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# Design and Implementation of a Control and Navigation System for a Small Unmanned Aerial Vehicle

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Abstract: This paper describes the development of a control and navigation system for a small scale unmanned aerial vehicle (UAV) using as strategy a combination of classical control and Fuzzy Inference Systems (FIS). In this sense, the air-plane has been modelled through analytical techniques that use empirical estimations to compute the force and moment components acting on the aircraft. The control systems were designed using the aircraft's transfer functions to reach a desirable response for each command. Finally, the navigation control system is designed using a FIS to control the roll of the aircraft and the yaw control system to control the aircraft's heading. A route composed of waypoints is generated following a rummage of a selected area. The control systems are, then, tested in a simulated environment to ensure they accomplish the desired mission when they work together.



*Keywords:* UAV, Aircraft control, Aircraft Navigation, Fuzzy inference, Control system, Modeling techniques

## 1. INTRODUCTION

Unmanned aerial vehicles (UAV) are currently being studied as cheaper and efficient alternatives to different tasks, in civil and military applications, as precision agriculture, natural disaster risk zones and border and critical infrastructure monitoring, etc. In the military, the development of these vehicles are getting great attention in different countries due to their economic advantages and to their main capability which is leaving people out of the combat zone (Yun 2013). In agriculture, their use extends from plantation disease focus detection (in precision agriculture) to terrain mapping and flock management. They also provide superior detailing when compared with other technologies such as satellite imaging (Efron 2015). This class of vehicle's use extends also to natural disaster response as they can be used to identify risk zones and identify victims.

This paper proposes solutions to the control and navigation of a small fixed wing UAV using Fuzzy Inference Systems (FIS) and Classic Control Techniques. A basic requirement of this aircraft is to use a solution that can be implemented in commercial low cost computation platforms, being still able to execute the correct navigation control and the desired movements. The airplane's control should be able to navigate the airplane through waypoints and to control the airplane's attitude between waypoints in the desired way. Initially, these system's implementation will be in a simulated environment using Matlab and Simulink software.

The airplane that is going to be used in this research has been designed specifically to the recognition and sweeping tasks. With a payload of 1 kg, the plane is 1,8 m long in wingspan, has a length of 1,5 m and a height of 0,7 m. The motorization is electric using an induction three phase motor rated at 1036 W and generating a 25 N thrust. The aircraft doesn't have fuselage as all of the payload goes inside the wing (including control and sensor hardware). The tail controls are a rudder and an all moving elevator. One of its important characteristics is the capability of taking off and landing in difficult terrain which is achieved by the use of removable landing gear (being able to use an airstrip or a launcher to takeoff and landing in difficult terrain or in an airstrip). The final design of the aircraft can be seen in Figure 1.

Figure 1. Final aircraft design

## 2. RELATED RESEARCHES

The small fixed wing UAV's modeling is analogous to the modeling techniques used in bigger aircrafts thus a wide variety of approaches can be used to accomplish this task. Analytic methods are used as proposed in (Roskam 2001; Nelson 1998; Yun 2013) that aim to model the aircraft through aerodynamic and cinematic equations to determine the dynamic response of the airplane. Linearization and approximation techniques are used to simplify the model that is inherently non-linear and very complex. There are alternative approaches to this problem such as the ones used in (Manerowski & Rykaczewski 2005), based in experimental

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data collection. Those methods use numeric regression techniques and are, then, used to help in the control modeling and design.

The control methods used in this kind of aircraft are also very similar to the ones used in bigger planes, in this way, there exists a wide variety of methods as well. In the analytic control theory, there are techniques such as the ones used in (Roskam 2001; Nelson 1998), which involve classic control theory and modern control theory which are the most used. There are alternative techniques using artificial intelligence approach such as Artificial Neural Networks like in (Shin et al. 2005) and Fuzzy Systems as in (Doitsidis et al. 2004), and it is possible to use hybrid approaches that use a combination of more than one method like in (Yu et al. 2011; Narenathreyas 2013; Esper & Rosa 2015). These kinds of approaches have as advantage the reasonable modeling of nonlinearities. In the other hand, they come at high data collection and processing amount as the model's fidelity is very dependent on the quality and quantity of collected data. The analytical approaches can be used without the need of experimental data collection and with lower computational costs. In the other hand, could be necessary to use part by part linearization to achieve a good approximation in operation points far from the equilibrium point.

