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PID CONTROL SYSTEM IN 3 AXIS FOR STABILITY OF A MODEL AIRCRAFT IN A WIND TUNNEL

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Abstract. *The inherent quality of an airplane to correct its balance and return to the original horizontal alignment after suffering any disturbance is called stability. The stability of an aircraft is a decisive factor for its design and commercial success, because a single disturbance can lead to misalignment that in turn can lead to time and fuel waste, damages, and in worst case disaster. The most common method to achieve stability is the alignment of the plane horizontal axis with the horizon line that can be done by onboard digital or mechanical systems, or even with a human manual control. Systems that ensure flight stability are a crucial part of an aircraft machinery and also expensive and maintenance costly. The present paper propose the development of a simpler and cheaper control and command system to detect and respond on time when an aircraft's alignment is off. A model aircraft was tested in a Wind Tunnel with a simple Arduino circuitry board, a digital gyroscope, and a set of servomotors as an onboard PID system that can optimize flight control and ensure stability. This method does not just provide an objective and in-depth assessment of flight stability, but it also provides a low-cost alternative to the expensive control and command systems currently in use.*

Keywords: *Aircraft, Flight stability, Flight control, PID, Arduino, Wind tunnel.*

1. INTRODUCTION

In aviation, the concept of stability encompasses both dynamic and static aspects. Static stability addresses an aircraft's immediate response to disturbances, while dynamic stability evaluates its ability to maintain equilibrium over time. These concepts are essential for ensuring aircraft stability in the presence of various disturbances without requiring a direct action from a human. The disturbances can come from external or internal sources, such as winds, turbulence, or maneuvers (D K Yadav and Mansor, 2022).

Efficient and secure flight stabilization of an aircraft is typically accomplished through onboard control and command systems. These systems have the crucial task of capturing, reading, and interpreting flight data, enabling them to issue the requisite commands for aircraft adjustments and stability maintenance (Pallett and Coyle, 1993).

Stabilization systems can be expensive and complex. Therefore, the objective of this paper is the development of a low-cost system for flight stability system to be onboard an aircraft, which in this paper is represented by a model airplane subjected to tests in a Wind Tunnel, that simulated adverse situations of a common flight.

The proposed system is a Proportional-Integral-Derivative (PID) control system, that achieves flight stabilization by dynamic control of the mechanical surface parts of the aircraft. The main goal being maintaining the aerodynamic balance, that is, the ability to return to the previous state of flight after suffering a disturbance. In the words of Parnell the PID controller is responsible for providing "a continuous variation of the output within a control loop feedback mechanism to precisely control the process, removing oscillation and increasing efficiency." (Parnell, 2014).

Systems similar to the proposed one typically fall under the umbrella of Autopilot systems. Autopilot systems encompass a comprehensive suite of tools and systems that ensure efficiency, stability, and autonomy during aircraft flight. These systems are employed in both self-operating and computer-controlled aircraft, providing essential support for safe and precise flight operations in the 3 Axis of flight, as shown in Fig. 1 (J Gouraud and Berberian, 2017).

Figure 1. Flight stability.

2. METHODOLOGY

To achieve cost-effectiveness, the proposed system utilizes an Arduino Uno circuit board in conjunction with a digital gyroscope (Stan, 2014) as seen in Fig. 2, and runs a custom-made software designed for this research.

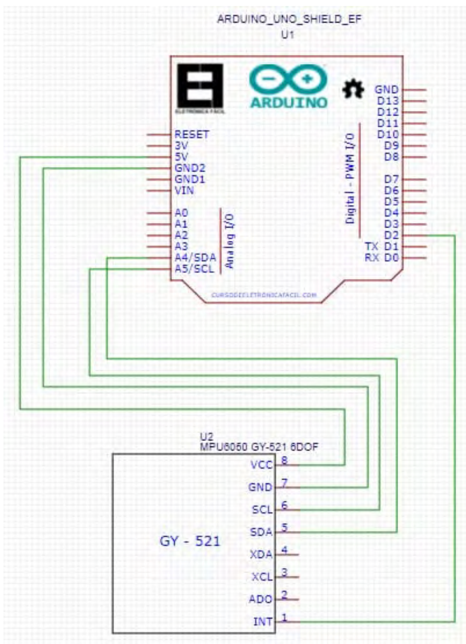

Figure 2. Propose onboard circuitry system and its connections.

