6 (1): 1-11 (2022)

Journal of Aviation

https://dergipark.org.tr/en/pub/jav

e-ISSN 2587-1676

The Experimental Study of Attitude Stabilization Control for Programmable Nano Quadcopter

Burak Tanyeri[1], Zehra Ural Bayrak[2*] and Ukbe Ucar[3]

[1] Firat University, School of Aviation, Aircraft Airframe-Engine Maintenance, 23119, Elazig, Turkey. (e-mail: btanyeri@firat.edu.tr).
[2*] Firat University, School of Aviation, Department of Avionics, 23119, Elazig, Turkey. (e-mail: zural@firat.edu.tr).
[3] Firat University, School of Aviation, Aircraft Airframe-Engine Maintenance, 23119, Elazig, Turkey. (e-mail: uuucar@firat.edu.tr).

Article Info

Received: Oct., 10. 2021
Revised: Nov., 24. 2021
Accepted: Dec, 28. 2021

Keywords:
Quadcopter
Stabilization
PID Control
Statistical Analysis
Experimental Study

Corresponding Author: *Zehra Ural Bayrak*

RESEARCH ARTICLE

DOI:https://doi.org/10.30518/jav.1007737

Abstract

Rotary-wing nano-quadcopters are unmanned technologies used for reconnaissance and surveillance operations in many areas, especially strategic missions such as security and military operations. The main problem for these devices, which reached a wide audience with the widespread use of civilian production, is stabilization. The most important parameter affecting the stable, effective and reliable flight of these UAVs in the air is PID elements. In this study, experimental studies are carried out in [x, y, z] coordinates using a programmable Nano-quadcopter Crazyflie 2.0 drone. In order to determine the relationship between stabilization and PID control parameters of these systems, each coordinate axis is analyzed statistically. As far as is known, there is no study in the literature regarding the performance of the PID parameters of the Crazyflie 2.0 drone. At the end of the analysis study with the SPSS program, it is determined that the related drone moves with a very high level of efficiency in the "z" axis and performs the task related to the high level of efficiency on the y-axis. It is also confirmed that the drone performs poorly in the stabilization movement on the "x" axis and as a result of the analysis study, the system becomes more stable by making the necessary adjustments in the "yaw_p" parameter. Thanks to the study, it is aimed to create a decision support system for the optimization of the PID control parameters of UAVs, which are used extensively in every sector.

1. Introduction

In recent years, unmanned aerial vehicle (UAV) also known as drone have become popular due to their relatively simple fabrication compared to other aircraft in the fields of robotics and control engineering (Ucar and Isleyen, 2019; Ucar and Isleyen, 2017; Kaya et al., 2017). Quadcopter, one of the unmanned aerial vehicles, is four-engine robot systems that is popular due to its simplicity, speed and wide application areas. It is used some applications such as delivery services, monitoring, mapping, military purposes, inspection of building and agricultural, etc. The scope of the quadcopter technology also changes over the years, as with every new technology. Due to its cost and reduced size, it now appeals to a wide audience, from researchers to hobbyists. However, manufacturers are seeking more autonomy, longer flight time, higher data processing capabilities and adaptability to changing environments. For this reason, there are many active researches and studies on the quadcopters. Studies on modeling, simulation and application of control algorithms are very important. Some research studies include the necessary automation techniques to control nonlinear dynamics.

Nanoquads are a new type of quadcopter with very low size and weight. Thus, it is made quadcopters an ideal platform for indoor use. In this study, a nano quadcopter named “Crazyflie 2.0” developed by Bitcraze company is used. It weighs 27 grams and has a length and width of 9.2 cm. For this reason, it is one of the preferred platforms for quadcopter researches recently.

In the literature, there are some articles and studies that give mathematical equations for modeling and control of UAVs and quadcopters. There are also theses that include both simulation and experimental studies for the development and testing of a mathematical model describing quadcopter dynamics. The open-source nano quadcopter named Crazyflie 2.0 is used to design the position and trajectory control algorithms as well as the system modeling of the nano quadcopter. Some of them also use the mathematical model for attitude, altitude and position controllers of the Crazyflie 2.0 (Zhou and Chen, 2021; Madhusudhan, 2016; Luis, 2016; Greiff, 2017; Murmu and Sharma, 2020).

Wang et al. (2020) have conducted a study including experimental and simulation results for the control of quadrotor systems. A new simple tracking control scheme with uncertain parameters in the dynamics have been presented in the study. This control scheme can be applied to parameters whose dynamics are unknown. It is also a useful study because it is a simple method that avoids complexity. Nguyen et al. (2020) has designed the tracking control for the multicopter. A two-layer hierarchical control scheme for trajectory tracking with mathematical equations has been examined. The simulation results have been compared with the experimental data. Oktay and Kose (2019) have modelled a quadrotor in MATLAB/Simulink with designed control system. They have used Proportional Integral Derivative (PID) control algorithm and mathematical model of longitudinal, lateral and vertical take-off and landing operations. In other study by authors (Kose and Oktay, 2019), they have used Newton Euler method for modeling of the quadrotor system. The PID control algorithm has been also performed in this study longitudinal and lateral flight. All quadrotor model with state space approach has been simulated in MATLAB/Simulink in their other study (Oktay and Kose, 2020). They have monitored differential morphing and PID algorithm for lateral flight performance.