In terms of navigation, path planning techniques are used as in (Ajami et al. 2013; Grankvist 2006). Those approaches have an elevated computational cost compared to the ones that are going to be used in this research, which are based in classic control reference tracking and through Fuzzy control. These methods are very computationally efficient and can be used to solve the navigation problem for a simple case such as the rummage of a region.

## 3. MODELING

The method chosen for this research is the analytical as described in (Roskam 2001; Nelson 1998). This was chosen having into account that the aircraft is still under construction while this system is being developed. The variables convention used to de movement description in this paper is the same as used in (Nelson 1998) and a summary of it is shown in Table 1.

Table 1. Variables convention

| | Roll Axis | Pitch Axis | Yaw Axis |
|---|---|---|---|
| Angular velocities | p | q | r |
| Velocity components | u | v | W |
| Aerodynamic force components | X | Y | Z |
| Aerodynamic moment components | L | M | N |

The aircraft's modeling can be divided in Longitudinal and Lateral, due to the decoupling of these two kinds of movements and can be developed using as reference the gravity center of the vehicle as shown in Figure 2. This approach has some advantages as it allows several simplifications due to the symmetry of the plane as well as to the rotation axis positions. After the modeling in this reference system, this can be transferred to an inertial reference in a fixed point using (1).

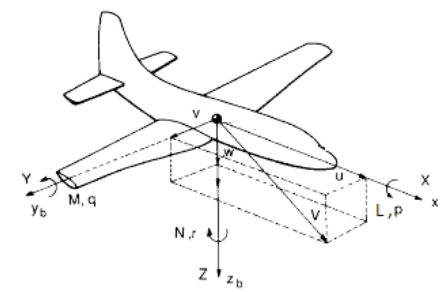


Figure 2. Body fixed coordinate system (Nelson 1998)

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{z}\end{bmatrix} = \begin{bmatrix} C_\theta C_\Psi & S_\Phi S_\theta C_\Psi - C_\Phi S_\Psi & C_\Phi S_\theta C_\Psi + S_\Phi S_\Psi \\ C_\theta S_\Psi & S_\Phi S_\theta S_\Psi + C_\Phi C_\Psi & C_\Phi S_\theta S_\Psi - S_\Phi C_\Psi \\ S_\theta & S_\Phi C_\theta & C_\Phi C_\theta \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix} \quad (1)$$

Being $\dot{x}$, $\dot{y}$, $\dot{z}$ the aircraft velocities with respect to the inertial coordinate system, $\Phi$, $\theta$ and $\Psi$ being respectively the roll angle, the pitch angle and the yaw angle and using $C_\theta = \cos(\theta)$, $S_\theta = \sin(\theta)$ and so on.

### *3.1 Parameters Posing*

The parameters utilized in the aircraft's behavior modeling were determined as described in (Roskam 1973; Roskam 2001; Nelson 1998) and are called stability and control coefficients (or stability and control derivatives). Those parameters define the state equations of the plane and allow the behavior analysis in open and closed loop.

Apart from the dynamic behavior of the airplane, the time response curve of the servomotors that will be used was obtained. To achieve this, a carefully positioned camera was used, capturing images at a frame rate of 118 frames per second. One of the captures frames can be seen in Figure 3

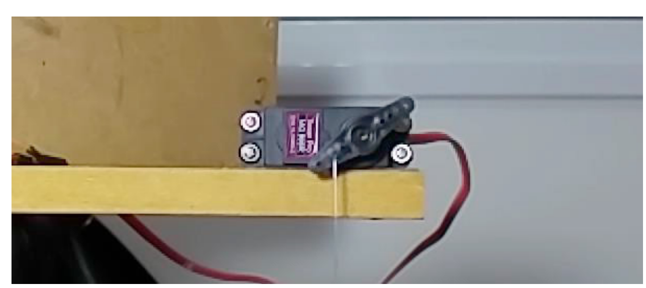

Figure 3. Step response obtaining for the servomotor.

From the obtained images, it was possible to use a CAD (Computer Aided Design) software to get the measurements of each frame and the time step response was obtained. The step response curve can be seen in Figure 4 as well as the first and second order approximations. The first order approximation was realized as proposed in (Bazanella & da Silva 2005), while the second one was obtained using the System Identification tool from the Matlab Software.