The stability system responds promptly upon detecting any misalignment during flight. It commands servomotors positioned throughout the model aircraft, as seen in Fig. 3, to make necessary adjustments. Each servo is attached to one of the four main flight control surfaces (both elevators count as one single surface due to the aircraft layout that was used).

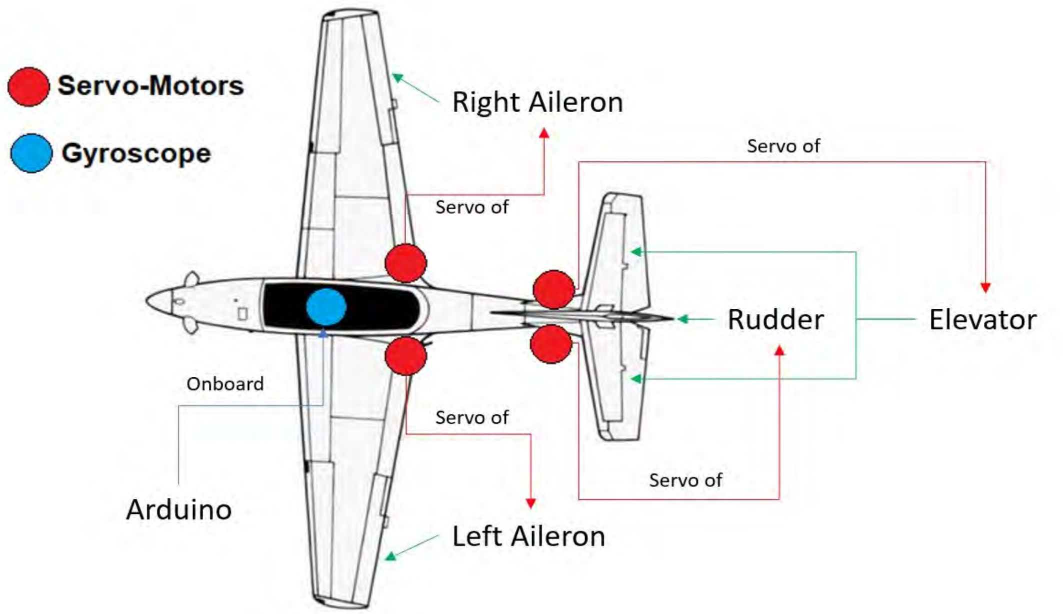

Figure 3. Model aircraft main components and control surfaces.

The validation tests were carried out within the closed-loop Wind Tunnel situated in the Experimental Aerodynamics Laboratory at the Federal University of Minas Gerais (UFMG). This wind tunnel is divided into 9 different sections and numbered according to Fig. 4 an the nomenclature of each section is presented on Fig. 5.

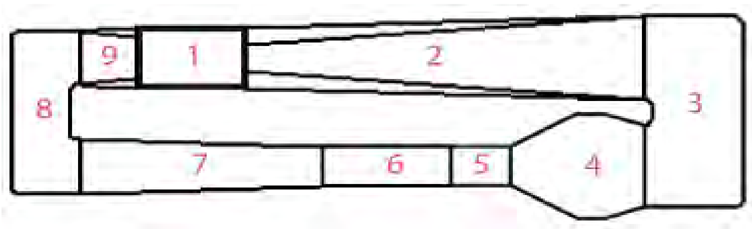

Figure 4. Wind tunnel sections.

Section number	Nomenclature
1	Motor Section
2	Tertiary Diffuser
3	Flow Redirector at Propeller Downstream
4	Nozzle at Test Section Upstream
5	Elongation
6	Testing Section
7	Primary Diffuser
8	Flow Redirector at Propeller Upstream
9	Secondary Diffuser

Figure 5. Nomenclature of the Wind Tunnel sections.