Lambert et al. (2019) have implemented experimental and simulation study for Crazyflie quadrotor. They have used model-based reinforcement learning method for low level controls. On the other hand, Silano et al. (2018), have modeled the Crazyflie 2.0 nano-quadcopter in a physics-based simulation environment. The proposed simulation package has provided a quick understanding of the behavior of the flight control system by evaluating different indoor and outdoor scenarios at a near-realistic level. In another simulation study (Gong et al., 2020), PID control parameters and control scheme of Crazyflie 2.0 nano quadcopter have been examined. In another study used PID controller (Nithya and Rashmi, 2019), it has been aimed to develop and implement control algorithms for autonomous aircraft. Since the developed control algorithms could not be tested on a physical quadrotor, a simulation-based test study has been conducted for Crazyflie 2.0 quadcopter. A simple PID controller has been used to achieve position control and trajectory tracking.

Candan et al. (2018) have presented a fuzzy logic-based position control structure for the position control problems of the Crazyflie 2.0 nano quadcopter. Necessary models for Crazyflie 2.0 have created, simulation study has been carried out and experimentally tested. The advantages of the proposed Fuzzy PID controller over the classical PID controller in terms of performance and noise have been given with experimental results. In another study used Crazyflie 2.0 (Garcia et al., 2017), both simulation and experimental studies have been carried out for trajectory tracking of an autonomous nano quadrotor. Three methods, PID, LQR and MPC, have been used for the dynamic model of the quadrotor and their performances have been compared with flight tests. Budaciu et al. (2019) have also investigated the dynamic behavior of Crazyflie 2.0 nano quadcopter with mathematical modeling and experimental study. Dynamic behavior has been extensively evaluated to understand deviations in ideal and actual operating conditions. Neumann et al. (2019) have worked an experimental study with a swarm of nano-air robots using a Crazyflie 2.0 quadrocopter. With this robotic swarm consisting of nano unmanned aerial vehicles, they have implemented indoor air quality monitoring for occupational health and safety of workplaces. Test scenarios have optimized by developing algorithms in line with the objectives. In another experimental study (Giernacki et al., 2017) using the Crazyflie 2.0 nano quadrotor has been aimed to test and teach autonomous flights for control and robotics engineering. MATLAB/Simulink software has been used for the mathematical model and position control of Crazyflie 2.0 dynamics.

In this paper, the stabilization of Crazyflie 2.0 quadcopter in x, y and z coordinates is analyzed by associating it with PID parameters. Analysis results are evaluated by performing multiple regression analysis in SPSS statistical program and PID parameters affecting the axes are determined. As far as is known, there is no study in the literature on statistical analysis and performance attitude determination on the stabilization of the related quadcopter. The aim of this study is to ensure that the quadcopters, which are used extensively in every field, move more stably and use them more effectively. In the second part of the study, the definition of the problem and materials is made. In the third part, experimental studies are carried out on the quadcopter in real environment and in the last part, general evaluations about the study are made.

2. Material and Method

2.1. On-board Control Architecture

The autonomous flight of programmable quadcopters is directly related to the efficiency of their control software. When the PID control software on Crazyflie 2.0 nano quadcopters produced by Bitcraze is examined, it is seen that the control architecture given in Fig.1 is used.

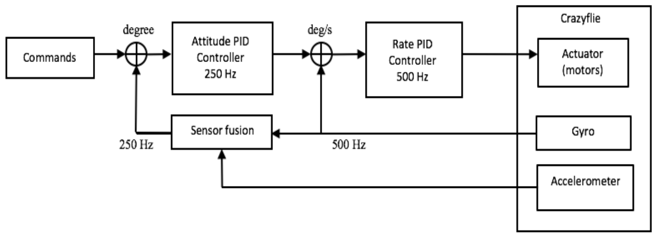

Figure 1. On-board control architecture, image courtesy of Bitcraze.

It appears that the control architecture given by the manufacturer is a two-stage PID control scheme. In this way, a control scheme given in stages can be analyzed by separating it into internal and external control loops. In the given diagram, it is understood that the outer loop regulates the inner loop, while the inner loop regulates the entire system. As a common rule in cascade systems, it is accepted that the inner loop should be organized faster than the outer loop. If the inner loop response is not as fast as it should be, or if the outer loop is faster than it should be, synchronization issues will arise between the two controllers. In applications this can be easily fixed by forcing the inner loop to be twice as fast as the outer loop as shown in the diagram (attitude controller running at 250Hz and speed controller running at 500Hz).

2.1.1. Inner Loop: Speed controllers

Speed control block inputs and outputs are shown in Fig. 2.

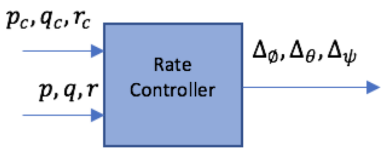

Figure 2. Speed control diagram

The purpose of this controller is to calculate the input variations of the motors at the equilibrium point to generate the required angular momentum with the state variables *p*, *q*, *r* in order to obtain p_c, q_c, r_c values. Therefore, three independent controllers are used. Roll Rate Proportional controller:

$$\Delta\phi\,(t) = K_{P,p}\,(p_c\,(t) - p\,(t)) \tag{1}$$

Using the given formula, the desired p_c value is calculated by the outer loop attitude controller. Pitch Rate Proportional controller:

$$\Delta_\theta\,(t) = K_{P,q}\,(q_c\,(t) - q\,(t)) \tag{2}$$

Similarly, the given equation is used to calculate the q_c value. Yaw Rate Proportional-Integral controller:

$$\Delta\psi(t) = K_{P,r}\,(rc\,(t) - r\,(t)) + K_{I,r}\int_0^t (rc\,(\tau) - r\,(\tau))\,d\tau \tag{3}$$

It is used to calculate the desired deviation (r_c) from the setpoint sent by an external system or specified by a teleoperation operator.

