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Design and Testing of a Low-Cost Sensor System for Fixed-Wing UAV Model Validation and Educational use

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***Abstract*— Unmanned Aerial Vehicles (UAVs) are increasingly utilized across various sectors, prompting task-specific design and optimization. Mathematical modelling plays a vital role in this process by enabling early-stage analysis and virtual validation. This paper presents the development of a compact, low-cost sensor system designed to collect flight data for validating a six-degree-of-freedom rigid body dynamic model of a fixed-wing UAV (FWUAV). The system integrates inertial measurement units (IMUs) for monitoring control surface angles, along with airspeed, altitude, and GPS sensors. A custom-built module comprising an Arduino microprocessor, SD card shield, and PCB was assembled, occupying a volume of 416 cm³. The system, implemented by final-year undergraduate students as part of a capstone project, was ground-tested to evaluate data quality and reliability. Results indicate that while control surface and aircraft orientation angles were accurately captured during slow movements, transient maneuvers introduced inconsistencies and noise in angular measurements. In contrast, angular rate data remained clean across all motion profiles. These findings underscore the potential of using angular rate data as a reliable input for validating advanced models in aeroservoelasticity, modal analysis, and UAV-based energy harvesting.**

***Keywords*— unmanned aerial vehicles (UAVs), sensor integration, arduino, inertial measurement units (IMUs), rigid body dynamics, prognostics and health management (PHM), aircraft structural health management (ASHM)**

I. INTRODUCTION

Experimentation with UAVs began shortly after the first manned flight with the development of an automatic control system in 1917 [1-3]. This and following efforts were geared towards delivering bombs during conflicts. The modern era of UAVs [1] began in the early 1960s with the development of remotely operated 'drones' for reconnaissance [3]. Today, drones for civilian use have a worldwide market size of US$35 billion [4,5] with a projected market size of US$54 bn by 2030 [6]. This market is divided into 2 categories: commercial and consumer drones [7]. Commercial drones' primary application in industries centers around the use of their onboard cameras, scanners and sensors for videography, inspection, monitoring, surveillance and surveying. Recent developments in battery energy densities, power units, control systems and composite materials have enabled UAVs to contribute to the goals of industry 5.0 [8,9]. For example, deploying UAVs for wireless base stations [10-13], aerial additive manufacturing [14-16] precision farming [17-20] and package delivery [21-25].

UAVs are usually designed to serve a specific purpose or mission. Designs include multi-rotor, single rotor helicopter, fixed-wing and fixed-wing hybrid VTOL (vertical take-off and landing) [26]. Unconventional designs derived from bio-inspired sources include flapping wings [27-30] and flexible flapping wings [31]. To increase efficiency and payload capacity, weight reduction is usually the first area of focus. This is typically achieved by structural optimization, utilizing motors with higher specific power and batteries with higher energy densities. More advanced methods of increasing efficiency include waypoint optimization [32], hybrid propulsion systems [32,33] and optimizing aerodynamic efficiency [34].

The recent surge in UAV research and development is largely driven by rapid technological advancements [35] and the increasing accessibility of rapid prototyping tools. To achieve comprehensive UAV designs, a multidisciplinary approach is essential [36-41]. This approach spans several key domains, including structural optimization [36,39], control systems design [42-44], aeroacoustics [45,46] and aerodynamic analysis [45,41,47].

To support and accelerate UAV development, digital twins (DTs) are increasingly utilized. These are high-fidelity virtual replicas of physical systems that simulate real-world behavior under varying conditions. Data collected from sensors on the physical UAV—capturing both input stimuli and system responses—are used to calibrate and validate the digital twin. Once validated, the DT can be leveraged to refine and improve the real-world system. A recent review by [42], which analyzed research on quadcopter UAVs (QUAVs) from 2020 to 2023, revealed a strong convergence between digital twin technology and artificial intelligence (AI), encompassing over 7,000 research articles. This integration of DT and AI has proven pivotal not only in UAV innovation but also shows transformative potential across various other industries.

