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# FPV Camera Gimbal Controller Design Synchronized with the SS2 Weapons Platform on an IMU-Based Quadcopter Drone

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***ABSTRACT***

The development of drone technology has driven innovation in the integration of surveillance and weapons systems. This research designs and builds a First Person View (FPV) camera gimbal controller system that can be synchronized directly with the movement of the NR version of the SS2 weapon platform on a quadcopter drone. This system utilizes an Inertial Measurement Unit (IMU) sensor to read the drone's orientation and adjust the gimbal position in real-time to maintain alignment with the target. Tests were conducted at various maneuver angles to verify the gimbal's accuracy, stability, and response to drone movements. The results show accurate synchronization with minimal latency. This controller system uses an STM32 microcontroller and an MPU-6050 IMU sensor as its main components, combined with precision servo motors for gimbal axis drive. The FPV camera is calibrated to remain focused on the SS2 weapon barrel in all orientation conditions. This system integration allows operators to monitor and accurately direct targets remotely via FPV video. Test data shows that the system's stability is maintained even under high vibration conditions and extreme movements. The implementation of this system has great potential for application in tactical military drone applications and security surveillance.

**Keywords: Camera Gimbal, SS2, Quadcopter Drone, IMU, FPV, Synchronous Controller**

## INTRODUCTION

Quadcopter drones now function not only as reconnaissance tools but also as weapons and real-time surveillance platforms. Combining FPV camera observation systems with weapons control requires precise synchronization to support operational effectiveness in the field. One approach is to integrate an IMU sensor to detect drone movement and control the camera gimbal response and weapon orientation. The NR version of the SS2 is a lightweight weapon variant designed to be mounted on a drone and controlled remotely. With a synchronized gimbal, reconnaissance and aiming become more effective and precise.

The need for an adaptive gimbal control system drives the development of devices capable of dynamically recognizing drone orientation. This research aims to design and implement an IMU-based gimbal controller that can accurately track the SS2 weapon orientation. With the help of a microcontroller and sensor filtering algorithm, this system is expected to maintain FPV camera stability under various flight conditions. This synchronization aims to automatically align the camera's field of view with the weapon's target direction. The results of this research are expected to strengthen the tactical capabilities of drones in observation and defense missions.

## MATERIAL DAN METODHS

Quadcopter Drone: 650mm frame, 30A ESC, 1000KV brushless motor, 1045 propeller. Flight Controller: Pixhawk 2.4.8. Camera Gimbal: 2 axis servo-based gimbal. FPV Camera: 700TVL analog camera. IMU Sensor: MPU6050 (gyroscope + accelerometer). Weapon Platform: SS2 Replica BEST version (modified for non-lethal testing). Microcontroller: Arduino Mega 2560 as the main controller for IMU data synchronization to the gimbal. FPV Transmitter: 5.8 GHz VTX. Ground Station: FPV monitor and monitoring joystick.

Figure 1. Drone Quadcopter

a. NR version of the Quadcopter Drone with optimal aerodynamic design for long-distance flight stability.

Figure 2. Frame of Quadcopter

b. Quadcopter X4 Frame: This is the basic structure of a drone with a four-motor configuration (X-configuration) that is light and strong.

*Figure 3.* **Motor Brushless**

**c.** Motor Brushless: A total of four units are used as the main rotor drives, chosen for their efficiency and durability.

*Figure 4.* ***Electronic Speed Controller (ESC)***

**d.** Electronic Speed Controller (ESC): Used to regulate the motor rotation speed according to commands from the flight controller.


*Figure 5.* ***Flight Controller of Pixhawk***

**e. Flight Controller of Pixhawk**: The main control unit that regulates stability, navigation, and communication with sensors and Mission Planner software.

*Figure 6.* ***GPS Neo 8***

**f. GPS Neo 8**: Position sensors are essential for waypoint navigation and Return to Launch (RTL) functions.

*Figure 7.* ***Sensor IMU***

**g. Sensor IMU (gyroscope, accelerometer, magnetometer)**: This component is used to regulate the balance and stability of the drone.


