Design of Balance Control System for Quadcopter Drone Using Ziegler-Nichols PID Method

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Abstract

Unmanned Aerial Vehicles (UAVs) are currently experiencing rapid development for both general and military applications. Among the various types of UAVs, the quadcopter stands out as a multirotor aircraft capable of vertical take-off and landing (VTOL). The primary factors affecting the imbalance of a quadcopter typically include payload weight and wind disturbances. The payload carried by the quadcopter can lead to instability during flight, while wind, as an external factor, significantly affects the aircraft's stability. Irregular wind direction and speed can shake the quadcopter's body, resulting in unstable flight conditions. Developing a quadcopter that remains stable during flight, selecting an appropriate control method is crucial to achieve the desired balance. One effective approach for controlling brushless motor speed is the Proportional-Integral-Derivative (PID) control method. Among various PID tuning methods, the Ziegler-Nichols method is considered effective for this application. The control of the roll (ϕ) and pitch (θ) angles of the quadcopter yielded the following PID parameters: Kp = 15, Ki = 0.55, and Kd = 0.13. The results indicate that the quadcopter has not yet achieved perfect stability in flight. This research represents an initial stage in designing a quadcopter balance control system using the Ziegler-Nichols PID tuning method.

Keywords: UAV; Drone; Quadcopter; Balance control; Ziegler- Nichols.

1. Introduction

Quadcopter is one type of unmanned aerial vehicle (UAV) that is increasingly popular because of its flexibility in various applications, such as monitoring, delivery of goods, and search and rescue. Quadcopter uses four propellers to generate lift and maneuver. Quadcopter is controlled automatically by the flight system (autopilot) or manually using a remote control [1]. The propeller on the quadcopter functions to generate lift and control movement by converting power from the motor into aerodynamic force [2]. The propeller rotates and creates low air pressure above it (based on Bernoulli's Law), producing upward lift, the faster the rotation the greater the lift produced [3].

The development of quadcopters has been carried out by many people, one of which is developing quadcopter drones in the military field that can carry weapons and detect targets using remote control [4]. In this research, balance is needed to carry the weapons and equipment needed. The balance of the quadcopter drone is also needed when the weapon system carried by the quadcopter drone is fired where to maintain the position of the quadcopter drone due to the recoil of the weapon shot. Of the several developments of UAV quadcopter, one that must be considered is the control in maintaining altitude or altitude hold and stability to be able to carry the required equipment [5]. Factors that affect the imbalance of the quadcopter are usually the load and wind thrust. The weight of the load lifted by the quadcopter can cause imbalance during flight and wind thrust, which is an external factor, greatly disrupts the stability of the quadcopter flight. Irregular wind direction and speed in the air can shake the quadcopter body and make it unstable in the air [6]. To overcome this challenge, an effective control system is needed, one of which is by using the PID (Proportional-Integral-Derivative) method [7]. The Ziegler-Nichols method has been widely used for tuning PID parameters because of its simplicity and effectiveness in achieving a stable system response. This approach allows for systematic adjustment of PID parameters (Kp, Ki, Kd) based on the system's oscillatory response. This study aims to design a quadcopter balance control system using the Ziegler-Nichols PID method to improve flight stability and performance by using the MPU6050 sensor as input, the Arduino Uno microcontroller as a controller using 2 parameters, namely with load and without load. The Ziegler–Nichols method was selected because it provides a systematic and experimentally straightforward approach to determine PID parameters for systems with oscillatory characteristics such as quadcopter attitude dynamics. Compared to other modern tuning techniques [8], Ziegler–Nichols requires minimal mathematical modeling, making it suitable for rapid prototyping using low-cost hardware like the Arduino Uno. The method also provides a reliable starting point for achieving responsive motor control under experimental constraints.

