Analysis, Design and Implementation of an Autopilot for Unmanned Aircraft - UAV's Based on Fuzzy Logic

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***Abstract*— The UAV (Unmanned Aerial Vehicles) they have demonstrated their enormous capabilities in military and civilian applications in recent years. They have become an indispensable tool in the field of defense, security and support for the development of a nation. Similarly, the technological development has allowed these aircraft to fly autonomously thanks to electronic control systems called autopilots. The functional architecture of the autopilot which has been presented in this paper bases its operation on fuzzy logic for complete control of the aircraft, in stability, altitude, course, direction and acceleration using the minimum possible controls, reducing the computational processing. The system presented is tested through multiple flight hours in different climatic conditions, the results are satisfactory and the system shows to be really promising. Both the hardware and software of the proposed control system are the result of teamwork of Ecuadorian researchers.**

Keywords*— *autopilot; UAV; fuzzy control; autonomous flight; fuzzy logic

I. INTRODUCTION

At present the UAV (for its acronym in English: Unmanned Aerial Vehicles) have demonstrated the great potential that can keep in different civil and military applications. Applications such as monitoring borders, recognition of areas at risk or natural disasters, determine areas polluted by hydrocarbon spill [15], agricultural monitoring or soil erosion [16], forest fire, or geographical uprisings are some examples of the applications that this technology has been fulfilling.

No doubt the future of aviation is closely linked to the field of UAVs, they have had considerable progress in recent years. The development and construction of a UAV is not an easy task, nor a single line of research, involving several branches of engineering and aerodynamics, power and propulsion systems, airframe structural analysis, and electronic flight control systems [1], with the sole purpose of putting these systems in air autonomously.

UAVs can be controlled or managed remotely via radio, but currently new control systems have been studied and developed to be capable of maintaining stable UAVs in the air along the proposed route, these intelligent systems called automatic pilot or autopilot are commonly on board of a UAV to replace the human factor in flight operations. Thus, they control the UAV autonomously by generating control signals, such signals allow to control the altitude, heading, speed and other variables of the aircraft [1].

Today it has been evidenced a variant in the algorithms of navigation and control of UAVs in automatic mode, although the traditional PID [9] [26] remain the most used and marketed autopilot systems due to its easy application and the ability to adapt to multiple platforms [10].

Most autopilot systems commercially available worldwide use PID controllers in closed loop, that is to say with feedback. Among the best known commercial autopilots we can mention the company Micropilot [11] which uses a PID cascade control with feedback loops. The autopilots of Piccolo series developed by the company Cloud Cap Technology [12] are based on PID control efficiency for autonomous flight. The autopilot model Kestrel of the company Procerus Technologies offers ease of tuning in real time PID constants on board [13]. The Guidestar autopilot was developed by Athena Technologies uses PID control techniques for the control path, both in altitude and heading [1] [14].

PID controllers are generally used on unmanned aerial vehicles due to its rapid implementation, but have limitations on the stability, robustness, in addition to how complex mathematical system identification could be [10] [1] because of the not linear aircraft characteristics. It is for this reason that universities and research centers around the world have developed technologies related to autopilot systems, based on different control techniques [27] [28] [29], such as monitoring based on fuzzy logic [2], state feedback control [3], models based on neural networks and neuro-fuzzy [4] models [5], multi-agent-based control [6] with self-tuning adaptive control [7] [17], nonlinear control [8] among others.

Of the many possible control techniques for controlling and monitoring UAVs so far, in this paper we present the design of an autopilot based on fuzzy logic, for the complete control of the aircraft that is stability control, altitude, track route, direction and acceleration. The proposed autopilot presented in this paper is implemented in a UAV of CIDFAE. Both the hardware and software design of the autopilot, as well as the structure of the aircraft were developed 100% in Ecuador.

This paper is organized as follows: In Section 2, autopilots based on fuzzy logic and similar projects are reviewed. In section 3, the overall design of the proposed fuzzy system is described. Section 4 discusses the results of the applied testing

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plan. Finally in Section 5 the conclusions and future work are presented.

