Sistema Aéreo no Tripulado para el Monitoreo de la Calidad del Aire y Gases Contaminantes Atmosféricos en la Tropósfera Baja

Unmanned Aerial System for Air Quality and Atmospheric Pollutants in the Lower Troposphere

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Abstract

In Colombia there are populated areas near cities that show accelerated industrial growth. The demographic distribution divides the residential zones from zones with the presence of industries. However, there are no studies on the impact of emissions on the population. It is necessary to know the behavior of anthropogenic emissions when interacting with air currents. For this reason, AeroTech Research Group of the University of San Buenaventura is developing a two-stage project for pollution research around industrial facilities. First stage determines the capabilities of a platform to fulfill the mission in high altitude and high temperature conditions. This article describes the integration of the automatic control system, the simulation and flights of the AQUILA aircraft. The flights were developed to configure the gains of the PID controllers and thus validate the performance using a pixhawk control system. The results are used to validate stability and control calculations and test the equipment developed by the University of San Buenaventura Medellin and the University of Medellin in the second stage. This research showed that the use of aircraft is essential to support government entities in the evaluation and control of air quality by flying in an air column with a diameter of 300 m and a maximum height of 1km.

Keywords: climate, simulation, quality control.

Resumen

En Colombia hay áreas pobladas cerca de las ciudades que muestran un acelerado crecimiento industrial. La distribución demográfica divide las zonas residenciales de las zonas con la presencia de industrias. Sin embargo, no hay estudios sobre el impacto de las emisiones en la población. Es necesario conocer el comportamiento de las emisiones antropogénicas, al interactuar con las corrientes de aire. Por esta razón, AeroTech Research Group de la Universidad de San Buenaventura está desarrollando un proyecto dividido en dos etapas, para la investigación de la contaminación alrededor de las instalaciones industriales. La primera etapa, determina las capacidades de una plataforma para cumplir la misión en condiciones de alta altitud y alta temperatura. Este artículo describe la integración del sistema de control automático, la simulación y los vuelos del avión AQUILA. Los vuelos fueron desarrollados para configurar las ganancias de los controladores PID y así validar el rendimientos, utilizando un sistema de control *pixhawk*. Los resultados se utilizan para validar los cálculos de estabilidad y control, y probar el equipo desarrollado por la Universidad de San Buenaventura-Medellín y la Universidad de Medellín, en la segunda etapa. Esta investigación demostró que el uso de aviones, es esencial para apoyar a las entidades gubernamentales en la evaluación y el control de la calidad del aire, volando en una columna de aire con un diámetro de 300 my una altura máxima de 1 km.

Palabras clave: clima, simulación, control de calidad.

Introduction

Nowadays atmospheric research is using remote sensor technology to assess environmental and atmospheric conditions to get information of air composition at different altitudes, positions, and time over populated areas. Therefore, an integrated system to manage sensor's data constitutes the foundation of air pollution studies. Unmanned Aerial Vehicles (UAV) prove to be a low-cost solution to carry payloads as sensors for obtaining pollution data, such as, carbon dioxide (CO_2), methane (CH_4), Nitrogen dioxide (NO_2), Ozone and PM10 particles (Angelov, 2012).

UAV's have become a powerful tool to support humans in military and civilian applications. As flying robots, UAV can perform high-risk missions, fly autonomously for long periods of time, work in hostile environments (e.g. high-altitude flights, toxic atmospheres, war zones) and perform repetitive tasks (Snyder, 2010). UAV technologies have been widely used in the last 10 years for many civilian uses (Gundlach, 2011) and have demonstrated potential for atmospheric field studies. For instance, Unmanned Aerial Vehicles have been successfully used over volcanoes (McGonile et al., 2008) and over the Arctic Ocean sea ice. Greenhouse gas sensors have flown on the NASA Unmanned Aerial Systems (UAS) in the atmosphere using large airplanes, including the Global Hawk; missions focused on upper tropospheric and lower stratospheric measurements. Small aircrafts and multicopters can take off and land anywhere flying for as much as 60 minutes and covering many hectares (Agudelo & Jiménez, 2013). Basically, the operator press a start button on a laptop, tablet or smartphone and the UAV flies the entire planned mission on its own allowing to sample inaccessible areas within the layer of the troposphere up to 1.5 km above the ground. By the other hand, satellites, balloons and kites do not have the plane spatial resolution to identify distributions of air pollutants and gases within the troposphere, they only can get data over a single location, and the deployment is limited to weather conditions (Bolton, 1994). Data acquisition of air at different conditions over populated areas imposes some design challenges for UAV platforms that will carry remote sensors. In the first place, Atmospheric Data acquisition system (ADAS – Aquila UAV) is able to take off and land in any reduced area to take samples in waypoints over populated cities. The first option is a vertical takeoff and landing UAV (VTOL), however, aerodynamic characteristics, endurance and payload capacity are very limited, up to 10 minutes and 1 kg of payload (Austin, 2010). For this reason, a fixed wing platform seems to be a reasonable solution to extend flight time and capacity. As requirements, reliability in all flight modes is another important fact; Aquila can fly in a controlled airspace and over high populated areas. Consequently, an electrical platform is the most affordable solution for AQUILA. This platform is going to be used in high impact applications that will benefit the inhabitants of Aburra Valley in Medellin, Colombia. However, AQUILA can be used to perform similar missions in other cities or townships operating at similar "Hot 'n high" conditions of South American Andes.

