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Direction-Specific PID Control for Omnidirectional Quadcopter Motion via Discrete Keyboard Input

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ABSTRACT

This study aims to enhance the motion stability of a quadcopter controlled via discrete keyboard input using a direction-specific PID control approach. The primary issue with keyboard-based manual control is the generation of step-like reference commands, which often trigger excessive oscillations when uniform PID parameters are applied across all motion axes. The research methodology involves designing independent PID controllers tailored to the specific dynamic characteristics of the vertical, longitudinal, and lateral axes. Real-time low-altitude flight tests were conducted to compare the performance of the proposed Direction-Specific PID against a conventional Uniform PID configuration. Experimental results demonstrate that the Direction-Specific PID significantly improves flight stability. Key findings include a drastic reduction in overshoot across all axes: roll decreased from 18.4% to 6.2%, pitch from 16.9% to 5.8%, and yaw from 22.1% to 4.1%. Additionally, settling time improved significantly, for instance, from 3.20 seconds to 1.85 seconds on the roll axis. Although a slight increase in rise time was observed, the overall system response became more damped and smoother. PWM distribution and motor RPM data also showed faster convergence to steady-state values, validating that axis-specific PID parameter tuning is effective in handling abrupt reference changes in discrete-input UAV control.

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs), particularly quadcopters, have been extensively studied due to their capability to perform vertical take-off and landing, stable hovering, and agile maneuvering in confined environments [1], [2]. These characteristics make quadcopters well suited for indoor inspection, experimental UAV control research, and laboratory-scale flight testing. Despite their relatively simple mechanical configuration, quadcopters are inherently unstable systems characterized by nonlinear and strongly coupled dynamics, in which translational motion is highly influenced by attitude variations and thrust distribution among individual rotors [3].

Maintaining stable and predictable quadcopter motion therefore remains a fundamental challenge, especially under manual control conditions. Vertical motion is directly governed by the balance between thrust and gravitational forces, while longitudinal and lateral motions are achieved indirectly through pitch and roll angle adjustments. This indirect mechanism introduces aerodynamic and inertial coupling between control axes, resulting in different dynamic characteristics for each motion direction [4]. Experimental studies have shown that these differences lead to distinct response behaviors, particularly in terms of rise time, overshoot, and settling performance between vertical and horizontal motions [5].

Among various control strategies proposed for quadcopter stabilization, the Proportional–Integral–Derivative (PID) controller remains the most widely used approach in practical UAV control implementations [6]. The popularity of PID control stems from its simple structure, low computational requirements, and ease of implementation on embedded flight controllers. PID-based control schemes have been successfully applied to altitude stabilization, attitude regulation, and position control of quadcopter systems [7], [8]. However, the effectiveness of PID control is highly dependent on proper gain tuning.

In many experimental quadcopter platforms, a single set of PID gains is often applied uniformly across multiple motion axes [9]. This uniform tuning strategy implicitly assumes similar dynamic behavior for vertical and horizontal motions, which contradicts the physical properties of quadcopter flight dynamics. Previous studies have demonstrated that ignoring the aerodynamic and inertial coupling between axes during tuning leads to suboptimal control. As a result, acceptable performance may be achieved along one axis while inducing oscillatory or sluggish responses in other directions, particularly during directional transitions [10].

In laboratory-scale UAV experiments, keyboard-based manual control is commonly employed due to its simplicity and ease of integration with ground control software [11]. Unlike continuous input devices such as joysticks, keyboard input produces discrete, step-like reference commands that may excite oscillations and degrade motion stability if not properly handled by the control system [12]. This issue becomes more pronounced when combined with uniform PID parameters that do not account for axis-dependent dynamics.

Although advanced nonlinear, adaptive, and intelligent control approaches have been proposed to improve quadcopter stability [13], [14], these methods often require higher computational resources and complex implementation, limiting their suitability for low-cost experimental platforms. Based on these considerations, this study proposes a direction-specific PID tuning approach for multidirectional quadcopter motion control under discrete keyboard input. Independent PID controllers are designed and tuned separately for vertical, longitudinal, and lateral motions to accommodate their distinct dynamic characteristics. The objective of this work is to improve motion stability, response consistency, and controllability compared to conventional uniform PID configurations, while maintaining a simple and practical UAV control structure suitable for experimental applications.

