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Implementation of Hexacopter for Package Delivery

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ABSTRACT:
This paper presents the engineering design of an unmanned aerial vehicle (UAV)/drone hexacopter and optimizes the PID (Proportional-Integral-Derivate) values for the Pixhawk 2.4.8 (PX4) flight controller. The design phase begins with component selection and identification, with the goal that the drone can carry loads up to 3 kg. Then install the main components and test the construction results. An analysis of the experimental results of the PID PX4 controller with no load and with load was performed. Results from direct field experiments with a home-built hexacopter show that the default PID must be tuned to be able to lift a load with a specific target.

KEYWORDS: Hexacopter Drone, Pixhawk 2.4.8, PID Controller Tuning, Delivery Packages.

1. INTRODUCTION

Drone technology or unmanned aerial vehicle (UAV) development has increased very rapidly since the 2000s. Due to the impact of the Covid-10 pandemic, online product purchase transactions have become increasingly enlivened, providing citizens with the opportunity to enjoy services anytime and anywhere. With the development of robotics research and the integration of artificial intelligence systems into drones, the use of drones in the civilian sector, whether for hobby or commercial purposes, is increasingly in demand. Many domestic companies, multinationals, and even start-ups are determined to build their business using drones as an alternative service provider. Examples include parcel delivery, surveillance, mapping and regional planning [1], media and arts [2], traffic monitoring [3], drone operations in agriculture [4], and more. Equipped with computer vision and Internet of Things technology, drones are becoming increasingly intelligent in analyzing objects and capable of making predictions. As governments begin to regulate their use in certain fields, there is no doubt that drones will become a major service provider for industries and businesses.

In line with the above promising developments, many researchers and companies have developed drones in the form of hexacopter for transportation. For example, there are many applications, such as document delivery at IPB University [5], disinfectant spraying [6], medical supplies delivery [7], and many more applications in different shapes and sizes. A few companies such as Amazon, FedEx, Fizza Hut, and Google are using drones to facilitate their business. However, how products are fabricated and tested is rarely published in the form of formal scientific papers. Also, the success of building a hexacopter drone for a specific project was not accompanied by an explanation of how to design a PID controller for different drone weights. To address this challenge, some research has been done on controlling PIDs using MATLAB simulations [8], [9], PID based on the quaternion method applied to Newton-Euler equations [10] using the

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Grey Wolf Optimization (GWO) algorithm [11], using deep neural networks [12], and Ardupilot as one of the open source providers in the form of Mission Planner, also provides a guide for PID optimization (https://ardupilot.org/copter/docs/tuning-process-instructions.html). We are interested in solving the PID problem. Because, in practice, various conditions and situational factors, and the nature of the drones being built, have proven difficult for drones to take off despite proper pre-flight procedures. Therefore, the discussion of the technical possibilities of PID and tuning has implications for position control.

The aim of this work is to report on the development of hexacopter drones for future cargo transportation. The drone's physical components are carefully selected for impact resistance, lightweight, and optimal performance. Most importantly, the system is expected to be able to ship items weighing less than 3 kg. To achieve this performance, the first step after component selection, frame fabrication, and assembly is airworthiness testing based on the manufacturer's PID values for the Pixhawk 2.4.8. The success of PID tuning will trigger further development, namely the design of a cargo component that can automatically load and unload packages. Therefore, the paper is structured as follows. In the method part, we describe the selection of components and identification of parameters to realize the hexacopter. The next section covers testing with the factory PID controller in Pixhawk 2.4.8 and providing test results. A PID tuning of the hexacopter with additional load is then performed based on trials and errors. The discussion part presents the experimental analysis of the hexacopter in the drone delivery development plan. Our report ends with a conclusion and improvement suggestions for further development.

2. MATERIALS AND METHODS

2.1. Component Selection

There is a wide selection of models in terms of weight, flight autonomy, and stability characteristics for each required drone component. This project proposes the realization of a hexacopter capable of transporting light packages and cargo in highly stable semi-stationary flight. Also, the system must be able to lift an additional load of up to 3 kg or more. Additionally, the flight time should be carefully calculated according to the distance traveled. Internal stability is therefore very important as the shipped packages must reach their destination within the allotted time.

Fig. 1 shows the main components selected for package delivery weighing less than 3 kg. The description of each part is as follows.

