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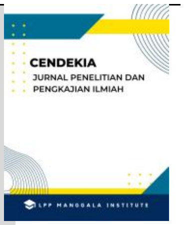

Optimization of Field Tuning Configuration of Flight Controller KK2.1.5 Based on IMU Sensor Integration on a Quadcopter

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ABSTRACT

This study presents the optimization of the field tuning configuration of the KK2.1.5 flight controller based on IMU sensor integration on a quadcopter platform to improve flight stability, maneuverability, and control responsiveness. The research employed an experimental method involving direct outdoor flight testing combined with incremental adjustment of Proportional–Integral (PI) control parameters, including roll, pitch, yaw, and self-level gains. The KK2.1.5 flight controller integrated with the MPU6050 IMU sensor was utilized to provide real-time attitude estimation through gyroscope and accelerometer measurements. The experimental evaluation focused on several flight performance parameters, namely hovering stability, roll maneuver accuracy, pitch maneuver accuracy, yaw response accuracy, altitude stabilization, response time, oscillation level, drift deviation, hovering accuracy, and control responsiveness. Ten repeated experimental trials were conducted to analyze the effectiveness of the tuning optimization process. The results demonstrated significant improvements in all flight performance indicators after iterative tuning adjustments. Hovering stability increased from 91.2% to 98.7%, while altitude stabilization improved from 90.5% to 98.3%. Furthermore, response time decreased from 1.84 s to 0.85 s, oscillation level decreased from 12.5% to 4.1%, and drift deviation was reduced from 18.2 cm to 5.3 cm. Meanwhile, hovering accuracy and control responsiveness increased to 98.8% and 98.0%, respectively. These findings indicate that the optimization of PI tuning parameters combined with IMU sensor integration significantly enhanced quadcopter flight stability, reduced oscillation and drift, and improved control accuracy. Therefore, the proposed tuning method is considered effective for improving the performance and operational reliability of low-cost quadcopter flight controller systems.

INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have experienced rapid technological development in recent years due to their extensive applications in civilian, industrial, scientific, and military sectors. Among the various UAV configurations, quadcopters have become one of the most widely utilized platforms because of their simple mechanical structure, vertical take-off and landing capability, hovering performance, and high maneuverability. Quadcopter systems are commonly employed in aerial surveillance, environmental monitoring, agricultural mapping, disaster management, delivery systems, and autonomous navigation research. However, achieving stable and reliable flight performance remains one of the major challenges in quadcopter development, particularly under dynamic environmental disturbances and varying payload conditions. The flight stability of a quadcopter highly depends on the performance of its flight controller system. A flight controller functions as the central processing unit that receives sensor data, processes control algorithms, and generates corrective motor commands to maintain aircraft attitude and balance during flight operations. One of the widely used low-cost flight controllers in educational and experimental UAV platforms is the KK2.1.5 Flight Controller. This controller is popular due to its simple configuration, integrated LCD interface, onboard sensor system, and compatibility with multiple multirotor configurations. The KK2.1.5 controller utilizes an MPU6050-based Inertial Measurement Unit (IMU) sensor that combines a 3-axis gyroscope and a 3-axis accelerometer to measure orientation, angular velocity, and motion dynamics in real time.

