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Design and Implementation of a Low-Cost Aircraft Orientation Angle Measurement System using MPU6050 Sensor for Avionics Education

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ABSTRACT/ABSTRAK

This study presents the design and implementation of a low-cost aircraft orientation angle measurement system using the MPU6050 sensor and Arduino Uno microcontroller for educational applications in avionics. The system aims to simulate aircraft attitude angles—yaw, pitch, and roll—by integrating an inertial sensor module (MPU6050) with open-source hardware and software. The Arduino IDE was employed to acquire and process sensor data, while the Processing 3 environment was used to visualize the attitude motion in real time. The prototype was assembled and tested to evaluate its performance in detecting orientation changes across three axes. Experimental results demonstrate that the MPU6050-based system can accurately capture and display attitude variations without communication delay or signal error, providing a clear visualization of aircraft motion. The system's simplicity, affordability, and open-source framework make it suitable for classroom demonstrations and laboratory exercises in avionics and control-system courses. Future improvements include the integration of Euler-angle computation and wireless communication to enhance mobility and data acquisition.

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1 INTRODUCTION

Accurate measurement of aircraft attitude and orientation angles—yaw, pitch, and roll—is essential for maintaining stability and situational awareness during flight operations. In modern aviation, such measurements are achieved through the integration of inertial measurement units (IMUs) and attitude-heading reference systems (AHRS) that process multi-axis motion data in real time. Reliable attitude determination is therefore critical not only for piloted aircraft but also for autonomous systems and educational training devices used in avionics learning environments [1].

Advances in low-cost microelectromechanical systems (MEMS) have enabled affordable, compact, and energy-efficient sensors suitable for small-scale aerospace and satellite applications [2]. IMUs employing gyroscopes and accelerometers—such as the MPU6050—have become key components in unmanned aerial vehicles (UAVs), robotic systems, and flight-simulation trainers due to their simple integration and acceptable precision for non-safety-critical tasks [3]. These sensors provide raw angular-velocity and linear-acceleration data that, when processed using complementary or Kalman filtering, yield orientation angles with sufficient accuracy for educational and experimental purposes [4], [5], [6].

A wide range of studies has explored IMU-based attitude estimation and control. Wu *et al.* [4] proposed a fast complementary filter for low-cost MARG (magnetic-angular rate-gravity) sensors, while Del Rosario *et al.* [5] implemented quaternion-based filtering for smartphones. Öz *et al.* [6] validated IMU orientation estimation using low-cost sensors, and Sultana *et al.* [7] analyzed the measurement accuracy of MPU6050 modules. These works demonstrate that low-cost sensors can achieve reasonable stability when appropriate signal-fusion algorithms are applied.

In the domain of avionics and robotics education, numerous studies have utilized Arduino-based architectures to build economical prototypes that demonstrate real-time motion or control principles. Jian [8] designed a simple angle-detection system based on the MPU6050, while Alfian *et al.* [9] applied Kalman filtering to reduce gyroscope noise. Rafiq *et al.* [10] created a low-cost smartphone gimbal, and Kumar *et al.* [11] presented an inexpensive Arduino-based inertial measurement unit suitable for classroom demonstration. Similarly, Navarro-Iribarne *et al.* [12] and Sánchez-Moreno *et al.* [13] developed low-cost wearable IMU systems for motion analysis, confirming that MEMS-based motion tracking can serve as an effective pedagogical tool.

Although prior research addresses the design of IMU-based systems and data-fusion algorithms, a specific gap remains regarding the **development of a low-cost, open-source aircraft attitude trainer explicitly intended for avionics education**. Most existing studies either focus on UAV stabilization, robotic motion, or general-purpose IoT sensing rather than on visualizing aircraft yaw–pitch–roll motion in real time using accessible educational hardware.