2. Method

2.1 Material

2.1.1 Quadcopter

Quadcopter is an evolution of helicopter that only uses one motor (bicopter). Quadcopter has four main motors that are equidistant from the load center. Quadcopter in applications is often used for surveillance, search, rescue and various other applications. In the development of a quadcopter drone, there are mechanical constraints of quadcopter, both dimensions and weight, which affect the stability of quadcopter control, where when there is a mechanical change, autotune is needed again so that the quadcopter can move stably according to the new value that has been obtained [9]. Quadcopter is driven by 4 rotors or also called quadrotor. The four rotors are placed on the sides of the quadcopter and are paired with the rotor in front of it. Each pair of rotors rotates in a different direction. One pair of motors rotates clockwise or Clock Wise (CW) while the other pair rotates counterclockwise or Counter Clock Wise (CCW). In principle, when the quadcopter is in the air there are four basic movements that work, namely, angular movement (roll, pitch), altitude movement (throuttle) and angular movement (yaw). Payload primarily affects the quadcopter by increasing inertia and altering its center of mass. During our experiments, adding the payload increased the required throttle and led to increased oscillation amplitude. Although detailed quantitative load-versus-oscillation data were not the main focus, preliminary observations showed that tilt deviations increased by 15–25% when load was applied. This demonstrates that load changes significantly influence system dynamics, reinforcing the importance of adaptive tuning in future work.

Figure 1. Quadcopter.

Specific limitations were encountered in achieving fully stable roll and pitch control. Several limiting factors were identified:

- •Sensor noise and drift in MPU6050 despite calibration.
- •Mechanical vibration from the BLDC motors influencing sensor readings.
- •Non-linear aerodynamic effects, especially at small tilt angles.

Hardware constraints, including the limited sampling rate of the Arduino Uno. These combined factors resulted in noticeable oscillations that prevented achieving a perfectly stable hover.

2.1.2 Proportional Integral Derivative Ziegler-Nichols

PID (Proportional, Integral, Derivative) control has been widely used in quadcopter control systems because of its ability to reduce steady-state errors and improve transient response. PID parameters (Kp, Ki, Kd) must be tuned precisely to achieve optimal performance [11]. PID is a controller that functions to determine the precision of an instrumentation system with the characteristics of feedback on the system. The ability of a quadcopter to maneuver well is influenced by the level of stability of the quadcopter in maintaining its degree of inclination [12]. Ziegler and Nichols have proposed rules for determining the proportional gain value Kp, integration time Ti, and time derivative Td based on the transient response characteristics of a given plant. Determination of PID controller parameters can be done by experimenting with the plant. The Ziegler-Nichols method is a PID tuning technique based on the system's response to disturbances. This method consists of two approaches: (1) Continuous Oscillation Method: Determining the critical gain (Ku) and oscillation period (Pu) to calculate Kp, Ki, Kd. (2) Step Response Method: Using the first order system response curve to determine the PID parameters [13]. In this Ziegler-Nichols method, first Ti and Td are given a value of 0, then the proportional control measurement, the Kp value is increased from zero to the critical value of Kcr. Here the output has oscillations with respect to the obtained Kp value. From the continuously oscillating output, the critical gain Kcr and the period Pcr can be determined. Ziegler and Nichols suggest adjusting the parameter values for Kp, Ti, and Td based on the formula in table [14].

Table 1. Basic rule ziegler nichols.

Controller	Ki	Kp	Kd
P	0.5 Kcr	∞	0
PI	0.45 Kcr	1/12 Pcr	0
PID	0.6 Kcr	0.5 Pcr	0.125 Pcr

Flights were conducted in indoor laboratory conditions to minimize uncontrolled disturbances such as wind. Therefore, natural wind disturbances were not tested during this phase of the study. The primary reason was to ensure repeatability and to isolate the effects of the PID controller. Testing under outdoor conditions is planned for future work once baseline stability is achieved.

2.1.3 Arduino Uno

The Arduino Uno is a microcontroller module based on the ATmega328P, which has 14 digital input/output pins, 6 analog inputs, and a USB connection for programming. This circuit module uses a DC voltage of 5V and can be powered via USB or an external power supply. The Arduino Uno is widely used to build digital devices and interactive objects, making it an ideal platform for educational purposes, such as demonstrating the concept of closed-loop feedback in electrical engineering [15]. The Arduino Uno is a low-power 8-bit AVR RISC-based microcontroller that runs at 16 MHz. This microcontroller is equipped with various peripherals for interaction, including external interrupts, timers with PWM, ADCs, and serial communication. The Arduino IDE makes programming and communication easy using a C-based language with built-in functions. Despite its limited computing power, the Uno can be modified for educational purposes in power electronics, supporting switching frequencies of around 100 kHz with additional libraries or direct register access [16].