(a) Flight Controller: Given the cost of controlling the entire system, Pixhawk 2.4.8 32-bit autopilot (PX4) is selected. This is an advanced high performance 32-bit CortexM4 ARM processor, known as FMUV2 in ChibiOS: 66e5de0d on ArduCopter V4.3.6 (0c5e999c).

(b) GPS Module: A module for determining the position of the vehicle relative to the earth. This module is a new generation Ublox GPS NEO-M8N with a compass module, and supports GPS/QZSS L1 C/A, GLONASS L10F, BeiDou B1 or other satellites.

(c) Electronic Speed Controller (ESC): The ESC function is designed to control the rotation of brushless DC (BLDC) motors by sending timed electrical signals that are translated into changes in motor speed. In the present work, a 30A 2-3S ESC that can constantly drive a BLDC motor under 1000 KV is selected.

(d) Brushless DC Motor (BLDC): The most common use of BLDC motors in drone operations is to control propeller movement after receiving the appropriate signal from the ESC. There are two types of motor rotation direction, clockwise (CW) and counterclockwise (CCW), and considering the size of the ESC, the motor capacity selected this time is Racestar 920 KV, which is compatible with 2-4s LiPo batteries.

(e) Propeller: It creates lift by creating a force differential between the top and bottom of each propeller. The propeller size chosen for this work is 9 inches (9450) with a pitch of 4.7 inches. Larger propeller sizes provide maximum lift and more stable flight but require more power. Additionally, a smaller pitch provides lower speed traction.

(f) Frame: This includes the power distribution board (PDB) that houses all the components including the payload. In this study, six arms housing ESCs and BLDCs (not shown here) were individually fabricated from hollow aluminum tubes. The wheelbase frame size is 560 mm and the PDB diameter is 21 cm (upper and lower).

(g) Power Module: A power module current voltage sensor with a damping platform provides the net power required for the flight controller (+5V) and ESC current sourced from LiPo/Li-Ion battery.

(h) Power Source: Lithium Ion (Li-Ion) works as well as LiPo (Lithium Polymer) with a flight time of less than 10 minutes. This battery type (3S-1P) was chosen for budgetary reasons. The charging mode of the battery is also the same as LiPo.

(i) Transmitter and Receiver: A radio controller is a remote control (RC) device with a radio frequency module (2.4 GHz) transmitter and receiver. Radio communication requires at least four channels: roll, pitch, yaw and altitude. The RC used in this project is a Flysky FS-i6 model upgraded to 10 channels, and the receiver uses Flysky FS-iA6B.

(a) Pixhawk 2.4.8 flight controller

(b) Ublox NEO M8N GPS module with compass and stand

(c) ESC brushless hobbywing skywalker 30A 2-3s

(d) 3 pairs BLDC Racestar BR2212 920KV

(e) 3 pairs propeller (9450) DJI model

(f) Manufacture hexacopter frame

(g) Power distribution board (PDB) with power module for Pixhawk and ESC

(h) Battery Li-Ion

(i) Flysky remote control FS-i6 with a FS-iA6B receiver

Fig. 1. The main component selected for hexacopter drone.

Once the key components have been selected, the drone parameters that can affect the performance of the system to be built are identified. The identification steps are as follows:

- Total weight (mass) of the drone.
- Describing the dynamics of the BLDC motor. This can be modeled as a transfer function that determines the voltage set point.
- A propeller's thrust coefficient indicates how consistently the propeller can lift a load. This is achieved by measuring reliability on a scale until the throttle reaches its maximum value.
- Identify the drag coefficient that slows down the drone, and finally the inertia of the frame, motors, controller, and battery.

2.2. PID Controller

PID controllers are usually designed based on error correction of loop systems. Error is defined as the difference between the setpoint (default) and the actual value of the system. There are three actions for error correction: proportional (P), integral (I), and derivative (D). A general PID equation is given by

$$u(t) = K_p e_i(t) + K_i \int_0^t e_i(\tau) d\tau + K_d \frac{de_i(t)}{dt} \tag{1}$$

where *u(t)* is PID controlled, K_p, K_i, and K_d not only improve speed, eliminate static errors, and improve accuracy, but also reduce response time and improve system stability. While indexed i is input contains of X, Y, Z, ϕ, θ, and φ. The X, Y, Z components are the input positions for hexacopter translation and rotation. The yaw angle, which consists of ϕ and θ, represents rotation, and φ represents the acceleration vector. where the relationship between ϕ and φ can be formulated as follows [13]:

$$\phi = asin\left(\frac{\ddot{X}sin\varphi - \ddot{Y}cos\varphi}{\sqrt{\ddot{X}^2 + \ddot{Y} + (\ddot{Z}+g)^2}}\right) \tag{2}$$

$$\theta = atan\left(\frac{\ddot{X}coss\varphi + \ddot{Y}sin\varphi}{\ddot{Z}+g}\right) \tag{3}$$

