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Experimental investigation of a low-cost drone testing setup for the performance evaluation

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Abstract
As the use of drones in agriculture, logistics, and surveillance industries continues to grow, there is an increasing demand for more affordable and dependable testing of drones, especially for smaller companies, schools, and hobbyists. Existing commercial alternatives are expensive, and most low-cost options either lack sturdiness or measurement accuracy. This research attempts to fill this void by creating a compact and inexpensive drone testing system that evaluates flight stability and assists in PID controller tuning. CAD tools were used to model the system, and its structure was optimized using ANSYS simulations to determine the most suit- able materials such as PLA, ABS, and PC based on simulated load and stress, deformation, and strain. For 3D printing, PLA was selected as it was cost-effective and had a favorable deformation range under stress (0.2 mm). The final prototype included universal couplings and load cells connected by steel wires to measure multidirectional forces. Testing confirmed accurate readings along roll, pitch, and yaw axes using real-time data from flights and simulations. While measurement accuracy and structural integrity were preserved, this setup achieved a 95% cost reduction compared to commercial testing platforms.

Keywords: *drone testing setup, 3D printing, ANSYS simulation, force calculation.*

Introduction

The application of drones in agriculture, logistics, and surveillance has heightened the importance of evaluation and tuning techniques. Current approaches struggle with PID controller optimization and drone stability testing. Although simulations remain cost-effective, they tend to ignore system-specific differences like unmodeled aerodynamic forces, which lead to the control implementation on physical systems lagging in performance [1][2]. Solutions that in-volve hardware inherently increase the cost to address problems, alongside damage costs due to iterative tuning attempts. Commercial test rigs mitigate some of these problems, but due to their steep cost, small-scale developers and educational institutions still lack access due to specialized equipment priced in the thousands [3].

Industry solutions include hybrid simulation frameworks and test stands tailored for specific industrial applications. For instance, Yamaha Motor has been integrating hybrid power units along with precision control systems for more than two decades, balancing simulation with physical validation [4]. Furthermore, low-cost 3D printed rigs, like the sub $50 tabletop gimbal, enable parameter estimation by measuring forces during constrained motion of drones [3]. However, these solutions come with trade-offs. The high-fidelity commercial setups are unaffordable, while robust budget alternatives often sacrifice measurement precision. Regulatory efforts, such as The Drone Rules 2021 in India, aspire to streamline routes for hardware certification, granting official validation, but undermine policy coherence and cause stagnation [5]. This study addresses these issues by creating a low-cost drone testing system and conducting experiments on it. The goal is to fabricate a demonstrator device using aluminum and 3D-printed components that include load cells for measuring reaction forces during simulated flights.

Methodologically, this research consists of four consolidated steps that form an iterative design process for the drone testing apparatus to ensure thorough refinement and validation. First, the ANSYS stress simulations provide optimization analysis of drone part longevity by deforming and doing safety analysis under anticipated loads of 50 to 200 N with PLA, PETG, and aluminum alloys to achieve economical material selection without compromising strength or durability standards.

Thereafter, critical structural features such as rotatable connectors are reinforced structurally and integrated with load-bearing 3D printed diaphragmed prototypes that have layer resolutions of 0.15-0.20mm, which reduces production time by 70% compared to traditional machining techniques. Electromechanical integration, capturing multi-axis reaction forces, occurs with stainless steel rope linkages, measuring motion in real time with precision

load cells of ±0.1% FS. Ultimately, PID adjustments are checked against real-drone flights measuring axial and rotational forces to compute the stability metrics of oscillation damping and setpoint tracking error.
Unfortunately, the hardware only achieved safe, repeatable tuning in open commercial environments that were roughly 95% more cost-effective than the commercial testing rigs [3]. This relatively simple problem, however, faces harsh limits on resource-constrained innovation in places like India, where about 60% of parts are imported and skilled engineers are scarce, creating good opportunities [5].

Literature review

Hakan Ucgun et al.[6] understood that flight controller parameter tuning in VTOL multi-rotor drone operation is of paramount importance, since improper tuning will likely lead to instability and crashes. Consequently, drone operations necessitate sufficient consideration of additional real-world dynamic factors for first-class pre-flight testing; simulations alone will not suffice. Advanced motion constraints can be considered and imposed for a test system, thus giving more perspective on flight dynamics evaluation. To address these restrictions, a new pre-flight controller and test system with 3D nested concentric circles was designed to offer more motion capabilities during testing. Users can adjust various control parameters wirelessly via test commands during real-time sensor data reception through a dedicated Graphical User Interface (GUI). Experimental results show that the six-rotor VTOLs were able to autonomously track given signals with very high precision in pitching and rolling, thereby ensuring the system's reliability. Thus, the whole approach may enable efficient and reliable verification of VTOL drones before actual flights.