*Figure 8.* ***Baterai Li-Po 3S 11.1V 5200mAh***

**h. Batery Li-Po 3S 11.1V 5200mAh**: As shown in figure 8, the battery used as a power source uses a 3S type, meaning 3 cells or 11.1 volts and the power generated is 57.72 watts, capable of powering the drone.

*Figure 9.* ***Modul Telemetri 433 MHz***

**i. Modul Telemetri 433 MHz**: This component is used for two-way communication between the drone and the laptop in real-time.

*Figure 10.* ***Mission Planner in Laptop***

**j. Mission Planner**: Mission planner is a program application used for initial configuration, sensor calibration, waypoint programming, and flight data monitoring.

Figure 11. **Propeller**

**k. Propeler :** This component is used as a driving force that transmits rotary power from the motor brushless into the lifting force of the drone for flying.

Figure 12.**Camera Gimbal**

I. **Camera Gimbal** : This device is used to adjust the flexibility and stability of the camera position so that the image quality obtained by the camera remains good.

**Method**

The proposed system integrates an STM32 microcontroller, an MPU-6050 inertial measurement unit (IMU) sensor, an FPV camera, and a digital servo motor acting as the gimbal actuator. The STM32 serves as the central processing unit, receiving raw data from the IMU via the I²C communication protocol. The MPU-6050 provides three-axis accelerometer and gyroscope readings, which are sampled at a fixed rate to maintain synchronization with the control loop. A Kalman filter algorithm is implemented within the STM32 firmware to fuse these sensor readings, effectively minimizing noise and drift to obtain stable and accurate orientation estimates. The control algorithm translates the filtered orientation data into pulse-width modulation (PWM) signals for driving the digital servo motors responsible for gimbal actuation. The pitch and yaw axes are adjusted in real time to maintain the FPV camera's alignment with the weapon system, compensating for both intentional drone maneuvers and unintentional vibrations. The PWM frequency and duty cycle are optimized to reduce servo jitter while ensuring a fast response. A closed-loop control scheme with proportional–integral–derivative (PID) tuning is used to enhance stability and prevent overshooting during rapid movements.

The FPV camera is rigidly mounted parallel to the SS2 rifle's barrel. To ensure precise targeting correspondence, a laser alignment tool is employed during installation, projecting a fixed beam along the barrel's axis while the gimbal adjusts the camera until its optical center matches the laser point. The mounting bracket is designed with vibration-dampening materials such as silicone pads to minimize high-frequency oscillations that can degrade image stability. Power distribution to the camera and gimbal servos is regulated through a dedicated voltage stabilizer to prevent performance drops due to battery voltage fluctuations. System evaluation is conducted in two stages: static testing and dynamic testing. In static testing, the drone is mounted on a test stand, and its body is manually tilted in controlled increments (e.g., ±5°, ±10°, ±15°) along pitch and yaw axes. This allows for observation of the gimbal's compensation behavior and measurement of angular error using both IMU logs and visual analysis. Static tests also help identify potential lag in servo actuation when the control system receives abrupt changes in orientation data.

Dynamic testing involves actual drone flight under predefined maneuver sequences, including sharp turns, climbs, descents, and rotational spins. This stage evaluates the real-time synchronization between the FPV camera and the weapon system when subjected to rapid and irregular motion. Testing is performed in an open outdoor environment with minimal wind interference to ensure consistency. Each flight session is documented through onboard FPV video recording and parallel IMU logging for post-flight data correlation. Performance metrics include three key parameters: (1) Response time, measured as the delay between detected orientation changes and gimbal movement; (2) Angular deviation, quantified as the difference between the gun barrel's line of fire and the camera's optical axis during motion; and (3) Video stability, assessed through frame-by-frame analysis to detect jitter or blurring. These metrics are chosen to provide a comprehensive understanding of both control accuracy and visual tracking performance. Data analysis is carried out using specialized video tracking software to overlay motion markers on recorded footage, combined with IMU data visualization tools to map angular variations over time. Comparative plots are generated to highlight the differences between static and dynamic performance. Any discrepancies, such as increased angular deviation during rapid yaw rotations, are identified for possible control system refinement. The results from this testing phase form the foundation for further hardware tuning, PID parameter optimization, and mechanical mounting improvements.