The test happened on section number 6 (Testing Section) with the aircraft facing towards section 7 (Primary Diffuser), the speed of the wind in all tests was capped at 10 meters per second due to the model aircraft dangerously stalling[1] in higher speeds.

[1] A stall is a condition in aerodynamics when, if the angle of attack on an aircraft increases beyond a certain point, the lift begins to decrease or stops.

2.1 Experimental data collection

Data essential for the control and command system was gathered by the onboard digital gyroscope, measuring the aircraft's angular position. Analysis of the test data revealed that the aircraft exhibited increased stability when under the control of the proposed system compared to scenarios without an automatic stability system, relying solely on human control. The use of the PID control mechanism provided precise and responsive control over the aircraft's movements, enabling it to recover from disturbances and maintain stability under varying wind conditions. The system's effectiveness was exemplified by a significant reduction in the aircraft's oscillations and overshooting, issues commonly encountered in traditional control systems, as noted by Gouraud (J Gouraud and Berberian, 2017).

To manage wind tunnel parameters, including velocity, and to record the strain gauge force values, a Data Acquisition (DAQ) system was employed. This DAQ system is programmed to gather data from the instrumentation and directly convert it using specialized data preparation software. Subsequently, within LabVIEW, the front panel is configured to display the converted data, enabling operators to effectively comprehend and control test parameters.

2.2 Data processing

A Proportional-Integral-Derivative controller is a powerful tool in the field of aeronautical engineering, enabling precise and reliable control of complex systems such as aircraft. Its effectiveness depends heavily on proper tuning, and its implementation can significantly improve the stability and efficiency of aircraft operations (Sudha and Deepa, 2016).

The PID controller operates by computing an error signal, which is the distinction between a desired set-point and the measured process variable. This error signal is then processed by the PID algorithm to determine the appropriate control action for error minimization and stability maintenance. The controller's efficacy is primarily contingent on three crucial tuning parameters: the Proportional Gain (Kp) that influences the controller's response speed by gauging the output response according to the current error signal; the Integral Gain (Ki) that addresses steady-state error by continually accumulating the error signal over time, ensuring precise set-point control; and, the Derivative Gain (Kd) that enhances the controller's sensitivity to error signal changes, improving system stability by minimizing overshooting and oscillations (Johnson and Moradi, 2005).

The parameters were determined using Simulink's PID Tuner, which employs heuristic-based[2] optimization algorithms to identify the optimal parameters for the PID controller. This tool scrutinizes the controller's input and output signals, ultimately computing parameters that maximize the desired response[3].

2.3 Code Writing

For this study to be possible, was necessary to write a code aiming both at data collection and application of the PID in the aircraft, as well as a simple implementation of an Arduino Uno. The programmed code receives data from a MPU6050 gyroscope to calculate the roll, pitch, and yaw angles. The code also includes debugging output to monitor the roll, pitch, and yaw angles.

It starts by defining several variables and objects used for controlling an aircraft's control surfaces. Four Servo objects are defined for controlling the left aileron, right aileron, rudder, and elevator control surfaces. The code defines variables for the positions of each servo, as well as variables for the gyroscope offsets and loop timing.

Every time the loop function runs, the MPU6050 sensor data is read, the PID control output is computed, and the control surfaces are adjusted. Each loop calculates the time taken by the previous loop since the last iteration. This time is used in subsequent calculations to ensure that the control loop runs at a consistent rate.

The code then calculates the errors in roll, pitch, and yaw angles by subtracting the set-point values from the current angle values. The loop then calculates the integral and derivative terms of the PID controller for each angle by integrating and differentiating the error signals over time.

The PID outputs for the aileron, rudder, and elevator servos take in consideration the current error, integral, and derivative terms, as well as the proportional gain (Kp), integral gain (Ki), and derivative gain (Kd) constants for each angle[4].