In general, from equations 1-3 above, the design of a PID for controlling a hexacopter can be expressed as shown in Fig. 2. A six-rotor hexacopter produces an upward thrust vector. It is a six-degree-of-freedom (DoF) system involving translation along and rotation around the X, Y, and Z axes within the body frame, with four inputs consisting of thrust, roll, pitch, and yaw. The input is usually provided by an RC (transmitter) controlled by the pilot on the ground, and this transmitter is connected to the drone's receiver. The total upward thrust of the throttle is used to control the translational motion and can be defined as follows [14]:

$$T = \sum_{i=1}^{6} T_i = b \sum_{i=1}^{6} \omega_i^2 \tag{4}$$

where b is the thrust constant that depends on a variety of factors including air density and propellers and ω_i is the rotational speed of each rotor.

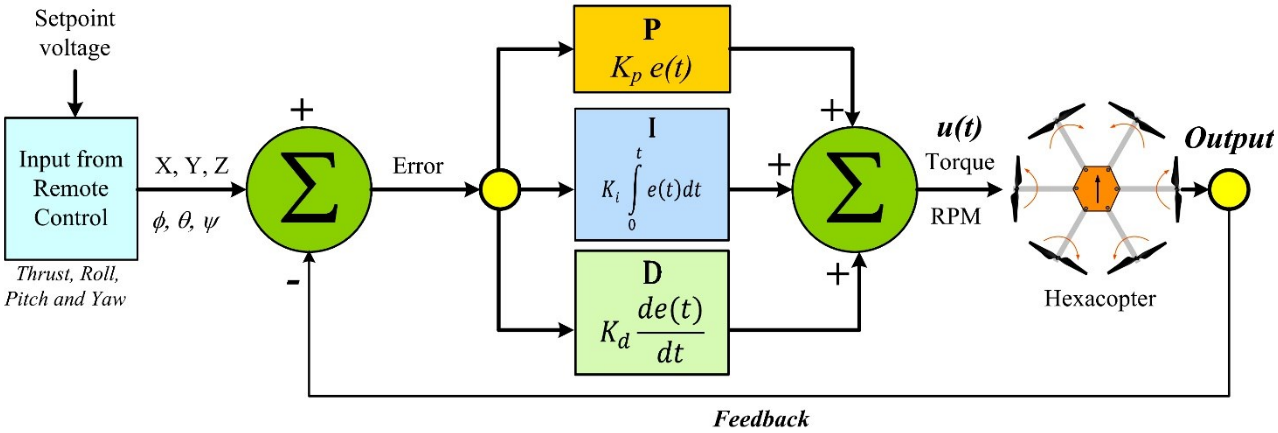


Fig. 2. Closed-loop PID scheme for hexacopter.

To tune the hexacopter based on Fig. 2 above, the open source software, namely the Mission Planner from https://ardupilot.org/ is employed. While there are many open source software available for performing automated optimization, such as Betaflight, QGroundControl, and others. A Mission Planner was chosen for its ease of use, pre-flight setup and calibration, and execution capabilities including simulation. On the other hand, the setup of the hexacopter and the PID tuning performed can be explained by the following flowchart (see Fig. 3). Our DIY hexacopter drone was first tested using the factory default PIDs. If field testing shows that the drone does not fly as stably as expected, and the drone itself crashes and rolls over, this indicates an adjustment process (tuning) is needed. After the unloaded drone has stabilized as expected, another test is performed to determine the drone's stability when loaded with additional cargo so that it can transport packages later to the customer's destination.

