# Design of a Real-Time Wireless-Based Flight Monitoring and Drone Surveillance System.

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**ABSTRACT**

Real-time motion monitoring of Unmanned Aerial Vehicles (UAVs) is critical for ensuring flight safety and mission effectiveness. However, wireless telemetry systems often suffer from transmission delays, leading to discrepancies between the actual drone position and the data displayed at the ground station. This study proposes the design and evaluation of a wireless-based flight monitoring system that prioritizes responsiveness and spatial accuracy. The system utilizes GPS to Universal Transverse Mercator (UTM) conversion for 2D position mapping. System performance was evaluated through flight experiments by measuring end-to-end monitoring delay, delay variation (jitter), and position monitoring error. Experimental results demonstrate that the system transmits motion data with an average monitoring delay of 45.8 ms and a low delay variation of 1.7 ms, indicating robust communication stability. Furthermore, position monitoring accuracy yielded an average absolute error of only 0.040 m on both the X and Y axes. These results confirm that the proposed system is capable of delivering accurate and timely motion information suitable for real-time surveillance applications.



## I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs), commonly referred to as drones, have become an essential platform in modern engineering applications requiring high mobility, remote operation, and real-time situational awareness, such as aerial surveillance, infrastructure inspection, environmental monitoring, and search-and-rescue missions [1]. In these applications, reliable observation of drone motion is critical, as operators must understand how the vehicle responds to control commands and environmental disturbances during flight [2].

Real-time flight monitoring plays a vital role in ensuring operational safety and mission effectiveness. Monitoring parameters such as position, movement trajectory, and dynamic response allow operators to detect abnormal behavior, instability, or control degradation during flight [3]. However, many existing UAV implementations still rely on monitoring systems that suffer from delayed or discontinuous data delivery, limiting the operator's ability to react promptly to unexpected conditions [4]. Therefore, the development of a reliable and low-latency monitoring system is essential to support effective decision-making during UAV operations.

Wireless communication is widely adopted for UAV control and monitoring due to its flexibility and ease of deployment [5]. Through wireless telemetry links, motion-related data can be transmitted from onboard sensors to a ground monitoring station. Nevertheless, wireless transmission inevitably introduces latency caused by packet handling, processing overhead, and network variability [6]. If such delays are not properly analyzed, the monitoring information displayed to the operator may no longer represent the actual flight state of the drone [7].

Several studies have demonstrated that delayed or unstable monitoring data significantly reduce operator situational awareness, particularly during dynamic maneuvers and surveillance tasks that require precise motion tracking [8], [9]. Inaccurate monitoring information may lead to incorrect interpretation of drone behavior and inappropriate control decisions.

Recent research has emphasized the importance of evaluating monitoring system performance using communication-oriented metrics, particularly end-to-end delay, delay variation, and monitoring accuracy [10], [11]. These metrics provide quantitative insight into how closely the monitoring information follows the actual drone motion in real time. Delay stability, in particular, is increasingly recognized as a key indicator of monitoring reliability in UAV surveillance systems [12].

Based on these considerations, this research focuses on the development and evaluation of a real-time wireless-based drone flight monitoring and surveillance system. The study emphasizes monitoring responsiveness and position accuracy rather than control performance. The main contribution of this work lies in presenting a structured monitoring system design and a quantitative evaluation framework based on monitoring delay and position monitoring error, which can serve as a reference for future UAV monitoring system development [13], [14].

## II. METHOD

This study adopts an applied engineering methodology focusing on system-level monitoring architecture, motion data flow, and quantitative performance evaluation. The methodology is structured to ensure that the proposed system supports real-time observation of drone movement through wireless communication. The overall system architecture is illustrated in Figure 1, which shows the relationship between onboard data acquisition, wireless transmission, and the ground monitoring interface [15].