Figure 2. Arduino uno modul.

2.1.4 Sensor MPU6050

The MPU6050 is a micro electromechanical sensor module that combines an accelerometer and a gyroscope, allowing it to be used in measuring acceleration and rotational speed. The MPU6050 module is an Inertial Measurement Unit (IMU) that uses the InvenSense MPU6050 chip. This module has a complete 6-axis motion tracking system, combining a 3-axis gyroscope, 3-axis accelerometer, and digital motion processor in one package. This module is also equipped with additional features in the form of a temperature sensor contained in one chip. The MPU6050 uses an I2C bus interface for communication with the microcontroller, with additional I2C buses available to connect other sensor devices such as 3-axis magnetometers and pressure sensors. The price of this sensor is quite cheap on the market with the advantage of data output in the form of digital data [17].

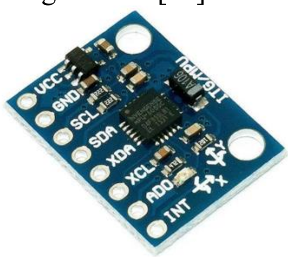

Figure 3. Sensor MPU 6050 module.

Before being fed into the PID controller, MPU6050 data underwent the following preprocessing steps:

- Averaging filter to reduce high-frequency noise.

• Calibration offsets were applied based on protractor-referenced measurements.

However, no advanced filtering such as complementary or Kalman filtering was implemented. This is recognized as an area for improvement, as sensor fusion could significantly enhance accuracy and reduce noise-induced oscillations

2.1.5 Motor Brush Less Direct Current (BLDC)

Brushless Direct Current (BLDC) motors are increasingly being used in a variety of applications due to their efficiency, compact design, and ease of maintenance. These motors operate without brushes, reducing wear, resulting in longer service life and lower noise levels. BLDC motors have a rotor and stator configuration where the rotor rotates around a central axis surrounded by a stator containing multiple windings. This design can increase efficiency and can reduce the overall size of the motor. Innovations such as the bracketless crossbeam structure contribute to the compact design, improve airflow and can reduce noise, while this system also has advantages that are very useful for applications such as dust removal systems [18].

Figure 4. Motor brushless A2212 2200KV [19].

2.1.6 Electronic Speed Control (ESC)

Electronic Speed Controller (ESC) is an electronic device that functions to regulate the speed and direction of rotation of an electric motor, especially a brushless motor (BLDC) and a DC motor. In addition, there are several ESC functions, including:

• Power conversion in BLDC motors, namely converting DC power from the battery into a 3-phase AC signal.

• System protection by: preventing damage due to excessive current, turning off the motor if the ESC overheats, cutting off power when the battery voltage is too low

• Communication with other systems, can be connected to a microcontroller (such as Arduino, Raspberry Pi) or RC receiver. In addition, some ESCs support protocols such as PWM, DShot, or CAN bus.

The ESC on the drone receives a signal from the flight controller, then regulates the speed of each BLDC motor so that the drone can fly stably. On drones that use remote control (RC), the remote control (RC) provides a signal pulse of at least 1000µS and at full speed of 2000µS. To determine the ESC to be used, it is very important to know the power (peak current) of the BLDC motor

Figure 5. *Electronic speed control (ESC)* for BLDC motor [20].

2.2 Method

2.2.1 Diagram Blok System

Gyroscope sensors are used to track the rotation or rotation of a device based on movement. In other words, gyroscope sensors are also known as devices used to maintain stable angular orientation. The MPU6050 gyro sensor sends data to the Arduino UNO, which outputs data in the form of analog data that detects the x coordinate, y coordinate, and z coordinate. The results will be data to be processed by the Arduino UNO microcontroller, so that it can be implemented on a quadcopter drone. A brushless motor is a motor consisting of a rotor in the form of a magnet and a stator in the form of a polyphase armature coil. The brushless motor as an actuator that functions to rotate the propellers on the quadcopter drone. The Proportional Integral Derivative controller functions to regulate the speed of the motor to obtain balance and stabilize the results of each data processing issued by the Gyro Sensor which produces an oscillation system when the quadcopter drone flies.