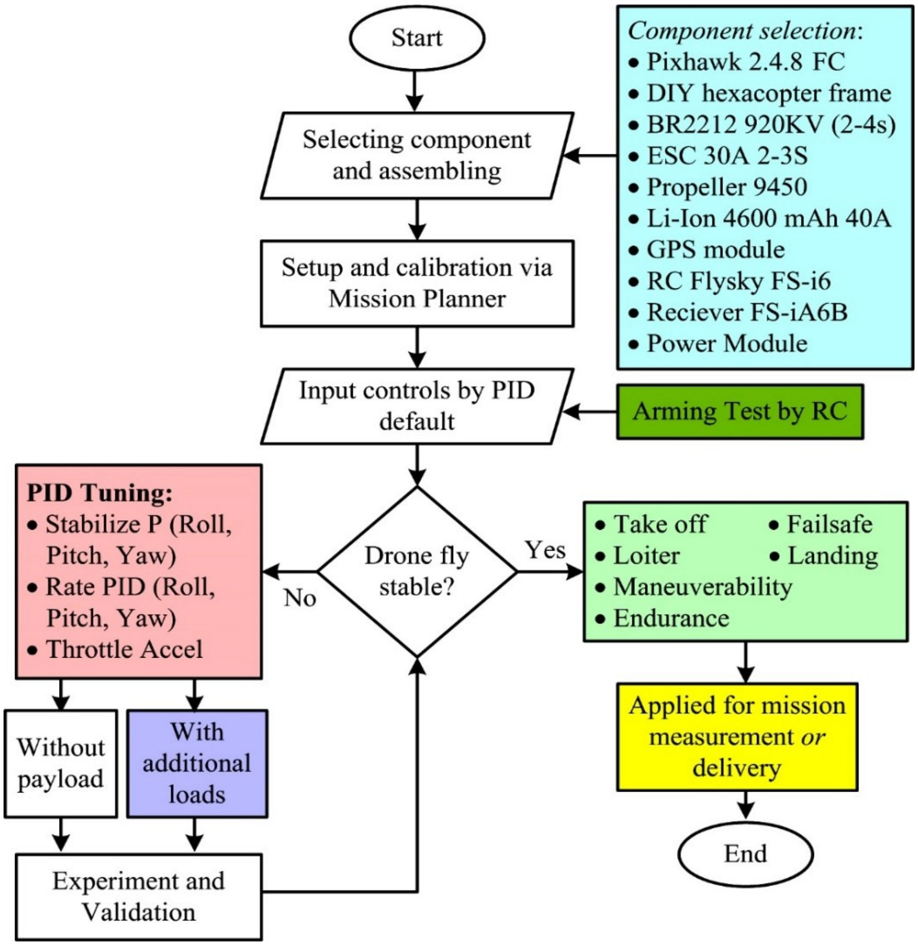


Fig. 3. A flowchart for hexacopter construction and PID tuning carried out in this project.

3. RESULTS AND DISCUSSION

3.1. Hexacopter Development

Fig. 4 shows the results of a DIY hexacopter drone development using the components and materials selected for this project. The image on the left shows a fully developed and flight-ready hexacopter from behind (as a pilot) and the image on the right shows the main parts of the drone. The total weight of the drone with lithium-ion battery is 1660 grams (1.66 kg). As shown in Fig. 4, the distance from each motor center on the arm to the other adjacent motor center is 28 cm. From this distance and the distance from the motor location point to the center of the drone, we can determine the propeller size to use. In this case, a suitable propeller diameter is 9-10 inches.

Fig. 4. A hexacopter drone developed for delivery plan.

3.2. Hexacopter Development

Factory default PID values are tested in the field before new PIDs are set into the Pixhawk. Our default PID values before the calibration process via Mission Planner (MP) are shown in Fig. 5. P-value for Stabilize (Error to Rate), i.e., Roll, Pitch and Yaw are set to 4.5000. On the other hand, the ACCEL MA values are set to 11000 for roll and pitch and 27000 for yaw. This value changes automatically when the initial setup parameters on MP are run as part of the initial setup. Once the Pixhawk is calibrated, the ACCEL MA values change to 125900 for roll and pitch, and 27900 for yaw. The values of FLTE (Error Frequency (Hz)), FLTD (Lead Frequency (Hz)), FLTT (Target Frequency (Hz)) and Base Filter are also changed automatically.