2.1.2. Outer Loop: Status check

In this Loop, the controller input and output values are as given in Fig. 3.

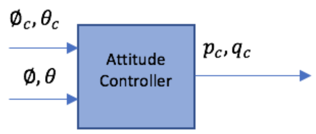

Figure 3. Attitude control diagram

This controller acts as the regulator of the speed controller by calculating the appropriate setpoints for the angular velocities around the X and Y axis to stabilize the quadrocopter in a particular desired angular position. The attitude controller takes the pitch and roll angles estimated from the sensor algorithm and compares them with external commands. The p_c *and* q_c, which are the desired angular velocities as output, are calculated with the following equations.

Roll Attitude Proportional-Integral controller: The desired (Pc) roll rate in the body frame is calculated using the control equation.

$$p_c\,(t) = K_{P,\phi}\,(\phi_c\,(t) - \phi\,(t)) + K_{I,\phi}\int_0^t (\phi c\,(\tau) - \phi\,(\tau))\,d\tau \tag{4}$$

Pitch Attitude Proportional-Integral controller: It works similarly to the Roll controller, using the corresponding variables.

$$q_c\,(t) = K_{P,\theta}\,(\theta_c\,(t) - \theta\,(t)) + K_{I,\theta}\int_0^t (\theta\,c\,(\tau) - \theta\,(\tau))\,d\tau \tag{5}$$

2.2. Off Board Position Controllers

A position controller is required to control the quadcopter by sending waypoints or trajectories through three-dimensional space. The workload of this controller can be divided into the following three different purposes.

1. Altitude controller to maintain position and thrust at a specified z altitude value as output data.
2. An x-y position controller with the required roll and pitch angles, whose output data will be edited by the on-board controller.
3. A yaw position controller that sends the required angular velocity to the on-board yaw velocity controller

As can be seen from the dynamic analysis of the quadcopter, the controllers of vertical, lateral, longitudinal and yaw movements can be adjusted independently of each other. This relatively simplifies the controller design task.

2.2.1. Altitude controller

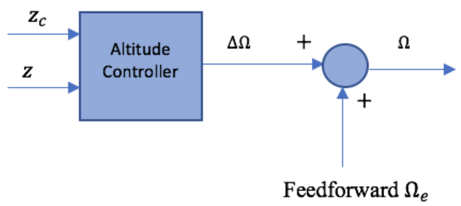

Figure 4. Block diagram of altitude controller

The altitude controller shown in Fig. 4 is a simple PID compensator whose input data comes from the orbital block for simulation and is the desired altitude for quadcopter dynamics. The controller equation that defines this PID is as follows.

$$\Delta\Omega\,(t) = K_{P,z}\,(zc\,(t) - z\,(t)) + K_{I,z}\int_0^t (zc\,(\tau) - z\,(\tau))\,d\tau + K_{D,z}\,\frac{d}{dt}(zc\,(t) - z\,(t)) \tag{6}$$

2.2.2. X-Y Position Controllers

The purpose of this controller is to regulate the on-board attitude controller by calculating the required roll and pitch angles to move the quadcopter between positions in X-Y plane. The block diagram in Fig.5 shows the inputs and outputs of this controller.

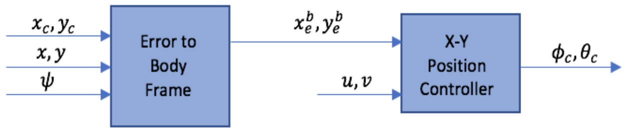

Figure 5. Block diagram of X-Y position controller

The first block given in Fig.5 calculates the error between the desired and actual X-Y position and performs the required rotation of the vehicle body with this error vector. This is done as follows:

$$\begin{bmatrix} x_e \\ y_e \end{bmatrix}^b = \begin{bmatrix} \cos(\psi) & \sin(\psi) \\ -\sin(\psi) & \cos(\psi) \end{bmatrix} \begin{bmatrix} x_e \\ y_e \end{bmatrix}^0 \tag{7}$$

when performing the calculations, the error in the body frame is defined as:

$$\begin{cases} x_e^b = x_e^0 \cos(\psi) + y_e^0 \sin(\psi) \\ y_e^b = -x_e^0 \sin(\psi) + y_e^0 \cos(\psi) \end{cases} \tag{8}$$

Then the error in the frame fixed to the body becomes the set point of the speed in the same frame. In this case, the larger the error, the faster the quadcopter must move to reach the desired point as soon as possible. Similarly, the smaller the error, the smaller the adjustment coefficient for the speed, as the quadcopter is closer to the desired point. Controllers satisfying the desired states use the equation given below.

X Position Proportional-Integral Controller:

$$\emptyset_c(t) = K_{P,x}\left(x_e^b(t) - u(t)\right) + K_{I,x}\int_0^t \left(x_e^b(\tau) - u(\tau)\right) d\tau \tag{9}$$

Y Position Proportional-Integral Controller:

$$\emptyset_c(t) = K_{P,y}\left(y_e^b(t) - v(t)\right) + K_{I,y}\int_0^t \left(y_e^b(\tau) - v(\tau)\right) d\tau \tag{10}$$

2.2.3 Yaw Position Controller

The block diagram showing the input and output data of the yaw position controller is given in Fig.6.