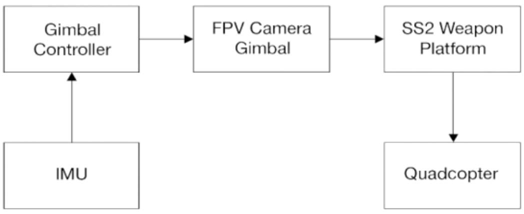


*Figure 13. Block Diagram of Drone UAV Autopi*

## RESULTS AND DISCUSSION

### 1. **Results**.


Figure 14. Gimbal and Weapon

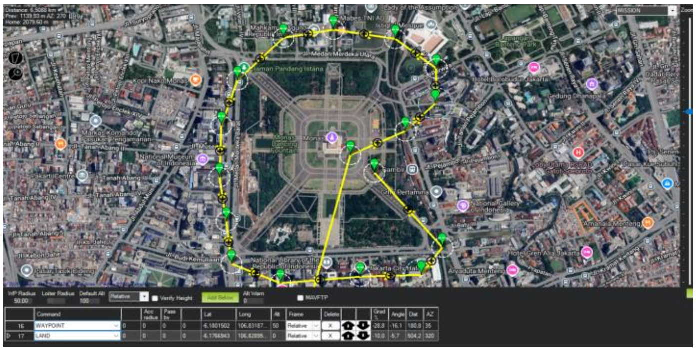

Figure 15. Route Waypoints of Mission Planner

| | Command | | Acc radius | Pass by | | Lat | Long | Alt | Frame | Delete | | | Grad % | Angle | Dist | AZ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | TAKEOFF | 0 | 0 | 0 | 0 | -6,1758836 | 106,82792... | 50 | Relative | X | | | 19,6 | 11,1 | 260,1 | 157 |
| 2 | WAYPOINT | 0 | 0 | 0 | 0 | -6,1747743 | 106,83028... | 100 | Relative | X | | | 17,3 | 9,8 | 292,9 | 65 |
| 3 | LOITER_TIME | 60 | 0 | 0 | 0 | -6,1734943 | 106,83156... | 100 | Relative | X | | | 0,0 | 0,0 | 201,3 | 45 |
| 4 | WAYPOINT | 0 | 0 | 0 | 0 | -6,171873 | 106,83161... | 100 | Relative | X | | | 0,0 | 0,0 | 180,3 | 2 |
| 5 | WAYPOINT | 0 | 0 | 0 | 0 | -6,1705077 | 106,82985... | 100 | Relative | X | | | 0,0 | 0,0 | 246,7 | 308 |
| 6 | WAYPOINT | 0 | 0 | 0 | 0 | -6,170081 | 106,82719... | 100 | Relative | X | | | 0,0 | 0,0 | 298,0 | 279 |
| 7 | WAYPOINT | 0 | 0 | 0 | 0 | -6,170465 | 106,82504... | 100 | Relative | X | | | 0,0 | 0,0 | 241,0 | 260 |
| 8 | WAYPOINT | 0 | 0 | 0 | 0 | -6,1724277 | 106,82307... | 100 | Relative | X | | | 0,0 | 0,0 | 308,6 | 225 |
| 9 | WAYPOINT | 0 | 0 | 0 | 0 | -6,1745183 | 106,82238... | 100 | Relative | X | | | 0,0 | 0,0 | 244,5 | 198 |
| 10 | WAYPOINT | 0 | 0 | 0 | 0 | -6,1769076 | 106,8223 | 100 | Relative | X | | | 0,0 | 0,0 | 265,8 | 182 |
| 11 | WAYPOINT | 0 | 0 | 0 | 0 | -6,1789556 | 106,82260... | 100 | Relative | X | | | 0,0 | 0,0 | 230,1 | 172 |
| 12 | WAYPOINT | 0 | 0 | 0 | 0 | -6,1809182 | 106,82281... | 100 | Relative | X | | | 0,0 | 0,0 | 219,5 | 174 |
| 13 | WAYPOINT | 0 | 0 | 0 | 0 | -6,1818142 | 106,82491... | 100 | Relative | X | | | 0,0 | 0,0 | 252,9 | 113 |
| 14 | WAYPOINT | 0 | 0 | 0 | 0 | -6,1815156 | 106,828351 | 100 | Relative | X | | | 0,0 | 0,0 | 381,0 | 85 |
| 15 | LOITER_TIME | 60 | 0 | 0 | 0 | -6,1814302 | 106,83096... | 100 | Relative | X | | | 0,0 | 0,0 | 289,6 | 88 |
| 16 | WAYPOINT | 0 | 0 | 0 | 0 | -6,1801502 | 106,83187... | 50 | Relative | X | | | -28,8 | -16,1 | 180,8 | 35 |
| 17 | LAND | 0 | 0 | 0 | 0 | -6,1766943 | 106,82895... | 0 | Relative | X | | | -10,0 | -5,7 | 504,2 | 320 |