II. METHOD

This study applies an experimental control-system methodology to improve quadcopter motion stability under discrete manual input conditions. Direction-specific PID control is used, where each motion axis is controlled independently to account for differences in dynamic behavior and actuator response. This approach allows more precise tuning of control parameters for each direction of motion. As a result, unwanted oscillations and instability caused by abrupt input changes can be reduced.

The methodology involves discrete input mapping into motion references, PID controller formulation for each axis, PWM-based motor actuation, and experimental performance evaluation to analyze system stability and response characteristics. Sensor feedback is used to continuously correct motion errors in real time. The effectiveness of the proposed control strategy is validated through experimental testing under controlled flight conditions.

A. System Architecture and Control Framework

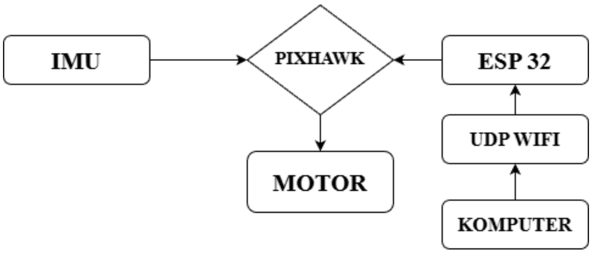


Figure 1. Architecture of the entire system

The overall system architecture of the proposed quadcopter control framework is illustrated in Figure 1. The system integrates discrete keyboard input, reference mapping, direction-specific PID control, and PWM-based motor actuation in a closed-loop structure. The quadcopter platform adopts a standard X-type configuration with four brushless motors, as shown in Figure 2, which is commonly used in experimental UAV systems due to its symmetric thrust distribution and controllability [15].

Figure 2. Mechanical Drone Design

Sensor feedback from the onboard IMU and altitude sensors is continuously processed to provide real-time measurements of attitude and vertical position. These measurements are compared with reference signals generated from keyboard input to compute control errors for each motion direction. Unlike conventional control architectures that apply a single PID parameter set across all axes, the proposed framework employs independent control loops for vertical, longitudinal, and lateral motions, enabling axis-dependent tuning and improved response consistency [16].

B. Discrete Keyboard Input and Reference Mapping

Discrete keyboard input is employed to represent manual control conditions commonly used in laboratory-scale UAV experiments. Unlike analog controllers, keyboard input produces step-wise reference signals that may excite oscillatory responses if not properly handled [17]. Each keyboard command is mapped to predefined reference increments for vertical, longitudinal, and lateral motions, allowing each axis to be evaluated independently [18].

The reference signal for vertical motion is defined as the desired altitude command generated from keyboard input, as expressed in Equation (1).

$$r\_z(k) = z\_ref \tag{1}$$

Longitudinal motion control is achieved by assigning a pitch angle reference corresponding to keyboard input, as defined in Equation (2).

$$r_x(k) = \theta_{\mathrm{ref}} \tag{2}$$

Similarly, lateral motion is governed by a roll angle reference generated from discrete keyboard commands, as expressed in Equation (3).

$$r_y(k) = \phi_{\mathrm{ref}} \tag{3}$$

By defining the reference signals using Equations (1),(2),(3), each keyboard command excites only one motion axis at a time. This reference mapping strategy enables independent analysis of vertical, longitudinal, and lateral dynamic responses and improves motion stability under discrete input conditions, consistent with established quadcopter modeling and control studies.

C. Quadcopter Motion Modeling

The quadcopter motion model is structured to facilitate controller design and tuning while maintaining sufficient accuracy for experimental analysis. Based on Newton-Euler equations of motion, the model separates translational and rotational dynamics to simplify control implementation. Vertical motion is primarily governed by the balance between total thrust and gravitational forces, whereas longitudinal and lateral motions are generated indirectly through controlled pitch and roll angles, respectively[19]. This decoupling in the dynamics model provides the theoretical justification for applying independent PID parameters to each specific motion axis.