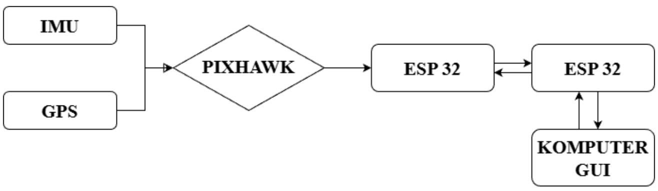


Figure 1. Architecture of the entire system

### A. System Architecture Overview

The proposed system is designed to perform flight monitoring and surveillance by continuously transmitting motion-related data from the drone to a ground monitoring station. As shown in Figure 1, the monitoring process operates in parallel with the flight control loop, ensuring that monitoring does not interfere with control execution. This architectural separation simplifies performance evaluation and follows best practices in modern UAV monitoring system design [16]. By decoupling monitoring and control tasks, the system maintains stable flight performance while enabling continuous data acquisition.

Additionally, this approach enables real-time observation and detailed post-flight analysis of system behavior. It also improves system scalability by allowing monitoring components to be extended or modified without affecting the core control logic. Furthermore, the separation enhances system reliability by reducing the risk of data transmission delays or processing loads impacting flight stability, thereby ensuring consistent and dependable monitoring performance during various flight operations.

Figure 2. Mechanical Drone Design

The mechanical structure of the drone used in this study is shown in Figure 2. A mechanically stable platform is essential to ensure consistent motion behavior, allowing monitoring performance to be evaluated without structural-induced disturbances [17]. From a system perspective, the monitoring design prioritizes low-latency data delivery rather than high data throughput, as timely information is more critical for real-time surveillance applications [18].

### B. Motion Monitoring Data Flow

Motion monitoring data are generated continuously during drone operation and transmitted to the ground station using a unidirectional telemetry link. Each monitoring packet represents a snapshot of the drone's motion state at a specific time instant. The overall monitoring data flow is illustrated in Figure 3, which reflects a typical UAV telemetry transmission model [19].

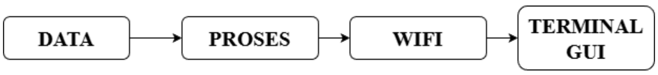


Figure 3. Overview of the system

To ensure fair and repeatable performance evaluation, the monitoring transmission interval is kept constant throughout all experiments. This design choice ensures that variations in monitoring performance are primarily caused by communication and processing behavior rather than fluctuations in data generation rate [20].

### C. End-to-End Monitoring Delay Analysis

The responsiveness of the monitoring system is evaluated by analyzing end-to-end monitoring delay. The monitoring delay for the i-th packet is formulated as shown in Equation (1). This equation defines the elapsed time between the moment a monitoring packet is transmitted by the drone and the moment it is received by the monitoring interface, representing the timeliness of motion observation.

$$D_i = t_{r,i} - t_{s,i} \quad (1)$$

To represent overall monitoring responsiveness, the average monitoring delay is formulated as shown in Equation (2). This equation combines individual packet delays to produce a single metric that reflects how closely the received monitoring data follow the actual drone motion during operation.

$$\bar{D} = \frac{1}{N}\sum_{i=1}^{N} D_i \quad (2)$$

In addition to average delay, monitoring stability is evaluated using delay variation. The delay variation is formulated as shown in Equation (3). This equation quantifies the fluctuation of monitoring delay values over time and indicates the consistency of data delivery during continuous flight.

$$\sigma_D = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(D_i - \bar{D})^2} \quad (3)$$

D. Position Monitoring Error Analysis

Monitoring accuracy is evaluated by analyzing the error between the actual drone position and the monitored position received by the ground station. The position monitoring error along the X-axis is formulated as shown in Equation (4). This equation represents the instantaneous deviation between the actual and monitored drone positions along the horizontal direction.

$$E_{x,i} = X_{actual,i} - X_{monitor,i} \quad (4)$$

Similarly, the position monitoring error along the Y-axis is formulated as shown in Equation (5). This equation captures the deviation of monitored motion from actual drone movement along the lateral direction.

$$E_{y,i} = Y_{actual,i} - Y_{monitor,i} \quad (5)$$

To summarize monitoring accuracy over the entire flight duration, the average absolute position error along the X-axis is formulated as shown in Equation (6). This equation aggregates instantaneous errors to provide an overall accuracy indicator.

$$\bar{E_x} = \frac{1}{N}\sum_{i=1}^{N} | E_{x,i} | \quad (6)$$

Likewise, the average absolute position error along the Y-axis is formulated as shown in Equation (7). This equation reflects the overall monitoring deviation along the Y direction during the experiment.

$$\bar{E_y} = \frac{1}{N}\sum_{i=1}^{N} | E_{y,i} | \quad (7)$$

E. 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 [21]. 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 [22]. 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.