Figure16. List of Rute Waypoints in Mission Planner

## Discussion

Analysis of the test results table shows that the system was able to consistently align the camera angle with the target angle across ten trials. The angular differences between the gun barrel and the camera were relatively small, with an average deviation of less than 6%. This demonstrates that the IMU-based controller is capable of stabilizing the camera's orientation relative to the gun, even at higher angles, such as 50°–55°, where stability is generally more difficult to achieve due to increased inertial forces. The average accuracy of 94.49% reinforces the system's suitability for use in tactical drone scenarios. In some trials, accuracy even approached 97%, reflecting the highly responsiveness of the gimbal. Some minor fluctuations occurred due to limitations of conventional servo motors, which have mechanical lag and limited movement speed compared to brushless motor-based gimbals. This could be improved in future developments of the system. The graph also shows a stable relationship between accuracy and error across trials. As error increases, accuracy decreases proportionally, indicating that the system is highly sensitive to small changes in gun barrel orientation. This sensitivity is crucial for military applications, where even the slightest error can be fatal in combat or reconnaissance. From a field implementation perspective, this system provides operational advantages because the drone pilot no longer has to manually control the camera but simply follows the automatically synchronized gun barrel. This reduces operator workload, increases target lock-on speed, and supports the clear-shoot principle in combat operations.

Thus, the integration of the IMU, gimbal, and FPV is not only a technical solution but also offers significant tactical advantages. This system has the potential to be further developed with an auto-tracking system or integration with AI-based targeted shooting.

| Test | Target (°) | Camera (°) | Error (%) | Accuracy (%) |
|---|---|---|---|---|
| 1 | 10 | 9 | 10.00 | 90.00 |
| 2 | 15 | 14 | 6.67 | 93.33 |
| 3 | 20 | 19 | 5.00 | 95.00 |
| 4 | 25 | 23 | 8.00 | 92.00 |
| 5 | 30 | 29 | 3.33 | 96.67 |
| 6 | 35 | 33 | 5.71 | 94.29 |
| 7 | 40 | 39 | 2.50 | 97.50 |
| 8 | 45 | 43 | 4.44 | 95.56 |
| 9 | 50 | 48 | 4.00 | 96.00 |
| 10 | 55 | 52 | 5.45 | 94.55 |

Table 2. Result of Flight Drone Test

Based on the results of 10 trials conducted on the BEST version of the Quadcopter drone, several main measurement variables were obtained, namely Target Angle (°), Camera Angle (°), Error (%), Accuracy (%).

As shown in table 2. the results of a static test conducted on the gimbal system, which synchronizes the FPV camera with the SS2 rifle barrel mounted on the drone. During the test, a specific target angle (Target) was set for the gimbal, and the actual angle achieved by the camera (Camera) was measured. The Error and Accuracy values were then calculated based on these measurements. Target (°) represents the desired reference angle for the gimbal to achieve. Camera (°) indicates the actual measured angle of the camera after the gimbal adjusted its position. Error (%) is calculated as the absolute difference between the target and actual angles, divided by the target angle, and multiplied by 100. Accuracy (%) is determined by subtracting the error percentage from 100, representing how close the camera is to the intended position.