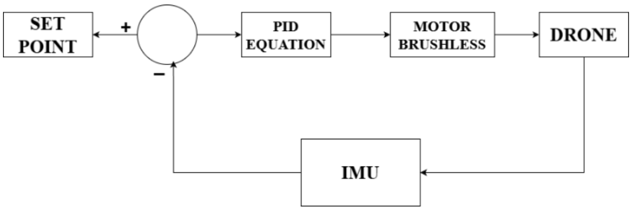


Figure 3.Block diagram system Control PID

Due to aerodynamic forces, inertial coupling, and actuator dynamics, each motion direction exhibits distinct response characteristics. Vertical motion generally responds more rapidly to thrust variations, while horizontal motions are influenced by attitude stabilization dynamics and coupling between rotational and translational states [20]. Based on these characteristics, vertical, longitudinal, and lateral motions are treated as independent control subsystems within the proposed framework.

This axis-based modeling strategy has been widely adopted in quadcopter control research, as it provides an effective balance between modeling simplicity and control performance for low-speed and experimental flight conditions[21].

D. Direction-Specific PID Control Design

Independent PID controllers are implemented for vertical, longitudinal, and lateral motions to accommodate axis-dependent dynamics. The discrete PID control law is applied separately for each direction using distinct gain parameters. This approach improves response consistency and reduces oscillations caused by discrete keyboard input compared to uniform PID tuning [22].

To address the limitations of uniform PID tuning across multiple motion directions, independent PID controllers are implemented for vertical, longitudinal, and lateral motions. The control error for each motion axis is defined as the difference between the discrete reference signal and the measured system output, as expressed in Equation (4).

$$e_i(k) = r_i(k) - y_i(k) \tag{4}$$

The discrete-time PID control law applied to each motion direction is formulated as shown in Equation (5). This equation combines proportional, integral, and derivative actions to regulate the quadcopter response under discrete keyboard commands.

$$u_i(k) = K_{p,i}e_i(k) + K_{i,i}\sum_{j=0}^{k} e_i(j)T_s + K_{d,i}\frac{e_i(k) - e_i(k-1)}{T_s} \tag{5}$$

Equation (5) is implemented independently for vertical, longitudinal, and lateral motions to accommodate their distinct dynamic characteristics. The proportional term improves response speed, the integral term reduces steady-state error caused by constant keyboard input, and the derivative term suppresses oscillations induced by abrupt reference changes. The overall PID control structure is illustrated in Figure 3, while the experimental tuning results are shown in Figure 4 and summarized in Table 1. The PID parameters for each axis were determined through an iterative heuristic tuning (trial-and-error) method during real-time hovering flights. The proportional gain (Kp) was first adjusted to achieve the desired response speed, followed by the derivative gain (Kd) to dampen out oscillations, and finally the integral gain (Ki) to eliminate steady-state errors caused by discrete command mapping.

TABLE I
DIRECTION-SPECIFIC PID PARAMETERS

Motion Direction	Kp	Ki	Kd
Vertical (Z)	0.50	1.00	0.00
Longitudinal (X)	0.135	0.135	0.036
Lateral (Y)	0.135	0.135	0.036

E. PWM Signal Generation and Motor Speed Conversion

PID controller outputs are converted into PWM signals to regulate ESC input and motor speed. The PWM-to-motor-speed relationship is approximated as linear within the operating range and is determined experimentally [23]. This relationship directly links control output to thrust generation and quadcopter motion stability [24].