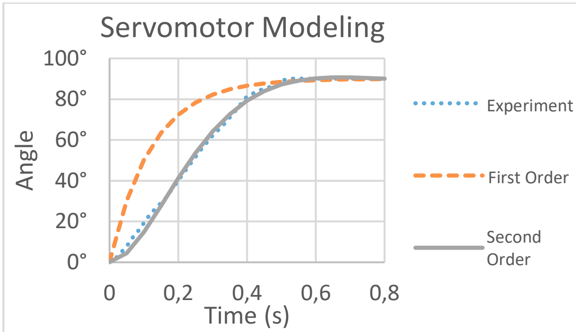


Figure 4. Step response comparison

It is possible to see that the second order approximation is very close to the real response of the servomotor and as such, this was used to model the servo's behavior. The approximate transfer function to the servomotor is shown in (2).

$$\delta_{Servo} = \frac{46.58}{s^2+10.18\,s+47.71} \quad (2)$$

### 3.2 Longitudinal Modeling

The longitudinal modeling of the aircraft has two components, the Phugoid and the Short Period components. The short period approximation is good in describing the fast movements such as the angle of attack variation and the pitch angle variation, as the phugoid movement can be considered as a disturbance. In the same way, the Phugoid approximation can be used to model slow dynamics such as the speed dynamics. After determining the correct approximations for each case, the control and stability coefficients were used to obtain the transfer functions of each of the degrees of freedom depending on each of the variables that have influence in every degree as shown in (Roskam 2001; Nelson 1998).

### 3.3 Lateral Modeling

The lateral modeling followed the same procedure as the longitudinal modeling. First the stability coefficients were calculated and then, the transfer functions of each degree of freedom were obtained

## 4. DEVELOPED CONTROLLERS

The aircraft control task was divided in two parts: Low Level Controls and Navigation Controls. This splitting was made to be able to develop a simpler navigation system that doesn't have to worry about flying the plane and can focus on achieving the waypoints while the low level controls can handle the flying control tasks.

### 4.1 Low Level Controllers

To this application, four systems were initially designed: Roll, yaw, altitude and speed control. These systems were developed using classic control approaches and the selected controller to accomplish the tasks was the PID. This kind of controller stands out due to its capability of obtaining null steady state error for step references and because it is extremely widespread and, as consequence, there are lots of researches that use it and can be of great help. The PID gains were chosen using the PID Tuner available in Matlab to achieve the desired responses for each degree of freedom. The selected gains can be seen in Table 2 and the step responses for each one of the degrees with their controllers can be seen in figures 5 to 8.