Finally, the programming constrains the servo positions based on the calculated output values and writes the resulting positions to the corresponding servo objects. The current roll, pitch, and yaw angles of the aircraft are also printed to the serial monitor for debugging purposes.

[2] Heuristics is a scientific method that uses prior knowledge to find optimal solutions to complex problems.
[3] The values were estimated by the Simulink datasheet, following the software's internal calculation parameters.
[4] The gains may need to be manually adjusted depending on the specific aircraft being used.

2.4 Model airplane restoration

In July of 2021, a model airplane of a Spitfire[5] was restored and adjusted for use in the control environment of the Wind Tunnel. The model aircraft was provided by the pedagogic coordination of the Aeronautical Engineering Course of the Pontifical Catholic University of Minas Gerais (PUC-MG), the main adjust was to proper cover the wooden structure of the craft, as shown in Fig. 6, using a self-adhesive vinyl covering.

Figure 6. Model airplane during restoration.

The complete covering of the model was done in such a way as not to allow the passage of air through the inside of the structure where the Arduino board, servos, engine, and wires are located, as shown in Fig. 7.

Figure 7. Model airplane after restoration.

[5]The Supermarine Spitfire is a legendary British fighter aircraft known for its pivotal role during World War II. Designed by R.J. Mitchell, it gained fame for its agility and significant contributions to the Allied victory in the air battles of the war. The Spitfire remains an iconic symbol of aviation history.

The model airplane was then placed hanging by the ceiling of the Wind Tunnel, to simulate the aircraft in flight but also allow air to clearly pass beneath the model due to the Spitfire's low-wing design[6], on non-stretching wires that prevented the aircraft from dissipating disturbances, as shown in Fig. 8.

Figure 8. Model airplane positioned in the Wind Tunnel.

The first test of the model airplane performance was without the use of the PID control system. The aircraft without the stability system ended up not supporting the forces and loads exercised on the wings and structure, resulting in a stall, whereupon the model airplane crashed onto the floor of the Wind Tunnel and suffered damages, as shown in Fig. 9 and Fig. 10.

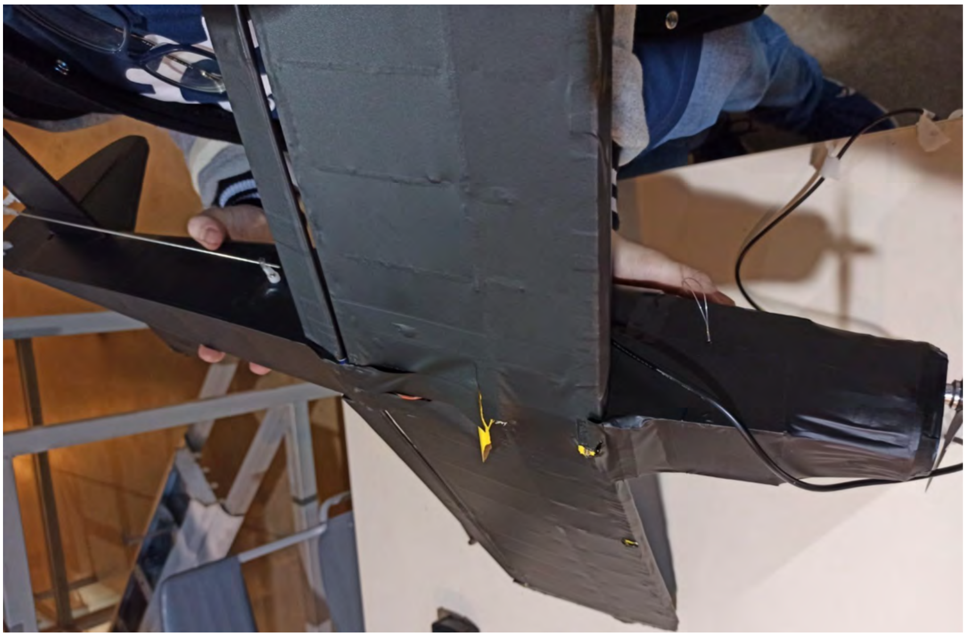

Figure 9. Model airplane with damages in the lower structure of the fuselage.