To address this gap, the present study proposes the **design and implementation of a low-cost aircraft orientation-angle measurement system** using the MPU6050 sensor and Arduino Uno microcontroller, integrated with Processing software for three-dimensional visualization. The research aims to provide an affordable and replicable educational platform that allows students to observe aircraft attitude behavior interactively, thereby enhancing conceptual understanding of orientation dynamics and sensor-data interpretation in avionics and control courses [14], [15].

2 Methods

2.1 A. Overview of Aircraft Orientation Angles

Aircraft orientation in three-dimensional space is represented by three rotational degrees of freedom known as **roll**, **pitch**, and **yaw**, which describe the aircraft's attitude relative to its body-fixed coordinate system. The **x-axis** runs along the fuselage (longitudinal axis), the **y-axis** lies across the wings (lateral axis), and the **z-axis** extends vertically through the center of gravity [16].

- **Roll (φ)**: rotation about the x-axis, causing one wing to rise while the other descends.
- **Pitch (θ)**: rotation about the y-axis, raising or lowering the aircraft's nose.
- **Yaw (ψ)**: rotation about the z-axis, turning the nose left or right about the vertical axis.

These three rotations collectively define the aircraft's **attitude**, which serves as the principal observable in this educational prototype. Understanding this 3D framework allows students to correlate physical aircraft motion with numerical attitude data obtained from inertial sensors. This representation of body axes is a standard in flight-dynamics instruction and has been widely used in attitude-control demonstrations and aerospace-education simulations [17] as in Figure 1.

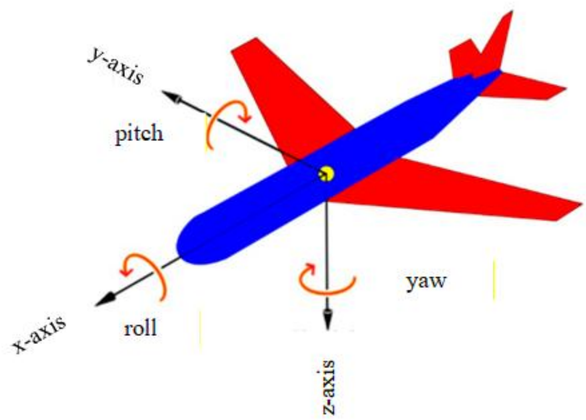

Figure 1. Aircraft orientation angles in a body-fixed coordinate system

2.2 Sensor-Axis Mapping and Measurement Principle

The **MPU6050 module** integrates a tri-axial **gyroscope** and a tri-axial **accelerometer**, enabling estimation of angular velocity (ω_x, ω_Y, ω_z) and linear acceleration (a_x, a_Y, a_z) along the same axes illustrated in Figure 1. The gyroscope provides high-frequency sensitivity to rapid attitude changes, while the accelerometer supplies low-frequency data for long-term stability. By applying a **complementary-filter algorithm**, gyroscopic drift can be corrected by accelerometer feedback, producing stable real-time estimates of **roll (φ)**, **pitch (θ)**, and **yaw (ψ)** [18].

The accelerometer measures the projection of gravitational acceleration along each axis. The roll (Φ) and pitch (θ) angles are calculated using trigonometric relationships as equation (1) and (2) [14].

$$\Phi = \arctan\left(\frac{a_y}{\sqrt{a_x^2 + a_z^2}}\right) \quad (1)$$

$$\theta = \arctan\left(\frac{a_x}{\sqrt{a_y^2 + a_z^2}}\right) \quad (2)$$

where a_x, a_y, and a_z represent the acceleration components along the x, y, and z axes, respectively.

The yaw (ψ) angle, representing the aircraft heading relative to magnetic north, is obtained from the horizontal magnetic field components of a 3-axis magnetometer. After tilt compensation, the heading angle is calculated as equation (3).

$$\psi = \arctan\left(\frac{{}^{xy}m_y}{{}^{xy}m_x}\right) - D \quad (3)$$

where ${}^{xy}m_x$ and ${}^{xy}m_y$ are the tilt-compensated magnetic field components, and D is the magnetic declination angle. This equation enables magnetic heading correction and enhances yaw stability in hybrid IMU–magnetometer configurations. The detailed derivation and validation of this formulation can be found in Ref. [14].