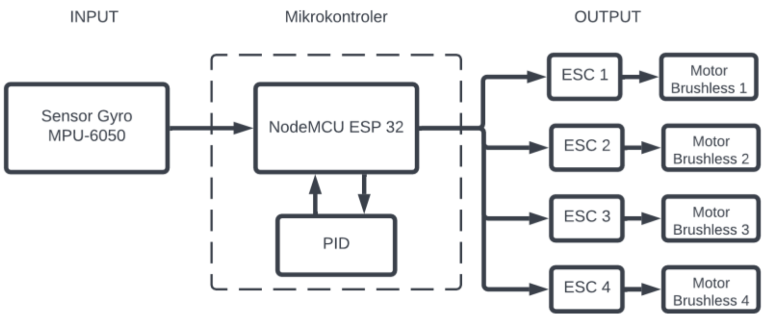

Figure 7. Diagram blok system.

2.2.2 Flow Chart

In reading the tilt there are several sequences that must be passed, namely first the drone will read the roll movement or tilt to the left and right after that read the pitch movement or tilt movement forward and backward. Based on the system diagram process in Figure 8. there are several stages to run a system, when the system starts working 4 brushless motors at each end of the quadcopter rotate then the gyroscope sensor reads the tilt coordinate data on the quadcopter in the form of X and Y data. The gyroscope sensor functions to track the rotation of a device based on movement. When the quadcopter drone tilts to the left, the two pairs of motors on the right have a higher speed, while if it tends to tilt to the right, the two pairs of motors on the left have a high speed. Also applies when the drone tilts or leans forward and backward.

In this research process, the PID Tuning method used is Ziegler-Nichols which functions to determine the critical constant value and the critical period value produced by the gyroscope sensor. If the tilt parameters are not met, the system will re-read the gyroscope sensor values to get the X and Y coordinate values. After entering the PID process with the PWM value output to regulate the motor speed, the system then ensures whether the X and Y set point values are met and in a balanced state.

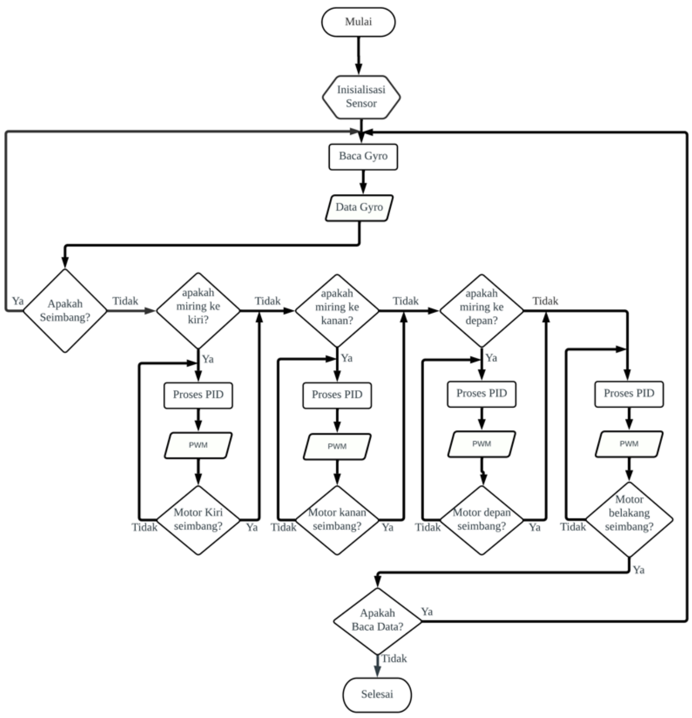

Figure 8. Flowchart system.