Stabilize Roll (Error to Rate)
P 4,500
ACCEL MA 110000

Stabilize Pitch (Error to Rate)
P 4,500
ACCEL MA 110000

Stabilize Yaw (Error to Rate)
P 4,500
ACCEL MA 27000

Position XY (Dist to Speed)
P 1,000
INPUT TC 0,150

☑ Lock Pitch and Roll Values

Rate Roll
P 0,135
I 0,090
D 0,00360
IMAX 0,5
FLTE 20
FLTD 5
FLTT 5

Rate Pitch
P 0,135
I 0,090
D 0,00360
IMAX 0,5
FLTE 20
FLTD 5
FLTT 5

Rate Yaw
P 0,180
I 0,018
D 0,00000
IMAX 0,5
FLTE 2,500
FLTD 5
FLTT 1

Velocity XY (Vel to Accel)
P 2,000
I 1,000
D 0,500
IMAX 100

Basic Filters
Gyro 20
Accel 20

Throttle Accel (Accel to motor)
P 0,500
I 1,000
D 0,000
IMAX 80

Throttle Rate (VSpd to accel)
P 5,000
Tune None
Min 0,000 1000

Altitude Hold (Alt to climbrate)
P 1,000

RC6 Opt
RC7 Opt Do Nothing
RC8 Opt Do Nothing
RC9 Opt Do Nothing
RC10 Opt Do Nothing

WPNav (cm's)
Speed 500
Radius 200
Speed Up 250
Speed Dn 150
Loiter Speed 1250

Filter Logs
Mask
Options 0

Static Notch Filter
Enabled Disabled
Frequency 10
BandWidth 5
Attenuation 5

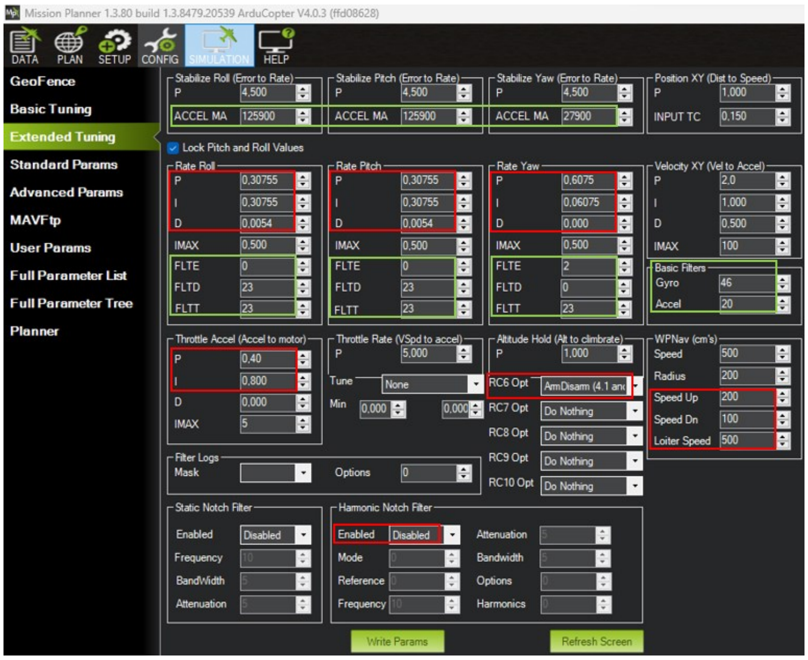
Harmonic Notch Filter
Enabled
Mode 0
Reference 0
Frequency 10
Attenuation 5
Bandwidth 5
Options 0
Harmonics 0

Fig. 5. Factory default PID on Pixhawk 2.4.8.

Fig. 6 shows the accident of using the default PIDs (see Fig. 5) for the DIY hexacopter case built in this project. In the first test in the afternoon (see Fig. 6(a)), the drone was flip-over after flying around 6 m from the take off point. One of the propellers was broken and torn, and the other was scratched by the sharpness of wild grass. In the second test in the early morning (see Fig. 6(b)) using default PID, the drone crashed again, and hitting the ground in the bushes. Based on the results of two field experiments using the default PID value for attitude control tests, it is necessary to do PID tuning. This measure was taken because the drone looks heavy and cannot climb smoothly even with maximum throttle opening. In this case, the tuning process was performed directly in the field by manually changing the PID values (trials and errors) via 3DR 915MHz radio telemetry. The final optimization result is marked with a red rectangular box as shown in Fig. 7. On the other hand, the color of the green rectangle is the value that will change automatically after the initial calibration is completed.

Fig. 6. A hexacopter testing using PID default (a) flip-over and (b) fell down in the bushes.