Mohamed Okasha et al.[7] realized that quadrotor flight is difficult to manage due to its intrinsic instabilities and under-actuation. This becomes even more pronounced in agile and dynamic settings. The core challenge remains in developing reliable quadrotor control systems that overcome these quadrotor instabilities ensuring dependable performance. The study conducted on Parrot Mambo mini-drones was carried out to test the performance of PID, LQR, and MPC controllers in indoor environments, where, on all occasions, the three approaches behaved comparably. Two factors can be identified here-to name a few: Why has there been less emphasis on implementing lower-cost platforms utilizing the guaranteed robustness of MPC in the presence of noise, disturbances, and model uncertainties? This clearly remains an interesting gap in the research. In the literature, a trend is observed where most scholars identify with linear approaches for ease of implementation; however, lately, the attention is shifting towards nonlinear approaches so that they can better contribute to real-world performance. Both the simulations and real-world testing found that from a universal standpoint, all the systems were stable but gave results with MPC outperforming the PID-Lagrange pair and LQR throughout all stages of testing. During simulations, the MPC controller showed the greatest control in exposed tests allowing smoother roll and pitch motions while response oscillations were observed by other control techniques in the experimentation.

Abdullah Irfan et al.[8] tackle the costly quadcopter UAVs, therefore which prohibit their use in poor areas of application. A model-based design (MBD) approach is introduced in the development of a cheap proof-of-concept quadcopter. Contrary to low-cost controllers that require trial-and-error tuning and are suitable for a particular application, this study provides full end- to-end system design and prototyping procedures, mathematical modeling, control design (PID, pole placement, LQR), validation via software-in-the-loop (SIL), processor-in-the-loop (PIL), hardware-in-the-loop (HIL), testing, rapid control prototyping (RCP), etc. With 94% position control accuracy, the prototype could attain a stable flight and deliver excellent practical performance; however, the controller lacked precision for fast changes in its path. Furthermore, the prototype offers a price reduction of above 25% in comparison with the cheapest commercially available alternatives.

H. Kauhanen et al.[9] present a workflow for designing and implementing an affordable survey drone, which meets the standards of expensive systems, thus addressing the challenge of costly commercial photogrammetric survey drones. The component selection must be executed care-fully; for example, the motor-propeller combinations that best lend themselves to efficiency and maximization of flight duration must be balanced against the contrary need for high thrust. The hexacopter then conducted a survey mission for 13 minutes under mild wind conditions, which corresponds well with the simulated flight time of 9-15 minutes. Finally, it is also illustrated how tools such as eCalc and open-source platforms such as ArduPilot can help support the proper design and implementation of cost-effective drones that meet the highest quality standards even for specialized applications. The paper highlights how low cost-off-the-shelf components can be tested and similar testing methods can be used for the design and development of other low-cost drone systems.

Patryk Szywalski et al.[10] addressed the critical need for robust and autonomous unmanned aerial vehicles (UAVs) capable of group flight, particularly for swarm algorithms, which are a significant problem given the current limitations of commercial UAVs for such applications. The researchers specifically tackled the challenge of designing and implementing a custom UAV construction, including its mechanical, electronic, and software components, to enable autonomous group flights. They developed a navigation system, a radio communication system, and control software, with a focus on cost-effectiveness and durability. Existing commercial UAVs are difficult to modify for applications like swarm algorithms, highlighting a gap in adaptable, purpose-built systems. The developed UAV demonstrated successful autonomous flight, with the mechanical components meeting expectations for durability. The system achieved satisfactory path errors using GPS, with the potential for further reduction using more accurate navigation systems. The software effectively controlled the device, an alyzed parameters, and enabled autonomous trajectory following, confirming the accuracy of the UAV's construction and control algorithms.

Tulio Dapper e Silva et al.[11] aimed to tackle performance analysis of fixed-wing UAVs, a domain that traditionally calls for expensive and highly complex flight data acquisition systems. Thus, there is a need for a cheaper alternative that could be used for student competitions such as SAE AeroDesign. The researchers provided a low-cost instrumentation platform capable of collecting the main flight data, comprising airspeed, orientation, altitude, and electric current consumption, with a telemetry system enabling the pilot to track the flight in real time. The identified research gaps include the influence of engine vibration on data accuracy, the effect of temperature variation on differential pressure sensors, and the position of the Pitot tube affecting airflow measurement. To resolve these problems, proposed improvements include the implementation of a better filtering technique, conducting studies into temperature effects, and performing wind tunnel tests. The platform correctly registered and transmitted much data from the flight and permitted the studies and analyses, both qualitative and quantitative, of the UAV performance.