II. STATE OF ART

A. Autopillots based on fuzzy logic

As mentioned previously, the classic PIDs based control, has certain limitations, new techniques of less complex and easy implementation with excellent results are sought, being the fuzzy systems a field to meet these conditions. Nowadays fuzzy systems are becoming more robust with new coping mechanisms, its easy implementation and efficient results, which enabled the development of more practical applications [18]. Currently, several approaches have been developed in the field of automatic control of UAV based on fuzzy logic. In this research field Óbuda University presented the AERObot [19] a UAV with an autopilot that bases its operation of flight (takeoff, cruise and landing) entirely in a fuzzy control, and analyze its applicability in comparison to other partial or hybrid Control [20] [21] having promising results.

Another clear investigation of an autopilot based on fuzzy logic, is the presented in [2] where the main navigation system is based on 3 modules of fuzzy logic to control the altitude, flight speed and trajectory respectively, being the error (difference between the desired value and output) and the rate of change in error the inputs of fuzzy modules. The results and robustness of the controllers were tested in flight simulators and systems of mathematical modeling, the results indicate the desired system performance.

Likewise, the autopilot developed for the Japanese aircraft Kiteplane presented in [22], bases its operation on fuzzy logic, where all the navigation process, modeling and trajectories generated by the UAV of the Kiteplane are described optimally and its robustness can be appreciated in the fuzzy control despite the disturbances generated by the wind, this research includes theoretical results and implementation with field tests of the system.

The fuzzy control using C-Means Clustering proposed by the University of Texas [23], the autopilot based on fuzzy adaptive control proposed by the Beijing Institute of Technology School of Aerospace Engineering [24] or the fuzzy controller for UAVs based on 3D visual estimation [25] are clear and specific research that the field of fuzzy logic is a feasible and developing area for keeping control and navigation of unmanned aircraft.

The vast majority of the above mentioned works were developed in Asia, Europe and the US, there is almost no information or record of this technology being developed in Latin America, for that reason we stress that the study and implementation of this research was developed entirely by Ecuadorian researchers from the CIDFAE.

III. ECUATORIAN UNMANNED AIRCRAF SYSTEMS

A. UAV general design and characteristics

The Ecuadorian Air Force through its Research and Development Center, has been a pioneer in the field of unmanned aviation in Ecuador since 1994, it has been built 5 types of aerial platforms with different designs, features, materials and equipment, all with the primary objective of monitoring, homeland security and development support

The control system proposed in this article is implemented in the aircraft called FAE-UAV-PELICANO that includes the following characteristics:

- Wingspan 4 meters; Cruising speed 80 km / h; Load 10lbs; 12000 feet ceiling operation; Takeoff 61 meters; Landing 91 meters; Autonomy 30 min

Figure 1. FAE-UAV-PELICANO Aircraft

Its programming logic and operation are based on the scalable and adjustable block diagram that is shown in Figure 2. Each module performs a specific task that allows autonomy, control and stability of the aircraft.

Below the main modules of the system are briefly described:

• Module of the power and propulsion system: It has an alternator 900 watts, 28 volts 32 amps, which is responsible for providing different levels of electrical potential (via voltage converters) required by the teams that interact in the aircraft being 8 volts for servo-actuators, 12V for the autopilot and 28 volts for cameras, datalink and instrumentation, additional is counted as a battery bank power backup in case of failure of the main generator. Regarding the propulsion system of the aircraft, it has a 342cc engine, with an output of 25hp 6500 rpm as maximum

• Module of the communication system: This module implements two radio links for communication with the ground station. The main link operates in a frequency band of 900MHz and in case of losing the main link has a redundant link of 2,46Ghz

•Module of sensors: the aircraft has 6 sensors to determine the conditions associated with it, plus the other modules process this information to make decisions corresponding to location, paths, high speed etc. The sensors in the aircraft are: GPS, inertial, altitude, airspeed, fuel, battery charging

• Module of actuators and control surfaces: The aircraft has nine servomotors for moving control surfaces, (2 for ailerons, 1 for rudder, 1 for elevator, 1 for throttle, 1 steering of the front axle, 2 for flaps, 1 for brakes). Additionally, it has a filter system and signals regeneration for the servomotors (power-box system) which ensures that the PWM signals received by servomotors are stable and noise-free.