2.2.3 Drone Desiqn

The frame is the quadcopter body that supports all quadcopter components and a place to place the components used such as flight controller, electronic speed controller, battery, brushless motor and MPU-6050 gyroscope balance sensor. The most common and frequently used frame is the F450 drone frame model because of its light weight and strength. To support this research, a custom frame was built based on the F450 shape. The F450 frame has an X-shaped frame that provides plenty of space for installing quadcopter components. The modeling and dimensions of the F450 are designed taking into account safety requirements, smoothness, optimal propellers, motors and other components. In the selection of components, there are several choices that determine the suitability in building a drone, namely a maximum weight of 2500g or 2.5 Kg, the battery used is Lipo OVONIC 5500mAh, with a maximum controller of 60A, a brushless motor of 1100rpm, and a propeller with a diameter of 10 inches with a pitch of 4.5 inches.

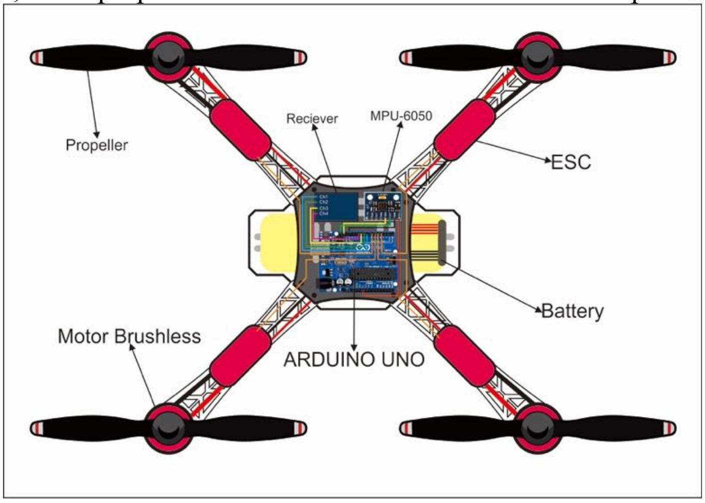

Figure 9. Drone quadcopter design.

3. Results and Discussion

3.1 Sensor MPU6050 Testing

The MPU-6050 gyro sensor is a sensor commonly used to measure the degree of inclination of an object. This sensor has two functions, namely, accelerometer and gyroscope. The values of the X, Y and Z axes on the sensor are taken simultaneously at one time. Before using the MPU-6050 gyroscope sensor, calibration must be carried out first to determine the accuracy of the MPU6050 sensor. Calibrate using a measuring instrument in the form of a protractor placed according to the axis to be measured. This calibration is intended to obtain a value that matches or is close to the calculation of the protractor measurement. The experiment was carried out on each movement, namely front pitch, rear pitch, front roll and rear roll 20 times on each movement with calibration at an angle of 10, 20, 30, 40 and 50 degrees.

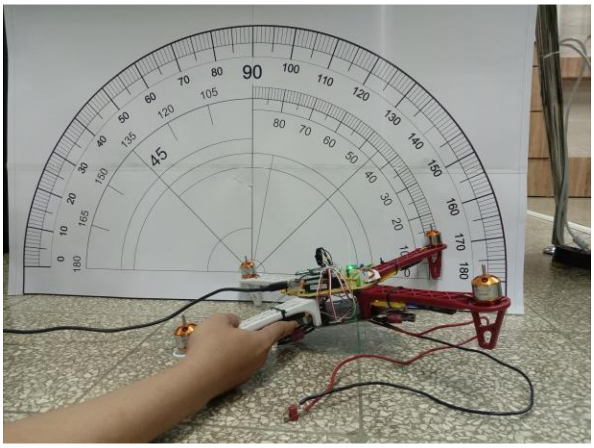

Figure 9. Sensor MPU6050 calibration.

The custom frame was based on the F450 layout but used different materials and thicknesses. The structure, while sufficiently rigid, exhibited higher vibration transmission compared to the standard F450 frame due to:

- differences in arm stiffness,
- mounting of the motors and ESCs,
- weight distribution.

These vibrations contributed to sensor noise and affected controller stability. Future improvements include using vibration-damping mounts and stiffer materials.