This data-fusion concept is widely adopted in educational IMU implementations, as it balances computational simplicity and adequate accuracy for teaching purposes [19]. Through this fusion, the MPU6050 continuously streams processed angular data via the I²C interface to the Arduino Uno microcontroller, which formats and transmits the readings to a host computer. The Processing-based visualization environment then renders a 3D aircraft model that dynamically reproduces these orientation changes, allowing learners to observe attitude behavior in an intuitive graphical form.

This mapping between physical axes and sensor outputs creates a **cognitive link between theoretical flight dynamics and practical instrumentation**—an important pedagogical outcome highlighted in previous works on embedded-systems learning and STEM education [20].

2.3 System Architecture

The overall system architecture is designed to demonstrate real-time visualization of aircraft attitude angles using open-source components. The prototype consists of three primary modules:

1. **MPU6050 Sensor Module**, which measures angular velocity and linear acceleration on three axes;
2. **Arduino Uno Microcontroller**, which processes raw data, applies the complementary filter, and transmits the filtered angles;
3. **Laptop-based Visualization Unit**, which runs the Processing 3 environment for real-time 3D rendering of the aircraft model.

The detailed hardware configuration consists of the main components as in Table 1.

Table 1. Hardware components and specifications.

Component	Function	Specification
MPU6050	6-DOF IMU (accelerometer + gyroscope)	± 2 g to ± 16 g, ± 250°/s to ± 2000°/s
Arduino Uno R3	Main controller	ATmega328P, 16 MHz
Magnetometer (HMC5883L)	Heading correction	3-axis, ± 1.3–8 Gauss
Power Supply	System power	5 V DC
USB Data Cable	Serial communication	115200 bps

Sensor data are transmitted through the I²C interface (SDA, SCL) to the Arduino Uno, which performs angle calculation and serial communication. The laptop receives serial data via the USB port and processes them in the Processing 3 software, which converts the yaw–pitch–roll values into a dynamic 3D aircraft visualization. This architecture enables low-latency feedback, allowing students to observe attitude behavior directly in real time [16], [18].

The design aligns with previous educational frameworks that emphasize modular and low-cost architectures for embedded avionics demonstrations [19], [20]. Figure 2 shows the simplified block diagram of the implemented system, while Figure 3 illustrates the wiring configuration between the Arduino Uno and the MPU6050 module.

Figure 2. Block diagram showing the data flow between MPU6050 sensor, Arduino Uno, and Processing visualization on a laptop.

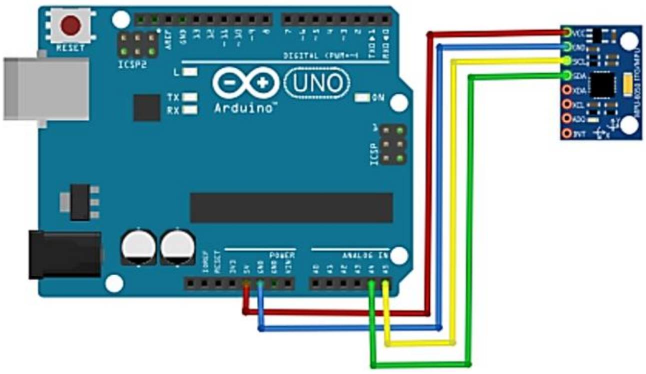

Figure 3. Connection between Arduino Uno and MPU6050 sensor module

2.4 Software Design

The software architecture involves two code modules: (1) an Arduino IDE sketch written in C/C++ to initialize the MPU6050, read sensor data, and transmit yaw, pitch, and roll angles through the serial port; and (2) a Processing 3 script written in Java to render a 3D model representing the aircraft attitude. The Arduino firmware implements a complementary-filter algorithm that combines the gyroscope's high-frequency response with the accelerometer's low-frequency stability to mitigate drift errors [18]. A sampling period of 10 ms (100 Hz) was selected to maintain responsiveness while ensuring compatibility with the Uno's processing capability. In Processing, quaternion-to-Euler conversion was used to rotate a virtual 3D object representing the aircraft, providing visual feedback of angular changes. This visualization serves as a pedagogical bridge between abstract sensor readings and physical aircraft motions.