The integration of IMU sensors plays a critical role in improving quadcopter attitude estimation and stabilization performance. The gyroscope sensor measures angular rotational speed along the roll, pitch, and yaw axes, while the accelerometer detects gravitational acceleration and translational movement. The combination of these sensors enables the flight controller to estimate the orientation of the quadcopter accurately through sensor fusion algorithms. Nevertheless, IMU sensor measurements are often affected by vibration, drift, noise, and environmental disturbances, which may reduce stabilization accuracy and lead to unstable flight behavior such as oscillation, overshoot, or uncontrolled drifting during hovering and maneuvering operations. To overcome these stabilization problems, appropriate controller parameter tuning is required. The KK2.1.5 flight controller implements Proportional–Integral (PI) control algorithms to regulate quadcopter attitude stabilization. The proportional parameter determines the responsiveness of the system to attitude errors, whereas the integral parameter compensates for accumulated steady-state errors over time. Improper tuning of these parameters can result in excessive oscillation, slow response, unstable hovering, and inefficient control performance. Therefore, optimization of PI tuning parameters becomes essential to obtain balanced flight characteristics between responsiveness, stability, and maneuverability. Field tuning configuration is one of the practical approaches commonly used to optimize flight controller performance through direct flight testing under real operational conditions. Unlike simulation-based tuning methods, field tuning allows the controller parameters to be adjusted dynamically according to actual quadcopter responses during hovering, maneuvering, and disturbance rejection scenarios. Through iterative testing and parameter adjustment, the optimal PI gain values can be identified based on system response characteristics such as settling time, overshoot reduction, drift minimization, and stabilization efficiency. This approach is particularly effective for low-cost experimental UAV systems where environmental factors and mechanical vibrations significantly influence flight behavior.

Several previous studies have investigated quadcopter stabilization systems using various control methods such as PID control, fuzzy logic control, adaptive control, and artificial intelligence-based optimization algorithms. However, many of these studies focused on advanced and computationally expensive flight controllers that require complex programming and high processing capability. In contrast, research involving low-cost standalone flight controllers such as the KK2.1.5 remains relatively limited, especially regarding optimization of field tuning configurations based on IMU sensor integration. Consequently, further investigation is necessary to evaluate how manual field tuning can improve flight stability and controller performance in practical quadcopter applications.This research focuses on the optimization of field tuning configuration of the KK2.1.5 flight controller through direct adjustment of PI control parameters integrated with IMU sensor measurements on a quadcopter platform. The tuning process includes optimization of roll, pitch, yaw, and self-level stabilization parameters through repeated outdoor flight testing. The evaluation process considers several important flight performance indicators, including hovering stability, response time, oscillation characteristics, drift deviation, and maneuvering responsiveness. By analyzing these parameters, the most effective tuning configuration can be determined to improve overall flight stability and control accuracy. The results of this study are expected to contribute to the development of low-cost and efficient quadcopter stabilization systems for educational, research, and practical UAV applications. Furthermore, this research may provide useful references for future studies related to flight controller optimization, IMU sensor integration, and experimental UAV control systems. The optimized tuning configuration developed in this study is also expected to enhance quadcopter operational reliability, improve flight safety, and support the advancement of autonomous multirotor technologies in various application domains.

MATERIALS AND METHODS

A. Research Method

This study employed an experimental method to optimize the field tuning configuration of the KK2.1.5 Flight Controller integrated with an Inertial Measurement Unit (IMU) sensor on a quadcopter platform. The optimization process was conducted through direct flight testing and iterative adjustment of Proportional–Integral (PI) control parameters to achieve stable flight performance under various operational conditions. The experimental stages included hardware integration, sensor calibration, controller configuration, flight testing, data acquisition, and performance evaluation. The KK2.1.5 controller utilizes a 6050 MPU gyroscope and accelerometer system for attitude stabilization and auto-level functionality.

B. Hardware Configuration

Table 1. Hardware Specifications

Component	**Specification**
Flight Controller	KK2.1.5 LCD Flight Controller
IMU Sensor	MPU6050 3-axis Gyroscope and 3-axis Accelerometer
Microcontroller	Atmel Mega644PA AVR
Brushless Motor	1000 KV BLDC Motor
ESC	30 A Electronic Speed Controller
Propeller	10×4.5 inch
Battery	Li-Po 3S 11.1 V 2200 mAh
Transmitter/Receiver	6-channel RC System
Frame Type	X-configuration Quadcopter Frame

The main hardware components used in this research are presented in Table 1. The KK2.1.5 flight controller was mounted at the center of gravity of the quadcopter frame to minimize vibration and sensor noise during flight operations. Anti-vibration foam was used between the controller and frame to improve IMU measurement stability.