Daniel Wolfram et al.[12] tackle the important problem of guaranteeing the safety and reliability of small multirotor Unmanned Aerial Vehicles (UAVs) while considering the effect of drive train faults on flight performance and mission risk. A Condition Monitoring (CM) system was created based on sensor signals to monitor the input and output power of single drivetrain com-ponents with the aim of detecting and isolating faults in power delivery. The work points to inadequacies in the literature regarding multirotor UAV flight performance parameters, forcing the authors to modify available helicopter data and point out discrepancies in existing coaxial propulsion models that overestimate torque contribution by the lower rotor. The CM system was successful in detecting defective parts and registering power losses, and some faults, such as short circuits, indicated appreciable thrust impact. In general, the study presents a strong CM model and simulation system for UAV drive trains that improves fault detection and performance estimation, although additional refinement and real-flight calibration are required.

Ankyda Ji et al.[13] address the inherent instability and nonlinear dynamics that render a quad- copter so difficult to control, especially when cheap, off-the-shelf components are used. The authors responded to the challenge by putting together their own autonomous quadcopter plat- form, coupled with the design of a novel Arduino software framework to provide advanced control laws. An important research gap arises, due to existing Arduino-based controllers such as Ardupilot or MultiWii being difficult to modify and thus affecting the implementation of more advanced control methods. Hence, the team created an open-source and modular architecture that allows for advanced control approaches, making it a valuable experimental research platform. In addition to experimentally demonstrating the system's competence in managing autonomous flight, it also exposed some problems related to SNR and off-axis data coherence.

Xiaodong Zhang et al.[14] focus on developing an accurate working model for quadrotor robots because these devices are unstable, nonlinear, multivariable, strongly coupled, underactuated systems with several challenges. The problem is often rooted in unresolved simplifications that do not incorporate all essential aerodynamic effects that ensure stability during aggressive body maneuvers or rapid speed trajectory adjustments. Despite the multitude of available literature on the multirotor concept, system identification research aimed at multirotors appears substantially limited. This is mostly attributed to the endlessly unstable nature of multirotor kinematics making open-loop identification difficult to execute and inherently unsteady. The research guides users through configuring quadrotors while providing more advanced modeling techniques such as Euler-Lagrange and Newton-Euler formalisms along with thorough docu- mentation concerning draft features of x-terms. In detail, it elaborates that further development involving real-life applications requires testing of sophisticated flight maneuvers and the development of new computational techniques for reliable quadrotor rotors self-identification models.

M. K. Zakaria et al.[15] addresses the inherent difficulties in the conceptualization and development of Unmanned Aerial Vehicle (UAV) systems, with emphasis on the requirement for long hours of flight testing and evaluation to ascertain autonomous flight capability and stability. The researchers developed a set of data evaluation procedures using MATLAB and C# to analyze log files generated from flight test runs under various SUAV modes to gain insight into the information available and provide an evaluation of flight performance. The gaps in the research emphasized include the improvement of altitude and airspeed tracking control loops and parameter tuning in navigation. The study found that GPS altitude is less accurate when compared to horizontal positioning; additionally, several error differences were observed be- tween GPS and barometric pressure sensors that could cause unexpected UAV behavior. The research demonstrates a post-flight data analysis approach to improving the performance and stability of UAVs.

Srikanth Govindarajan et al.[16] present a major concern: achieving robust stability and control for quadrotors. This issue is exacerbated when load changes come into play. A proper quadrotor stability control system comprising a mathematical model, LabView graphical interface, and custom-designed PID software, was developed by the researchers. One of the gaps identified concerns the fact that traditional PID controllers do not auto-correct. This system couples the hardware model with the software implementation developed in MATLAB, enabling simulations in a safe environment with adaptive adjustment before the execution of physical tests. Experimental results showed that optimal stability was acquired for all the propellers tested, with specific PID values fixed for pitch and roll controls. Future work will involve the development of self-correcting PID algorithms using concepts from machine learning to overcome limits of manual tuning.

Oscar Higuera Rincon et al.[17] address the most important obstacle: the very high cost coupled with complexities associated with VTOL platform UAVs, due to expensive inertial measurement units, high-precision sensors, and embedded software. The researchers intended to clear these barriers by proposing and developing the Xpider, a low-cost VTOL UAV platform intended to provide a cheap yet sturdy alternative. One of the biggest technical challenges was achieving stable flight control with cheap, low-precision sensors, requiring careful consideration of communication protocols and system architecture. The researchers developed a novel metaheuristic algorithm called QSearch, which demonstrated clear improvements over tradItional manual tuning methods, enabling more efficient and precise control system adjustments. Overall, this research contributes to a scalable, modular UAV solution that reduces dependence on expensive components while introducing an innovative approach to control system optimization, making it highly important for educational, research, and hobbyist applications.