The widespread accessibility of UAV technology has opened new opportunities to enhance STEM education and spark interest among students. Specifically, multicopters are described by [48] as an 'intersection' of various STEM principles. The authors describe a 'multicopter design challenge' for students pursuing technology and engineering-based courses. To generate interest in STEM [49] described how multicopters can be introduced at the elementary level. However, teacher adoption and integration into classroom practice remain a primary challenge. In a study conducted by [50], readiness of 10 teachers regarding drones in high school STEM education were assessed (drone assembly, path programming and operation). Results showed that teachers struggled with identifying learning objectives and integrating pedagogical and subject area knowledge. Given the nature, complexity, and safety issues involved in testing, UAVs are best suited as a learning conduit in university-level teaching. Mature students are more well suited to navigate ethical and privacy issues as cited by [51].

UAVs have the potential to strengthen critical thinking and problem-solving skills across a range of disciplines [52]. Their operational training is commonly integrated into courses that require aerial data collection, such as geomatics [52-54]. Beyond operational use, the design, construction, and programming of UAVs offer valuable opportunities for multidisciplinary learning and assessment—particularly in capstone projects within aeronautical engineering programs. Unlike traditional build-and-fly models, the inclusion of coding and simulation adds a distinctive layer of complexity and innovation [55].

To further support research in areas such as control systems, navigation, and UAV-specific algorithms, the University of Minnesota established a low-cost, open-source small UAV research facility [56]. By employing off-the-shelf fixed-wing remote-controlled (RC) aircraft, the facility eliminates the need for custom builds, allowing students and researchers to concentrate on simulation, algorithm development, and flight testing.

This work focuses on employing sensors to collect data for validating mathematical models. The implementation of various sensors for monitoring the structural health and systems reliability of UAVs are reviewed in section I.A and I.B. The development and testing of a low-cost, open-source sensor module for a FWUAV is then described in sections II and III. The proposed module is intended to capture experimental parameters, corresponding to that of a six-degree-of-freedom (6-DOF) rigid body FWUAV dynamic model. Testing results and data gathering for models considering aeroelasticity and energy harvesting are discussed in section IV. Finally, section V concludes with considerations for future work.

A. Aircraft Structural Health Management (ASHM)

Aircraft structural health management (ASHM) is a critical aspect of aviation safety and efficiency. It encompasses a variety of techniques and technologies aimed at monitoring, diagnosing, and predicting the health of an aircraft's structure. The primary goal is early detection of potential issues such as cracks, corrosion, and fatigue damage. It facilitates condition-based maintenance (CBM) which reduces maintenance costs and aircraft downtime, improving overall operational efficiency [57].

There are 4 levels of SHM which are damage detection, damage location, damage assessment and structural life prediction [58]. As the implemented level increases, the required sensors, data acquisition, processing, and analysis correspondingly increases. Level 4 requires further engineering analyses such as finite element modelling (FEM) on flaws to predict crack growth. Sensors collect data on impact loading, strain, pressure distribution, vibration crack formation, corrosion and temperature. In the case of composite materials, delamination and debonding parameters are obtained from sensors placed within the laminate structures [59]. An overview of traditional SHM sensor technologies is provided in [57], while recent advancements in experimental sensor development are explored by [60] and [61].

Literature on SHM applied to UAVs is not forthcoming as its application is predominately military [62]. Given the high cost of military UAVs, structural health monitoring (SHM) and event monitoring are deemed more critical for UAVs than for manned aircraft [63]. In manned systems, pilots serve as real-time observers, providing immediate feedback on aircraft behavior and anomalies [64]. In contrast, UAVs rely entirely on onboard systems to detect and interpret such events. An example of this is presented by [62] who described an aerial surveillance fixed-wing UAV (FWUAV) equipped with an integrated SHM system. Fiber Bragg Grating Sensors (FBGS) were surface bonded to the wing that measured temperature and strain. Strain gauges and temperature sensors were also fitted to the upper and lower surfaces of the wings and measured flexural and torsional strains. The system writes data to an SD card but can wirelessly transmit data via a serial interface to a ground station. Flight testing indicated maximum strains during the climb after take-off. In another full UAV application, [65] integrated data from inertial measurement units (IMUs) with FBGS data from a FWUAV. During a 2-hour test flight, peak strains were reported during the catapult take off and parachute recovery landing phases. However, being a military application, this was the extent of data available for this implementation.