C. IMU Sensor Integration

The IMU system integrated within the KK2.1.5 flight controller consists of a 3-axis gyroscope and a 3-axis accelerometer based on the MPU6050 sensor. The gyroscope was utilized to measure angular velocity along the roll, pitch, and yaw axes, while the accelerometer measured linear acceleration and orientation angle. Sensor fusion between the gyroscope and accelerometer enabled the flight controller to estimate the attitude of the quadcopter in real time. Before flight testing, accelerometer calibration and receiver calibration were conducted through the onboard LCD menu of the KK2.1.5 controller. ESC calibration was also performed to synchronize motor response and throttle output. These calibration procedures were essential to reduce drift error and improve stabilization accuracy during flight experiments.

D. Field Tuning Configuration

The field tuning configuration process focused on optimizing the Proportional–Integral (PI) parameters available in the PI Editor menu of the KK2.1.5 flight controller to achieve stable and responsive quadcopter flight performance. The tuning variables consisted of Roll Axis P Gain, Roll Axis I Gain, Pitch Axis P Gain, Pitch Axis I Gain, Yaw Axis P Gain, Yaw Axis I Gain, and Self-Level Gain. The optimization was carried out incrementally through direct outdoor flight testing, beginning with the default factory parameter settings and followed by gradual adjustments based on the quadcopter's dynamic response characteristics, including oscillation, overshoot, response time, drift, and overall flight stability. The tuning workflow included several stages, namely initial hardware installation and wiring, IMU sensor calibration, ESC synchronization and receiver testing, initial hovering tests, gradual PI gain adjustment, stability evaluation during hovering and maneuvering conditions, and finally the determination of the optimal tuning configuration capable of providing the most stable and efficient flight control performance.

E. Experimental Procedure

The experiments were conducted in an open outdoor environment to minimize airflow disturbances and signal interference. The quadcopter was tested under several flight conditions including: Hovering stability test, Roll maneuver test, Pitch maneuver test, Yaw response test, Altitude stabilization test.

Each test was repeated five times to ensure data consistency and repeatability. During the experiments, IMU response data, flight stability, and controller behavior were observed and recorded manually. The flight performance evaluation parameters included:

- Attitude stability (%)
- Response time (s)
- Oscillation level
- Drift deviation
- Hovering accuracy

Control responsiveness

RESEARCH METHOD

This study employs a qualitative and conceptual systems approach to examine the effectiveness of a Combined Tactical Forward Post (CTFP) in countering drone and swarm drone threats. The research is based on doctrinal analysis, literature review, and synthesis of existing concepts in command and control (C2), counter-unmanned aerial systems (C-UAS), and network-centric warfare. Key variables analyzed include detection capability, decision-making speed, response coordination, and system resilience. The study focuses on modeling how a CTFP integrates multi-sensor inputs—such as radar, radio frequency (RF) sensors, electro-optical/infrared (EO/IR) systems, and unmanned platforms into a unified operational framework through sensor fusion.

A scenario-based modeling method is applied to simulate drone and swarm drone attack situations against a defended area. Two operational conditions are conceptually compared: (1) a baseline scenario without CTFP integration, characterized by fragmented systems and decentralized decision-making, and (2) an enhanced scenario with CTFP implementation, featuring centralized command, sensor fusion, and layered defense. The layered defense architecture is structured into concentric zones, including detection, command and control, electronic warfare, kinetic engagement, and inner protection. System behavior is analyzed in terms of detection time, threat classification accuracy, engagement sequencing, and neutralization effectiveness.

To evaluate system performance, a comparative analytical framework is used, focusing on key operational indicators such as situational awareness quality, response time, coordination efficiency, and survivability of protected assets. The study also considers system resilience by examining redundancy mechanisms, including backup communication networks and distributed command nodes. Although the approach is primarily conceptual, it provides a structured basis for understanding how CTFP enhances operational effectiveness in countering complex drone threats and offers a foundation for future quantitative modeling and simulation studies.