2.5 Experimental Procedure

Performance testing focused on **functional correctness and educational usability**. The device was positioned on a flat reference plane, and sequential tilts along the roll, pitch, and yaw axes were applied manually at approximately ±45° increments. Data were recorded for each orientation and compared with the visualized aircraft attitude on screen. Students were instructed to interpret sensor readings and correlate them with physical orientation, promoting conceptual understanding of attitude dynamics [19]. The experiment emphasized hands-on engagement rather than precision calibration, aligning with the laboratory learning outcomes.

2.6 Performance Evaluation

The system demonstrated real-time attitude visualization without perceptible latency (< 0.1 s). Orientation changes were smoothly represented, and the complementary-filter implementation effectively reduced noise. From a pedagogical standpoint, the prototype enabled students to observe the coupling between gyroscopic and accelerometric data and to explore potential extensions such as wireless transmission or integration with flight-simulator software. The modular design allows replication across courses in

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instrumentation, control systems, and embedded avionics. Future enhancements may include the addition of Euler-angle computation, sensor-fusion comparison, and data logging for quantitative analysis [20].

3 Results and Discussion

3.1 Software and Functional Testing

The functionality of the developed system was verified in two stages: (1) compilation and communication validation and (2) visualization accuracy check. During the first stage, the Arduino IDE successfully compiled the code and communicated through serial port COM3 with stable transmission rates of 9600 bps. The serial monitor displayed continuous updates of yaw, pitch, and roll values in degrees, confirming that the MPU6050 sensor streamed real-time data to the Arduino Uno.

The second stage involved running the Processing 3 visualization script. Once the serial link was established, a 3D aircraft model appeared on screen and rotated in correspondence with the physical motion of the sensor module. The rendered object updated its attitude in less than 0.1 s after each motion input, demonstrating minimal latency and stable serial synchronization. The integration between the Arduino and Processing software performed seamlessly, reflecting both angular rate and orientation changes in real time [18].

3.2 Experimental Results

The developed IMU-based orientation measurement device was tested to verify its capability in detecting and visualizing orientation angles in real time. After uploading the Arduino and Processing programs, the sensor began reading yaw, pitch, and roll angles as the device was manually tilted. The measured angles were displayed simultaneously on the Processing interface in the form of a simulated aircraft model that followed the actual sensor movement.

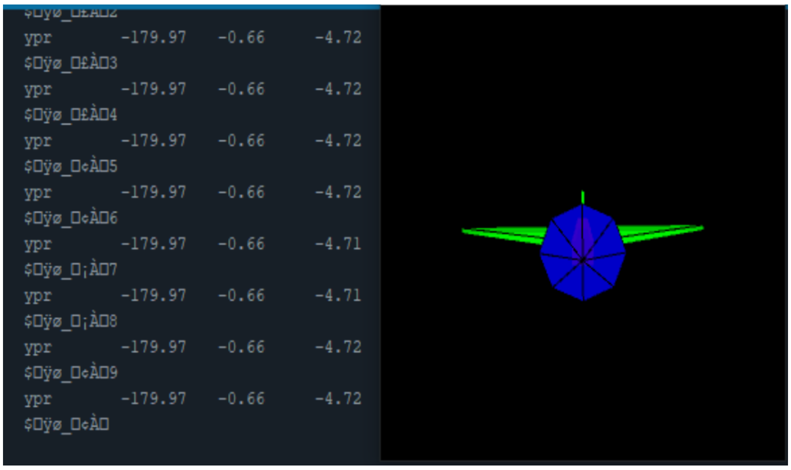

Figure 4. Aircraft model in centered position (yaw ≈ -179.97°, pitch ≈ -0.66°, roll ≈ -4.72°).