• Module of Navigation: This module builds its working principle in generating trajectories based on waypoints where you want the aircraft to go, this module operates and generates the route based on an algorithm we designed, which takes the data from the GPS and the inertial sensor on board the aircraft to calculate distance and angle of rotation, to bring the aircraft to the corresponding waypoint.

• Module of processing and central control: Coordinates all processes in the aircraft from communication (with the ground station), flight control, navigation, as well as interaction between modules. This module is the brain of the autopilot and is implemented on the FPGA NI MyRio pro-card and AVR micro-controllers.

Additionally, according to the mission assigned to the aircraft, it can be equipped with more sensors or equipment such as electro powerful cameras, infrared cameras, etc.

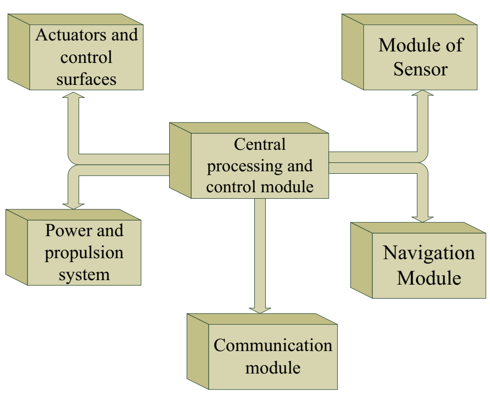

Figure 2. Modular Structure of the System

B. Autopilot System Based on Fuzzy Logic

The control system based on fuzzy logic we propose must be able to largely control the throttle and the control surfaces (elevator, ailerons, flaps and rudder) according to the information provided by the sensors (airspeed, altitude, angle stability, position, etc.). In this paper, we explain both the design and operation of the overall controller.

The principle of operation of the fuzzy system is illustrated in Figure 3. For the aircraft to achieve a stable flight according to the conditions and the prompted trajectory, we mainly divide the operation in four control loops.

A control loop responsible for the navigation and compliance with the established route, a second control loop which is responsible for the stability of the aircraft, a third control loop verifies that the altitude of the aircraft is in the desired value, and finally the fourth control loop is responsible for the verification and monitoring of the airspeed of the aircraft, all these drivers work together to keep the aircraft in the air stably.

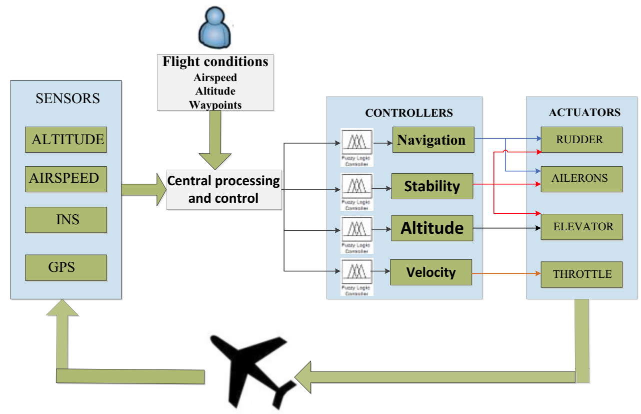

Figure 3. Control scheme and operating principle of the fuzzy system

In Figure 4, the control loop implemented for the stability control of the aircraft, the target of this loop is to keep aircraft straight, leveled and stable on all 3 axes, regardless of disturbances such as turbulence, crosswinds, etc.

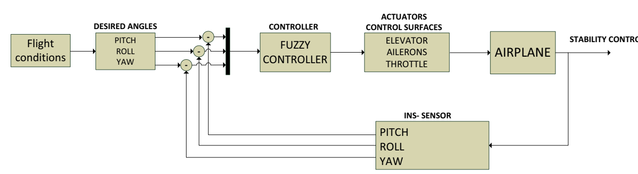

Figure 4. *Stability Control Loop*

As shown in Figure 4, this system is a closed loop controller. The input for the fuzzy controller is the difference between each of the desired for each axis and the present aircraft angles to these axes determined by the inertial sensor on board. Stated another way, it is desired that the aircraft flies up straight and leveled at its 3 axes (pitch, roll, yaw), before any variation or disturbance the controller must take immediate action and correct the variation moving control surfaces, placing the aircraft again in a stable position.