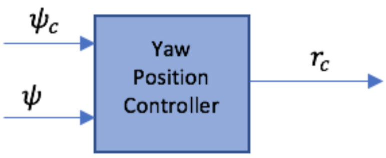

Figure 6. Block diagram of yaw position controller

The controller calculates the error between the desired deviation position and the actual position and sends it to a proportional controller whose output is the desired deviation rate regulated by the onboard speed controller. So, the action taken by the controller is given as:

$$\boldsymbol{r_c(t) = K_{P,\psi}\left(\psi_c(t) - \psi(t)\right)} \tag{11}$$

2.2.4 The Equations of Motion

Euler-Lagrangian formalism is used in the equations of motion of the CrazyFile Quadcopter 2.0. Considering quadcopter aerodynamic forces and moments, the equations of motion is derived and represented in Equations (12), (13), (14).

$$\ddot{\phi} = \frac{1}{Ixx}(Iyy - Izz) + Jr\,(W1 - W2 + W3 - W4) + lb\,(W_4^2 - W_2^2) \tag{12}$$

$$\ddot{\theta} = \frac{1}{Iyy}(Izz - Ixx) + Jr\,(W1 - W2 + W3 - W4) + lb\,(W_1^2 - W_3^2) \tag{13}$$

$$\ddot{\psi} = \frac{1}{Izz}(Ixx - Iyy) + (W_1^2 - W_2^2 + W_3^2 - W_4^2) \tag{14}$$

($\ddot{\phi}$, $\ddot{\theta}$, $\ddot{\psi}$) are the angular acceleration of quadcopter, (p, q, r) are the angular rates of roll, pitch and yaw angles, ($W1$, $W2$, $W3$, $W4$) are the angular rate of propellers, b is the thrust coefficient, d is the drag coefficient, l is length of the quadcopter from the center of gravity, (Ixx, Iyy, Izz) are the moment of inertia of x, y and z axis and Jz is the moment of inertia of motors.

2.3. Material Used in the Experiment Quadcopter

The physical characteristics of the Crazyflie 2.0 quadcopter used in the experimental studies is given in the Table 1 and the picture of the quadcopter is also given in Fig.7.

Table 1. Physical characteristics of the Crazyflie 2.0

Parameter	Description	Value	Unit
m_{quad}	Mass of the quadcopter alone	0.27	kg
m_{uwb}	Mass of the UWB module	0.04	kg
m_{vicon}	Mass of the VICON marker	0.02	kg
m	Total mass	0.33	kg
d	Arm length	39.73×10^{-3}	m
r	Rotor radius	23.1348×10^{-3}	m
I_{xx}	Principal moment of inertia around x axis	1.395×10^{-5}	$kgxm^2$
I_{yy}	Principal moment of inertia around y axis	1.436×10^{-5}	$kgxm^2$
I_{zz}	Principal moment of inertia around z axis	2.173×10^{-5}	$kgxm^2$
k_T	Non-dimensional thrust coefficient	0.2025	-
k_D	Non-dimensional torque coefficient	0.11	-

Figure 7. Crazyflie 2.0 quadcopter

2. Experimental Study

The experiment is carried out in a 3.5mx3.5mx3.5m closed environment free from disturbing factors indicated in Fig. 8. By using an autonomous flight software written in Python on the computer and a 2.4 GHz radio dongle, the quadcopter is raised to an altitude of 1m from the ground and it is requested to remain stable in the sent position for 50 seconds. Status information, instant position and altitude is recorded every second from the quadcopter. Then, the performance of the controller software is interpreted by converting the received data into graphics. Loco position node is used for area positioning and flow deck elements is used for altitude control. During the experimental study, the quadcopter and field positioner sensor images are given in Fig. 9.

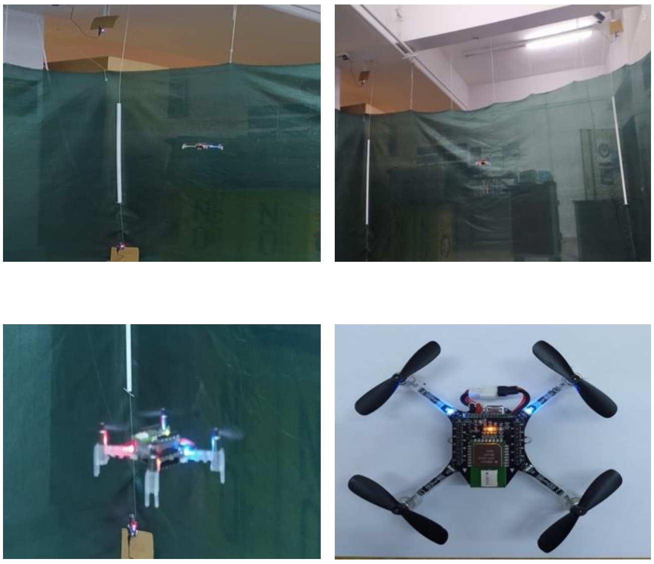

Figure 8. Experimental environment

Figure 9. Quadcopter and field positioner sensor images during the experiment

In the studies, the quadcopters are moved on the [x, y, z] coordinates and the movement started from the [0,0,0] point and completed its movement at the [0,0,1] point. For each operation of the quadcopter, the data is analyzed by averaging the times in each second of hang in the air. In the analysis study, in addition to these data, 18 different PID control parameters affecting the flight are stored as specified, and based on these data, correlations between PID parameters and targeted coordinates are determined for the Crazyflie 2.0. quadcopter. Furthermore, using the developed software, the quadcopter coordinates and PID parameters per second are recorded in the system with the help of “Loco positioning deck” and “flow deck v2”. In line with this information, the instantaneous average [x, y, z] coordinates within 50 seconds are shown in Fig. 10.