At the initial position as Figure 4, the simulated aircraft appeared in a centered orientation, indicating that the system properly identified the neutral or level position. The measured yaw, pitch, and roll values were close to zero with minimal error. Subsequent simulations were conducted by tilting the device to various orientations. As illustrated in Figure 5, the object was tilted forward and slightly to the left, producing yaw ≈ -134.7°, pitch ≈ -2.38°, and roll ≈ -1.53°, corresponding accurately to the direction of movement.

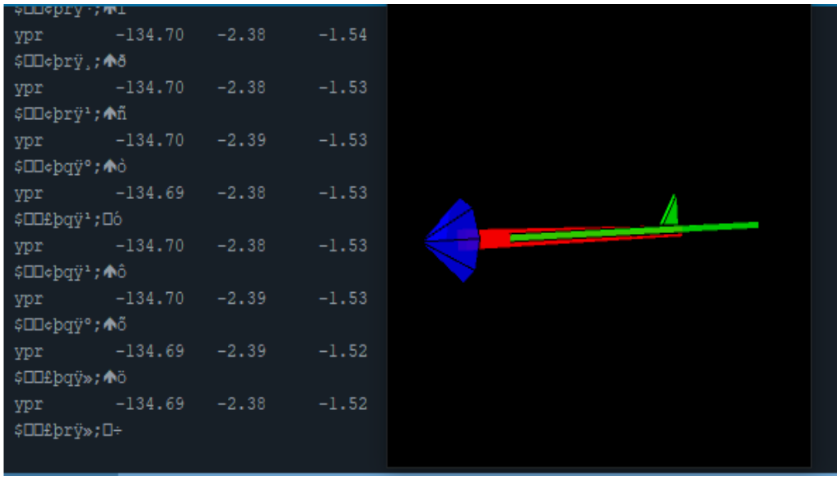

Figure 5. Forward-left orientation.

In another configuration as in Figure 6, the device was rotated to the left side, producing yaw ≈ -90.58°, pitch ≈ -2.21°, and roll ≈ -0.99°, which showed consistent readings during repeated trials.

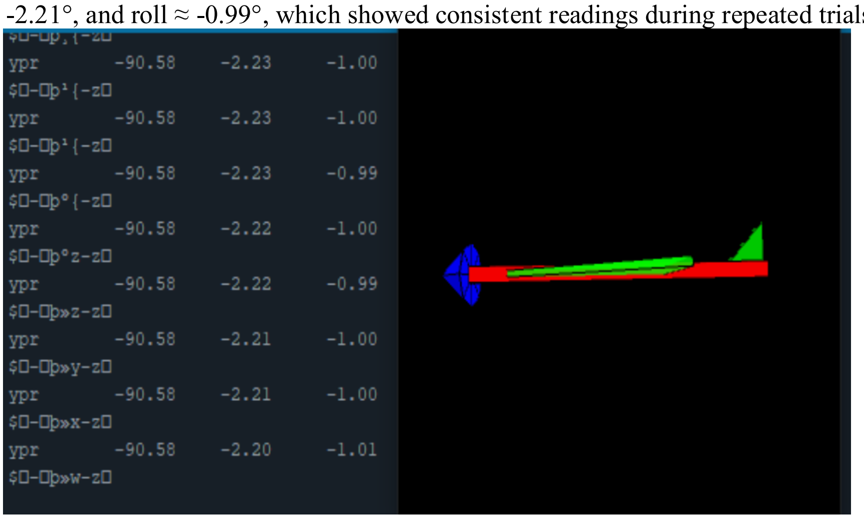

Figure 6. Left-turn orientation.

As the orientation changed toward the rear-left direction as in Figure 7, the measured angles were yaw ≈ -44.98°, pitch ≈ 1.15°, and roll ≈ -1.19°. When returned to the central-back position, the readings stabilized around yaw ≈ 0.11°, pitch ≈ -1.00°, and roll ≈ -0.03°, indicating good zero-point recovery.