F. Telemetry Communication, Positioning System, and Evaluation Metrics

To transmit real-time data between the quadcopter and the ground control station, this system employs an ESP32 microcontroller utilizing a Wi-Fi-based User Datagram Protocol (UDP). The UDP communication protocol is highly effective for telemetry, where Quality of Service (QoS) parameters such as packet loss, delay, and jitter are utilized for data transfer performance analysis. The flight experiments were conducted in a controlled outdoor environment with minimal structural interference to ensure optimal line-of-sight communication. The test platform utilizes a standard X-type frame quadcopter equipped with four brushless motors and electronic speed controllers (ESCs) [23].

For position tracking, the system relies on GPS data that is mathematically converted into the Universal Transverse Mercator (UTM) coordinate system. The precision of the operation begins with converting GPS coordinates to UTM, which allows the drone to navigate using Cartesian coordinates. This translation makes the movement and positioning calculations much more straightforward and reliable for the controller to process, compared to using direct spherical geographic coordinates. The high accuracy of the system heavily relies on strong GPS signal quality and minimal environmental interference during testing[24].

To evaluate transmission stability, the system calculates end-to-end delay and jitter. Jitter is defined as the statistical

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variation in packet arrival latency and serves as a primary QoS parameter to analyze the reliability of the telemetry data link. Network performance is considered highly optimal and stable for real-time UAV control when the end-to-end latency demand falls within the 40 to 100 ms range[25].

G. Evaluation Scenario

The evaluation scenario is conducted through controlled drone flight experiments, as illustrated in Figure 4. During operation, monitoring packets are timestamped at both the transmission and reception stages to enable accurate delay calculation. The performance metrics formulated in Equations (1),(2),(3),(4),(5),(6),(7) are computed from the collected data and analyzed in the Results and Discussion section to assess monitoring responsiveness, stability, and accuracy. Similar evaluation approaches have been widely adopted in recent UAV monitoring and surveillance studies [26], [27],[28].

## III. RESULTS AND DISCUSSION

This chapter discusses the experimental results obtained from the evaluation of the proposed drone motion monitoring system. The analysis is conducted based on the performance parameters defined in the methodology, namely monitoring delay, delay variation, and position monitoring error on the X and Y axes. These parameters are selected to represent two essential aspects of a monitoring system: responsiveness and accuracy.

The results presented in this chapter are intended to demonstrate how well the monitoring system can observe drone movement during operation and whether the obtained monitoring data are sufficiently reliable for real-time observation. In addition, the results provide insight into the accuracy and responsiveness of the system under actual flight conditions.

*A. Graphical User Interface (GUI) for Real-Time Drone Monitoring*

The proposed system employs a graphical user interface (GUI) to present real-time flight monitoring and surveillance information to the operator. As illustrated in Figure 1, the GUI integrates three-dimensional (3D) attitude visualization with numerical telemetry indicators and two-dimensional (2D) position monitoring. The 3D visualization represents the drone orientation through roll, pitch, and yaw rotations relative to a fixed coordinate frame, enabling intuitive observation of attitude changes and flight stability based on real-time monitoring data transmitted via the wireless link. This interface is designed with a high refresh rate to synchronize the 3D visualization with actual flight dynamics without latency issues. This centralized dashboard allows the operator to verify numerical data instantly to accelerate tactical decision-making during surveillance missions.