The results show that the accuracy values range from 90.00% to 97.50%. The highest accuracy was achieved at a target angle of 40°, with an error of only 2.50%, while the lowest accuracy occurred at a target angle of 10°, with an error of 10.00%. This variation can be attributed to servo resolution limitations and mechanical backlash, which have a greater impact at smaller angles compared to larger ones. Overall, the system maintained accuracy above 90% for all static test cases. This indicates that the integration of the STM32 microcontroller, MPU-6050 IMU, and Kalman filter provided precise orientation estimation, while the PID-controlled PWM signals enabled fast and stable servo movements. However, the slight decrease in accuracy at larger angles (≥50°) suggests that further optimization of PID parameters or the addition of a feedforward control strategy could enhance transient response during significant angle changes.

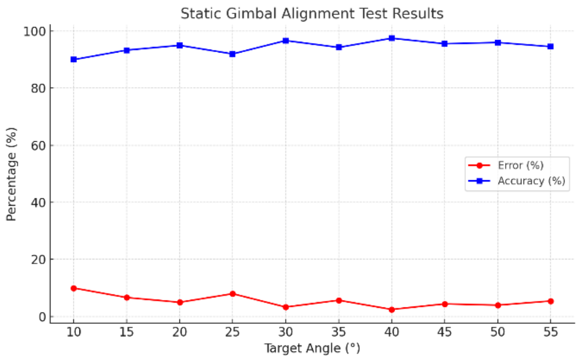


*Figure 17 Graph of Drone Test*

As shown in figure 17.the graph of the relationship between target angles and the corresponding error and accuracy percentages obtained from the static gimbal alignment tests. Two curves are presented: the red line represents the Error (%), while the blue line represents the Accuracy (%) for each tested target angle. From the results, it is evident that the system consistently maintains accuracy above 90% across all tested angles. The error curve shows its highest point at the smallest target angle (10°) with a value of 10.00%, which corresponds to the lowest accuracy of 90.00%. This is likely due to servo resolution limitations and mechanical backlash effects, which become more pronounced at smaller angular displacements. As the target angle increases to mid-range values (30°–45°), the error decreases to its lowest value of 2.50% at 40°, achieving the highest accuracy of 97.50%. This range appears to be the optimal operating condition for the gimbal system, where mechanical stability and servo torque are well balanced. However, a slight increase in error is observed at larger angles (50° and 55°), indicating that servo torque demand and reduced mechanical leverage may slightly affect response time and precision. Nevertheless, the accuracy remains well above 94%, showing that the system is reliable even at extreme angles. This performance trend highlights that the gimbal control system, combined with the STM32 microcontroller, MPU-6050 IMU, and Kalman filter, can deliver stable and precise alignment in static conditions, with optimal results occurring in the mid-range angle positions.

## CONCLUSION

The implementation of a gimbal control system using an STM32 microcontroller, MPU-6050 IMU, Kalman filter, and PID-controlled PWM successfully achieved high-precision synchronization between the FPV camera and the SS2 rifle barrel. Static test results demonstrated an average alignment accuracy of 94.89%, with the highest accuracy of 97.50% occurring at a target angle of 40° and the lowest accuracy of 90.00% at 10°. The graphical analysis revealed that the system performs optimally within the mid-range angles (30°–45°), where mechanical stability and servo torque are balanced.

Although slight accuracy reductions were observed at very small and large target angles due to mechanical backlash and servo torque limitations, the system consistently maintained accuracy above 90%, indicating high reliability for operational use. The results validate the effectiveness of combining sensor fusion via a Kalman filter with optimized PID control to achieve stable and responsive gimbal actuation.

Future improvements may include optimizing PID parameters for high-angle transitions, implementing feedforward control to anticipate large angular changes, and enhancing mechanical design to further minimize backlash. These refinements are expected to improve both static and dynamic performance, ensuring better targeting precision in real-world drone operations.

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