Table 1. Calibration Result Sensor MPU6050

No	Reference Degree	Error			
		Front Pitch	Backward Pitch	Right Roll	Left Roll
1	10	1,15%	0,19%	0,73%	1,1%
2	20	0,11%	0,28%	0,3%	0,05%
3	30	0,23%	0,36%	0,16%	0,07%
4	40	0,10%	0,11%	0,09%	0,2%
5	50	0,13%	0,11%	0,16%	0,12%

From the calibration data in Table 1, a value is obtained that corresponds to the actual degree of slope or more or less the data is close to the actual measurement value, and an error is obtained as a reference for the accuracy of the MPU6050 sensor.

3.2 Akses FlySky Fs-i6

FlySky Fs-i6 is a remote control consisting of a receiver and transmitter used to control the movement of the drone. FlySky Fs-i6 has 6 channels or channels connected to the remote control or transmitter, for the channels used are channel 1, channel 2, channel 3 and channel 4. By accessing FlySky Fs-i6, it is expected that the data taken can be used to control the movement of the drone during the flight test. The data obtained through the serial monitor is in the form of a hexa value between 1000 and 2000 which is used to control the signal on the ESC.

Figure 10. FlySky Fs-i6 receiver and transmitter.

Safety mechanisms were included during flight tests to prevent damage in case of instability. Several safety precautions were implemented:

- Propeller guards to minimize damage risk.
- Immediate kill-switch function via the FlySky FS-i6 transmitter.
- Tethering system during initial take-off trials to limit uncontrolled movement.
- Ground testing of each motor/ESC before integrated testing. These measures ensured safe operation during experimental phases.

3.3 Pcr and Kcr

Determination of Kcr and Pcr is based on peak-to-peak values, based on a graph showing the peak value of the maximum value obtained from the target calculation. The Kcr value is determined based on the maximum peak value produced by the oscillating MPU6050 sensor. The Pcr value is then obtained based on the oscillation period based on time on the graph. In taking the Kcr and Pcr values, there are two parts, namely pitch and roll, where each part has its own Kcr and Pcr values. From several experiments to find the Kp value to obtain oscillations in pitch and roll movements, it can be seen in Table 2. From these experiments, the Kp value was obtained for pitch and roll which showed oscillation, for pitch Kp = 5.0 and roll Kp = 6.0. However, the oscillation obtained is still not very visible, as can be seen in Figure 11. So it is necessary to make adjustments to the Kp value in order to obtain the desired oscillation. By making adjustments to the Kp value between the limits of the values that show oscillation and do not show oscillation.

Table 2. Experiment to find Kp value.

No	Kp Velue	Sudut berosilasi	
		Pitch	Roll
1	1,0	No	No
2	2,0	No	No
3	3,0	No	No
4	4,0	No	No
5	5,0	Yes	No
6	6,0	No	Yes
7	7,0	No	No
8	8,0	No	No
9	9,0	No	No
10	10,0	No	No

From several adjustments, the Kp value on the pitch and roll was obtained which appeared to oscillate with a Kp value of 6.1 on the pitch and a Kp value of 5.5 on the roll as shown in the graph. After obtaining the Kp value which began to appear to oscillate, the next stage was to adjust the Kp value obtained to obtain the desired conditions from each side, both pitch and roll. From several adjustments, the Kp value was obtained = 6.1 for the pitch angle and the Pcr value was obtained = 1.117 and Kcr = 25 for the roll, the appropriate Pcr and Kcr values were obtained. From the adjustment experiment, the Kp value was obtained = 5.5 with a Kcr value = 25 and Pcr = 1.028.