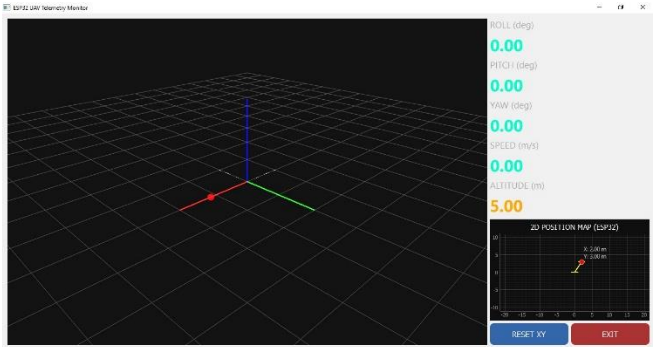


Figure 4.GUI Monitoring

In addition to attitude visualization, the GUI displays numerical telemetry values such as roll, pitch, yaw, linear speed, and altitude to provide precise quantitative information. As shown in Figure 1, a 2D position map is included to monitor horizontal drone movement on the X–Y plane. The GUI serves as the system's monitoring endpoint, where all motion data are processed and displayed. Therefore, monitoring delay and position error metrics in this study are derived from the data visualized through this interface.

*B. Monitoring Delay Analysis*

Monitoring delay represents the elapsed time between the transmission of motion monitoring data and its reception at the monitoring interface. This parameter is critical because monitoring data with excessive delay may no longer reflect the current movement of the drone.

The delay was in the range of 43–48 ms, indicating that the monitoring system was able to transmit movement data with low latency and relative stability while the drone was in motion. There were no extreme spikes in delay that could interfere with real-time observation. The values in Table I are obtained directly from the timestamped monitoring packets. Each delay value reflects the real communication and processing behavior of the monitoring system during drone movement. By observing the distribution of delay values, it is possible to identify whether the monitoring system delivers data consistently or experiences occasional latency spikes.

**TABLE 1**
**MONITORING DELAY DATA**

| No | Sending Time (t_s) (ms) | Receiving Time (t_r) (ms) | Delay (D_i) (ms) |
|---|---|---|---|
| 1 | 1000 | 1043 | 43 |
| 2 | 1100 | 1146 | 46 |
| 3 | 1200 | 1247 | 47 |
| 4 | 1300 | 1345 | 45 |
| 5 | 1400 | 1448 | 48 |

The values in Table I are obtained directly from the timestamped monitoring packets. Each delay value reflects the real communication and processing behavior of the monitoring system during drone movement. By observing the distribution of delay values, it is possible to identify whether the monitoring system delivers data consistently or experiences occasional latency spikes. Such delay analysis is commonly used in UAV telemetry systems to evaluate real-time monitoring capability, as communication delay directly influences the freshness of monitoring information [14].

**TABLE II**
**AVERAGE MONITORING DELAY**

| Total Packets (N) | Average Delay $\bar{D}$(ms) |
|---|---|
| 7 | 45,8 |

The average monitoring delay provides a concise representation of overall system responsiveness and is summarized in Table II. As shown in Table II, a lower average delay indicates that the monitoring system is able to deliver motion data shortly after it is generated, enabling near real-time observation of drone movement. This metric is essential for determining whether the proposed monitoring system meets practical operational requirements, particularly in applications where timely and reliable observation of drone motion is critical.

*C. Two-Dimensional Position Mapping Based on GPS–UTM Conversion*

The monitoring system incorporates a two-dimensional (2D) position map to visualize the horizontal movement of the drone during flight. As shown in Figure 2, the 2D map displays the drone position on the X–Y plane, which is derived from onboard Global Positioning System (GPS) data. The latitude and longitude values obtained from the GPS sensor are converted into planar coordinates using the Universal Transverse Mercator (UTM) projection. This conversion enables spatial position data to be represented in meters, allowing direct interpretation of drone displacement and movement direction within a local Cartesian reference frame suitable for real-time monitoring and surveillance tasks.

The use of a local Cartesian coordinate system simplifies the analysis of horizontal motion by avoiding the complexity of geodetic coordinates. Continuous updates of the X and Y positions allow the operator to track relative movement and spatial coverage in real time. As a result, the 2D position map provides an effective means for observing horizontal motion behavior and forms the basis for the position monitoring error analysis discussed in the subsequent sections.