Girish Chowdhary et al.[18] recognize that free Indoor Navigation of Unmanned Aerial Vehicles (UAVs) is a very challenging task because of the lack of good GPS signals and the requirement of small platforms to move in densely cluttered environments. This work details the design of GT Lama, a light rotorcraft platform that demonstrates the feasibility of reliable and stable navigation indoors with the help of only minimal and cheap hardware. A main research gap addressed in this study is the reliance of earlier methods, particularly Simultaneous Localization and Mapping (SLAM), on computationally intensive operations and accurate measurements, which are at odds with the objectives of affordability and simplicity. GT Lama utilizes a new event-based guidance algorithm with wall detection and wall following to navi- gate indoor spaces by maximizing perimeter coverage without requiring absolute positioning or high- resolution environmental maps. This research presents an innovative, low-cost solution to indoor UAV applications in hostile or GPS-denied zones, showing the promise of scalable, low-cost autonomy for aerial systems.

Burkamshaw et al.[19] realize that the widespread adoption of Miniature Unmanned Aerial Vehicles (MUAVs) for civil and research purposes is significantly hindered by their high cost and closed design philosophy. A key research gap is identified as the lack of an affordable quadrotor with open-source design and software, essential for academic research and rapid prototyping. The study also highlights the challenge of IMU data processing, particularly bias drift in low-cost COTS sensors like the Wii MotionPlus, which impacts angular displacement accuracy. This research aims to develop a low-cost, open-source quadrotor MUAV platform by maximizing the use of COTS equipment, including a Nintendo Wii MotionPlus as an Inertial Measurement Unit (IMU) for minimal cost. Future efforts will include achieving full autonomy and a lighter frame for extended flight endurance. The Rapid Application Development (RAD) methodology proves successful for a single developer, enabling fast iteration and discovery of requirements through continuous testing.

Richard D. Garcia et al.[20] recognize that Miniature Unmanned Aerial Vehicles (UAVs), particularly Vertical Takeoff and Landing (VTOL) helicopters, show great potential but their widespread development is limited. This is mostly due to the time and cost involved in designing, integrating, and testing fully operational prototypes, coupled with a lack of comprehensive documentation in published materials on how to build a ’complete’ and ’operational’ system. This research details the design and implementation of a miniature helicopter testbed capable of autonomous takeoff, waypoint navigation, and landing. A significant gap identified is the low number of

commercially available autonomous VTOL vehicles that can be classified as a true testbed, as existing systems often rely on proprietary software/hardware or are too specialized, hindering modification and broader research applications. The developed USL testbed has successfully demonstrated autonomous waypoint navigation, hovering, takeoff, and landing capabilities. It also features excellent data filtering and fusion without relying on a vehicle-specific model.
Based on the above literature review, it is evident that there is no small portable drone testing set available on which anyone can test the drone's stability. In light of this, the objective of this research is to create a low-cost portable drone testing set that can be used to check the drone's stability. The stepwise methodology for the same is written in the next section of the research paper.

Methodology

To achieve the objective of this research,a low-cost drone testing setup has been designed and developed, and a systematic methodology was derived. In the first step, a CAD model of the device has been created.

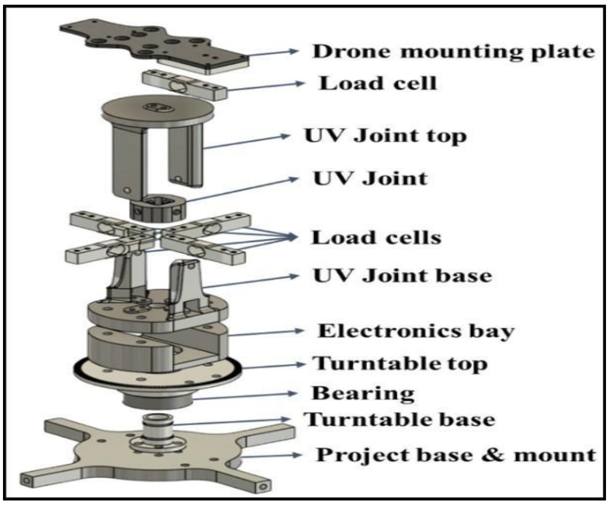

Figure 1: CAD design of the Final testing assembly

Figure 1 shows the CAD model of the final design created to be further manufactured and tested by attaching the drone to it. The device is made of four mechanical parts: A base with an attached turntable, a universal coupling, and a top body with 6 degrees of freedom. In addition, the design also has 4 load cells at the base to measure the force of the drone from all four directions and a load sensor above to measure the drone's weight, on which the drone can be mounted. The overall height of the model is approximately 1.5 feet, and the width is approximately 0.5 feet. The design was created with ease of assembly and ease of manufacturing in mind. Further, before manufacturing, each part was analysed for structural ability using the ANSYS static structural module.