Figure 1. Atmospheric Data Acquisition System ADAS – AQUILA.

This paper describes the first stage in the design process of AQUILA UAV designed to operate in the typical Andes mountains of Colombia, the implementation of automatic control systems, telemetry devices and sensors payload to interpret data for air pollution studies that will be used to decrease environmental impact in areas nearby industrial facilities beside to populated areas. AeroTech research group has decided to begin the design process with the integration of the automatic control systems, PID controllers tuning, HIL simulations and flight testing that are the initial reference to meet de design requirements of AQUILA UAV.

Therefore, it is presented an experimental validation of autopilots to determine a standard method for tuning PID controllers. First, airplanes are assembled using traditional fabrication techniques in balsa wood manufacturing and fiberglass fuselage, reinforcing critical joints, as wing root, with carbon fiber-epoxy layers. In the second place, experimental flights are conducted to get telemetry data and the time response of the airframe. Also, data of Hardware in the Loop simulations in AeroSim R/C simulator is used to compare the dynamic behavior in order to determine transfer functions in pitch, roll and yaw. Finally, tuning methodology is proven in automatic flight paths; similar to the real operations of AQUILA UAV.

Methods and Materials

Development of Atmospheric Data Acquisition System ADAS – AQUILA takes into account three stages. First, design and implementation of sensors and the aerial platform is considered. Second, integration of pixhawk controller, as reference platform to configure control, navigation systems, and performance capabilities. Finally, the third stage that involves detailed design of AQUILA UAV and the manufacturing process.

Design requirements of second phase are influenced by the environmental measurement Research Group at Universidad de San Buenaventura, Medellin Colombia (Cárdenas, Echeverri, & Jimenez, 2010). Instrumentation is composed of different subsystems capable of measuring and acquiring concentrations of carbon dioxide, methane, nitrogen dioxide, carbon monoxide and ozone using infrared technology and semiconductors. IR-EK2 evaluation board, MISC-EK1 and MICS-OZ-47 devices allow to get data that is saved and transmitted to the Ground control station (GCS).

In Colombian Andes, the elevation of the ground can change dramatically in very short distances. Aburra valley is an example of a 1500-meter height altitude change in less than 70 km horizontal distance. For this reason and limitations of performance and altitude above the ground required to study pollution of lower troposphere, 12,500 ft seems to be a reasonable altitude for pollution data collection. Flying at 80 kph, AQUILA UAV can cover 80 km from the ground central base in one hour. The wider part of Aburra Valley corresponds to the municipality of Medellin with 80 to 90 kilometers. It means that in 1,5 hours an UAV could cross the entire valley in a single pass. To ease the platform operation and versatility, a short takeoff and landing concept is considered for the final design. Circular flight paths are proposed to get data for a complete column of air over the designated area of the study. Finally, electric power plant is used in order to increase reliability and avoid interferences between the measurements with the combustion engine exhaust gases.

