proportional constants are controller functions, where the action is linearly valued for the error value

\[ U(s) \rightarrow \frac{K}{\tau s + 1} \rightarrow C(s) \] (2.6)

From the block diagram equation above extracted into a function as follows:

\[ (K) = K_p e(k) \] (2.7)

In the form of an algorithm to be:

\[ P = K_p \times \text{error} \] (2.8)

2.3.2. Proportional-Integral constant

Proportional integral (PI) is a controller whose controller action has a proportional and integrative nature of error signals.

\[ E(s) \rightarrow K_p \times 1 + \frac{K}{\tau_i s} \rightarrow U(s) \] (2.9)

We can change these values in numerical form integral functions

\[ u(k) = ki \sum_{i=0}^{k} e(i)Tc \rightarrow u(k) \]

\[ u(k) = KiTc[e(0) + e(i) + \ldots + e(k - 1) + e(k)] \]

\[ u(k) = KiTc[e(k - 1) + e(k)] \] (2.10)

If we change the above function in the form of an algorithm, it becomes the following form :

\[ PI = P + Ki \times (\text{error} + \text{last_error}) \] (2.11)

2.3.3. Proportional-Integral-Derivative Constant
PID is a type of controller that is perfect in terms of signal amplification, response to time, and correction has met the desired target, in this case reaching the steady state at the setpoint. The block diagram of the PID controller is as follows:

$$E(s) \rightarrow K_p \left(1 + \frac{1}{\tau_i s} + \tau_d s\right) \rightarrow U(s)$$  \hspace{1cm} (2.12)

From the above function it is discretized to become:

$$PID = P + I + K_d \frac{e(k) - e(k-1)}{T_c}$$  \hspace{1cm} (2.13)

If we change the above function in the form of an algorithm, form it as follows:

$$PID = P + I + K_d \ast (error - last_error)$$  \hspace{1cm} (2.14)

2.4. Rules of Ziegler-Nichols (ZN)

Broadly speaking, the use of close loop control systems can have a significant effect on the process of controlling a plant. In this case study, a humanoid soccer robot that fully uses the PID controller's close loop control system, which in a block diagram is illustrated in the Figure 3.

![Figure 3. PID controller](image)

The effect of the close loop control system control block above is to change the input value function in the form of a transfer function and then plotted it into a sigmoid linear graph as Figure 4.

![Figure 4. Sigmoid graph](image)

Ziegler-Nichols provides a parameter for optimizing the tuning process for each PID controller constant such as (Kp, Ki, Kd) which aims to facilitate the user in giving the constant value. There are two tuning concepts in Ziegler-Nichols rules, but in this paper, the use of ZN perimeter in tuning (Kp, Ki, Kd) uses the second ZN, which has the properties as illustrated below:

2.4.1. Oscillation

In the second ZN rule, it uses the turbulent system conditions, because the gain (Kp) effect is too large, but here is the second optimization of the ZN control, as Figure 5.

![Figure 5. ZN control optimization](image)

Where the Pcr is the Kp function control parameter that exceeds the set-point value.
Table 1. PID Controller

| Type of Controller | $K_p$ | $T_i$ | $T_d$ |
|--------------------|-------|-------|-------|
| P                  | 0.5$K_p$ | $\infty$ | 0 |
| PI                 | 0.45$K_p$ | $\frac{1}{12}T_p$ | 0 |
| PID                | 0.6$K_p$ | 0.5$T_p$ | 0.125$T_p$ |

By applying the tuning constant table 1, the second ZN function produces an optimal control value and with a short response reaches the steady-state setpoint.

2.4.2. Ideal Function

The final result of the PID control is expected that the PID constant value can reach the setpoint quickly and optimally, as in Figure 6.

![Figure 6. Set point](image)

Where $T$ is the time of the reinforcement function, then $L$ is the effect of the integrator function which shows the gain slope (speed) towards the setpoint, and the final value of $K_d$ gain reaches a steady-state setpoint.

3. Implementation

The results of the complementary filter attenuation level with the algorithm function value are as follows:

$$angle=(a)\ast(angle+out\_gyro\ast dt)+(1-a)\ast(angle\_acc);$$

Where:

- $a$ = filter coefficient (0.93)
- $dt$ = sampling time (1 us)
- $angle$ = filter output (/deg)
- $out\_gyro$ = output gyro (rad to deg)
- $angle\_acc$ = output accelerometer

produces a damping graph like in the Figure 7,8.

![Figure 7. Damping graph](image)
Figure 8. Damping graph

The two images (Figure 7,8) show the efficiency of the sensor fibration attenuation level caused by the servo motor vibration and the motion of the robot. From the results of the experiment above it is expected that the filter is able to compensate for drastic vibrations so that the PID overshoot value can easily reach the steady state point and be able to quickly shorten the slope cycle.

3.1 PID Controller

\[ K_p = 1.10, \quad K_i = 0.00, \quad K_d = 0.00 \]

Figure 9. Result 1

The harmonic oscillation response Figure 9 showed that the system tries to reach the setpoint value, but because the gain is too large so it overshoots.

\[ K_p = 0.80, \quad K_i = 0.05, \quad K_d = 0.00 \]

Figure 10. Result 2

With the increase in overshoot and fast transient response so that robots appear to be drastic oscillations but are fast steady-state to reduce excess oversoot values, derivative controls help reduce the slope of the transient response effect (Figure 10).

3.2 Positioning

Positioning calibration to find the setpoint as a center point point.
Centre Position (Figure 12)
Normal position of setpoint value after calibration. The normal position after the setpoint calibration is also very influential on robot stabilization when the robot experiences the forward force of the pendulum and the rear force.

Upper Position (Figure 13)
The sensor value position exceeds the setpoint value in the center position.
Figure 13. Upper Position

Lower Position (Figure 14)
The sensor value position is less than the setpoint value in the center position

Figure 14. Lower Position

4 Conclusion
From the results of the experiments as well as tuning filters and continuous control of PID, a conclusion was reached regarding the difference in sensor values that have not been and have undergone filtration and the effect of changing robot attitudes, with the ultimate goal of being able to increase the effectiveness of using the IMU sensor as a robotic balancing sensor when experiencing interference effects external environment disturbance so that the performance of the PID controller can be more optimal. For next research it is need to better movement than before with another method and mechanic.

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