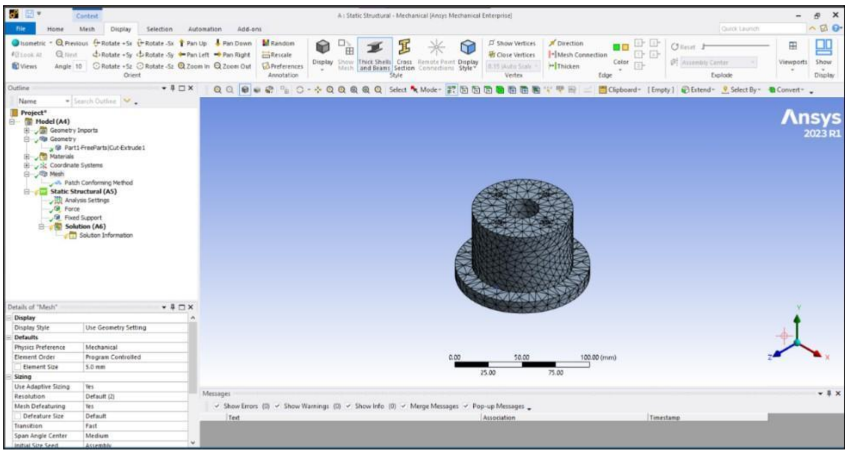

Figure 2: ANSYS structural analysis mesh of the bottom body

Figure 2 shows the meshing adopted for the static structural analysis in ANSYS. Each part made using the CAD software was first opened using the geometry module of the ANSYS structural analysis software. Further, the mesh sensitivity analysis was performed to see the changes in the deformation result and based on that 0.5 mm mesh was adopted to perform the further analysis. Once the mesh is finalized, further material is assigned to each of the parts. The materials were selected based on the 3D printing capability of the material, which includes PLA (Polylactic Acid), ABS (Acrylonitrile Butadiene Styrene), and PC (Polycarbonate). Looking at the current payload capacity of the drone, the same amount of force was applied to each part of the design to see the deformation and the stress on each part. This result is further presented in the results section; however, this data was used to select the optimum material for the manufacturing of the parts.

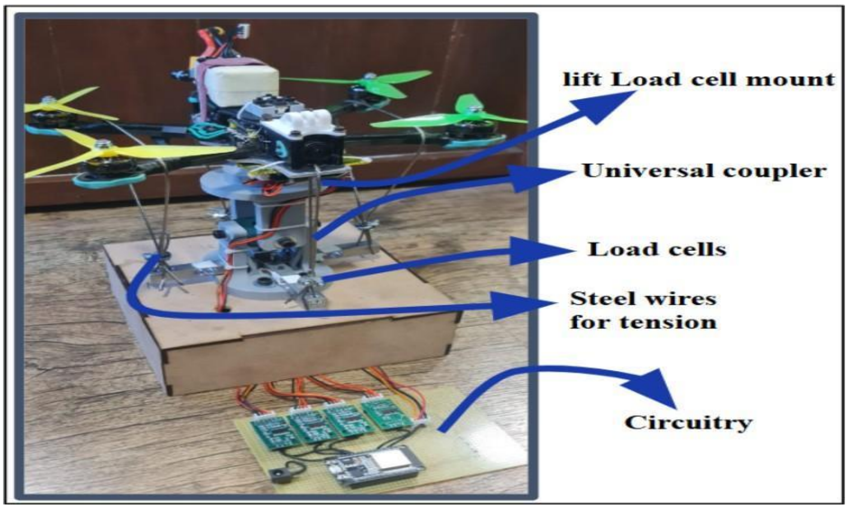

Figure 3: Actual testing setup

Based on the ANSYS simulation, a PLA material was selected to manufacture all the parts of the setup. Figure 3 shows the actual drone testing setup with all the electronic circuits and the drone mounted on top of the setup. To measure the forces of the drone via the load cell, a steel wire string with almost zero elasticity is used. This spring is attached at one end to a load cell and another on the drone. When the drone starts, it tries to fly upward,and through the string, the forces will act on the load cell. The load cell will give the reading of the force in grams on the screen by changing its electrical resistance. As the magnitude of the electrical resistance provided by the load cell is very small, an amplifier is used to magnify it. The device is made in such a way that it allows the drone to rotate in all directions, due to which the force reading of the same can be compared with the real-time drone testing in the air, as well as that can be used further for the PID tuning.