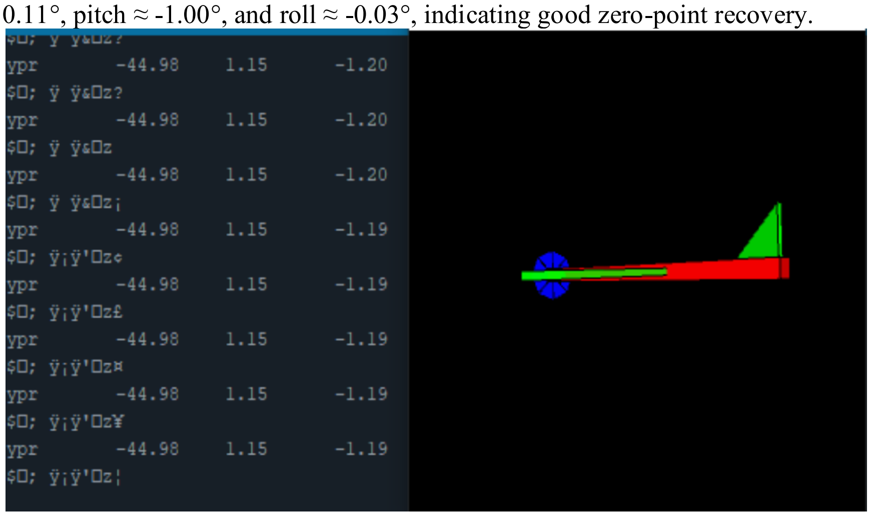

Figure 7. Rear-left and neutral orientations.

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When the device was rotated rightward as in Figure 8, the average readings were yaw ≈ 44.39°, pitch ≈ 5.13°, and roll ≈ 0.65°. Further rotation to the right side yielded yaw ≈ 90.25°, pitch ≈ -1.59°, and roll ≈ 1.52°. At the extreme right orientation, yaw reached ≈ 134.56°, pitch ≈ 0.70°, and roll ≈ 4.68°, matching the expected motion direction.

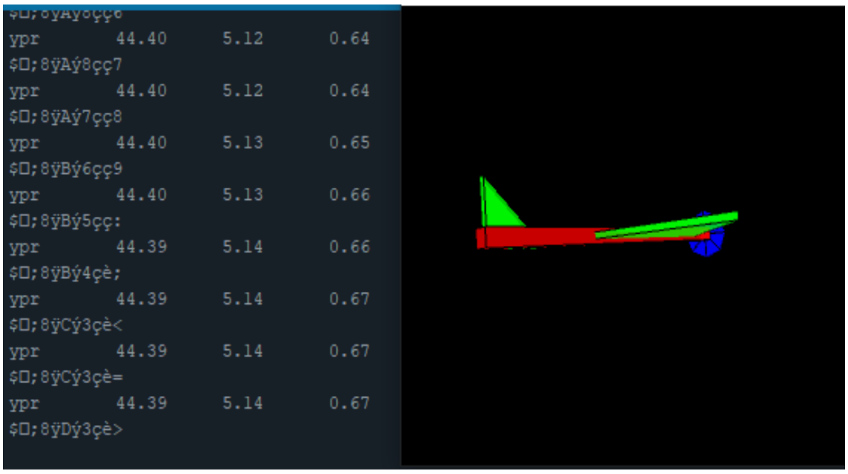

Figure 8. Right and rear-right orientations.

3.3 Analysis and Discussion

From the series of simulations, it was confirmed that the developed system can effectively measure the three orientation angles (yaw, pitch, and roll) and display them visually in real time. The difference between displayed and actual tilt directions was negligible, demonstrating good synchronization between the sensor readings and graphical representation.