Fuzzy inputs

For the stability control of the aircraft are considered 3 inputs for the fuzzy system being these, the error in each axis (difference between the desired angle of roll, pitch, yaw and the current angle of the aircraft for these axes).

In order to characterize the different levels of error the following membership functions are defined for each axis (Figure 5).

Very Large Left Error (-50 to -22), Big Left Error (-25 to -15), Left Medium Error (-20 to -10), Small Left Error (-15 to -5) Very Small Left Error (-10 to -1.5), Close to Zero (-3 to 3), Very Large Right Error (22-50), Large Right Error (15-25), Medium Right Error (10-20), Small Right Error (5-15) Right Very Small Error (1.5 to 10)

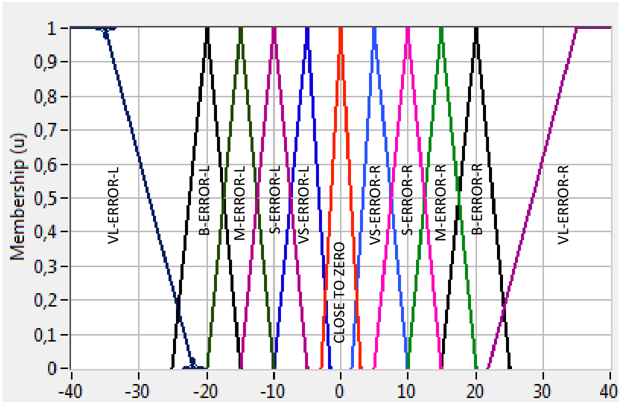

Figure 5. Role of membership for input, Axis Roll

Fuzzy outputs

The output of the fuzzy controller represents the angle correction to be sent to the actuators, which consequently move the control surfaces by changing the attitude of the aircraft, achieving the stability of the same. Y is defined by the following membership functions for each axis (Figure 6):

Very Large Left Correction (-40 to -23), Big Left Correction (-25 to -10), Medium Left Correction (-12 to -5), Small Left Correction (-5.5 to -2.5), Very Small Left Correction (-3 to -0.25) Maintain position (-0.5 to 0.5), Very Large Right Correction (23-40), Large Right Correction (10-25), Medium Right Correction (5 12) Small Right Correction (2.5 to 5.5), Very Small Right Correction (0.25 to 3)

Fuzzy rules

To define the rules of the drivers, a ratio of input-output should be established in order to adjust the correction values to the parameters given by the operator. For the stability control in 3 axes 30 rules were established.

The shape and values of the membership functions and the rules listed above has been established on the basis of multiple testing platform considerations by air and aviation experts.

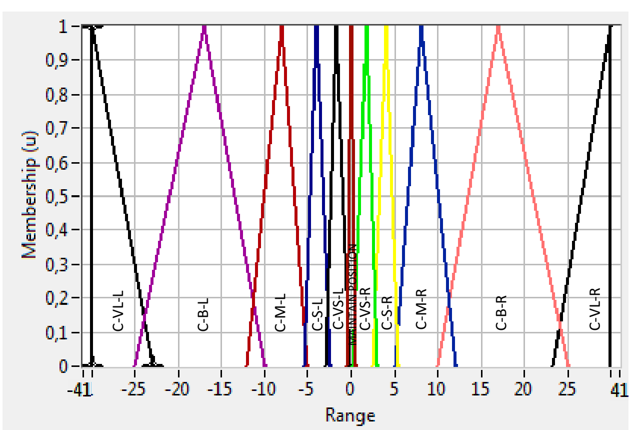

Figure 6. Membership function for output. Axis Roll

1) Navigation

One of the main features of the autopilot is the ability to autonomously follow a route specified by the operator. The control algorithm designed for navigation, based its operating principle in generating trajectories based on waypoints where you want the aircraft to go, this module operates and generates the route taking the data provided by the GPS and sensor INS to calculate distances and angles of rotation, and thus bring the aircraft to the appropriate waypoint. These values are passed on to the fuzzy controller, which modifies the position of the actuator carrying the aircraft to the desired point.