Several research activities are centered around specific aircraft components, opting for laboratory instead of flight testing. An example is the composite UAV wing developed by [66] for SHM testing. It was outfitted with 20 low-speed FBGS for static strain, 6 high-speed FBGS for dynamic strain, and 5 piezoelectric (PZT) sensors for hot spot damages. Data from the PZT sensors can indicate the presence of a damage causing event while Ultrasonic Propagation Imaging (UPI) pinpoints the location and size of the defect. Coupon specimens were fatigue tested with the FBGS proving to be superior to conventional strain gauges. FBGS can also be multiplexed rendering data acquisition easier for a vast number of sensors. In another laboratory setting, [67] embedded FBGS into a composite wing box section of a FWUAV. Seven flaws were artificially located on the section and load tested with a hydraulic rig. The proposed algorithm was able detect localized flaws with effects larger than the flaw itself. The sensor placement in this setup was deemed adequate for detecting flaws below a critical size. Given the limited space available on UAVs, determining both the optimal number and placement of sensors is crucial.

A machine learning (ML) method was employed by [68] to optimally determine the locations of PZT sensors for detecting damage of a UAV wing. Statistical data from a grid of sensors were obtained for an undamaged and damaged wing section undergoing bench loading. This dataset was used to train the ML algorithm which, by combining sensor data, were able

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reduced the number of required sensors through optimal placement.
Earlier efforts in sensor integration and data-driven damage assessment were demonstrated by [64], who embedded eight fiber Bragg grating sensors (FBGS) into the composite rectangular hollow-section tail booms of the Nishant UAV during manufacturing—two at the center and two near the edge on both the top and bottom surfaces. An artificial neural network (ANN), trained using finite element model (FEM) data, was employed to estimate loading on the tail based on optical strain data. Through principal component analysis (PCA), the study revealed occurrences of local buckling during high-impact landings, though the structure remained intact. Reference [69] extended the use of sensor data toward fault characterization in multi-rotor UAVs. Their work employed vibration spectral analysis to detect subtle mechanical faults such as loose motor mounts, unbalanced propellers, and poorly secured propeller mounts. Despite their relatively small amplitudes, these faults were found to affect inertial measurement unit (IMU) readings, which are critical for maintaining stable feedback control in UAV operations.

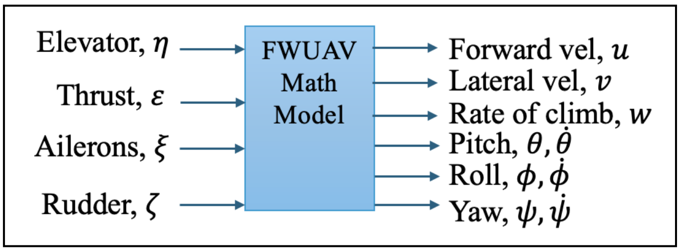
B. Prognostics and Health Management (PHM)

Prognostics and health management (PHM) encompasses monitoring, evaluating and assessing remaining useful lifetimes (RUL) for both structural and non-structural aircraft systems. The prognostic approach traditionally utilizes statistical methods with a particular system's sensor data such as [70]. More recent methods include the use of AI with a hybrid of sensor data from multiple systems [71]. For a FWUAV, [72] devised a health status assessment algorithm for the attitude control system based on a multivariate state estimation method. The system utilized data from an angle of attack sensor, 3 IMUs, propeller rpm and control surface (elevator, rudder and aileron) actuators. By simulating their algorithm, the authors were able to ascertain the overall health of the system in addition to determining specifically what components in the system were not functioning properly.
The flight endurance predictions for battery operated UAVs take advantage of both statistical and ML methods. Current and voltage data was used by [73] to determine the remaining operating time of a UAV. Reference [74] included temperature with a Deep Neural Network which estimated the state of battery charge and health. The authors suggested that future work can consider additional data sets of battery surface temperature and altitude.
System redundancies are neglected in UAVs as the impact of failure usually does not involve the direct loss of life. For critical applications however, reliability improvements should be made [75,76]. A FWUAV control surface actuator with built in redundancy was designed by [75] to address the possibility of actuator jams during flight. Position, current, voltage and temperature data were used to construct a PHM module that can detect faults and component degradation. Degradation quantification included mechanical wear, permanent magnet degradation in the brushless DC motors (BLDM), actuator driver electronics and the insulating material around the BLDMs.