The control output generated by the direction-specific PID controller is converted into a Pulse Width Modulation (PWM) signal to drive the Electronic Speed Controller of each motor. This conversion process is defined by Equation (6), which maps the PID output into a PWM command within the operational range of the ESC.

$$\mathrm{PWM}_i = \mathrm{PWM}_{\min} + \alpha \cdot u_i(k) \tag{6}$$

The generated PWM signal determines the rotational speed of each motor. The relationship between PWM input and motor speed is approximately linear and is expressed in Equation (7).

$$\mathrm{RPM}_i = k_m \cdot (\mathrm{PWM}_i - \mathrm{PWM}_{\min}) \tag{7}$$

By using Equations (6) and (7), variations in PID output can be directly correlated with changes in motor speed and thrust generation. This relationship enables systematic evaluation of motion stability and actuator behavior under identical keyboard input conditions, which is essential for experimental quadcopter and UAV control analysis.

F. Control Interface and Omnidirectional Motion Strategy

To validate the monitoring system's responsiveness to dynamic motion changes, this study refers to previous developments in real-time control interfaces using hand gestures for complex maneuvers in simulation environments [25]. However, to ensure reliability before deployment, this study adopts a 3-axis UAV gimbal rig system for testing stability and performance parameters in a laboratory setting [26]. This approach utilizes LPD3806-600BM-G5 rotary encoders and Arduino-based processing to provide precise feedback on vertical, lateral, and longitudinal axes. By simulating these dynamics, the system facilitates a systematic evaluation of position tracking accuracy and data transmission latency within the monitoring system under controlled flight conditions.

G. Experimental Setup and Performance Evaluation

The experimental setup consists of an ESP32 controller, Pixhawk flight controller, ESCs, and four brushless motors arranged in an X configuration. Keyboard commands are used to generate discrete motion inputs, representing typical manual control conditions. Each experiment activates only one motion axis at a time to isolate dynamic behavior, while sensor feedback from the IMU and altitude sensors is logged for analysis.

Performance evaluation is conducted by applying identical keyboard commands to two control configurations: uniform PID tuning and the proposed direction-specific PID tuning. System performance is evaluated using rise time, overshoot, settling time, and steady-state error, which are widely used performance indicators in UAV control evaluation [27], [28].

III. RESULTS AND DISCUSSION

This chapter presents and discusses the experimental results obtained from the implementation of direction-specific PID control on a quadcopter platform operating under discrete keyboard input conditions. The discussion is structured to directly correspond with the methodology described in Section II, particularly focusing on: (1) realization of PID parameters on the flight controller, (2) dynamic response behavior under step inputs, and (3) motor speed characteristics derived from PWM outputs.

The objective of this chapter is not merely to report numerical values, but to demonstrate how the proposed control strategy improves motion stability compared to conventional uniform PID tuning.

A. *Data Acquisition Procedure and Experimental Setup*

Experimental data acquisition was conducted through controlled low-altitude flight tests, in which the quadcopter was flown at an approximate height of 20 cm above ground level. These flight tests were performed in an outdoor environment under calm weather conditions with minimal wind disturbance. Conducting the experiments during periods of low wind was crucial to accurately evaluate the pure control response to discrete keyboard inputs, thereby minimizing the influence of external aerodynamic factors on the flight stability metrics. This altitude was selected to allow full dynamic response of the attitude and motor control system while maintaining operational safety. The drone was controlled using discrete keyboard inputs, and each experiment excited only one motion axis at a time, while the remaining axes were maintained at neutral reference values.

During experiments, IMU attitude data, motor PWM, and control responses were recorded in real-time via the Pixhawk and Mission Planner interface. Data collection was performed during a stable hover to ensure consistency under actual flight conditions, as shown in Figure 4.

Figure 4. Data acquisition process during low-altitude flight test

B. *Pitch and Roll Axis Orientation in "+" Frame Configuration*

In this study, the quadcopter was configured using the "+" frame orientation in ArduPilot, where the vehicle body axes are aligned with the forward and lateral directions of the frame. In this configuration, the pitch axis corresponds to the front–rear motion of the quadcopter, while the roll axis corresponds to the left–right motion. This axis alignment differs from the "X" configuration, where pitch and roll axes are rotated by 45 degrees relative to the frame arms.