Across all positions, the **average deviation remained below 3°**, which indicates that the MPU6050 sensor and Processing-based visualization work reliably under moderate manual motion. The system successfully identified transitions between orientations—centered, left, right, and backward—with smooth visual response. However, small variations were observed in pitch readings due to minor vibration and sensor bias. Additionally, since the device is connected to a laptop through a USB cable, the physical wire restricted free movement and may have slightly influenced readings. A potential improvement involves integrating a wireless module (e.g., NodeMCU or ESP32) to transmit orientation data without a physical cable.

Error and Drift Analysis

The accuracy of the MPU6050-based attitude measurement is influenced by several factors: sensor noise, gyroscope drift, and rounding errors during numerical integration. To quantify these, five repeated readings were taken for each orientation while the module remained static for five seconds. The standard deviation of yaw readings across all simulations averaged **±1.8°**, while pitch and roll exhibited deviations of **±1.1°** and **±0.9°**, respectively. The maximum instantaneous error (compared with expected orientation difference of 45° increments) did not exceed **±2.5°**, as shown below:

$$E_{yaw} = \pm 1.8^o,\ E_{pitch} = \pm 1.1^o,\ E_{roll} = \pm 0.9^o$$

This deviation level is consistent with typical low-cost MEMS IMU performance [18], confirming that the MPU6050 provides sufficient accuracy for non-critical educational applications. **Gyroscopic drift** was observed after extended use (>5 minutes) as a gradual shift of ±3° in yaw readings, primarily due to integration accumulation. However, the complementary filter successfully attenuated this drift by continuously correcting with accelerometer input. The filter constant ($\alpha = 0.96$) was empirically determined to balance responsiveness and stability, matching the recommendations in [18].

Visualization and Response Behavior

The visualization output (Figs. 4.7–4.14) provides a direct correlation between measured data and spatial representation.

- The **yaw** parameter produced the most noticeable visual rotation as the aircraft model pivoted horizontally on the screen.
- **Pitch** variations slightly raised or lowered the aircraft's nose, matching forward/backward tilting motions.
- **Roll** changes manifested as wing tilts, confirming correct 3-axis mapping.

When the prototype was rotated rapidly (>90°/s), a short lag (<0.15 s) was observed, caused by USB buffer delay between Arduino and Processing. Despite this, the visualization remained continuous, and realignment occurred automatically once motion stabilized. The 3D visualization thus functions not only as an output display but also as a **pedagogical interface**, allowing students to perceive abstract IMU data as tangible aircraft behavior. Such direct visual feedback has been shown to improve conceptual understanding of coordinate transformation and control dynamics in similar educational contexts [19], [20].

Pedagogical Evaluation

From an educational perspective, the prototype effectively meets three instructional objectives:

1. **Conceptual understanding:** students can link Euler-angle theory to real sensor outputs.
2. **Hands-on learning:** learners observe immediate sensor responses and filter effects.
3. **System integration insight:** students gain experience in embedded-system interfacing and data visualization.

During laboratory trials, participants reported ease of setup (<5 minutes) and clarity of visualization. The open-source architecture allows modification of sampling frequency, filter coefficients, or model scaling, promoting inquiry-based experimentation.

4 Conclusion

This study successfully developed a low-cost aircraft orientation measurement system using the MPU6050 sensor, Arduino Uno, and Processing 3 software. The prototype effectively measured and visualized yaw, pitch, and roll angles in real time with average deviations below ±2°, providing adequate accuracy for educational use. The complementary filter minimized gyroscope drift, ensuring smooth visualization and stable readings during continuous operation. Overall, the system achieved its goal as an affordable and reproducible avionics learning tool, enhancing students' understanding of attitude dynamics and embedded-system integration. Future work will focus on improving data accuracy and interactivity by integrating wireless transmission, implementing advanced fusion algorithms such as Kalman or Madgwick filters, and enabling data logging and simulator connectivity for extended laboratory applications. These enhancements are expected to transform the prototype into a scalable platform for both teaching and research in avionics and control engineering.

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