Planned and instant [x, y, z] coordinates of the quadcopter within 50 seconds are shown in Fig. 2. The planned coordinates are in the form of [0,0,1] and the distance of the quadcopter to these points every second is analyzed on the relevant figure. According to these results, we observe that the quadcopter moves with low deviations on the "z" axis, and these deviations increase moderately on the "y" axis. Looking at the movement of the drone on the "x" axis, it is determined that the deviations are higher compared to the "y" and "z" axis. The graphic regarding the deviation amounts is shown in Fig. 11.

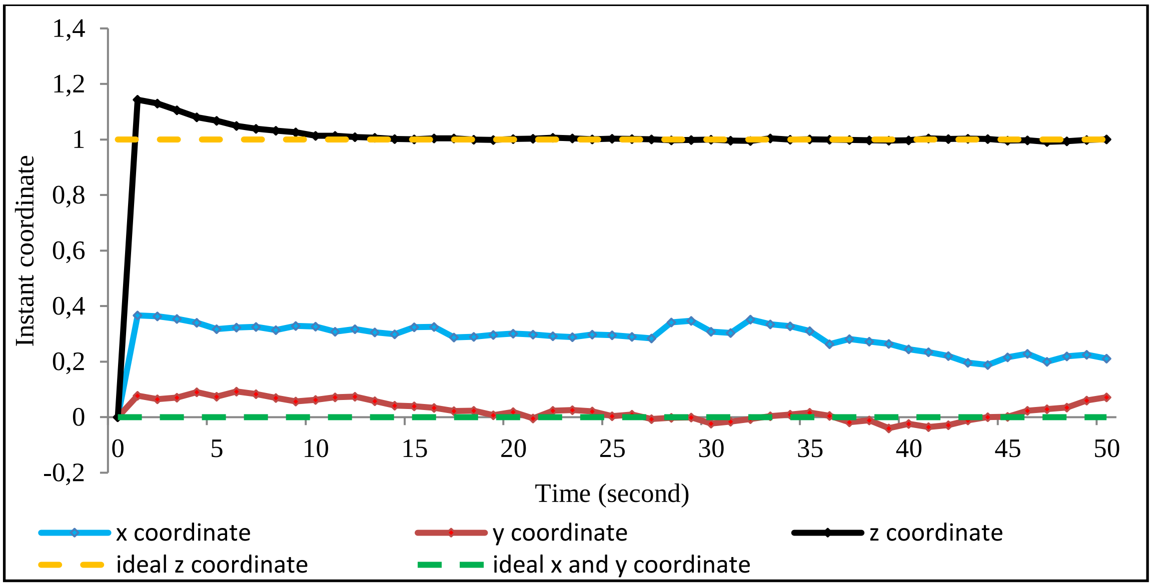

Figure 10. Instant x, y and z coordinates

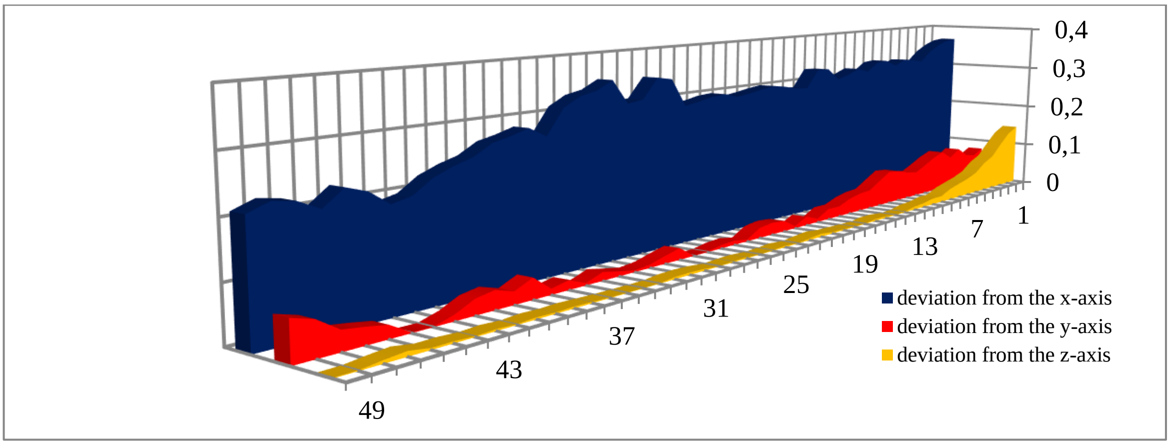

Figure 11. Deviations of the drone from the x, y and z axis during 50 seconds

In Fig. 11, the deviations of the experimental results from the ideal coordinates are expressed. Based on these results, it is understood that the deviation in the "x" axis is quite high and the quadcopter moves best and stable on the "z" axis. There are 18 different PID parameters that affect the relevant results and these parameters are expressed below.