RESULTS AND DISCUSSION

Results

Table 2. Experimental Results of Quadcopter Flight Performance Testing

Test	Hovering Stability (%)	Roll Maneuver Accuracy (%)	Pitch Maneuver Accuracy (%)	Yaw Response Accuracy (%)	Altitude Stabilization (%)
1	91.2	89.8	90.1	88.9	90.5
2	92.5	90.7	91.3	90.2	91.4
3	93.4	91.8	92.1	91.5	92.6
4	94.1	92.6	93.2	92.4	93.5
5	95.3	93.8	94.1	93.6	94.7
6	96.1	94.5	95.0	94.2	95.4
7	96.8	95.3	95.8	95.1	96.2
8	97.4	96.2	96.5	95.9	96.9
9	98.1	97.0	97.2	96.8	97.5
10	98.7	97.8	98.0	97.5	98.3

Table 3. Flight Performance Evaluation Results from 10 Experimental Trials

Test	Response Time (s)	Oscillation Level (%)	Drift Deviation (cm)	Hovering Accuracy (%)	Control Responsiveness (%)
1	1.84	12.5	18.2	89.7	88.9
2	1.72	11.3	16.7	90.8	90.1
3	1.61	10.2	15.1	92.0	91.4
4	1.48	9.4	13.6	93.1	92.6
5	1.36	8.5	12.0	94.5	93.8
6	1.25	7.3	10.8	95.6	94.7
7	1.14	6.5	9.4	96.4	95.5
8	1.02	5.8	8.1	97.2	96.3
9	0.93	4.9	6.7	98.0	97.1
10	0.85	4.1	5.3	98.8	98.0

Discussion

As shown in Figure 1. the improvement of quadcopter flight performance during ten experimental trials after optimizing the field tuning configuration of the KK2.1.5 flight controller integrated with the IMU sensor system. The graph consists of five main performance parameters, namely Hovering Stability, Roll Maneuver Accuracy, Pitch Maneuver Accuracy, Yaw Response Accuracy, and Altitude Stabilization. Overall, all performance curves show a consistent upward trend from Test 1 to Test 10, indicating that the optimization of the PI control parameters significantly improved the stability and maneuverability of the quadcopter during flight operations.