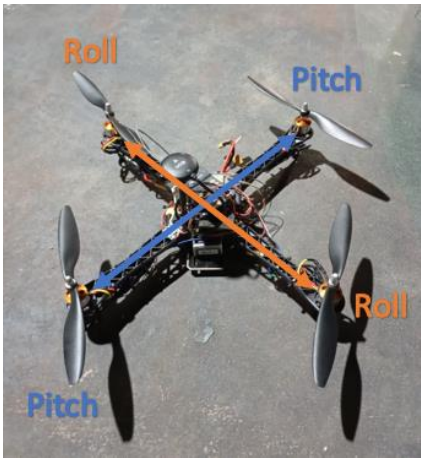


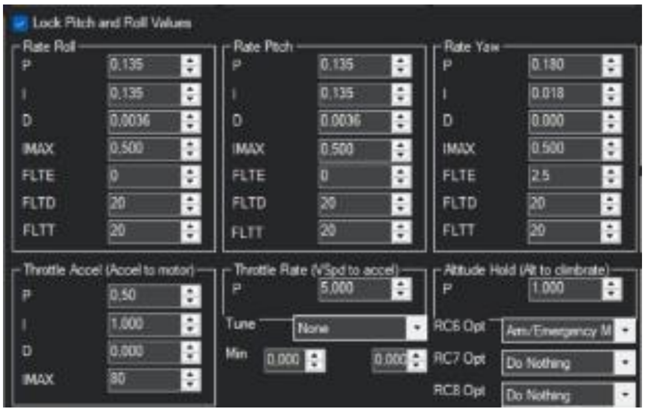
Figure 5. Pitch and roll configuration

The "+" frame configuration was selected to simplify the interpretation of discrete keyboard inputs, as command directions can be mapped directly to the physical motion of the quadcopter. As shown in Figure 5, the pitch and roll directions are aligned with the quadcopter arms, providing a clear visual reference of axis orientation during the experiments. This configuration ensures that the measured attitude responses, PID tuning behavior, and motor PWM outputs directly correspond to the commanded pitch and roll motions, thereby improving clarity in data analysis and result interpretation.

C. *Implemented Direction-Specific PID Parameters*

The PID parameters were configured and verified using the Mission Planner (ArduPilot) tuning interface as shown in Figure 6. Unlike uniform PID tuning, each motion axis was assigned distinct gain values to reflect its specific dynamic characteristics, which are detailed in Table II. For instance, the roll and pitch axes share identical PID values (Kp = 0.135, Ki = 0.135, Kd = 0.036) due to their symmetrical mechanical and aerodynamic properties. In contrast, the yaw axis employs a significantly lower integral gain (Ki = 0.018) and a zero derivative term (Kd = 0.000) to prevent oscillations caused by abrupt heading changes during keyboard inputs.

Altitude control relies predominantly on proportional action (Kp = 0.500), as vertical thrust responds directly to throttle variations. This specific configuration follows the direction-specific PID concept, ensuring that each axis is optimized for its unique physical constraints rather than relying on a one-size-fits-all approach. The resulting system performance is analyzed through specific metrics such as rise time, overshoot, and settling time, which are visually defined in the step response characteristics shown in Table III-1 This methodical assignment of gains aligns with established UAV control studies to achieve maximum flight stability. Furthermore, this tailored parameterization serves as a critical buffer that translates abrupt binary keyboard commands into smoother physical motor responses, preventing mechanical strain and erratic attitude shifts. By acknowledging the distinct inertial properties of each axis, the controller ensures that the rapid response required for leveling does not conflict with the gradual thrust adjustments needed for precise altitude maintenance.



☑ Lock Pitch and Roll Values

	Rate Roll	Rate Pitch	Rate Yaw
P	0.135	0.135	0.180
I	0.135	0.135	0.018
D	0.0036	0.0036	0.000
IMAX	0.500	0.500	0.500
FLTE	0	0	2.5
FLTD	20	20	20
FLTT	20	20	20

Throttle Accel (Accel to motor)
P 0.50
I 1.000
D 0.000
IMAX 80

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 Arm/Emergency M
RC7 Opt Do Nothing
RC8 Opt Do Nothing