- pitch_p
- pitch_i
- pitch_d
- roll_p
- roll_i
- roll_d
- yaw_p
- yaw_i
- yaw_d
- x_p
- x_i
- x_d
- y_p
- y_i
- y_d
- z_p
- z_i
- z_d

These parameters affect each axis stabilization and can affect each other. Multiple Regression Analysis is used to determine the effect of more than one independent variable on the dependent variable in statistics (Ucar and Isleyen, 2019; Ucar and Isleyen, 2020; Ucar et al., 2021). In this study, the effects of PID parameters on the stabilization of the axes are determined by using the related analysis method.

Multiple Regression Analysis is a statistical method used to determine the relationship of a dependent variable with more than one independent variable and the explanation rate of these independent variables for the relevant dependent variable (Statistics lecture notes, 2021). In the multiple linear regression model, the aim is to explain the total change in the dependent variable (response variable) using the independent variables (explanatory variables) (Kayaalp et al., 2015). The model created for Multiple Regression Analysis is expressed below.

$$Y_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \varepsilon_i \quad (15)$$

β_0 in the model; It shows the fixed effect when all independent variables take the value 0. β_1; represents the partial effect of a one-unit change in independent variable X_1 on the dependent variable. β_2; It expresses the partial effect of a one-unit change in the independent variable X_2 on the dependent variable. βk; demonstrates the partial effect of a one-unit change in the independent variable X_k on the dependent variable (Statistics lecture notes, 2021). Analysis process is carried out in SPSS 15.0 program, analysis results are shown and interpreted in the tables below for “x”, “y” and “z” axis.

Table 2. Multiple Regression Analysis – Descriptive Statistics Results

	Mean	Std. Deviation	N
x_coordinate	,2909	,04656	50
pitch_p	-,3833	2,62762	50
pitch_i	,0886	,25842	49
pitch_d	,0000	,00000	50
roll_p	,5262	2,30192	50
roll_i	,0549	,24456	50
roll_d	,0000	,00000	50
yaw_p	-,1937	3,34741	50
yaw_i	,0167	1,80139	50
yaw_d	,0753	,46143	49
x_p	-,0407	,28371	49
x_i	,0000	,00000	50
x_d	,0000	,00000	50
y_p	-,0008	,00791	50
y_i	,0000	,00000	50
y_d	,0000	,00000	50
z_p	-,0286	,06769	50
z_i	,0298	,06925	50
z_d	,0000	,00000	50

When Table 2 is examined, it has been determined that the quadcopter generally moves on 0,2909 point in x coordinate and deviations of ±0,04656 from these points for 50 seconds. In addition, the average values reached by the PID parameters along the x-axis are given in the table.

Table 3. SPSS model summary output for “x” axis PID parameter analysis

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,746(a)	,557	,422	,03540

a Predictors: (Constant), z_i, roll_i, yaw_d, yaw_p, x_p, pitch_p, roll_p, pitch_i, yaw_i, y_p, z_p

In Table 3, there are 3 different statistical indicators, “R”, “R Square” and “Adjusted R Square”, which summarize the analysis work, and the information about them is given below.

The Multiple Indication Coefficient (R square - R^2) in Table 3 shows the ratio of independent variables to explain the dependent variable.

In multiple linear regression, the coefficient of determination is found by the ratio of the sum of squares of the regression to the sum of the overall squares. If all observations are on the regression line, $R^2=1$. In addition, if there is no linear relationship between the dependent and independent variable, $R^2=0$.

The coefficient of determination for multiple regression analysis with “k” independent variables is calculated with the following formula (Statistics lecture notes, 2021).

$$R^2 = \frac{\widehat{B_1}\ \Sigma y_i x_1 + \widehat{B_2}\ \Sigma y_i x_2 + \cdots + \widehat{B_k}\ \Sigma y_i x_k}{\Sigma y_i^2} \tag{16}$$

In addition, coefficient of determination for two independent variables is calculated with the following formula [26].

$$R^2 = \frac{SRS}{SGS} = \frac{\Sigma \widehat{y_i}^2}{\Sigma y_i^2} = \frac{\widehat{B_1}\ \Sigma y x_1 + \widehat{B_2}\ \Sigma y x_2}{\Sigma y_i^2} \tag{17}$$

In the above formula, it is defined as $x_1 = (X_1 - \overline{X_1})$, $x_2 = (X_2 - \overline{X_2})$ ve $y = (Y - \bar{Y})$. In addition, it stands for "SRS=Sum of Regression Squares" and "SGS=Sum of General Squares" [26].

In Table 3, the R^2 value is calculated as “0.557”. When we look at the R Square value, the PID control parameters is explained the stabilization “x” at a medium level.

The Multiple Correlation Coefficient (R) value is a measure that shows how much of a relationship there is between the combination of independent variables and the dependent variable.

This value is equal to the square root of the coefficient of determination (Statistics lecture notes, 2021).

$$R = \sqrt{R^2} \tag{18}$$

In line with the above information, according to Table 3, the R value is calculated as 0,746. Accordingly, it is understood that there is a high degree of agreement between the model created and the observed model.

When unrelated independent variables are added to the regression equation, the multiple coefficients of determination is corrected to obtain the "corrected coefficient of determination R^2_{adj}” value. The adjusted coefficient of determination shows how well the model fits the population and is used when the number of explanatory variables is large. The adjusted coefficient of determination is calculated with the following formula (Statistics lecture notes, 2021).

$$R^2_{adj} = 1 - \frac{\frac{RKT}{(n-k)}}{\frac{GKT}{(n-1)}} \tag{19}$$

The “R^2_{adj}” value in Table 3 shows what percentage of the variance in the dependent variable is explained by the independent variables. Accordingly, 18 different PID values explain 42.2% of the variation in quadcopter stabilization.