Integration and manufacturing process. The type and size of AQUILA UAV depends on the payload volume and weight, as discussed in the design requirements. In addition, the larger the aircraft, the less it would be affected by environmental conditions such as wind. Enough payload space inside the airframe allows working easily inside the aircraft. By the other hand, larger airplane does produce limitations and problems, it is more expensive to build and operate than smaller aircraft and require a larger vehicle to transport it from the laboratory to the test site. Two flying sites are used to perform tests, all of them located near Universidad de San Buenaventura campus. To reduce time to design and test a platform, an Almost Ready to Fly (ARF) kit is used. After performing an investigation about model airplanes in the range of 3 to 7 kilograms of maximum takeoff weight and its availability, the 2600 mm FPV model Swallow airplane became the best choice (Dantsker, Johnson, Selig, & Bretl, 2013). The ARF airplane has 2-piece wings with a wingspan of 2600 mm, and an empty weight of 3300g. Also, it has a high load capacity in its fuselage due to its internal space, and then it is a perfect airplane to install the electronic systems of control and payload. It is a good platform to take extra weight for payload. That is the reason whereby the R/C is equipped with an onboard instrumentation system, in order to perform more than 20 flights in which parameters are varied, among them velocity, magnitude of control deflections, power, and altitude to set the aircraft for autonomous flights. The instrumentation provides the telemetry of each flight, time histories of the trajectory, aircraft attitude, global position, airspeed, groundspeed, velocity, R/C channels and servo information. Moreover, powerplant selection has to be made. By using an electric system, the center of gravity does not shift during flight due to weight change of fuel consumption. Finally, electric motors have constant performance and do not need to be tuned at different altitudes (Ragheb, Dantsjer, & Selig, 2013). A disadvantage compared with gasoline engines would be endurance, but for the first stage of the project there is no need of performing long range flights, in fact, the calibration process requires great number of short duration flights to adjust gains in the flying field and verify the airplane behavior. The aircraft is powered by a Hacker A60 Outrunner Motor fitted with a 19 X 10 APC propeller.

To provide the necessary energy to the powerplant and other systems a 120 Amp electronic speed controller and 10 000mAh 8S 30C LiPo Battery. This power source provided approximately 55 min of flight time. To transmit real-time data obtained in each flight, a set of Optima 9 Ch. 2.4 GHz Receiver and a 900 MHz transmitter are used. From the requirements shown above, it is stated that aircraft maximum takeoff weight will be exceeded. It is necessary to make a modification to improve structural integrity (Jiménez, 2013). Moreover, changes included upgrading of the servos and plywood reinforcement near components that would support heavy structural loads such as servos housing. Carbon fiber is applied in the wing center section, to increase the structural integrity of the wing. Due to the axial and shear stresses, fibers must be stacked up at 45 and 0 degrees in 2 layers above and under the wing. It is used wet layup process because it is a low-cost solution. Images below show the procedure and the results.

Since the propulsion system is converted to electric, several changes need to be made. Modifications include a motor mount, firewall alteration to allow wiring to come from main battery and cooling ducts designed over the motor cowl to ensure a proper ESC and motor operation temperature. Battery is placed after the firewall near cooling holes to prevent overheating and consequent damage. It can be moved aft or forward to adjust CG location depending on the payload installed. Results are shown in the images below.

Figure 2. Power plant installation.

Autopilot system implementation. Pixhawk works over an open source code that allows modifications to enhance the UAV capabilities, such as the integration and manipulation of different equipment onboard from the ground control station. It uses a telemetry module and a 900 MHz antenna to transmit flight data to the ground control station in real time. The images below show the final location of equipment. A 3000 mAh and 11.1 volts LiPo battery is used to power autopilot, servos (Agudelo, Zuluaga, & Jiménez, 2014). A Ground Control Station (GCS) was also configured. It contains a video receiver, a telemetry modem recovers, a monitor to visualize real time images sent from the airplane and a laptop that runs the software to interact with the autopilot system.

Results

More than 15 flights were conducted to verify systems operation and reliability, and to prove autopilot system capabilities following flight paths while maintaining adequate airplane attitude. PID gains calibration is conducted to improve the flight capabilities to follow a specific flight plan while maintaining adequate pitch, roll and yaw angles and speed with respect to the ground. The airspeed sensor has a great influence to maintain airplane attitude during windy conditions, slow flight and autonomous landing. AQUILA UAV is a low speed platform, by this reason the speed sensor has to be calibrated. By default, the system has a correction factor to establish the error between the ground speed, measured from the GPS indication, and the airspeed measured by the pitot probe. Initial experimentations stated a huge mistake range from both measures. Applying calibrations methods, which include a large circular flight patterns and a comparison of data obtained, allows us to recalculate the correction factor. The system shows good ability to follow specific trajectories determined by GPS coordinates, as well as controlling different payloads though the autopilot software. Long range communications are tested as far as 6 kilometers proving a reliability and safety link between the airborne module and the GCS. Many high-altitude tests are conducted in order to validate the system performance under low temperature environment. Maximum flight time was 55 minutes carrying two 14,8 volts and 10 000 mAh batteries onboard. Maximum take-off weight for maximum endurance was 9,4 kilograms. Finally, AQUILA UAV performs the test flight phase, to validate the theory and establish the operating characteristics for missions, this set of flights allows detecting the load and maximum weight configurations, to get operational limitations, in the following figure it is shown the first flight.