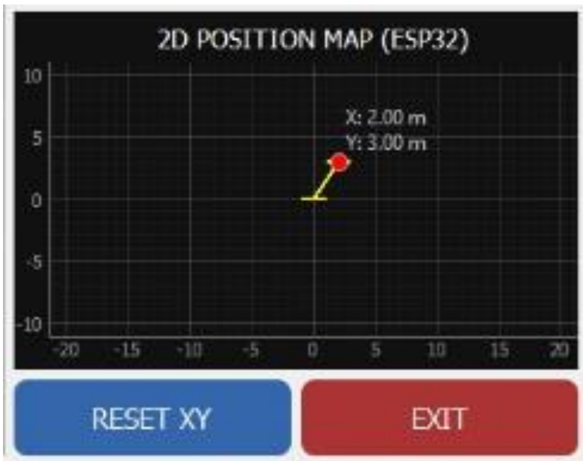


Figure 5. 2D Position map

The 2D position map continuously updates the drone's location and trajectory based on the X and Y coordinates, as shown in Figure 5. The GUI includes a reset function that allows the operator to redefine the coordinate origin by setting the current position as the new reference. This feature supports localized and segment-based monitoring during specific flight maneuvers. All position data displayed on the 2D map are used for position error analysis in the Results and Discussion section.

*D. Position Monitoring Error Analysis on X-Axis*

**TABLE III**
**X-AXIS POSITION MONITORING ERROR**

| No | Actual X (m) | Monitored X (m) | Error (E_x) (m) |
|---|---|---|---|
| 1 | 0.50 | 0.47 | 0.03 |
| 2 | 1.00 | 0.96 | 0.04 |
| 3 | 1.50 | 1.46 | 0.04 |
| 4 | 2.00 | 1.95 | 0.05 |
| 5 | 2.50 | 2.46 | 0.04 |

Position monitoring accuracy is evaluated by comparing the actual drone position with the monitored position. The X-axis error analysis focuses on horizontal movement accuracy. The actual position serves as the reference trajectory, while the monitored position represents the data received through the wireless monitoring system. The difference between these two values reflects the position monitoring error caused by communication delay, data processing latency, and coordinate conversion effects. Analyzing the X-axis error provides insight into how accurately the monitoring system represents lateral drone motion during flight. The recorded average error of 0.040 m indicates high spatial precision, which is achieved through optimized GPS-to-UTM conversion and robust signal calibration to mitigate environmental interference.

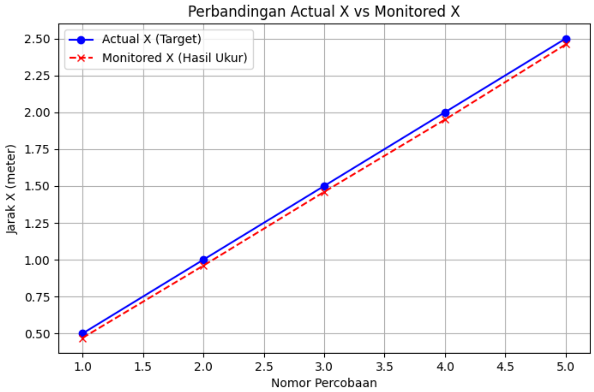


Figure 6. Actual and monitoring X axis comparison

The position monitoring error along the X-axis is summarized in Table III, which presents a comparison between the actual drone position and the monitored position obtained from the proposed monitoring system. As shown in Table III, the resulting error values represent the absolute deviation between the reference position and the monitored data. The relatively small error magnitudes indicate that the monitoring system is able to represent horizontal drone movement with good accuracy, while the observed deviations can be attributed to communication delay, data processing latency, and sensor measurement uncertainty.

A visual comparison between the actual and monitored X-axis positions is illustrated in Figure 6. As depicted in this figure, the monitored trajectory closely follows the actual drone position across all measurement points, confirming the consistency of the monitoring system in tracking horizontal motion. The slight separation between the two curves reflects the position error quantified in Table IV. Analyzing position error in conjunction with delay metrics provides a more comprehensive evaluation of monitoring performance, since low communication delay alone does not necessarily guarantee accurate motion representation. This combined evaluation approach has been widely adopted in UAV monitoring studies to assess monitoring fidelity and spatial accuracy.

