Abstract. In the field of aeronautical engineering, the inherent quality of an airplane to correct its balance and return to the original horizontal alignment after suffering any disturbance is called stability. This is essentially a design feature, as the stability of an aircraft is a decisive factor for its commercial success, because a single disturbance can lead to unalignment 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 the human sight. Systems that ensure flight stability are crucial parts of aircraft machinery and are an expensive one of that. The present project studies the development of a simpler and cheaper control and command system to detect and respond on time when the aircraft's alignment is off, by developing a model aircraft and testing it in a Wind Tunnel. The model aircraft utilizes a simple Arduino circuitry board, a digital gyroscope, and a set of servomotors as a PID system that can optimize onboard flight controls 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. The main objective of this study is to determine the feasibility and effectiveness of the proposed system in maintaining the stability of an aircraft in varying wind conditions. The results of the Wind Tunnel tests are analyzed, and the advantages and limitations of the system are discussed. This project aims to contribute to the ongoing research in the field of aeronautical engineering by providing a new, cost-effective solution to ensure flight stability, which can potentially benefit the whole aviation industry.

Keywords: Aircraft, Flight stability, Flight control, PID, Arduino, Wind tunnel.
Flight stabilization of an aircraft can be efficiently and safely achieved when control and command systems are onboard of the plane. Said systems are responsible for capturing, reading, and interpreting the flight data, and then give the necessary command to reposition the aircraft (Pallett et al., 1993).

Stabilization systems can be expensive and complex, due to that, the goal of this paper is the development of a low-cost system for a flight stability system onboard the aircraft, which in this paper is represented by a model airplane. To test the system proposed the model aircraft was submitted to a Wind Tunnel, that simulates adverse situations of a common flight that would pass through the automatic stabilization control of a conventional aircraft.

The proposed system works with a PID controller, a proportional-integral-derivative control system, to achieve flight stabilization of an aircraft by a dynamic control of the mechanical surface parts. 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). The main goal being maintaining the aerodynamic balance, that is, the ability to return to the previous state of flight after suffering a disturbance.

Systems like the one proposed are usually under the umbrella of the Autopilot, which brings together all the tools and system used during the flight of an aircraft that guarantees efficiency, stability, and autonomy (Gouraud et al., 2017).

2. METHODOLOGY

Using an Arduino Uno circuitry board combined with a digital gyroscope in a circuitry proposed by 42 Bots (2014) in Figure 2, the stability system deals with the subjects of PID by running a software created for this paper research.
The commands given by the stability system in the aircraft happen when it detects flight unalignment, said commands are relayed to the servomotors located across the model aircraft, each are attached to one of the four main flight control surfaces (both elevators count as one single surface due to the aircraft layout used).

![Model aircraft main components and control surfaces.](image)

The validation tests occurred in the closed-loop Wind Tunnel located in the Experimental Aerodynamics Laboratory at Universidade Federal de Minas Gerais, Papini et al. (2020) provided with all measurements of the Wind Tunnel that they divided into 9 different sections and numbered according to Figure 4, to facilitate manufacturing and handling. The nomenclature of each section is presented on Table 1.

![Wind tunnel sections.](image)

<table>
<thead>
<tr>
<th>Section number</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Motor Section</td>
</tr>
<tr>
<td>2</td>
<td>Tertiary Diffuser</td>
</tr>
<tr>
<td>3</td>
<td>Flow Redirector at Propeller Downstream</td>
</tr>
<tr>
<td>4</td>
<td>Nozzle at Test Section Upstream</td>
</tr>
<tr>
<td>5</td>
<td>Elongation</td>
</tr>
<tr>
<td>6</td>
<td>Testing Section</td>
</tr>
<tr>
<td>7</td>
<td>Primary Diffuser</td>
</tr>
<tr>
<td>8</td>
<td>Flow Redirector at Propeller Upstream</td>
</tr>
<tr>
<td>9</td>
<td>Secondary Diffuser</td>
</tr>
</tbody>
</table>

The model aircraft was placed on section number 6 (Testing Section) facing towards section 7 (Primary Diffuser), the speed chose for the experiment was of around 10 meters per second.
2.1 Experimental data collection

The collection of necessary data for the control and command system began with the construction of a code that enabled the implementation of the PID algorithm in the aircraft. This code was designed to allow the onboard digital gyroscope to measure the aircraft's angular position and then send the data to the Arduino circuitry board. The Arduino, in turn, processed the data using the PID algorithm, and the resulting control signal was transmitted to the servomotors, which adjusted the aircraft's control surfaces to maintain stability.