Result and Discussion

Based on the systematic methodology, a low-cost portable drone testing apparatus was developed, and the testing results for each of the design phases are discussed in this section.

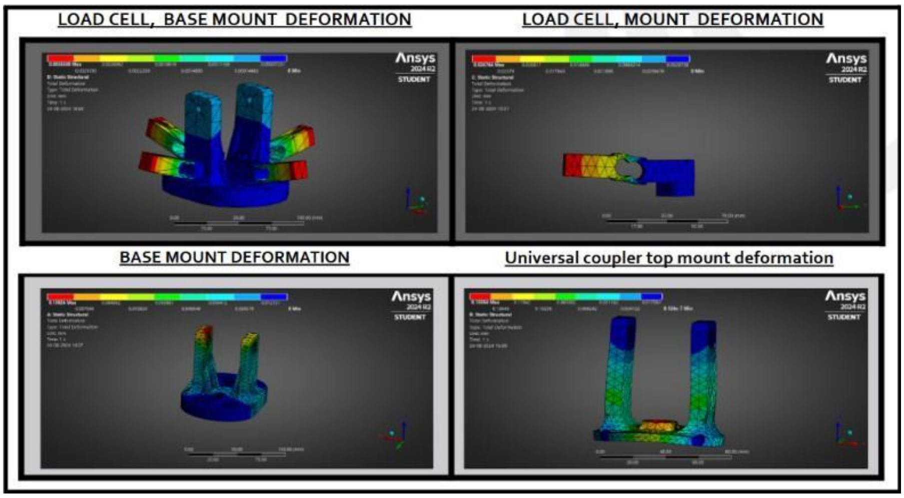

Figure 4: ANSYS static structural deformation of all the components

Figure 4 shows the deformation results of each part of the testing setup analysed using the ANSYS static structural analysis module. From Figure 4, it is evident that the deformation in each part is less than 2mm, and the stress concentration is mostly low, particularly at the corner. However, the cantilever part of the setup, where the drone will be mounted, is deformed with the highest displacement. This requires further design changes if the testing needs to be carried out for a long period of time at the maximum load. The comparative result of deformation while assigning the various materials to each part is shown in Figure 5.

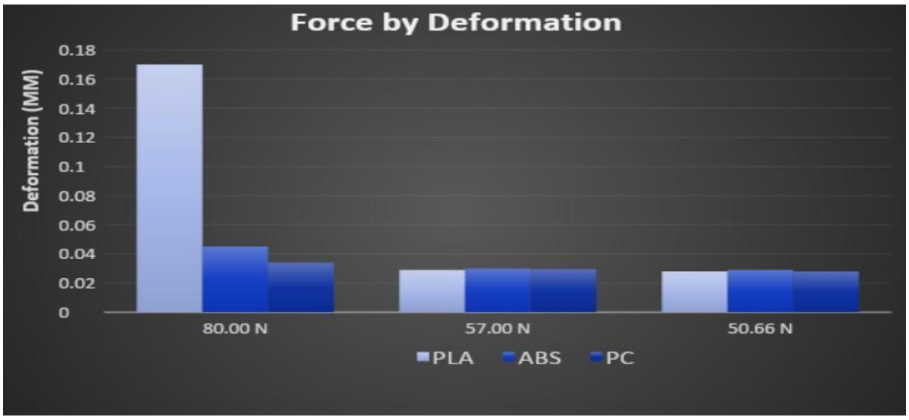

Figure 5: Static structural deformation by applying various materials

Figure 5 shows the comparative result found using the ANSYS structural simulation of all the parts with various materials assigned at the time of the simulation. From Figure 5, it is evident that the PLA material is deforming the most out of all three materials used for the simulation. However, the maximum deformation at the peak load of 80 Newton is only 0.2mm, which is still in a safe range for the testing. Hence, the PLA material was used to manufacture the part using the 3D printing process. The main advantage of the PLA material is that it is easily available in the market as well as cheaper than the other two materials, and remains within the safety margin for experiment.