Table 4. ANOVA table for “x” axis PID parameter analysis
ANOVA(b)

Model-1	Sum of Squares	df	Mean Square	F	Sig.
Regression	,057	11	,005	4,116	,001(a)
Residual	,045	36	,001		
Total	,102	47			

The results in Table 4 indicate whether the independent variables have a significant effect on explaining the dependent variables. Since the significance value is “0,001” here, it is understood that the relevant PID parameter values have a significant effect on explaining the “x” axis stabilization.

Table 5. Coefficients table for “x” axis PID parameter analysis
Coefficients(a)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.		Correlations		Collinearity Statistics	
		B	Std. Error	Beta	Zero-order	Partial	Part	Tolerance	VIF	B	Std. Error
1	**(Constant)**	,274	,007		40,383	**,000**					
	pitch_p	1,73E-005	,002	,001	,008	,994	-,010	,001	,001	,860	1,162
	pitch_i	,054	,033	,301	1,654	,107	,518	,266	,184	,371	2,693
	roll_p	,008	,004	,394	2,007	,052	,014	,317	,223	,320	3,129
	roll_i	,029	,033	,154	,879	,385	-,193	,145	,097	,400	2,499
	yaw_p	-,006	,002	-,397	-3,042	**,004**	-,280	-,452	-,337	,724	1,381
	yaw_i	,003	,004	,100	,583	,563	,458	,097	,065	,416	2,405
	yaw_d	,013	,013	,129	1,040	,305	,113	,171	,115	,796	1,256
	x_p	,010	,020	,058	,476	,637	-,089	,079	,053	,829	1,206
	y_p	2,927	1,249	,498	2,343	,025	,110	,364	,260	,273	3,666
	z_p	-,883	,782	-1,283	-1,129	,267	-,515	-,185	-,125	,010	105,082
	z_i	-,617	,734	-,918	-,840	,406	,498	-,139	-,093	,010	97,003

a Dependent Variable: x_coordinate

In Table 5, we see the individual relationship between the independent variables and the dependent variables. It is understood from these results that the "constant term" and "yaw_p" parameters should be present in the relevant Multiple Regression Analysis Model for the "x" axis. In addition, it is another result from the table that a one-unit increase in "yaw_p" causes a decrease of "-0,006" points on the "x" axis.

When the "Descriptive Statistics" analysis is performed for the "y" axis, it has been revealed that the drone generally moves at the "0,02490" point and can show deviations of "±0,036290" from this value. The model summary table for this axis is shown in Table 6.

Table 6. SPSS model summary output for “y” axis PID parameter analysis

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,780(a)	,609	,489	,02594

a Predictors: (Constant), z_i, roll_i, yaw_d, yaw_p, x_p, pitch_p, roll_p, pitch_i, yaw_i, y_p, z_p

When Table 6 is examined, it is understood that the R value is 0,780 and the fit between the model created and the observed model is quite good. R Square value in Table 6; it states that the PID control parameters explain the stabilization results in the "y" axis at the medium-high level.

Table 7. ANOVA table for “y” axis PID parameter analysis
ANOVA(b)

Model-1	Sum of Squares	df	Mean Square	F	Sig.
Regression	,038	11	,003	5,090	,000(a)
Residual	,024	36	,001		
Total	,062	47			

Model-1	Sum of Squares	df	Mean Square	F	Sig.
Regression	,038	11	,003	5,090	,000(a)
Residual	,024	36	,001		
Total	,062	47			

a Predictors: (Constant), z_i, roll_i, yaw_d, yaw_p, x_p, pitch_p, roll_p, pitch_i, yaw_i, y_p, z_p
b Dependent Variable: y_coordinate

The results in Table 7 explain the significant “y” axis stabilization of the PID parameter values.

Table 8. Coefficiencts table for “y” axis PID parameter analysis
Coefficients(a)

		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Correlations			Collinearity Statistics	
Model		B	Std. Error	Beta	Zero-order	Partial	Part	Tolerance	VIF	B	Std. Error
1	(Constant)	,020	,005		3,932	,000					
	pitch_p	,000	,002	-,036	-,320	,751	-,049	-,053	-,033	,860	1,162
	pitch_i	,038	,024	,267	1,562	,127	,591	,252	,163	,371	2,693
	roll_p	-,005	,003	-,322	-1,746	,089	-,265	-,279	-,182	,320	3,129
	roll_i	,015	,024	,103	,626	,535	-,068	,104	,065	,400	2,499
	yaw_p	-,001	,001	-,056	-,457	,650	,040	-,076	-,048	,724	1,381
	yaw_i	,004	,003	,214	1,323	,194	,635	,215	,138	,416	2,405
	yaw_d	-,005	,009	-,059	-,503	,618	-,061	-,084	-,052	,796	1,256
	x_p	-,001	,015	-,011	-,094	,925	-,200	-,016	-,010	,829	1,206
	y_p	-,115	,915	-,025	-,126	,901	,099	-,021	-,013	,273	3,666
	z_p	-1,138	,573	-2,123	-1,986	**,055**	-,604	-,314	-,207	,010	105,082
	z_i	-,968	,538	-1,847	-1,799	,080	,567	-,287	-,188	,010	97,003

a Dependent Variable: y_coordinate

From the results in Table 8, it is predicted that the "constant term" value in the relevant Multiple Regression Analysis Model for the "y" axis should only be in the model, in addition, the "z_p" value may affect the model compared to other values.