By analyzing the data collected from the flight tests, it was observed that the aircraft was more controllable and stable when its control surfaces were under the control of the proposed system. The use of the PID algorithm provided precise and responsive control of the aircraft's movements, allowing it to recover quickly from disturbances and maintain stability in varying wind conditions. The effectiveness of the proposed system was demonstrated by the significant reduction in the aircraft's oscillations and overshoot, which Gouraud et al. (2017) cites as the most common problems in conventional control systems.

Overall, the collection and analysis of the data proved the effectiveness of the proposed control and command system in ensuring the stability of aircraft operations. The use of the Arduino board provided a low-cost and efficient solution to the challenges of aircraft stability, which can potentially benefit the aviation industry by reducing costs and improving safety. The successful implementation of the PID system in this study paves the way for further research and development in the field of aeronautical engineering, with potential applications in other areas of aviation technology.

2.2 Data Processing

The PID controller calculates an error signal as the difference between a desired setpoint and the measured process variable. The error signal is then processed by the PID algorithm, which computes the appropriate control action to minimize the error and maintain stability. The effectiveness of the PID controller depends largely on the values of its three tuning parameters: the proportional gain (kp), the integral gain (ki), and the derivative gain (kd). The proportional gain determines the output response based on the current error signal, meaning it affects the overall speed of the controller response. The integral gain eliminates the steady-state error by continuously summing the error signal over time, which is useful when the PID needs a precisely setpoint. The derivative gain increases the controller's responsiveness to changes in the error signal and is used to increase the system's stability by reducing overshoot and oscillation (Johnson, 2005).

Therefore, the correct tuning of these three constants is crucial to ensure the proper functioning of the PID system and the stability of the aircraft. In the proposed control and command system using an Arduino circuitry board, a digital gyroscope, and a set of servomotors, the PID algorithm is implemented to optimize the onboard flight controls and ensure stability. The values of kp, ki, and kd are determined based on the aircraft's physical properties, flight conditions, and desired performance objectives.

Overall, the PID 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.

Table 2 shown below indicates the values entered for the constants kp, ki and kd.

<table>
<thead>
<tr>
<th>Constants</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>kp</td>
<td>0.721</td>
</tr>
<tr>
<td>ki</td>
<td>0.006</td>
</tr>
<tr>
<td>kd</td>
<td>1.220</td>
</tr>
</tbody>
</table>

Table 2. Constants applied in the PID Controller.
To find the parameters, Simulink's PID Tuner was used, which uses heuristic-based optimization algorithms to find the best parameters for the PID controller. It analyzes the input and output signals of the controller and calculates the parameters that maximize the desired response. Heuristics is a scientific method that uses prior knowledge to find optimal solutions to complex problems. It is noteworthy that the values found were estimated by the Simulink datasheet, following the software's internal calculation parameters.

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 code receives data from a MPU6050 gyroscope to calculate the roll, pitch, and yaw angles. The PID controller is used to calculate the output needed to adjust the aircraft's orientation, and the servos are used to move the control surfaces to achieve the desired orientation. The code also includes debugging output to monitor the roll, pitch, and yaw angles.

The code implements the PID in a control loop that calculates the roll, pitch, and yaw angles of the aircraft using data from a gyroscope, and then uses these angles to calculate errors and PID outputs for the ailerons, rudder, and elevator servos, which control the aircraft's movement.