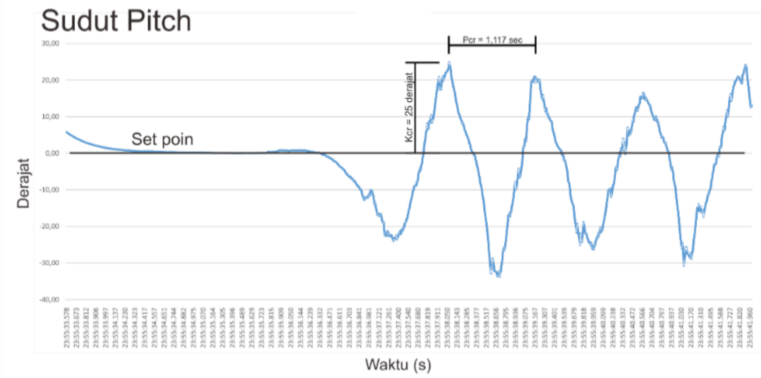

Figure 11. Pcr and Kcr values of pitch angle

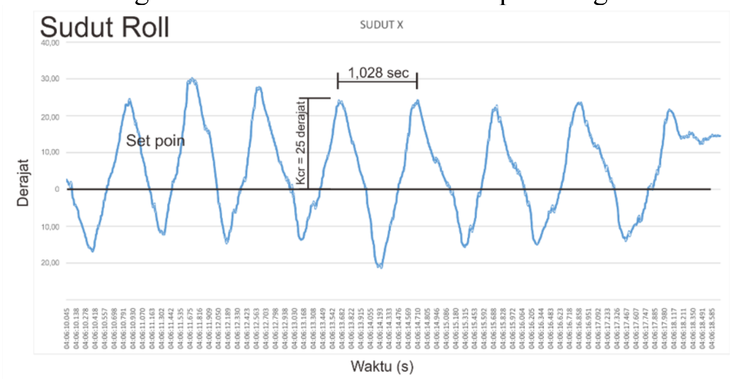

Figure 12. Pcr and Kcr values of roll angle.

Measurements of Kcr and Pcr were performed multiple times for both pitch and roll. Across repeated trials:

- Kcr varied within ±5%,
- Pcr within ±3%.

Small variations occurred due to sensor noise and slight differences in motor response. Despite this, the consistency was sufficient for applying Ziegler–Nichols tuning, though averaging the values could further improve accuracy.

3.4 Trial Flight

From the experiment, the values obtained at the roll angle are, Kp = 15, Ti = 0.55 and Td = 0.13 with values of Ki = 1.95 and Kd = 27.2. At the Pitch angle, Kp = 15, Ti = 0.51 and Td = 0.12 are obtained with values of Ki = 1.8 and Kd = 29.4.

3.5 No-Load Flight Trial

At this stage, it is carried out to test the system when flying without a load based on the values obtained from the MPU6050 sensor through readings on the pitch and roll sides. In this flight trial, the Ziegler-Nichols PID method will be implemented based on the calculations that have been carried out to determine whether the applied system can balance the quadcopter drone.

From the trial, the pitch and roll angle movement values were obtained from the MPU6050 sensor readings. During the flight test, the quadcopter drone was seen to be able to maintain balance when flying at pitch and roll angles. To find out the maximum angle value maintained when balancing the drone, the angle value obtained from the MPU6050 sensor is displayed in graphic form.k

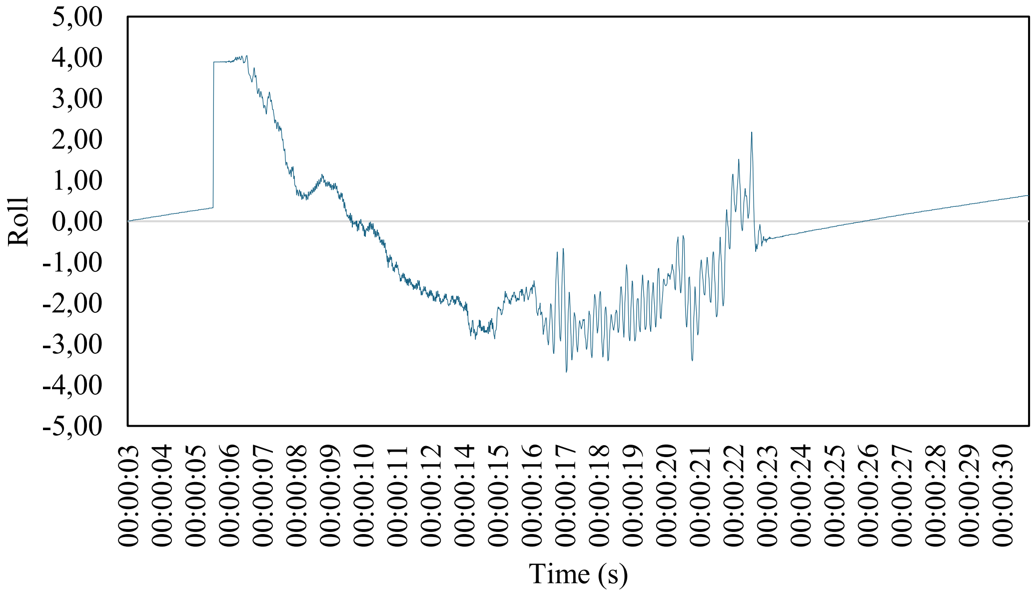

Figure 13. Roll angle graph of unloaded flight test.