Finally, the "z" axis is obtained statistically. As a result of the analysis, when the mean value analysis is performed for the "z" axis according to "Descriptive Statistics", it is found that the drone generally moved at the "1,0143" point and could show deviations of "±0,03379" from this value. The model summary table for this axis is shown in Table 9.

Table 9. SPSS model summary output for “y” axis PID parameter analysis

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	1,000(a)	1,000	1,000	,00059

a Predictors: (Constant), z_i, roll_i, yaw_d, yaw_p, x_p, pitch_p, roll_p, pitch_i, yaw_i, y_p, z_p

From the results in Table 9, it is determined that the R value is 1, and the fit between the created model and the observed model is very high. The R Square value indicates that the PID control parameters “y” explains the stabilization at a very high level.

Table 10. ANOVA table for "z" axis PID parameter analysis
ANOVA(b)

Model-1	Sum of Squares	df	Mean Square	F	Sig.
Regression	,054	11	,005	13926,054	,000(a)
Residual	,000	36	,000		
Total	,054	47			

a Predictors: (Constant), z_i, roll_i, yaw_d, yaw_p, x_p, pitch_p, roll_p, pitch_i, yaw_i, y_p, z_p
b Dependent Variable: z_coordinate

The results in Table 10 explain the "z" axis stabilization with PID parameter values in a meaningful way.

From the results in Table 11, it is determined that the "z" axis should have "constant term" and "z_p" values in the Multiple Regression Analysis Model.

Based on all analysis results, it is determined that the "z" axis has a very stable flight and the "PID" parameters for this axis show high performance. It is determined that the stabilization in the "y" axis is at a medium to high level and the analysis data explains this performance in a meaningful way. As a result of the analyzes on the "x" axis, it is understood that the stabilization is low, the "PID" parameters have to be redefined here and the "yaw_p" parameter has a great importance in the multiple regression model.

Table 11. Coefficiencts table for "z" axis PID parameter analysis
Coefficients(a)

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Correlations			Collinearity Statistics	
Model-1	B	Std. Error	Beta	Zero-order	Partial	Part	Tolerance	VIF	B	Std. Error
(Constant)	1,000	,000		8813,136	**,000**					
pitch_p	4,01E-005	,000	,003	1,133	,265	-,116	,186	,003	,860	1,162
pitch_i	,000	,001	-,001	-,332	,742	,555	-,055	-,001	,371	2,693
roll_p	-2,33E-005	,000	-,002	-,351	,728	-,102	-,058	-,001	,320	3,129
roll_i	-6,14E-005	,001	,000	-,110	,913	-,017	-,018	,000	,400	2,499
yaw_p	6,10E-005	,000	,006	2,013	,052	,178	,318	,005	,724	1,381
yaw_i	-2,96E-005	,000	-,002	-,398	,693	,620	-,066	-,001	,416	2,405
yaw_d	-2,47E-005	,000	,000	-,118	,907	-,057	-,020	,000	,796	1,256
x_p	,000	,000	-,001	-,322	,749	-,227	-,054	-,001	,829	1,206
y_p	-,005	,021	-,001	-,256	,800	,088	-,043	-,001	,273	3,666
z_p	-,496	,013	-,993	-37,899	**,000**	-1,000	-,988	-,097	,010	105,082
z_i	,004	,012	,008	,327	,746	,991	,054	,001	,010	97,003

a Dependent Variable: z_coordinate

From the results in Table 11, it is determined that the "z" axis should have "constant term" and "z_p" values in the Multiple Regression Analysis Model.

Based on all analysis results, it is determined that the "z" axis has a very stable flight and the "PID" parameters for this axis show high performance. It is determined that the stabilization in the "y" axis is at a medium to high level and the analysis data explains this performance in a meaningful way. As a result of the analyzes on the "x" axis, it is understood that the stabilization is low, the "PID" parameters have to be redefined here and the "yaw_p" parameter has a great importance in the multiple regression model.

3. Results and Discussions

Unmanned Aerial Vehicles, which have many application areas, have been reduced to nano dimensions with the developing technology and have been equipped with high computing. These technological devices, called nano-quadcopters, have been used extensively in many sectors, especially in military operations, and with their programmable feature, they can respond quickly and effectively to the personal purposes of the users. It is very important for these systems to fly stably in terms of safety and efficiency. In this study, PID control parameters affecting the stable movement of rotary-wing nano quadcopters in the air have been analyzed statistically. Crazyflie 2.0 nano quadcopter has been taken into account in the analysis study and statistical analyzes have been performed with the average values obtained from 20 different flights.

As a result of the analysis study, it has been determined that the related drone moves quite stable in the z-axis and performs the task of staying in the air with high efficiency in the y-axis. In the "x" axis, it has been understood that the stabilization has quite bad and, in this context, the PID parameters has to be updated again. In addition to these, it has been determined from the analysis results that the parameter affecting the "x" axis with a high degree of importance is "yaw_p". Thanks to the methodology followed in the study, it is aimed to contribute to the more reliable and stable movement of the UAV systems. In addition, a decision support system is tried to be created before parameter optimization. In future studies, it is predicted that researchers will develop faster and more effective control algorithms by creating hybrid technologies.

Ethical approval
Not applicable.

Funding
No financial support was received for this study.

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Cite this article: Tanyeri, B., Bayrak, Z.U., Ucar, U. (2022). The Experimental Study of Attitude Stabilization Control for Programmable Nano Quadcopter. Journal of Aviation, 6(1), 1-11.