II. MATERIALS AND METHODS

The system proposed in this work aims to validate a rigid body dynamic model of a fixed-wing UAV (FWUAV). For a rigid body aircraft—neglecting the effects of onboard rotating components such as engines and propellers—the six coupled Newton-Euler equations of motion are well established, with one formulation presented by [77]. An alternative derivation using a vector-based approach is provided by [78]. The resulting dynamic model is summarized in Fig. 1.

Fig. 1. Schematic of a coupled rigid body dynamic model



Validation of the model, therefore, involves measuring the angles of the control surfaces, thrust, the aircraft's velocity, rate of climb, pitch, roll, and yaw during flight. While control surface actuation can be obtained from the servo actuation signal, aeroservoelastic effects in flight can induce measurement errors depending on the rigidity of the surface and linkage [79]. Direct measurement of the control surface therefore is proposed. An inertial measurement unit (IMU) is a single sensor package that comprises accelerometers, gyroscopes and magnetometers. A moveable surface angular measurement system using IMUs is described in [80] for measuring control surface angles during aircraft ground testing. The algorithm developed was able to derive an accurate angle of a pivoted surface, from an IMU placed arbitrarily not coincident with the pivot axis. Using raw IMU data, [81] was able to determine rotation and angular velocities about three axes with a root mean squared error (RMSE) of less than 6 degrees with 25 minutes of data. The authors have made available the MATLAB script files for these computations. For the proposed system (Fig.2.), the MPU6050 IMU on a breakout board (GY-521) was selected to measure control surface angles and aircraft orientation. The MPU6050_light Arduino library [82] computes angles by measuring linear acceleration relative to the Earth's gravitational vector and integrating gyroscopic velocities (with Kalman filtering). Angles are then fused using a complementary filter. The 20 mm x 15.6 mm IMU weighs less than a gram and uses the I2C communication protocol, allowing multiple sensors to be used on a single bus. Given that all the IMUs would have the same I2C address, the PCA9548A multiplexer was used.
An airspeed sensor comprising of a pitot tube and the 4525D 5AI, I2C differential pressure sensor was selected to measure the relative airspeed between the moving aircraft and headwind. For absolute speed, the GPS module NEO-6M-001 on the breakout board GY-GPS6MV2 with serial communication was selected [83].

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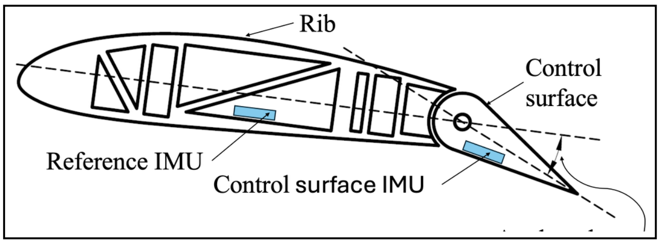

Fig. 2. Location of IMUs on the wing and ailerons, horizontal stabilizer (HS), vertical stabilizer (VS) and rudder.

Altitude measurement was implemented using the BMP390 barometric pressure sensor—an I2C device with an accuracy of ±0.25 m. The radio receiver interprets analog joystick positions from the transmitter and converts them into pulse-width modulation (PWM) signals for servo actuation. The electronic speed controller (ESC) converts a single PWM input into three-phase PWM signals to drive the brushless DC motor (BLDM). The ServoInput library [84] is an Arduino library that counts PWM pulses to determine servo position or the RPM of a BLDM. All sensor data are recorded onto an onboard SD card in a plain text (TXT) format. Details of the sensor system are shown in Figs. 3, 4 & 5 with the locations of system's components on the UAV shown in Fig. 6.