Figure 3. AQUILA UAV First Flight.

High altitude flight was performed to prove data link at 1 kilometer above the ground, emulating the flight pattern AQUILA UAV will perform to obtain air quality information. As a result, the performed automatic circular flight pattern is shown in the following figure.

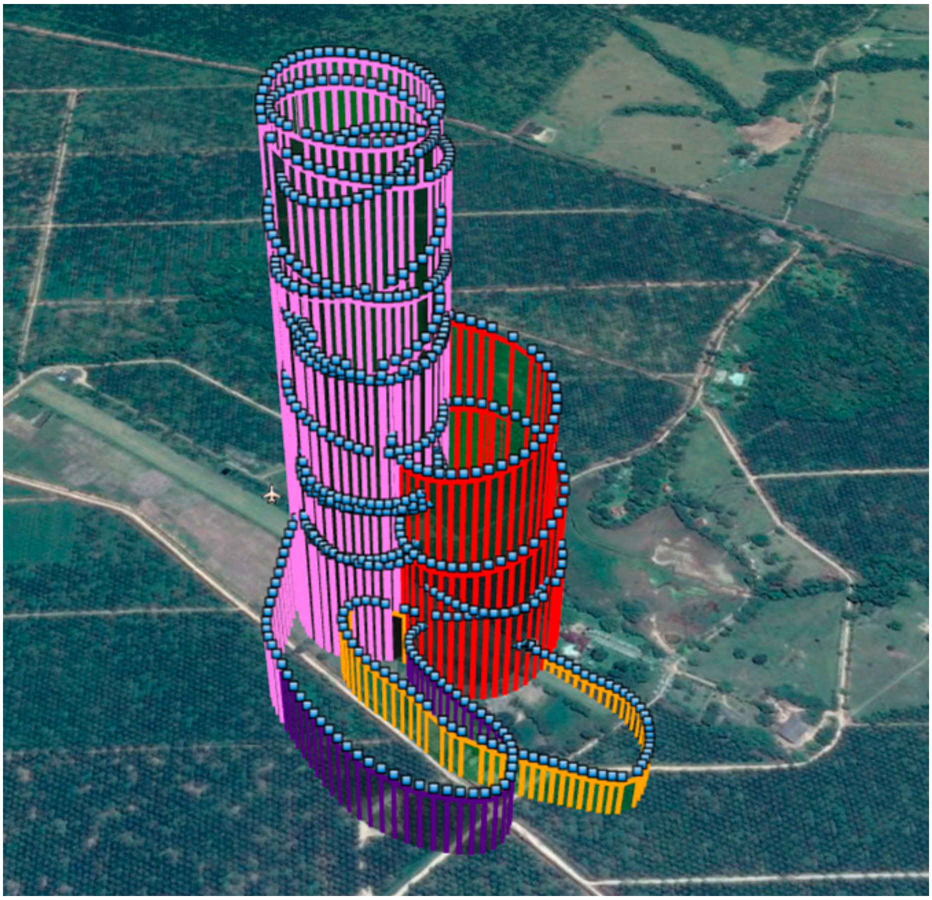

Figure 3. Circular flight pattern 1km above the ground.

PID tuning is based on experimental assessment, following the classical techniques to tune the controller. The actuating signal for PID control is given by,

$$e_a(t) = e(t) + T_d \frac{de(t)}{dt} + K_i \int e(t)dt \qquad (1)$$

In Laplace domain,

$$E_a(s) = E(s) + T_d sE(s) + \frac{K_i}{s} E(s) = (1 + sT_d + \frac{K_i}{s})E(s) \qquad (2)$$

The block diagram of a second order system incorporating PID control is shown in figure below.