From the PID tuning results shown in Fig. 7, enabling RTL (Return To Launch) allows the hexacopter to take off, hover, and land smoothly. The key to this PID tuning is the Lock Pitch and Roll values. If the **P**-value is too low, the drone will not have enough thrust and the motors will not be able to keep up with the drone's movements, and vice versa if the P-value is too high make the drone vibrate and oscillate. The **D** component determines the smoothness of the drone's movements. If the D value is too high, the drone will descend slowly before reaching the desired balance point, whereas if D = 0, the drone will move violently/randomly on landing. In the case of the **I** component, it has the function of stabilizing the drone when it is subject to interference or pressured by external forces such as strong winds. Too high a I value; it will make the drone overactive. Therefore, tuning should be in the order P > D > I. In the case of drones without additional cargo such as carrying packages, the optimized P and I values for Rate Roll and Rate Pitch are equally increased by about 56%, and the D value is increased by 33% over the default value. For the Yaw rate, the ratio of P and I is P = 10 × I, which increases to over 90% of the default value. Furthermore, the loiter speed value is reduced to 500 cm/s, or 60% of 1250 cm/s. Overall, the P values for Stabilized Roll, Pitch, and Yaw were unchanged. Fig. 8(a) shows the hexacopter in a raised position at a height of 37 m above the ground. The drone has a maximum flight altitude of 100 m and a maximum range of 3 km.



Mission Planner 1.3.80 build 1.3.8479.20539 ArduCopter V4.0.3 (ffd08628)

Stabilize Roll (Error to Rate)
P 4,500
ACCEL MA 125900

Stabilize Pitch (Error to Rate)
P 4,500
ACCEL MA 125900

Stabilize Yaw (Error to Rate)
P 4,500
ACCEL MA 27900

Position XY (Dist to Speed)
P 1,000
INPUT TC 0,150

☑ Lock Pitch and Roll Values

Rate Roll
P 0,30755
I 0,30755
D 0,0054
IMAX 0,500
FLTE 0
FLTD 23
FLTT 23

Rate Pitch
P 0,30755
I 0,30755
D 0,0054
IMAX 0,500
FLTE 0
FLTD 23
FLTT 23

Rate Yaw
P 0,6075
I 0,06075
D 0,000
IMAX 0,500
FLTE 2
FLTD 0
FLTT 23

Velocity XY (Vel to Accel)
P 2,0
I 1,000
D 0,500
IMAX 100

Basic Filters
Gyro 46
Accel 20

Throttle Accel (Accel to motor)
P 0,40
I 0,800
D 0,000
IMAX 5

Throttle Rate (VSpd to accel)
P 5,000
Tune None
Min 0,000 0,000

Altitude Hold (Alt to climbrate)
P 1,000
RC6 Opt ArmDisarm (4.1 and
RC7 Opt Do Nothing
RC8 Opt Do Nothing
RC9 Opt Do Nothing
RC10 Opt Do Nothing

WPNav (cm's)
Speed 500
Radius 200
Speed Up 200
Speed Dn 100
Loiter Speed 500

Filter Logs
Mask
Options 0

Static Notch Filter
Enabled Disabled
Frequency 10
BandWidth 5
Attenuation 5

Harmonic Notch Filter
Enabled Disabled
Mode 0
Reference 0
Frequency 10
Attenuation 5
Bandwidth 5
Options 0
Harmonics 0