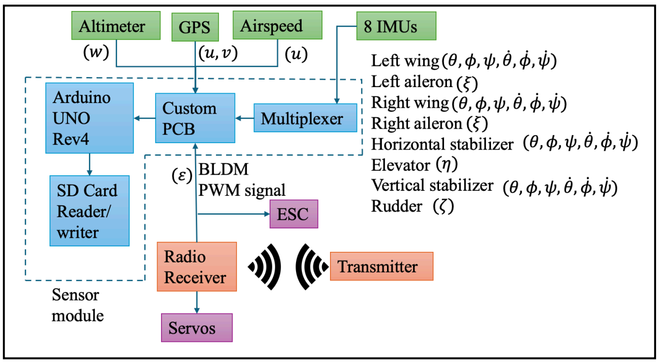

Fig. 3. Overview of the integrated sensor system

An Arduino UNO Rev4 was paired with an SD card reader/writer shield for data logging. A custom printed circuit board (PCB) was developed as an additional shield to accommodate the IMU multiplexer and various sensor inputs. These stackable shields formed a compact sensor module with a footprint of 97 × 64 × 67 mm and a total weight of 200 g. Using the ServoInput library [84], a transmitter (TX/RX) channel was mapped to a switch on the controller, serving as a trigger to initiate data recording. This feature helped eliminate irrelevant data captured during aircraft setup. Logged data were stored on the SD card in comma-separated format, allowing for seamless import into MATLAB. A breakdown of the system's component costs is provided in Table 1.

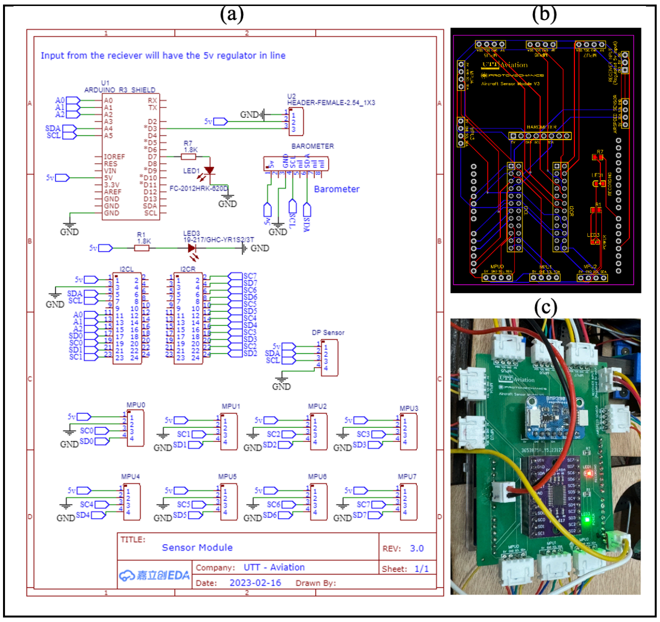

Fig. 4. (a) Schematic of the custom PCB with upper- and lower-layer copper traces shown in (b). Completed PCB shown in (c).

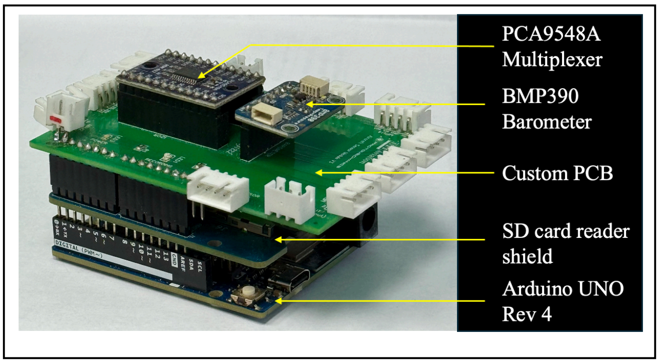

Fig. 5. Sensor module stack

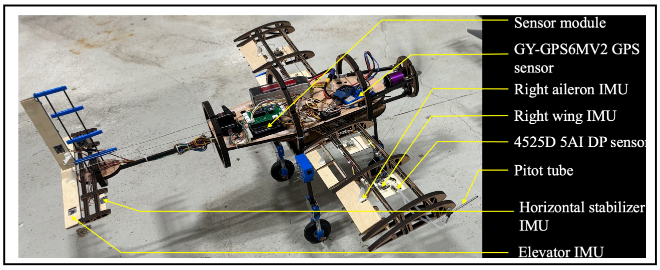

Fig. 6. FWUAV (shown without skin) with implement sensor system.