[6]Placing the wing low allows good visibility upwards, frees the central fuselage from the wing spar carry-through and reduces pendulum stability making the aircraft more manoeuvrable.

Figure 10. Model Airplane with damages in the upside of the wings covering.

After the first test the model airplane was then repaired.

In the following tests the proposed control system was used and provided satisfying results. The main objective of those tests was to determine the feasibility and effectiveness of the proposed system in maintaining the stability of an aircraft in varying wind conditions.

3. RESULTS

After two successful tests where the aircraft would start unaligned with its flight path and then the PID stability system would act upon detecting the aircraft current alignment and then reposition the aircraft with the control surfaces. The data was then collected and the first 10 iterations (loop cycles of the code) of both tests are presented in Tab. 1 where each value represents the angle (rad) on a unit of time (second).

Table 1. Angles collected from each iteration of the software.

Iterations	1	2	3	4	5	6	7	8	9	10
Pitch	0,282	0,195	0,126	-0,052	-0,465	-0,401	-0,366	-0,322	-0,284	-0,255
Test 1	0,283	0,195	0,126	-0,052	-0,465	-0,402	-0,366	-0,323	-0,284	-0,256
Test 2	0,282	0,195	0,126	-0,052	-0,465	-0,401	-0,366	-0,322	-0,284	-0,255
Yaw	0,322	0,321	0,321	0,320	0,319	0,318	0,317	0,315	0,314	0,311
Test 1	0,323	0,321	0,321	0,319	0,320	0,317	0,317	0,314	0,314	0,311
Test 2	0,322	0,322	0,321	0,320	0,319	0,318	0,317	0,315	0,313	0,311
Roll	0,023	0,042	0,058	0,071	0,082	0,092	0,100	0,107	0,113	0,117
Test 1	0,023	0,042	0,059	0,070	0,083	0,092	0,100	0,107	0,113	0,117
Test 2	0,023	0,042	0,058	0,071	0,082	0,092	0,100	0,107	0,113	0,118

3.1 Outcome comparison

Fig. 11 showcase an desired aircraft stabilization as proposed by J. Gordon Leishman (Leishman, 2022).

In his PHD thesis for the Institute of Science and Technology at the Istanbul Technical University, Serdar Ates designed an autopilot system for a micro-air vehicle which enables the vehicle to navigate given waypoints autonomously. The performance results of his autopilot are shown in Fig. 12 (Ates, 2009).

The values of the this paper's proposed Proportional-Integral-Derivative (PID) control system are plotted on graph in Fig. 13.

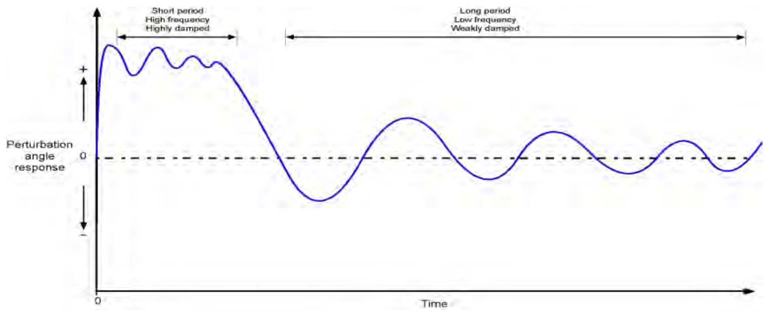

Figure 11. A representative dynamic response showing the short period (high frequency, heavily damped) and the long period (low frequency, lightly damped).