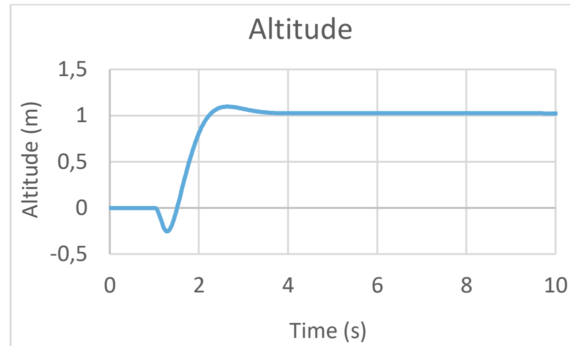


Figure 5. Altitude step response

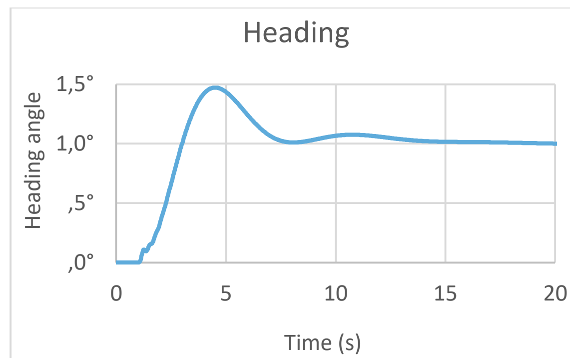


Figure 6. Heading step response

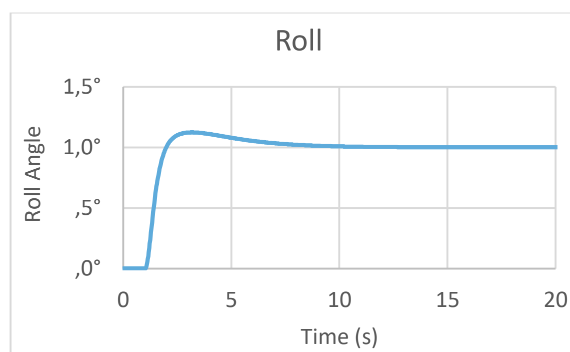


Figure 7. Roll step response

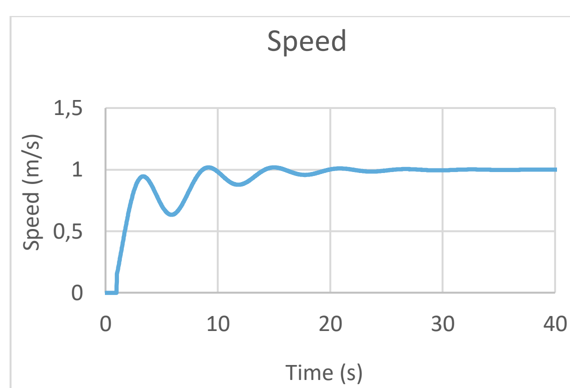


Figure 8. Speed step response

Table 2. PID Gains

| Controller | P | I | D |
|---|---|---|---|
| Altitude | 0,0123 | 9,285 | 0,361 |
| Roll | 75,329 | 25,017 | 5,891 |
| Speed | 30,392 | 20,172 | 11,170 |
| Yaw | 4,924 | 0,181 | 32,933 |

### *4.2 Navigation Control*

The navigation of the plane was very simplified by the choice made to the low level controllers. Initially, the waypoints composed trajectory was generated. A waypoint is considered as reached when the aircraft's distance to the waypoint reaches a specified threshold. During the simulations, the waypoints were spaced in 50 meters, the threshold was set to 25 meters and the distance between the passes is 100 meters. To achieve the trajectory tracking, every instant, the angle between the plane's heading angle (plane's nose direction) and the relative angle between the aircraft's position and the next waypoint is calculated and fed to the yaw controller. In this way, in every instant, the airplane tends to align with the next waypoint. When realizing tests using only this strategy, the airplane was incapable of doing the necessary maneuvers to reach every As a solution, a fuzzy system that controls the Roll angle of the aircraft was introduced to help the aircraft executing tight turns. The results of the hybrid strategy used to the navigation control can be visualized in Figure 9.

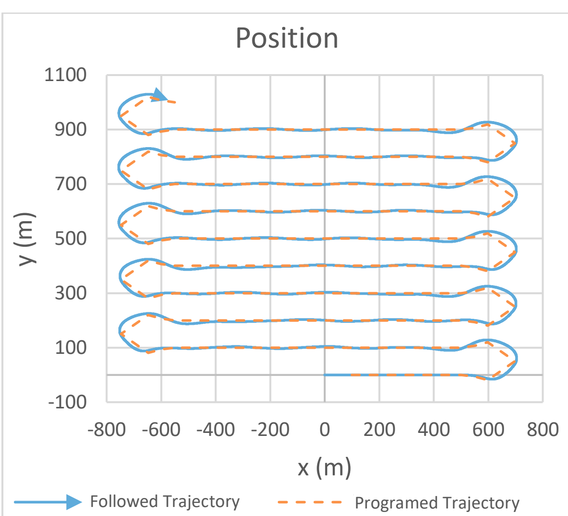


Figure 9. Followed trajectory x Programmed trajectory

In Figure 9 it is possible to verify that the programmed trajectory (area rummage) is followed with a reasonable precision. Figure 10 shows the position error achieved by the airplane in the straight part of the trajectory. It is possible to see that the maximum error is approximately 10 meters. Considering the pass spacing is 100 meters, a 10% positioning error for a sweeping task is acceptable. Besides that, it is possible to reduce the maximum error using a bigger space (and longer time) to do the turn, using a less aggressive turn and reducing this way the overshoot of the trajectory.