TABLE I. COST BREAKDOWN OF SENSOR SYSTEM.

Item	Cost (USD)
MPU6050, IMU (qty – 8)	30
PCA9548A Multiplexer	7
4525D 5AI DP sensor and pitot tube	50
GY-GPS6MV2 GPS sensor	9
BMP390 Barometric sensor	15
SD card reader shield for Arduino	10
Arduino UNO Rev 4	28
2.54 mm JST connector kit	10
Custom PCB	51
Total	200

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Ground testing was conducted to evaluate the initial performance of the IMUs in capturing control surface deflections and overall aircraft orientation. The objective was not to assess the absolute accuracy of the IMU data, but rather to examine the characteristics and consistency of the sensor signals. Three tests were performed: (1) control surface actuation with the propeller motor off, (2) control surface actuation with the motor running to assess the impact of propeller-induced vibration, and (3) evaluation of the aircraft's orientation sensing capabilities.

III. RESULTS

Fig. 7(a). shows the measured angles of all control surfaces during actuation with the propeller motor off. The actuation sequence followed left and right aileron inputs, up and down elevator inputs, and finally left and right rudder inputs. This sequence was repeated at approximately 55 seconds. During the first sequence, the recorded angles of the left and right ailerons, as well as the rudder, responded as expected. However, the recorded angles of the elevator exhibited a delayed return to its neutral position, taking approximately 20 seconds to settle. A similar delay was observed in the aileron responses during the second sequence.

When the propeller motor was activated at 7000 rpm (Fig. 7(b).), this settling behavior became more pronounced across all control surfaces. The increased vibration likely introduced noise in the IMU signals, contributing to the observed fluctuations and delay in stabilization.

Fig. 8 presents the aircraft orientation angles (pitch, roll, and yaw) and their respective angular rates, as recorded by four onboard IMUs located on the vertical stabilizer (VS), horizontal stabilizer (HS), and each wing. While angular orientation (top row) showed some variation between IMUs—particularly in yaw—the angular rates (bottom row) remained consistent across all devices. This suggests that although absolute orientation readings may diverge due to drift or noise, the rate data, which is typically less prone to integration error, provides a more reliable measure of dynamic motion.

Additional sensor data collected included readings from the barometric pressure sensor, GPS module, and differential pressure sensor. These readings remained static, as expected, since the aircraft was stationary during testing. The barometric altitude was measured at 32.5 m (standard deviation = 0.48 m, n = 16,700), assuming a sea-level pressure of 1013.25 mbar. This estimate deviated from the actual station elevation of 21 m, likely due to uncalibrated pressure offsets. The GPS module provided accurate coordinates, consistent with online mapping tools up to four decimal places, and correct date and time information. However, it required outdoor exposure for satellite acquisition, limiting its use during indoor testing or troubleshooting.

Lastly, the electronic speed controller (ESC) output was calibrated against a handheld non-contact tachometer (AGPtek DT-2234C). This allowed for the development of a calibration curve to estimate motor RPM from measured PWM signals.