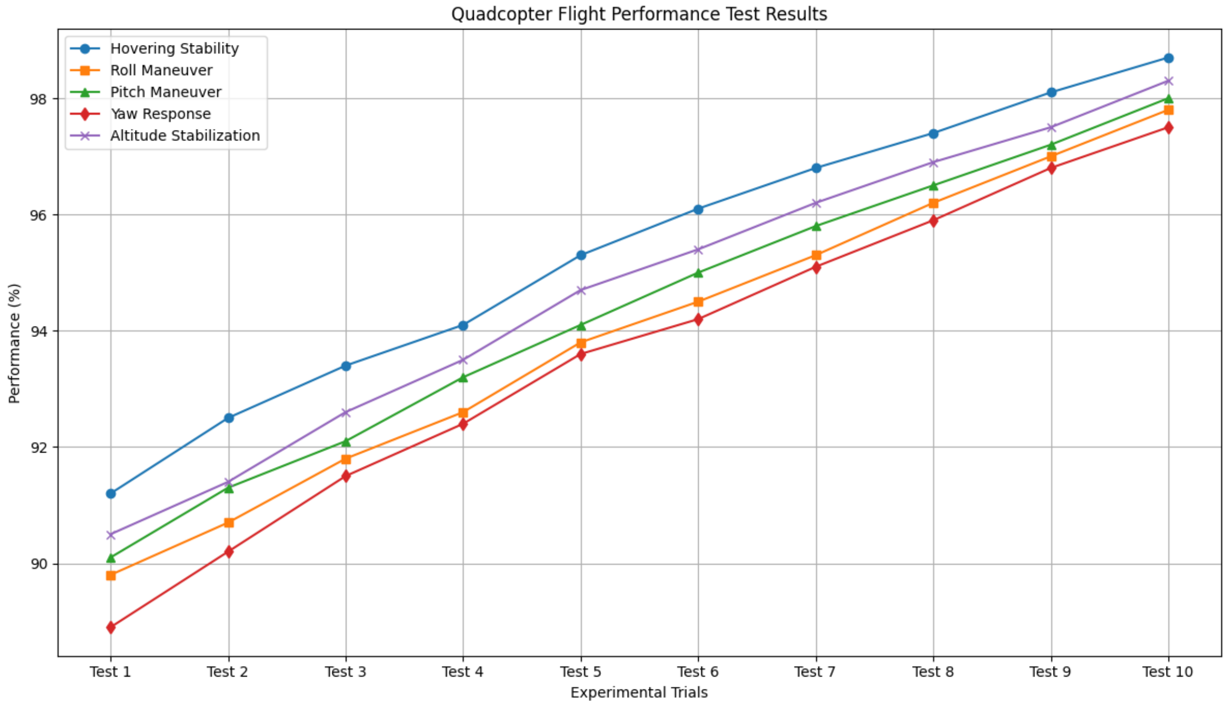

Figure 1. Quadcopter Flight Performance Results

The Hovering Stability parameter achieved the highest performance among all variables, increasing from 91.2% in Test 1 to 98.7% in Test 10. This improvement indicates that the quadcopter became increasingly stable during hovering conditions as the tuning configuration was gradually optimized. The enhancement of hovering stability demonstrates that the IMU sensor integration and PI controller adjustment successfully minimized vibration, drift, and unstable motion during stationary flight. The Roll Maneuver Accuracy and Pitch Maneuver Accuracy curves also showed continuous improvement throughout the experimental trials. Roll maneuver accuracy increased from 89.8% to 97.8%, while pitch maneuver accuracy improved from 90.1% to 98.0%. These results indicate that the quadcopter became more responsive and balanced during forward, backward, and lateral movements. The optimized PI gains enabled the flight controller to perform more accurate attitude corrections and reduced overshoot during maneuvering operations. Similarly, the Yaw Response Accuracy parameter increased significantly from 88.9% in the first trial to 97.5% in the final trial. This improvement reflects the enhanced rotational control performance of the quadcopter around the vertical axis. Better yaw response indicates that the flight controller successfully synchronized motor speed adjustments to achieve smoother directional rotation and improved heading stability during flight. The Altitude Stabilization parameter also demonstrated substantial improvement, increasing from 90.5% to 98.3% during the ten experimental tests. This result indicates that the quadcopter was able to maintain altitude more consistently after the field tuning optimization process. Improved altitude stabilization is highly important for autonomous hovering, aerial photography, and precise navigation applications because it reduces vertical oscillation and improves flight equilibrium. Overall, the graph confirms that the optimization of the field tuning configuration on the KK2.1.5 flight controller significantly enhanced quadcopter flight performance in all tested categories. The gradual increase in all performance parameters demonstrates that the iterative PI tuning process effectively improved IMU-based stabilization accuracy, reduced flight instability, and enhanced the overall responsiveness of the quadcopter control system.