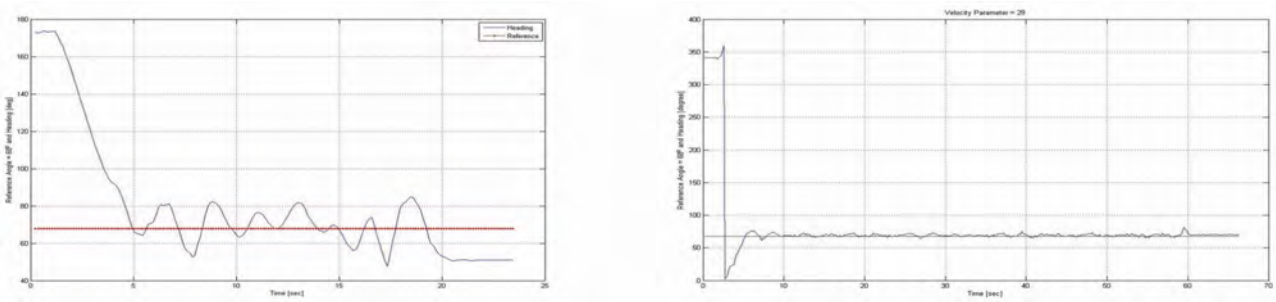

Figure 12. PD-controller performance results for heading of the ground vehicle from the real outside tests. The reference heading angle is taken as 68 [deg] in these tests. The left one is untuned controller result, which has 66.03 [deg] mean value with the 10.71 [deg] standard deviation. The right one is tuned controller result, which has 69.27 [deg] mean value with the 1.74 [deg] standard deviation.

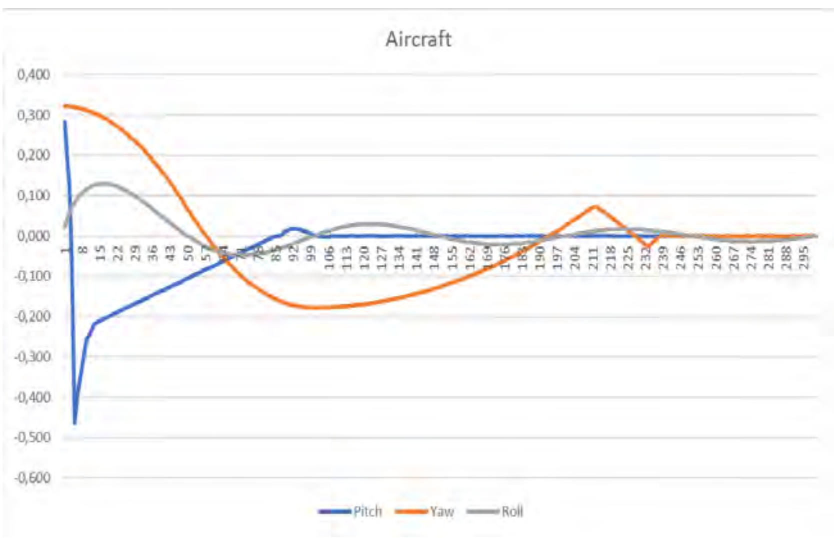

Figure 13. Angle per Time graph representing roll, pitch, and yaw angles of the combined tests results.

4. CONCLUSION

This project's primary achievement is the creation of a cost-effective flight stability control system with wide-ranging implications for the aviation sector. The proposed system holds the potential to enhance the stability of various aircraft, encompassing commercial airplanes, helicopters, and drones. By offering a more affordable alternative to the currently expensive control and command systems, this initiative may lead to reduced aircraft manufacturing expenses, thus broadening public accessibility to air travel.

Moreover, the results have yielded tangible and quantifiable outcomes. The proposed stability control system exhibited a substantial reduction in aircraft oscillations and overshoot, highlighting its effectiveness. Comparative data analysis against traditional control systems, like the one designed by Serdar Ates (Ates, 2009), showcased a significant improvement in flight stability, close of a desired one (Leishman, 2022).

This paper aims to encourage successful PID system implementations, thereby opening doors for further research and development in the field of aeronautical engineering. Beyond its technical achievements, the system's cost-effectiveness has the potential to bring down aircraft manufacturing expenses, a development with wide-reaching implications for the aviation sector.

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7. RESPONSIBILITY NOTICE