Fig. 7. PID tuning results for our hexacopter without payload

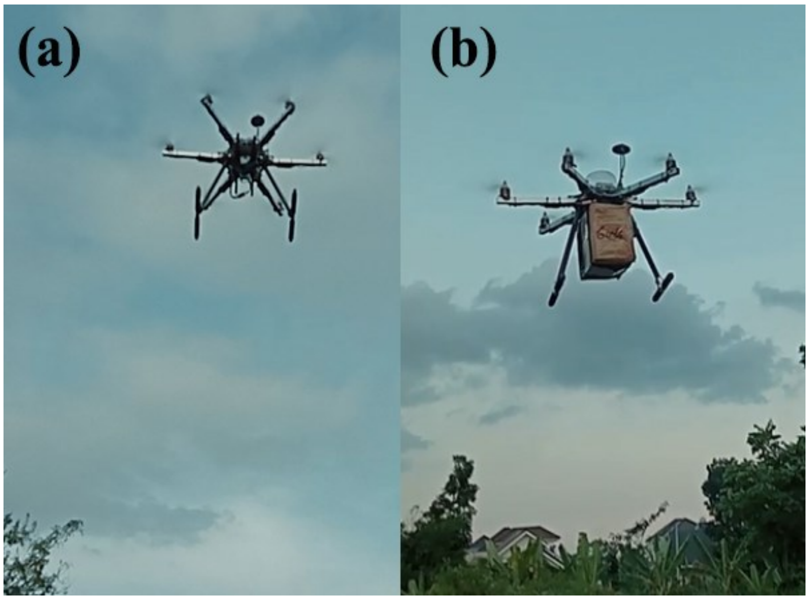
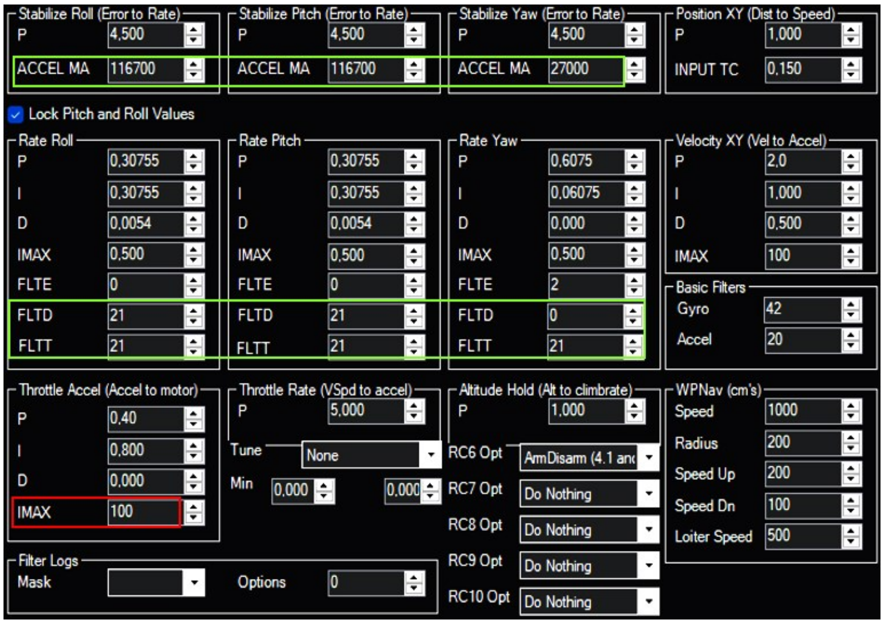


Fig. 8. A hexacopter testing using new PID tuning for (a) drone without additional load and (b) with additional load 686 grams.

For a hexacopter with extra weight to plan the delivery of the packages to the consignee using the previous PID as in Fig. 7, drones with an extra weight of 686 grams consisting of books and stationery cannot hang around or hover (see Fig. 8(b)). In this case, the drone takes off and climbs to an altitude of about 5 meters (throttle position is already at max). It then becomes unstable, spinning in circles and eventually falling headfirst. This incident opened an alternative to resetting the PID and various new PID combinations were tried. However, the drone still could not fly more than 10 meters of height even if landed safely. Drones lack power or upward thrust. The final solution proposed is to replace the 9-inch propeller (9450) with a 10-inch propeller (carbon fiber 1045 propeller). This propeller type will improve the air-powered efficiency and aerofoil stability resulting each pair of propellers has perfect dynamic poise and static balancing. However, additional current is required to provide upward thrust, therefore two 3S 4600 mAh batteries have been connected in parallel, resulting in a theoretical current of 9200 mAh. In addition, the default value of IMAX = 5 is increased to 100 (see Fig. 9).



Stabilize Roll (Error to Rate)
P 4,500
ACCEL MA 116700

Stabilize Pitch (Error to Rate)
P 4,500
ACCEL MA 116700

Stabilize Yaw (Error to Rate)
P 4,500
ACCEL MA 27000

Position XY (Dist to Speed)
P 1,000
INPUT TC 0,150

☑ Lock Pitch and Roll Values

Rate Roll
P 0,30755
I 0,30755
D 0,0054
IMAX 0,500
FLTE 0
FLTD 21
FLTT 21

Rate Pitch
P 0,30755
I 0,30755
D 0,0054
IMAX 0,500
FLTE 0
FLTD 21
FLTT 21

Rate Yaw
P 0,6075
I 0,06075
D 0,000
IMAX 0,500
FLTE 2
FLTD 0
FLTT 21

Velocity XY (Vel to Accel)
P 2,0
I 1,000
D 0,500
IMAX 100

Basic Filters
Gyro 42
Accel 20

Throttle Accel (Accel to motor)
P 0,40
I 0,800
D 0,000
IMAX 100

Throttle Rate (VSpd to accel)
P 5,000

Tune None
Min 0,000 0,000

Altitude Hold (Alt to climbrate)
P 1,000

RC6 Opt ArmDisarm (4.1 an
RC7 Opt Do Nothing
RC8 Opt Do Nothing
RC9 Opt Do Nothing
RC10 Opt Do Nothing

WPNav (cm's)
Speed 1000
Radius 200
Speed Up 200
Speed Dn 100
Loiter Speed 500

Filter Logs
Mask
Options 0

Fig. 9. A new PID tuning for DIY hexacopter with loads of 942 grams.