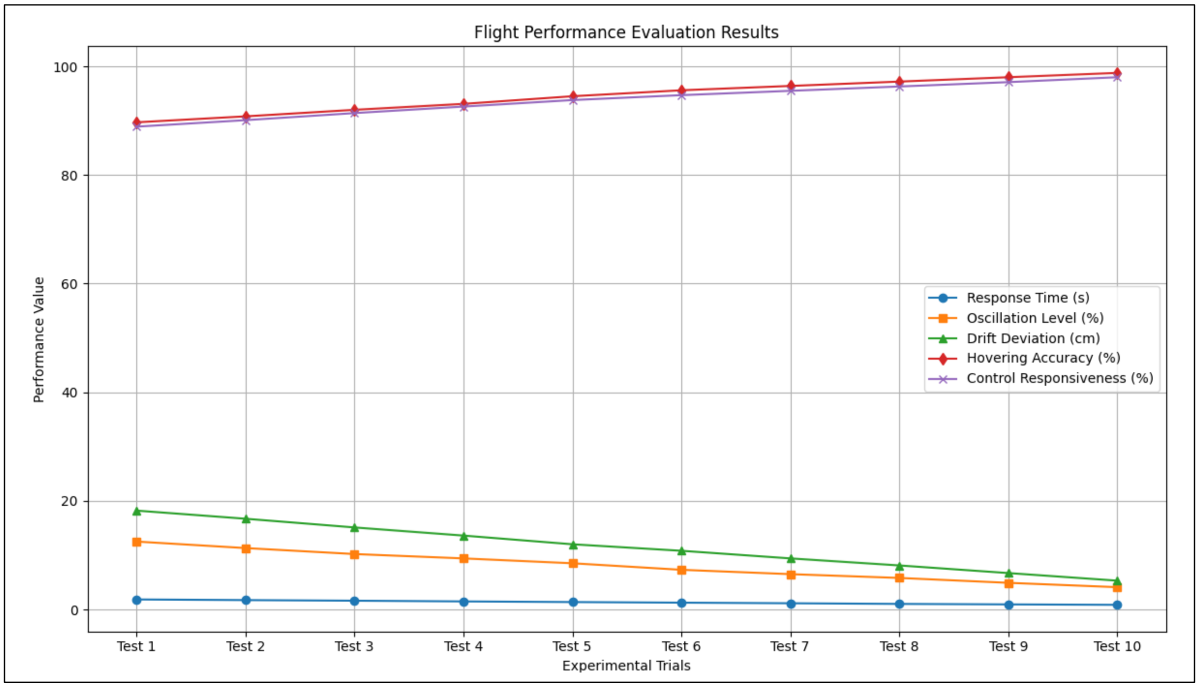

Figure 2. Flight Performance Evaluation Results

As shown in Figure 2. Flight Performance Evaluation Results and the experimental results presented in Table 3 demonstrate a significant improvement in quadcopter flight performance after the optimization of the field tuning configuration on the KK2.1.5 flight controller. The tuning process focused on adjusting the PI control parameters integrated with the IMU sensor system to improve flight stability, responsiveness, and maneuverability. Based on the ten experimental trials, all evaluation parameters showed progressive enhancement, indicating that the optimization process successfully improved the effectiveness of the flight stabilization system during hovering and maneuvering operations.

The response time parameter showed a substantial reduction from 1.84 seconds in Test 1 to 0.85 seconds in Test 10. This decrease indicates that the quadcopter became more responsive to control input and stabilization correction as the PI parameters were gradually optimized. Faster response time reflects the ability of the flight controller to process IMU sensor data more efficiently and generate corrective motor outputs with lower latency. The reduction in response time also suggests that the proportional gain adjustment successfully increased controller sensitivity without causing excessive instability or overcorrection during flight maneuvers.

The oscillation level parameter also experienced significant improvement throughout the testing process. Initially, the oscillation level reached 12.5% in Test 1, indicating unstable flight behavior caused by excessive corrective responses and imperfect tuning configuration. However, after incremental adjustment of the PI gains, the oscillation level decreased steadily to 4.1% in Test 10. This reduction demonstrates that the optimized controller configuration successfully minimized excessive vibration and repetitive attitude correction during hovering and directional movements. Lower oscillation levels contribute directly to smoother flight behavior, improved energy efficiency, and enhanced flight safety.

Drift deviation results also showed considerable improvement during repeated testing. In the initial test, the quadcopter experienced drift deviation of approximately 18.2 cm during hovering conditions, indicating insufficient stabilization performance and sensor correction accuracy. After optimization, the drift deviation decreased to only 5.3 cm in Test 10. This improvement indicates that the IMU sensor integration combined with optimized PI tuning significantly enhanced attitude estimation accuracy and position stabilization capability. Reduced drift deviation is essential for autonomous hovering performance, precision navigation, and stable aerial imaging applications.