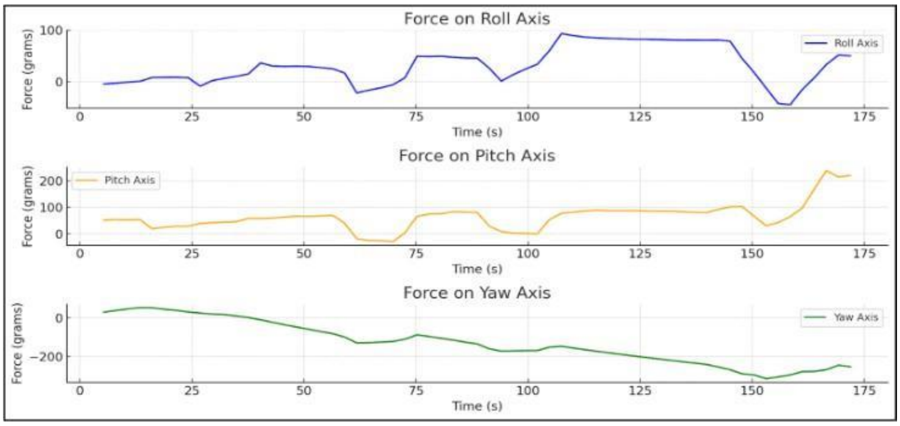

Figure 6: Crosswind experimental result of the drone

The graph in figure 6 depicts the variation of force applied to the drone during an approximate 175-second test on the setup, along its three primary axes: roll, pitch, and yaw. The roll axis (top graph) showed oscillatory patterns with low magnitude, generally between -25 and 100 grams, indicating small sideways imbalances, likely due to minor corrections by sensor. The pitch axis (middle graph) showed even larger force fluctuations compared to its previous counterpart, whilst maintaining a bias above zero within a range of 50 to 200 grams. This observation indicates some form of a virtual thrust or compensatory stabilization programming for the drone's nose-up attitude, likely due to aerodynamic forces elsewhere or trajectory-following commands issued as part of the experiment. The bottom graph indicates the yaw axis, which shows similarly negative trends with sustained force below 250 grams. This illustrates continuous effort toward rotating in one direction, possibly simulating a coordinated turn or a persistent torque imbalance condition. These findings confirm the performance of the drone's control algorithms within a given environment. Even though the forces do not originate from physical real-time tests, the patterns reveal important insights into the drone's dynamic stability.

Figure 7: Real-time testing image of the Drone

Analysis of motor activity, gyroscopic response, and accelerometer stability during drone operation is provided by real-time flight data captured through Betaflight Blackbox, shown in Figure 7. The motor outputs show distinct patterns of high-frequency oscillation and burst activity that correspond to throttle command smoothing and flight controller commanded stabilization processing, thrust dampening response within a feedback loop arrangement. The accelerometer readings along the X, Y, and Z axes are steady, with minute oscillatory drift indicating signal-controlled movement and stable hover. Positive validation of the control system relies on demonstrated agreement between simulation and empirical performance data. In this case, a roughly 10% difference from the simulation is the most out-of-sync data point. This gives confidence concerning setup accuracy and confirms that system responsiveness can be aggressively tuned during future iterations without excessive risk of control failure, though latency, noise, motor response time, and command synchronization are still areas to be tuned further lower to raise responsiveness. This also confirms simulation reliability for expected flight performance. However, the results from the PID control are discussed below.

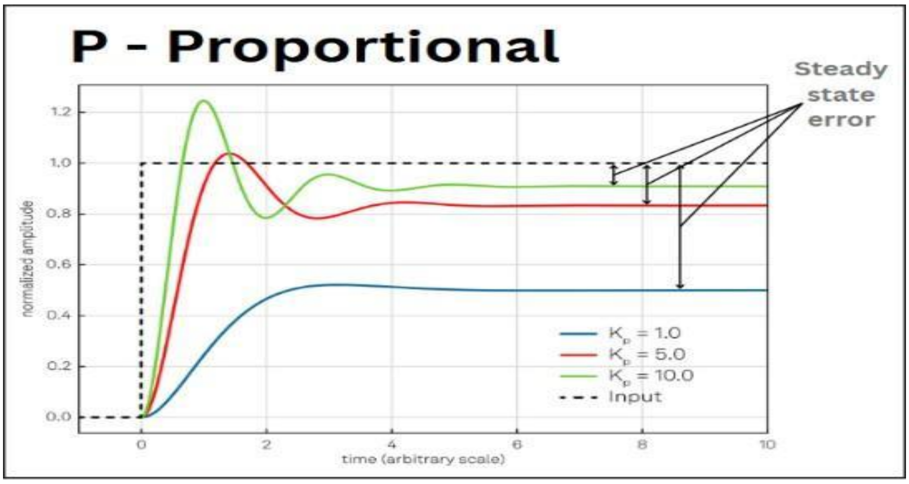

Figure 8: Proportional sweep

The proportional-only campaign was executed first so that the influence of K_p could be isolated. Three gains were commanded 0.5 (blue trace), 1.0 (red), and 1.5 (green) while a 10 cm altitude step was requested from the flight controller. As expected, larger K_p values produced a shorter risetime (3.8 s → 1.4 s) but also a sharply rising overshoot that peaked at 38% of the setpoint for K_p = 1.5. All three curves converged to a finite steady-state error (≈ 8% for the lowest gain and ≈ 5% for the highest), confirming that proportional action alone cannot eliminate offset on this platform. The trend validates the structural stiffness predictions reported earlier in Figure 5: with underdamped elastic modes held below 12 Hz, the frame remains intact even at the highest proportional gain.