The fuzzy controller in charge of the navigation of the aircraft receives as an input parameter the error of direction, that is to say the difference between the desired course and the actual heading of the aircraft, for the calculation of course we assume that the aircraft has a constant height.

First the distance D between the current location of the aircraft (determined by GPS) and the waypoint where the aircraft must go is calculated. This is done by known geometric calculation points [31], as shown in Figure 7.

Similarly, by means of geometric calculation, the azimuth angle (β) that forms the straight line connecting the position of the aircraft with the corresponding waypoint is calculated. The angle α is the angle or course that has the aircraft relative to magnetic north, this value is determined on the INS sensor.

$$\beta = atan2\ (Dy,\ Dx) + 180 \quad (1)$$

$$\alpha = \text{value determined on the INS Sensor} \quad (2)$$

$$\theta = \beta - \alpha \quad (3)$$

The θ variable will be provided as input to the fuzzy controller to take care of correcting heading and guide the aircraft to the appropriate waypoint.

Since the system is prone to small errors due to factors such as the used sensors, presence of disturbances and flight speed, condition or criterion arrival was designed in order to prevent the aircraft to take sharp curves or on the worst case to start spiral travel trajectories trying to reach a point.

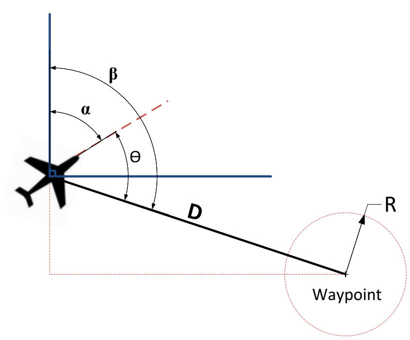

Figure 7. Scheme of angles and distances of the navigation system

A waypoint is considered achieved if the current distance (D) of the aircraft to the point is less than a threshold value R, in other words if the aircraft reaches or passes within a circle centered at the target point of radius R (Figure 7), is deemed to reach the waypoint, Figure 8 presents a flowchart of the algorithm implemented

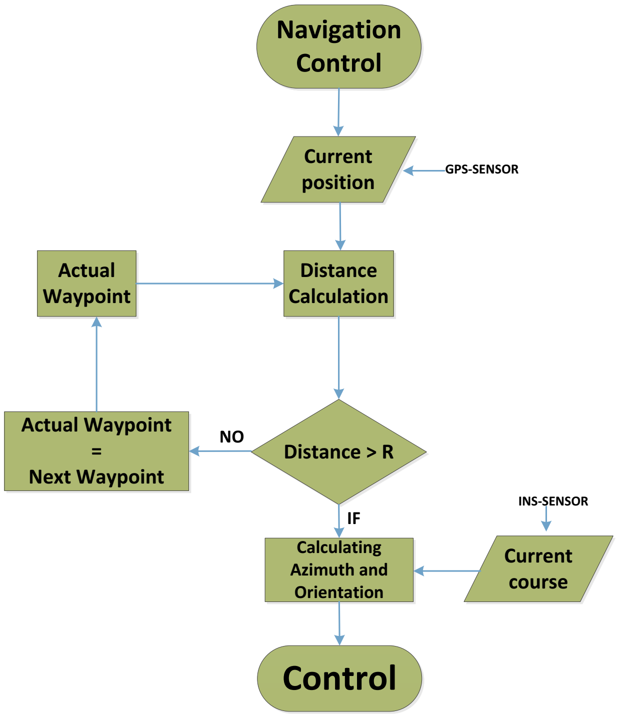

Figure 8. Flowchart of the navigation

For the autopilot to decide the optimal side that the aircraft should turn, that is the smallest shift that the aircraft should give to reach the target point, rotation conditions were created: If the value of θ is positive the aircraft turn right if θ is negative the aircraft turn left. Additionally, a third condition is included: if the aircraft must rotate more than 180 ° is preferable to change the direction of rotation as the angle to be traveled will be smaller.

The other two subsystems responsible for controlling the altitude and speed remain the same principle as the previously exposed controllers, which differs are the reference parameter and input to the controllers in conjunction with the fuzzy rules.