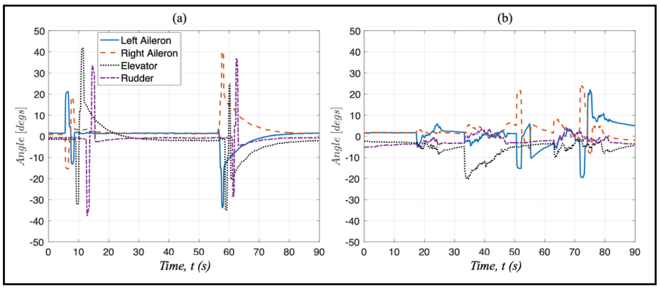

Fig. 7. Actuation angles of control surfaces with the propeller (a) off and (b) on at 7000 rpm

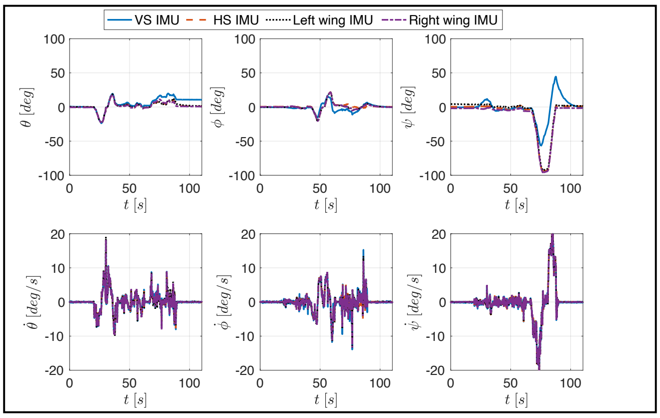

Fig. 8. Aircraft orientation angles and angular rates. VS – vertical stabilizer, HS- horizontal stabilizer. (θ - Pitch, ϕ - Roll, ψ - Yaw)

IV. DISCUSSION

The use of multiple IMUs to determine angular displacements relative to a fixed reference frame proved effective, particularly for steady-state measurements. During testing, slow control surface actuations yielded accurate angle estimates. However, during transient inputs, the IMUs exhibited a settling time effect, where the angle measurements lagged or fluctuated before stabilizing. This phenomenon can be attributed to the combined method used by the IMUs to determine orientation: resolving the acceleration due to gravity in three axes and integrating the gyroscopic angular velocities over time [82].

Transient maneuvers introduce linear and angular accelerations that distort these measurements, leading to inaccurate angle estimations during dynamic motion [85]. This limitation was quantitatively confirmed by determining the coefficient of variation (CV) for orientation angles between the four IMUs (Fig. 9(a).). High CV values were observed between 20 and 90 seconds, correlating with periods of aircraft movement. In contrast, the CV of angular rates (Fig. 9(b).) remained consistently low during the same interval, with pitch rate measurements demonstrating the greatest consistency. Since angular rate is a direct IMU output that does not rely on sensor fusion or integration, it provides a more reliable and immediate representation of dynamic aircraft behavior. Consequently, only angular rate data should be relied upon for in-flight state estimation using this system.

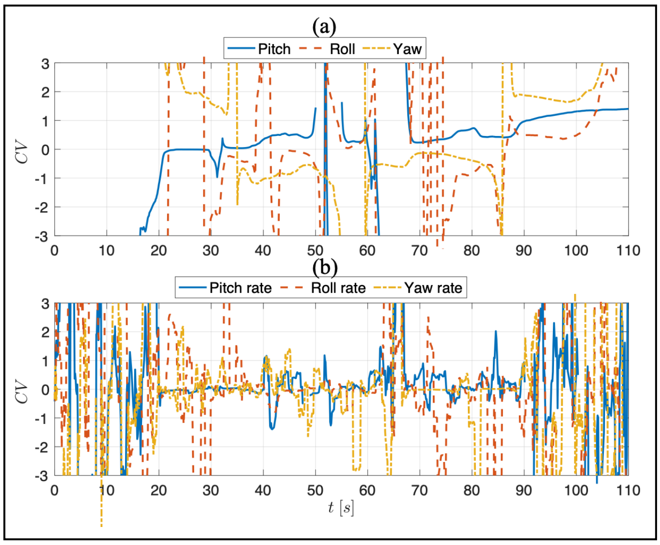

Fig. 9. Coefficient of variance (CV) between 4 IMUs for (a) aircraft orientation angles and (b) angular rates. Note: Y axes have been truncated to enhance clarity for values 0 – 3.