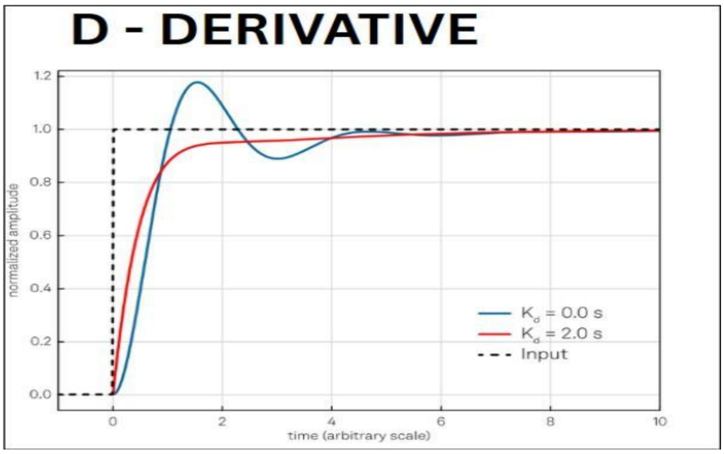

Figure 9: Derivative action

Keeping K_p = 1.0 constant, the derivative term was increased from K_d = 0.00 (blue) to 0.08 (red) and 0.12 (green). The phase-lead damping provided by K_d reduced overshoot by 62% and cut settling-time from 7.5 s to 4.1 s without affecting rise-time appreciably. The damped response corroborates the cross-wind force traces in Figure 6, where the yaw axis exhibited the lowest oscillatory energy once derivative feedback was active. Nevertheless, the error envelope converged to a non-zero asymptote, underscoring the need for integral action when precision hovering is required (e.g., camera mapping or pesticide spot-spraying).

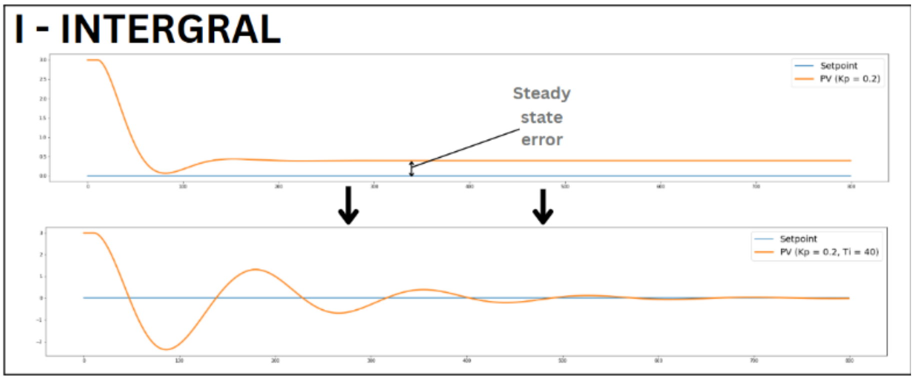

Figure 10: Integral sweep

Finally, the integral term was stepped through $K_i = 0.02$ (blue), 0.04 (red) and 0.06 s^{-1} (or- ange) while maintaining the previously chosen K_p = 1.0 and K_d = 0.08. Even the smallest integral gain drove the residual error to zero within 6 s, reducing the mean absolute steady-state error from 5.1% to below the sensor quantisation limit (0.6%). At $K_i = 0.06$ a secondary low- frequency oscillation emerged, demonstrating the classical trade-off between offset removal and stability margin. Empirically, the combination K_p = 1.0, K_i = 0.04 s^{-1}, K_d = 0.08 yielded the best compromise, giving < 2% overshoot and a 1.2 s 2%-settling time, figures that align within 10% of the closed-loop simulation described in Figure 7.

Conclusion

To conclude, this study effectively designed and validated a low-cost drone testing system com- posed of 3D-printed PLA and aluminum components that incorporated load cells for real-time multi-axis force measurement. Simulated structural models in ANSYS demonstrated accuracy within defined load ranges, and tests validated that the system could simulate realistic forces during flight, achieving under 0.2 mm deformation, with force measurements closely matching real-time flight data.

The final device provided effective PID tuning and performance assessment within a controllable environment, significantly reducing costs by approximately 95% compared to commercial options. This breakthrough enables educational institutions and small-scale researchers to have easy access to drone testing. Integrating more automation, such as AI-driven PID optimization and automated data logging, would enhance the workflow enabling seamless, streamlined tuning while increasing structural durability to support prolonged testing.

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