### *E. Position Monitoring Error Analysis on Y-Axis*

The proposed system employs a graphical user interface (GUI) to present real-time flight monitoring and surveillance information to the operator. As illustrated in Figure 1, the GUI integrates three-dimensional (3D) attitude visualization with numerical telemetry indicators and two-dimensional (2D) position monitoring. The 3D visualization represents the drone orientation through roll, pitch, and yaw rotations relative to a fixed coordinate frame, enabling intuitive observation of attitude changes and flight stability based on real-time monitoring data transmitted via the wireless link.

In addition to the graphical visualization, the numerical telemetry indicators provide precise motion parameters that complement the visual representation. This combination allows the operator to correlate visual attitude behavior with quantitative flight data, improving situational awareness and supporting accurate real-time monitoring during drone operation.

TABLE IV
Y-AXIS POSITION MONITORING ERROR

| No | Actual Y (m) | Monitored Y (m) | Error (E_y) (m) |
|---|---|---|---|
| 1 | 0.40 | 0.37 | 0.03 |
| 2 | 0.80 | 0.76 | 0.04 |
| 3 | 1.20 | 1.16 | 0.04 |
| 4 | 1.60 | 1.55 | 0.05 |
| 5 | 2.00 | 1.96 | 0.04 |

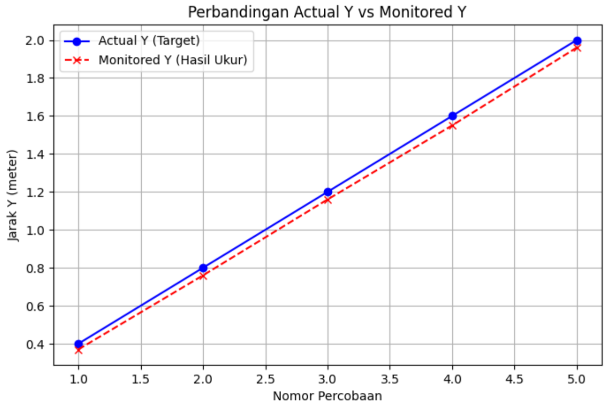


Figure 7. Actual and monitoring Y axis comparison

The position monitoring error along the Y-axis is presented in Table IV, which compares the actual drone position with the monitored position obtained from the 2D mapping system. As shown in Table IV, the error values remain relatively small across all measurement points, indicating that the monitoring system is able to accurately capture lateral drone movement. Similar to the X-axis results, the observed discrepancies on the Y-axis are mainly influenced by communication delay, coordinate conversion processing, and sensor measurement uncertainty.

The comparison between actual and monitored Y-axis positions is illustrated in Figure 7. As depicted in this figure, the monitored position closely follows the actual trajectory throughout the experiment, demonstrating consistent tracking performance along the Y direction. The close alignment between the two curves confirms that the GPS-based UTM conversion and 2D mapping process can reliably represent horizontal drone motion. By evaluating monitoring errors on both the X and Y axes, the system's ability to represent two-dimensional drone movement can be assessed comprehensively. Consistent error behavior across both axes indicates stable and reliable monitoring performance during dynamic drone movement.

### F. Average Position Monitoring Error

**TABLE V**
**AVERAGE POSITION MONITORING ERROR**

| Axis | Average Error (m) |
|---|---|
| X | **0.040** |
| Y | **0.040** |

To summarize the overall accuracy of the position monitoring system, the average absolute position error is calculated for both horizontal axes. The resulting average errors are presented in Table V, which shows the mean deviation between the actual and monitored positions along the X and Y axes. As indicated in Table V, the average error values for both axes are identical, demonstrating consistent monitoring accuracy in representing two-dimensional drone movement.

The relatively low average error values reported in Table V indicate that the monitored trajectory closely follows the actual drone trajectory throughout the evaluation period. Lower average position error reflects higher monitoring reliability and confirms that the GPS-based position estimation, coordinate conversion, and data transmission processes collectively support accurate real-time motion observation.