In contrast, control surface deflection angles are not directly measured but are inferred from IMU data, which is susceptible to inaccuracies during transient conditions. Moreover, these angles can be affected by aeroelastic phenomena—particularly structural oscillations or flutter caused by aerodynamic forces. Flutter in control surfaces and stabilizers is a well-known source of instability in small UAVs [79]. While existing aero-servoelastic models e.g. [86] typically assume rigid surfaces, such assumptions limit model fidelity. Incorporating flexible surface behavior is critical to improving control system robustness and accuracy without adding structural weight.

The use of IMUs directly mounted on control surfaces opens the possibility of capturing real-time oscillatory behavior for validating aeroservoelastic models. This data can support the development of active flutter suppression systems, where servo actuators counteract measured oscillations using IMU angular rate feedback. Such systems would mark a significant advance in the flight stability of lightweight UAVs.

Beyond flight control, the dynamic deformation of aircraft structures presents an opportunity for onboard energy harvesting. Pioneering work by [87] demonstrated the feasibility of embedding PZT patches in UAV wings to convert vibrational energy into electrical power. Though their system, based on a 1.8 m wingspan UAV, generated significantly less energy than photovoltaic panels (0.011 J/cm³ vs. 32.0 J/cm³), their results indicated the potential of full-wing PZT coverage—including multilayer integration in fiberglass composites for meaningful power recovery.

More recently, [88] used analytical and finite element models to estimate voltage generation from PZT patches on a 600 mm wing UAV. Their models achieved voltage predictions within 7.5% agreement, guiding optimal patch placement for energy yield. Reference [89] further identified ideal excitation conditions for various PZT materials, in terms of both frequency and amplitude of vibration.

Given that the Arduino Uno Rev4 and PCA9548A I2C multiplexer used in the current system are capable of sampling at 400 kHz—significantly higher than the natural frequencies identified by [88]—the platform is well-suited to experimentally validate modal analyses and energy harvesting strategies. This compatibility offers exciting prospects for integrating structural monitoring and energy recovery into the UAV design cycle, introducing a new set of performance-driven, energy-aware constraints during the design phase.

V. CONCLUSION

Mathematical modeling plays a crucial role in the design and control of UAVs, enabling iterative optimization and virtual testing of aircraft configurations. Validated models not only support control system development but also inform sensor placement for ASHM and PHM systems, as well as guide the integration of energy harvesting devices.

This study presented a low-cost, modular sensor system designed to capture both input and output data from a fixed-wing UAV, with the goal of validating a six-degree-of-freedom (6-DOF) rigid body model. IMUs were employed to estimate control surface deflection angles. While these angle estimates showed inconsistencies during transient conditions, angular rate measurements remained stable and consistent across sensors. This suggests that IMU angular rate data may be better suited for validating aeroservoelastic models and conducting modal analysis.

The system was assembled using inexpensive, off-the-shelf components, making it accessible for student-led projects. The hands-on nature of sensor integration and coding provides an excellent educational platform, especially in capstone or design-and-build UAV courses. Students can extend their designs by validating aerodynamic models from tools such as XFLR5, creating a meaningful link between theoretical modeling and practical implementation.

At an approximate cost of USD 210, the sensor suite is comparable to a Pixhawk 4 flight controller equipped with GPS, IMUs, airspeed sensors, and barometric altimeters. The Pixhawk, when used with the PX4 autopilot software and Simulink's Processor-in-the-Loop (PIL) interface, provides an accessible environment for developing and testing control schemes. The PX4 Simulink blockset further enhances this by allowing students to interact with and visualize the nonlinear flight dynamics of UAVs.

A future iteration of the sensor system—capable of reliably capturing true control surface angles—could integrate seamlessly with this workflow, bridging the gap between open-loop identification and closed-loop control. Even without high-fidelity models, tools like MATLAB's System Identification Toolbox can be used to derive linear transfer functions around operating points. This enables control system design and tuning within Simulink, followed by real-world experimental validation using off-the-shelf RC aircraft.

Ultimately, the proposed system offers a flexible and educationally valuable platform that brings advanced modeling and experimental validation within reach of students, researchers, and developers alike.

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