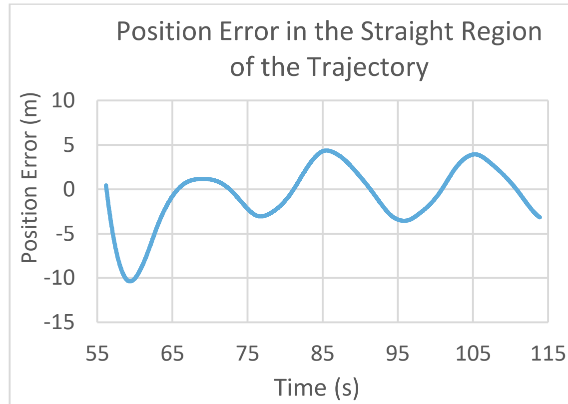


Figure 10. Position Error in the straight region of the trajectory

It is important to notice that the developed fuzzy controller should keep a constant and close to 0° roll angle while in the straight line part of the trajectory because of the camera that will be attached to capture images. This requirement can be achieved by using a dead zone in the input fuzzification set that is realized by a trapezoidal function with a constant area in in the domain's center. In this way, the controller starts to act only if the desired heading variation is bigger than a threshold that was defined, for this case to be 2° in each side. The fuzzy sets used in the roll navigation controller can be seen in Figures 11 and 12 and the rules set used can be seen in Table 3.

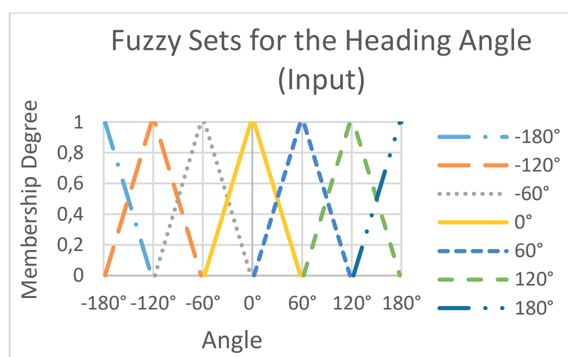


Figure 11. Fuzzy Sets for the Heading Angle (Input)

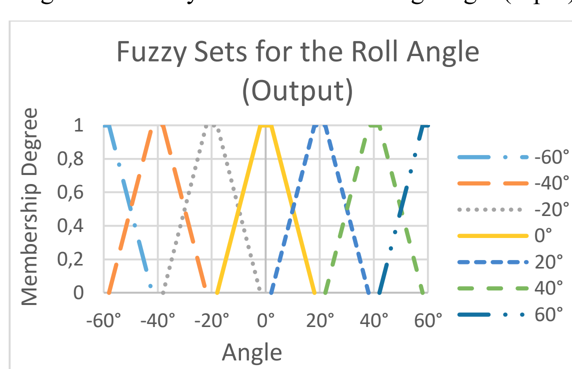


Figure 12. Fuzzy Sets for the Roll Angle (Output)

Table 3. Fuzzy Inference System Rules Set

| Heading Angle (°) | Roll Angle (°) |
|---|---|
| -180 | 60 |
| -120 | 40 |
| -60 | 20 |
| 0 | 0 |
| 60 | -20 |
| 120 | -40 |
| 180 | -60 |

As result, the roll angle seen during the straight line trajectory stays close to 0° as can be seen in Figure 13, with a deviation of approximately 2 degrees positive and negative in most of the trajectory.

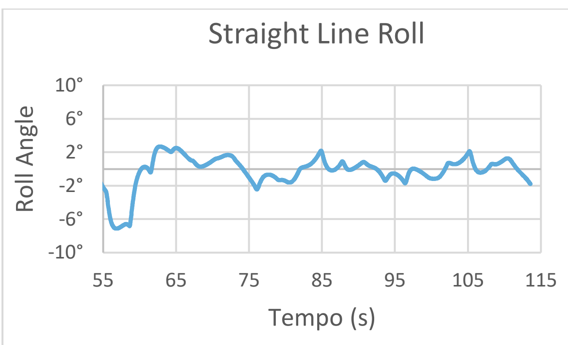


Figure 13. Straight Line Roll

## 5. CONCLUSIONS

This paper presents the design and implementation of a control and navigation system of a unmanned aerial vehicle. The systems designed presented satisfactory results against the mission requirements for a fixed wing aircraft used to an area rummage task. Controllers from the classic control field and a controller using fuzzy logic were used. The overall performance achieved by this combination has been satisfactory, taking into account the simplicity of this kind of controller when compared to other alternatives based on modern control and artificial intelligence. With this, the requirement of using commercial low computational power and low cost platforms to realize the control of the aircraft is achieved. As future implementation to complement this research, there is a wide variety of possibilities, between them, the implementation of a takeoff and landing system, an onboard telemetry system that can monitor its flight, and the physical implementation of the systems developed in this research using onboard microcontrollers and sensors.

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