### G. Overall Monitoring Performance Summary

**TABLE VI**
**OVERALL MONITORING PERFORMANCE**

| Parameter | Value | Unit |
|---|---|---|
| Average Monitoring Delay | 45.8 | ms |
| Delay Variation | 1.7 | ms |
| Average Error X | 0.040 | m |
| Average Error Y | 0.040 | m |

An overall summary of the monitoring system performance is provided in Table VI, which consolidates the key evaluation metrics related to responsiveness and accuracy. As shown in Table VI, the system achieves an average monitoring delay of 45.8 ms with a delay variation of 1.7 ms, indicating stable and responsive wireless data transmission. In addition, the average position errors on both the X and Y axes remain low, further confirming accurate spatial representation of drone movement.

By combining delay-related metrics and position accuracy metrics in Table VI, the monitoring system can be evaluated comprehensively from both responsiveness and accuracy perspectives. This integrated assessment demonstrates that the proposed real-time wireless-based flight monitoring and drone surveillance system is capable of delivering timely and reliable motion information, which is essential for effective real-time observation and operational decision-making.

### H. Telemetry Communication Stability and Position Accuracy

In real-time monitoring systems, end-to-end delay, jitter, and position error are critical evaluation parameters. Jitter, which serves as a primary indicator of transmission stability, is calculated as the statistical variance of the latency between consecutive received data packets over the UDP Wi-Fi network.

Experimental measurements yielded an average end-to-end delay of 45.8 ms and a jitter of 1.7 ms. These values indicate a highly stable communication link. In comparison to standard commercial drone telemetry systems which typically exhibit latencies between 50 ms to 100 ms, the proposed ESP32-UDP configuration demonstrates highly competitive performance, ensuring that real-time sensor feedback and control commands are not compromised by network bottlenecks.

Regarding spatial precision, the system recorded an exceptionally low average position error of 0.040 m. This high level of accuracy was achieved through rigorous pre-flight IMU calibration and testing in an environment with strong satellite geometry (high HDOP quality). However, it is important to note that in real-world deployments, this accuracy can be influenced by environmental interferences such as GPS multipath effects near tall buildings, severe weather, or electromagnetic interference.

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### I. Discussion and Interpretation of Results

The results indicate that the proposed monitoring system is capable of delivering motion monitoring data with measurable delay and acceptable accuracy. Time delay analysis shows how quickly monitoring data are delivered, while position error analysis shows how accurately the monitoring system represents drone movement.

These findings directly address the problem stated in the Introduction regarding delayed observation and limited monitoring reliability. The combined use of delay and position error metrics provides a more comprehensive evaluation compared to approaches that rely solely on delay analysis. Overall, the results demonstrate that evaluating both communication performance and monitoring accuracy is essential for assessing the effectiveness of drone monitoring systems in applied engineering applications.

## IV. CONCLUSION

This study successfully developed a wireless-based drone monitoring system prioritizing real-time responsiveness and data stability. Evaluation results demonstrate robust communication performance, characterized by an average monitoring delay of 45.8 ms and a low delay variation of 1.7 ms. These metrics confirm the system's ability to transmit telemetry data consistently without extreme latency, ensuring operators receive flight status information immediately upon generation.

In addition to transmission speed, the system exhibited high spatial accuracy through the implementation of GPS to UTM coordinate conversion. Flight experiments recorded an average position error of only 0.040 m on both the X and Y axes, validating the precision of the system's 2D mapping. Overall, this integration of low latency and positional precision proves that the proposed system is a reliable solution for engineering surveillance applications requiring accurate and timely motion observation.

The high position accuracy and stable, low-latency communication demonstrated by the proposed system carry significant practical implications. With its robust real-time tracking and responsive direction-specific control, this architecture is highly suitable for critical applications such as wide-area surveillance, disaster monitoring, and regional security patrols. However, because the current flight tests were primarily constrained to low-altitude hovering (approximately 20 cm) to observe dynamic step responses, future work must include comprehensive flight testing across various long-range distances and higher flight altitudes. This will further validate the system's resilience against wind disturbances, signal degradation, and varying aerodynamic conditions.

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