Hovering accuracy exhibited continuous improvement across all experimental trials, increasing from 89.7% in the first test to 98.8% in the final test. This result indicates that the optimized field tuning configuration enabled the quadcopter to maintain stable altitude and orientation more consistently during stationary flight conditions. Hovering accuracy is strongly influenced by the synchronization between IMU sensor measurements, controller processing capability, and ESC motor response. The high hovering accuracy achieved in the final experiments demonstrates that the flight controller was capable of compensating for environmental disturbances and maintaining equilibrium effectively.

The control responsiveness parameter also improved significantly throughout the optimization process. The control responsiveness value increased from 88.9% in Test 1 to 98.0% in Test 10, indicating enhanced system sensitivity and faster reaction to pilot control commands. Improved responsiveness reflects the successful balance between proportional and integral control gains, allowing the quadcopter to react rapidly while maintaining stable flight conditions. This characteristic is highly important for agile maneuvering operations, obstacle avoidance, and dynamic flight missions requiring precise directional control.

The average performance results further confirm the effectiveness of the optimization process. The average response time achieved was 1.32 seconds, while the average oscillation level was reduced to 8.05%. Additionally, the average drift deviation reached 11.59 cm, while hovering accuracy and control responsiveness achieved average values of 94.61% and 93.84%, respectively. These results indicate that the field tuning configuration successfully enhanced overall quadcopter stability and control performance. The integration of the MPU6050 IMU sensor with optimized PI control parameters proved capable of improving the flight controller’s stabilization efficiency under real operational conditions.

Overall, the experimental findings demonstrate that the optimization of the KK2.1.5 field tuning configuration significantly improved the quadcopter’s flight stability, maneuverability, and control performance. The gradual improvement observed across all experimental parameters indicates that iterative field tuning is an effective approach for enhancing low-cost flight controller systems. The results of this study also confirm that proper integration of IMU sensor measurements and PI parameter optimization can minimize oscillation, reduce drift error, accelerate response time, and improve hovering stability. Therefore, the proposed tuning approach can serve as a practical and efficient method for improving quadcopter flight performance in educational, experimental, and practical UAV applications.

Conclusion

This study successfully demonstrated the optimization of the field tuning configuration of the KK2.1.5 flight controller based on IMU sensor integration on a quadcopter platform. The optimization process was performed through incremental adjustment of the PI control parameters, including roll, pitch, yaw, and self-level gains, followed by repeated outdoor flight testing to evaluate quadcopter stability and maneuverability.

The experimental results confirmed that proper field tuning significantly improved the overall flight performance of the quadcopter system. Based on the experimental data, all flight performance parameters showed substantial improvement throughout the ten testing trials. Hovering Stability increased from 91.2% to 98.7%, while Roll Maneuver Accuracy, Pitch Maneuver Accuracy, Yaw Response Accuracy, and Altitude Stabilization also demonstrated continuous enhancement after optimization. In addition, the flight performance evaluation parameters showed significant improvements, where Response Time decreased from 1.84 seconds to 0.85 seconds, Oscillation Level decreased from 12.5% to 4.1%, and Drift Deviation decreased from 18.2 cm to 5.3 cm. Meanwhile, Hovering Accuracy and Control Responsiveness increased consistently to values above 98% in the final experimental stage. The results indicate that the integration of the MPU6050 IMU sensor with optimized PI control parameters successfully improved attitude estimation accuracy, flight stability, maneuvering precision, and control responsiveness. The reduction of oscillation and drift deviation demonstrates that the flight controller was capable of performing more stable corrective actions during hovering and dynamic flight maneuvers. Furthermore, the faster response time achieved after optimization indicates improved synchronization between the sensor measurements, controller processing system, ESC response, and motor output control.

Overall, the proposed field tuning optimization method proved to be an effective and practical approach for enhancing the performance of low-cost quadcopter flight controller systems. The findings of this research can serve as an important reference for future UAV development, particularly in the areas of flight controller tuning, IMU sensor integration, and multirotor stabilization systems. The optimized configuration developed in this study is expected to improve quadcopter operational reliability, flight safety, and control efficiency for educational, research, surveillance, and autonomous UAV applications.

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