The new calibration results with a 10-inch propeller are shown in Fig. 10, where the drone can land safely and smoothly at the destination point. The Fig. shows the result of the last experiment for an additional load of 942 grams. With a battery capacity of 3S 9200 mAh, this drone can take off vertically, hover, maneuver and fly at a distance of less than 1.3906 km and height of 50 m until it lands smoothly. Packages are shipped via waypoint method (Do_Gripper) which is coupled using a servo motor. Packages start dropping at a height of 5 m above the ground. The coordinates of the destination where the package should be placed are 7.7467742°S, 110.4377072°E, and the launch point (HOME) is 7.7468773°S, 110.4394371°E with an altitude of 198.94 m ASL. Table 1 summarizes the PID tuning by trials and errors in the field. Note that RPM can ideally be calculated based on the propeller size and motor specifications used as shown in equation 5. The larger the size of the propeller used will generate more thrust but will decrease the efficiency of the drone.

$$RPM_{ideal} = \left(\frac{2}{\pi}\right)^{\frac{1}{2PF}} \left(\frac{(g.m)^{\frac{3}{2}}}{PC.D\sqrt{\rho}}\right)^{\frac{1}{PF}} \qquad (5)$$

where g is gravity acceleration (9.81 m/s^2), m is mass of thrust (kg), D is diameter of propeller (m), ρ is air density (1.225 kg/m^3), PF = power factor of drones, and PC is power coefficient of drones.

Table 1. Summary of PID tuning for hexacopter on frame 560 mm.

Control	Default RPM = 4189			Optimization RPM = 3500		
Rate	*Roll*	*Pitch*	*Yaw*	*Roll*	*Pitch*	*Yaw*
P	0.135	0.1350	0.1800	0.3076	0.3076	0.6075
I	0.090	0.0900	0.0180	0.3076	0.3076	0.06075
D	0.0036	0.0036	0.0000	0.0054	0.0054	0.0000

Fig. 10. Hexacopter testing using 10-inch propellers for drones with an additional load of 942 grams (a) in the takeoff position and (b) moving up to the first waypoint. All images in this work are original.

4. CONCLUSION

This research enabled the production of a hexacopter-type drone with a wheelbase of 560 mm and a weight of 1.66 kg including the 3S Li-Ion battery. A selection of motors, ESCs, and landing gear components are included in the durability category, resulting in a crash-safe and high-performance system. This hexacopter is intended to transport packages and light packages to and from customers in a single trip with a range of up to 3 km. To achieve high flight stability with an estimated total weight of 5 kg, it is expected that the drone will be able to accurately place the packages at the customer's coordinates. Therefore, we performed PID tuning with expected loads. Initial test results in the field using the waypoint method with a flight altitude of 50 m showed that the drone could fly stably and place objects on targets. In this case of the drone without loads, the drone moved 1.2 m to the left of the landing site, which is likely due to atmospheric conditions during the landing process. For the case of a total drone weight of 2,602 grams or with an additional load of 942 grams, the drone can fly as expected and transport the package. After placing the packages, the drone returns to the starting point and lands safely.

A follow-up study for this project is to prepare a package unloading system with either a servo-based gripper or automatic box clamping. This depends on the location and environmental conditions of recipients. Equipped with four angle clamps if the drone lands on the ground or a building. However, if the recipient position does not allow the drone to land, a parachute model will be built. Apart from that, battery capacity also needs to be a major consideration if the range is the key to shipping packages. These are all challenging opportunities, and these developments have good prospects for the future, especially in locations unreachable by traditional service providers.

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Data Availability. Data underlying the results presented in this paper are available from the corresponding author upon reasonable request.

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Conflicts of interest. The authors declare no conflict of interest.

Ethics. The authors declare that the present research work has fulfilled all relevant ethical guidelines required by COPE.

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