From the graph shown in Figure 13, it can be seen that the quadcopter drone can maintain roll angle balance with setpoint = 0 and a maximum tilt obtained of 4 degrees.

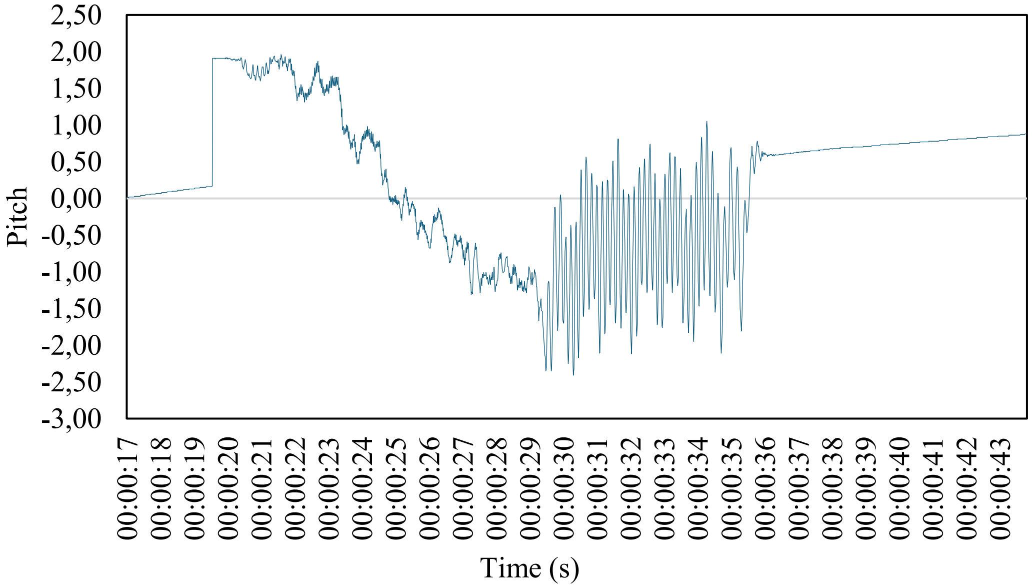

Figure 14. No-load flight test pitch angle graph.

Meanwhile, the pitch angle can be seen from the graph shown in Figure 14. It can be seen that the quadcopter drone can maintain roll angle balance with setpoint = 0 and a maximum tilt obtained of 2 degrees.

4. Conclusions

From the experiments and data analysis that have been carried out in this study, it can be concluded that the design of the quadcopter drone balance control system using the Ziegler-Nichols PID still needs to be refined to be able to maintain balance at the roll angle and pitch angle stably. The PID design for the roll angle produces a value of Kp = 15, Ki = 0.55 and Kd = 0.13. The PID design for the pitch angle produces a value of Kp = 15, Ki = 0.51 and Kd = 0.12. In the no-load test, it managed to maintain balance at a roll angle with a maximum slope of 4 degrees, at a pitch angle with a maximum slope of 2 degrees from the predetermined setpoint of 0 degrees. The next steps planned to improve control accuracy and reduce maximum tilt deviation :

1. Implement complementary or Kalman filtering for better sensor fusion.
2. Upgrade to a flight controller with higher sampling rate (e.g., STM32-based).
3. Refine mechanical structure using vibration-dampening materials.
4. Test under various payload weights and outdoor wind conditions
5. Adopt advanced tuning methods, such as auto-tuning, fuzzy-PID, or model-based control.

These improvements are expected to reduce tilt deviation significantly below the current 2–4° range

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