It starts by defining several variables and objects used for controlling an aircraft's control surfaces using a MPU6050 gyroscope and PID control. 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 is computed, and the control surfaces are adjusted based on the PID output. Each loop calculates the time taken by the previous loop since the last iteration, using the millis() function. This time is used in subsequent calculations to ensure that the control loop runs at a consistent rate. The mpu.getRotation() function is used to obtain data from the gyroscope, which is used to calculate the current roll, pitch, and yaw angles of the aircraft. These angles are stored in the roll_angle, pitch_angle, and yaw_angle variables. The code then calculates the errors in roll, pitch, and yaw angles by subtracting the setpoint values from the current angle values. These errors are stored in the error_roll, error_pitch, and error_yaw variables. 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. These terms are stored in the int_error_roll, int_error_pitch, int_error_yaw, der_error_roll, der_error_pitch, and der_error_yaw variables.

The PID outputs for the aileron, rudder, and elevator servos are then calculated using 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. These outputs are stored in the output_roll, output_pitch, and output_yaw variables.

Finally, the code 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.

Note that the PID gains may need to be adjusted depending on the specific aircraft being used.

2.4 Model airplane restoration

Starting on July 2021, the restoration and adequacy of a Spitfire model airplane for use in the control environment of the Wind Tunnel took place, the model aircraft was provided by the pedagogic coordination of the Aeronautical Engineering Course of the Pontifícia Universidade Católica (PUC), the first adequations were to proper seal the holes of the wooden structure of the craft as shown in Figure 6, using a self-adhesive vinyl covering.
Bruno Petrocchi de Sena Azevedo, Daniel Goulart Miranda, Isabelle de Assis Melo Franco, Arthur Felipe Gonçalves Pereira, Matheus Lucas Monteiro de Sales Pereira, João Vítor do Nascimento, Rosely Maria Velloso Campos, Guilherme de Souza Papini and Fernando Basílio Felix

PID Control System in 3 Axis for Stability of a Model Aircraft in a Wind Tunnel

Figure 6. Model airplane in 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 Figure 7.

Figure 7. Model airplane after restoration.

The model airplane was then placed and tested in the Wind Tunnel at the Universidade Federal de Minas Gerais (UFMG), as shown in Figure 8.
At first, the model airplane performance was tested without the use of the PID control system. The result for such test was as expected, wherein the aircraft without the stability system ended up not supporting the forces and loads exercised on the wings and structure, resulting in a stall\(^1\), whereupon the model airplane crashed onto the floor of the Wind Tunnel and suffered some damages as shown in the Figures 9 and 10.

\(^1\) Stall is a condition in aerodynamics that can be defined as a sudden reduction in the lift generated by the wings when the angle of attack beyond a certain point, it is called critical angle of attack.
After the initial trial the model airplane was repaired. In the proper tests in the Wind Tunnel of UFMG, the aircraft flight stability performance was tested this time using the proposed PID system, with satisfying results. Figure 11 shows the aircraft maintaining stable horizontal flight inside the Wind Tunnel during test.

3. RESULTS

After two test with 300 iterations (loops of the code) each, 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 collected, the first 20 iterations of the 300 total are presented in Table 3.
Table 3. Angles collected from each iteration of the software.

Each value represents the angle (rad) on a unit of time (second) that can be plotted as shown in Figures 12 to 15.

Figure 12. Angle per Time graph representing roll, pitch, and yaw angles of the combined tests results.

Figure 13. Angle per Time graph representing roll angles of each test.
4. PROPOSITION

The main outcome of this project is the development of a low-cost flight stability control system that can potentially benefit the aviation industry. The system can be used to ensure the stability of different types of aircraft, including commercial airplanes, helicopters, and drones. By providing a low-cost alternative to the expensive control and command systems currently in use, this project can potentially reduce the manufacturing costs of aircraft, making them more accessible to the general public. Additionally, the Wind Tunnel test results can contribute to the ongoing research in the field of aeronautical engineering and provide insights into the optimization of onboard flight controls to ensure flight stability.

5. ACKNOWLEDGEMENTS

The authors are grateful for the patronage of the project by PUC Minas specially the Departamento de Engenharia Mecânica.

6. REFERENCES


7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.