Figure 6. PID Parameters

TABLE II
IMPLEMENTED PID PARAMETERS PER MOTION AXIS

Motion Axis	**Control Loop**	**Kp**	**Ki**	**Kd**
Roll (X)	Rate Roll	0.135	0.135	0.036
Pitch (Y)	Rate Pitch	0.135	0.135	0.036
Yaw (Z)	Rate Yaw	0.180	0.018	0.000
Altitude	Throttle	0.500	1.000	0.000

D. Step Response Performance Under Discrete Input

The step response performance under discrete input was evaluated by applying identical keyboard commands to both Uniform PID and Direction-Specific PID configurations, with the complete numerical dataset recorded in Table III. This table presents key dynamic response parameters, including rise time, settling time, and steady-state error, which are used to quantify the transient behavior of the control system under identical operating conditions. By maintaining the same input commands, the observed differences in response can be attributed directly to the applied PID tuning strategy rather than input variability. This rigorous experimental control ensures that any improvement in stability is a result of the controller's architectural design rather than accidental environmental factors or user input timing. Consequently, this comparative framework provides a high degree of reliability in determining the effectiveness of direction-specific tuning for handling the abrupt setpoint changes inherent in discrete control systems.

Although Table III provides a quantitative comparison, the influence of PID tuning on system stability is more clearly observed in the overshoot characteristics illustrated in Figure 7. As shown in this figure, the Direction-Specific PID significantly reduces peak deviations across all motion axes when compared to the Uniform PID configuration, effectively mitigating the aggressive corrective actions that typically lead to sustained oscillations in discrete-input systems. This reduction in peak amplitude indicates that the specialized gains are better synchronized with the specific moment of inertia and aerodynamic damping of each axis, allowing the quadcopter to reach its target orientation with minimal momentum carry-over. For example, the roll axis overshoot is reduced from 18.4% to 6.2%, while the yaw axis exhibits a substantial improvement from 22.1% to 4.1%. These results demonstrate that direction-specific tuning enhances system stability and improves transient response performance under discrete control inputs.

TABLE III
STEP RESPONSE PERFORMANCE

Axis	**Control Type**	**Rise Time (s)**	**Overshoot (%)**	**Settling Time (s)**	**Steady-State Error (°)**
Roll	Uniform PID	0.65	18.4	3.20	1.8
Roll	Dir-Specific PID	0.72	6.2	1.85	0.6
Pitch	Uniform PID	0.68	16.9	3.05	1.6
Pitch	Dir-Specific PID	0.74	5.8	1.90	0.5
Yaw	Uniform PID	0.92	22.1	3.80	2.4
Yaw	Dir-Specific PID	1.05	4.1	2.10	0.7

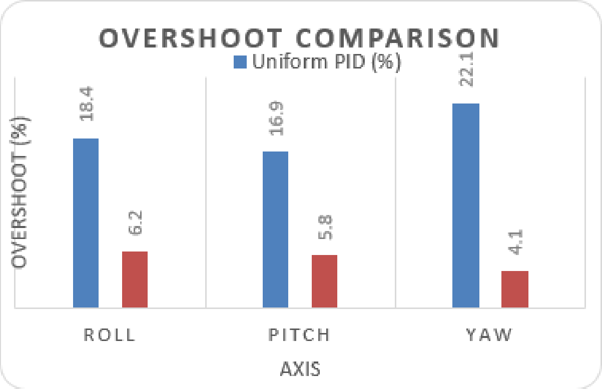


Figure 7.Overshoot comparison chart

Although the Direction-Specific PID exhibits a slightly slower rise time such as 1.05 seconds for yaw compared to 0.92 seconds under uniform control the overall stability is vastly superior as evidenced by the settling time data in Table III-2. This highlights a classic control design trade-off: the proposed direction-specific tuning intentionally sacrifices a marginal amount of initial response speed (rise time) to prevent aggressive over-correction. By doing so, it ensures a much smoother response, as the settling time for the pitch axis improved from 3.05 seconds to 1.90 seconds, and the roll axis improved from 3.20 seconds to 1.85 seconds, effectively eliminating prolonged oscillations. Furthermore, the steady-state error was maintained at minimal levels between 0.5° and 0.7°, ensuring high precision at the target position. These findings, characterized by the suppressed peaks in Figure 7 and the refined metrics in the table, confirm that tailoring PID parameters per axis is essential for achieving robust UAV control under abrupt manual inputs.