For attitude control it has been considered as input the error between the desired altitude and altitude of the aircraft, the functions of belonging for both input and output follow the same principle as discussed above with 15 fuzzy rules that control the actuator- elevator of the aircraft. Similarly, for speed control an input parameter to the error between the desired speed and the speed of the aircraft, with 12 fuzzy rules has been considered.

IV. PRELIMINARY RESULTS

In order to determine the accuracy of the fuzzy controllers and the complete operation of the system, flight tests were conducted. The tests consist on following a defined path, determined to maintain a stable altitude and keep the aircraft on its axes. The results are shown in Figure 9 to 12th

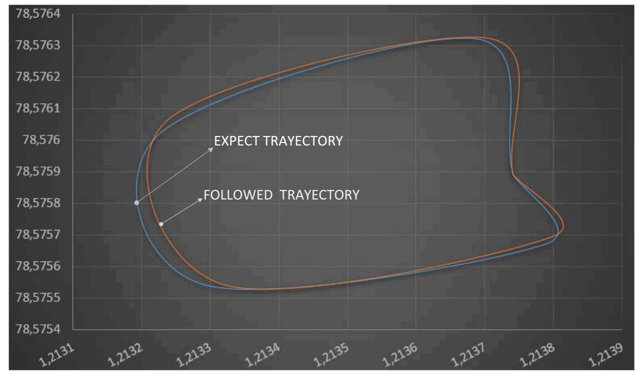

Figure 9. Expected Trajectory vs Followed Trajectory

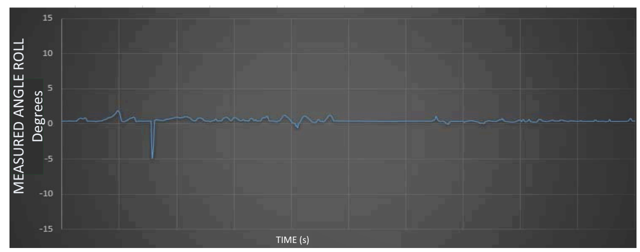

Figure 10. Axis roll angle of the aircraft during the test

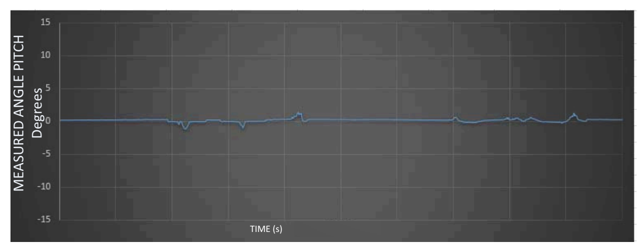

Figure 11. Pitch angle axis of the aircraft during the test

Figure 12. Desired Altitude vs altitude measured during the test

V. CONCLUSIONS

As shown in Figures 9 to 12 the system has the expected behavior, the aircraft maintains a constant stability in their axes, while continuing the expected trajectory, there are curve paths where the aircraft leaves the route, this is due to external disturbances and winds, but the driver corrects that error. Finally, it can be appreciated that the aircraft maintains a constant altitude based on the expected parameter.

As indicated in Figure 3 this system has 4 fuzzy controllers for complete control of the aircraft, which significantly reduces computational processing. Having only this number of controllers (based on fuzzy logic) simplifies the system, making it more efficient, fast, and above all easy to implement. Also if we compare costs of the proposed system with other systems such as Micropilot® or Piccolo® autopilots, our system is more economical because the commercial value of the mentioned systems is around $ 40,000 and the cost of our system does not exceed the 5,000. An extra advantage of our system is that it has been implemented and tested on aircraft of considerable size (length of 4 meters wings) unlike the vast majority of commercial autopilots that have only been tested on small aircraft.

This paper begins a line of research in UAV autopilots for Ecuadorian production. As future work we propose to implement this system in the aircraft UAV- Gavilan-2 which is the most advanced prototype developed by the CIDFAE. The system to be implemented would remain the principle of operation but adapting it to the characteristics of the aircraft as Gavilan-2 has a Spam (7.5 meters), weight (293 lbs), range of 5 hours, a roof flight (15,000 feet), full speed (130km / h)

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