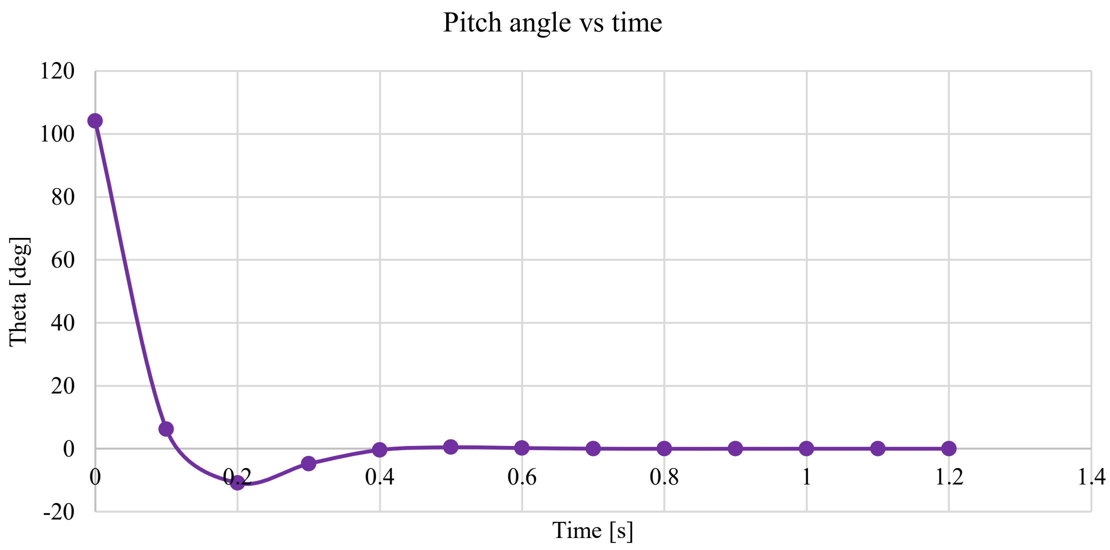

Figure 4. Second order system PID control.

Consequently, during flight testing each gain is tuned considering telemetry of pitch, yaw, and roll angles and rates, altitude, airspeed ad navigation parameters. Then, a validation process is performed for pixhawk in Hardware in the loop simulations (HIL) AeroSim R/C and the system identification toolbox in MATLAB. Pixhawk uses different strategies to tune PID gains. Following tables show PID controllers based on architecture.

Table 1. PID Controls Implemented on Flight Stabilization and Navigation by pixhawk.

PID name	Controls	From
Aileron from roll	Ailerons	Roll angle difference
Elevator from pitch	Elevator	Pitch angle difference
Rudder from Y accelerometer	Rudder	Y accelerometer angle
Rudder from heading	Rudder	Heading angle difference
Throttle from speed	Throttle	Speed difference
Throttle from altitude	Throttle	Altitude difference
Pitch from altitude	Pitch	Altitude difference
Pitch from AGL (Above Ground Level)	Pitch	AGL altitude difference
Pitch from airspeed	Pitch	Airspeed difference

PID name	Controls	From
Roll from heading	Roll	Heading difference
Heading from cross track error	Roll and yaw	Heading difference
Pitch from descent	Pitch	Descent rate difference

Table 2. PID Controls Implemented on Flight Stabilization and Navigation by Ardupilot.

PID name	Controls	From
Servo Roll	Ailerons	Roll angle and rate
Servo Pitch	Elevator	Pitch angle and rate
Servo Yaw	Rudder	Yaw angle and rate
L1-Turn Control	Navigation	Navigation
TECS (Total Energy Control System) for Speed and Height Tuning	Height and speed	Barometric altitude, GPS altitude and airspeed

During the process of validation, telemetry was analyzed to determine the best series of data for each gain. Transfer functions were identified using the "cleanest" data. Following figure shows pitch as an example.

Finally, HIL simulation was a very useful tool to validate the PID tuning. It was possible to determine accurate gains before to complete a flight test.