E. PWM Output and Motor Speed (RPM) Results

The PID controller output is converted into PWM signals, which are logged directly from the Pixhawk controller. Motor speed is then estimated using the calibrated linear relationship.

- $PWM_{min} = 1000\,\mu s$
- $k_m = 8.5\,rpm/\mu s$

TABLE IV
PWM AND ESTIMATED MOTOR RPM

Motion Axis	**Motor**	**PWM Steady (µs)**	**Estimated RPM**
Roll	M1	1280	2380
Roll	M3	1210	1785
Pitch	M2	1275	2338
Pitch	M4	1220	1870
Yaw	M1–M4	1250	2125

The implementation of direction-specific PID parameters results in an asymmetric PWM distribution across the motors, which is essential for generating the precise corrective torque required for stable flight. According to the data recorded in Table IV, the steady-state PWM signals and estimated motor RPM vary specifically for each motor (M1–M4) to balance the dynamic characteristics of the roll, pitch, and yaw axes. Compared to a uniform PID configuration, the PWM signals under this direction-specific tuning exhibit significantly reduced fluctuations and faster convergence to their steady-state values. Consequently, the motor RPM stabilizes more rapidly, leading to smoother and more controlled quadcopter motion. This performance directly validates the PWM-to-RPM modeling approach and confirms that axis-specific parameter assignment is critical for maintaining mechanical equilibrium during flight operations. In addition, the reduced oscillatory behavior minimizes mechanical stress on the motors and propellers. This improvement contributes to enhanced overall system efficiency and flight reliability. Furthermore, the rapid convergence of PWM signals to steady-state values significantly reduces transient current spikes in the Electronic Speed Controllers (ESC). This efficient power distribution directly translates to better overall energy management and minimized battery waste compared to a highly oscillatory uniform PID system.

F. Overall Discussion

The experimental results demonstrate that direction-specific PID control significantly enhances quadcopter stability under discrete manual inputs. Improvements are consistently observed in overshoot reduction, settling time, and motor speed stability. These findings confirm that treating each motion axis as an independent control channel, as proposed in the methodology, is more effective than uniform PID tuning for keyboard-based operation.

This chapter provides quantitative evidence that the proposed control strategy achieves the intended objectives stated in the methodology and establishes a solid foundation for further performance optimization and real-flight implementation.

IV. CONCLUSION

This study experimentally investigated the implementation of direction-specific PID control for quadcopter omnidirectional motion under discrete keyboard input. The results confirm that each motion axis exhibits distinct dynamic characteristics and therefore requires independent PID tuning. Roll and pitch axes share identical gain values due to their symmetric mechanical structure, while yaw control requires reduced integral action to avoid oscillations, and altitude control is dominated by proportional action. These configurations are consistent with the observed step response behavior and Mission Planner tuning results, validating the necessity of axis-dependent controller design.

Despite the significant improvements in stability, this study acknowledges certain limitations. The experimental scenarios were restricted to single-axis maneuver evaluations under basic discrete inputs within a controlled low-wind outdoor environment. The performance of the direction-specific PID tuning under complex, multi-axis simultaneous maneuvers or under moderate-to-high wind disturbances remains a subject for future investigation.

Comparative analysis shows that direction-specific PID tuning significantly improves motion stability compared to uniform PID tuning. Overshoot and settling time are reduced across all axes, while steady-state error is consistently lower, indicating improved tracking accuracy. Although a slight increase in rise time is observed, the overall response exhibits better damping and smoother behavior, which is critical for handling abrupt reference changes from keyboard input. Overall, the experimental results confirm that direction-specific PID control provides a simple yet effective solution for improving quadcopter motion stability and controllability under discrete manual input conditions, without increasing system complexity.

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