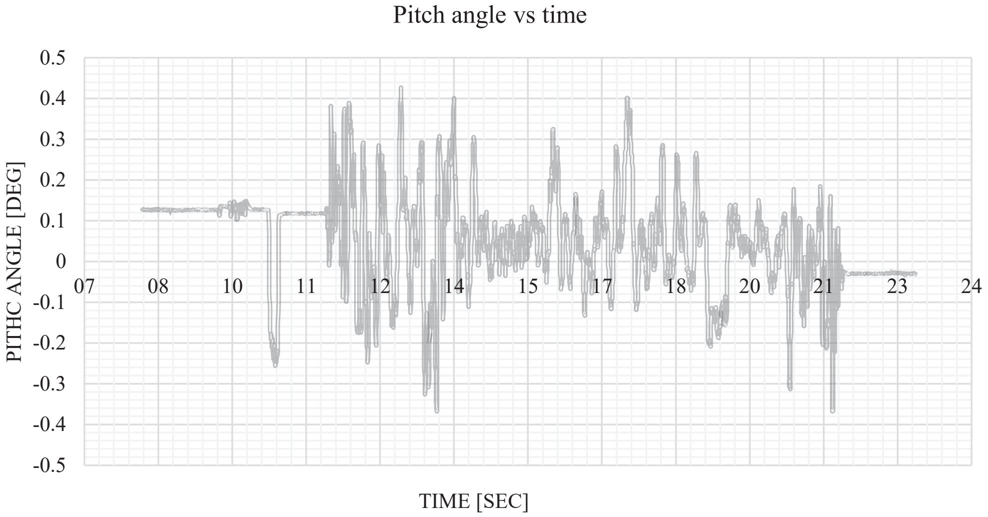

Figure 5. Telemetry data from Pixhwak.

From the telemetry data, pitch transfer functions are determined with MATLAB. From the gathered information, PID gains calibration is conducted. The pitch transfer function is shown.

$$G(S) = \frac{-0.3345\,s^2 - 1.877\,s - 0.04617}{s^4 + 15.72\,s^3 + 480.2\,s^2 + 4.385\,s + 76.08} \quad (3)$$

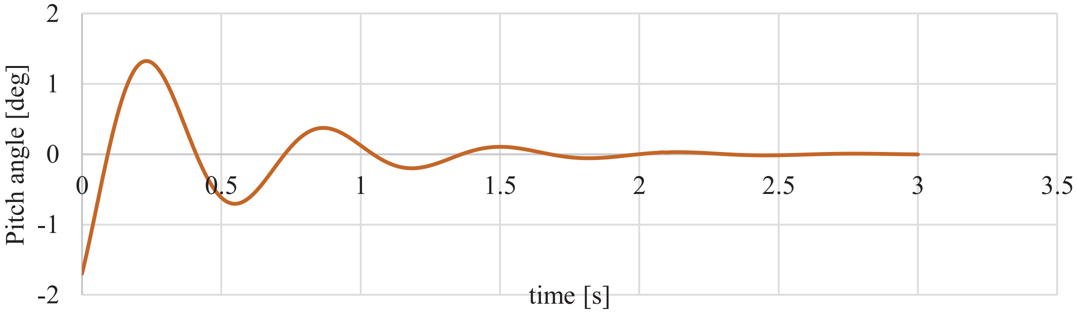

Figure 6. Pitch transfer function expression.

Conclusions

The first phase of Atmospheric data acquisition system AQUILA UAV was developed to calibrate automatic flight control systems and to evaluate Unmanned System capabilities for pollution studies. The airplanes flew as predicted in the design configuration, had good handling qualities along the entire range of speeds, excellent electric motor reliability, low levels of vibrations and good automatic navigation behavior.

The airplane was able to takeoff from grass runways and paved roads in less than 15 meters at a density altitude of 3,200 m. Payload weight was verified carrying 4260 gr of additional equipment. Desired 5kg of payload was not able to reach due to aerodynamic, performance endurance requirements. It is suggested to maintain sensors weight as low as possible.

Data provided in real time by the autopilot control system proved that stall speed, maximum speed, range, endurance, operating ceiling, and takeoff and landing distance were met. Circular flight paths of 1 km above the ground were also encountered.

UAV flight endurance was a very complex task due to limitations of performance in an R/C model. Maximum flight time was 55 min. 1,5 hours can be possible to reach optimizing critical performance parameters as L/D ratio, W/S, T/W, motor selection, propeller and the most important, battery technology. Exact maneuvers such as flying at constant altitude, heading and speed, were accomplished using the Pixhwak system. The information retrieved from the test flights was of great value to configure the autopilots for autonomous flight. The information obtained from autopilots systems was used to formulate a dynamic model of the aircraft to configure PID gains based on systems identification. Valued experience on navigation and flight plan programming was acquired in the test flights.

Several PID gains were tuned experimentally using flight tests and Hardware in the loop simulations in AeroSim R/C simulator, validated with system identification toolbox in MATLAB. Seventeen transfer functions were calculated for AQUILA UAV platform.

More than 15 flight tests were performed during the validation process to configure automatic control systems and flight paths.

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