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FUZZY ADJUSTED PID CONTROLLER APPLIED IN A PARALLEL PROPELLER SYSTEM

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Abstract. *A parallel propeller system was successfully controlled by a PID controller with gains adjusted by fuzzy sets. Parallel propeller system is composed by three pairs of bearings which permits movements in three degrees of freedom, the yaw, pitch and roll. The system has two propellers and electric motors. The roll and yaw movements are coupled due to the geometry of the system and the number of propellants. It's a useful tool to study control in helicopters and other rotor aircrafts. Fuzzy controller was designed to determine the gains for a PID control system which controls the attitude of the parallel propeller system. Fuzzy sets use the desired attitude and the system's state to determine the gains of the PID controller. The error signal used in the PID is the difference between the desired angle of attitude and actual angle of attitude. This error is used to calculate the voltage signal sent to each engine. This controller was used in the parallel propeller system designed by the Airspace Control Laboratory of Escola de Engenharia de São Carlos of USP and its results can be used as a base in studies of controller for similar system or aircraft and the development of a fuzzy-PID-based control system to be used in unmanned aerial vehicles.*

Keywords: *parallel propeller; PID controller; fuzzy sets; attitude control*

1. INTRODUCTION

Rotorcrafts are very difficult dynamic systems to control. In order to study the control of such type of aerial vehicles, the Airspace Control Laboratory of Escola de Engenharia de São Carlos of USP constructed a parallel propeller system. It is a useful tool to these studies because it represents three degrees of freedom of a rotorcraft, the rotations.

Previous control studies were done in the parallel propeller system. Breganon (2009) implemented a tracker control system for pitch and yaw movements, obtaining satisfactory results. Besides, Lopes (2006) tested the possibility of implementing a space-state model predictive control (MPC) law in a similar parallel propeller system. The study proved that the MPC strategy can be applied to this fast dynamic plant due to improvements of real-time computational resources and that this is an effective strategy.

There are also previous studies covering the application of fuzzy adjusted PID in rotorcraft control problems. Xianxiang (2012) used the fuzzy-PID approach on the velocity control of an unmanned helicopter simulation and reached good results, proving the effectiveness and feasibility of this technique.

Considering the complexity of the system's dynamics, the performance of a simple proportional-integral-derivative (PID) controller was not considered satisfactory after implementation and tests. It occurs because of the PID's limitations in dealing with high order systems and with coupled degrees of freedom. As a solution to this problem, it was proposed to implement a fuzzy variable gain PID in the system to achieve best performance.

In this study it was evaluated a controller that uses simple fuzzy sets logics that varies the PID's gains K_P, K_D and K_I according to the systems state. The developed system was tested in the parallel propeller system and it's time responses were compared to the pure PID controller responses.

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2. PARALLEL PROPELLER SYSTEM

The parallel propeller system is composed by a pair of engines and propellers coupled to a three axis systems that allows rotations and restrings translations. The system can be seen in the Fig. 1.

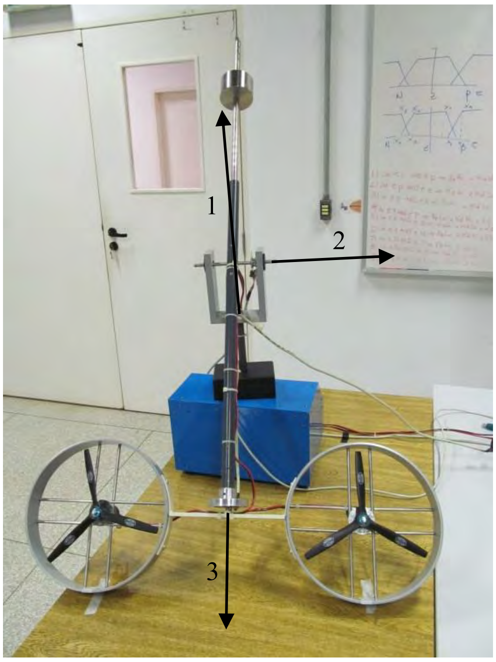

Figure 1. Parallel Propeller System

The three degrees of freedom (DOF's) of the system were numbered for convenience in Fig. 1. These DOF's can be analyzed as typical rotorcraft rotations. The first DOF represents the yaw movement, around axis 1, while the second DOF represents the pitch movement, around axis 2 and the last DOF represents the roll movement, around axis 3.

The three rotation angles are measured with optical encoders. This way, it provides the measurement of the system's state. The encoders mounted in the system can be seen in Fig. 2.

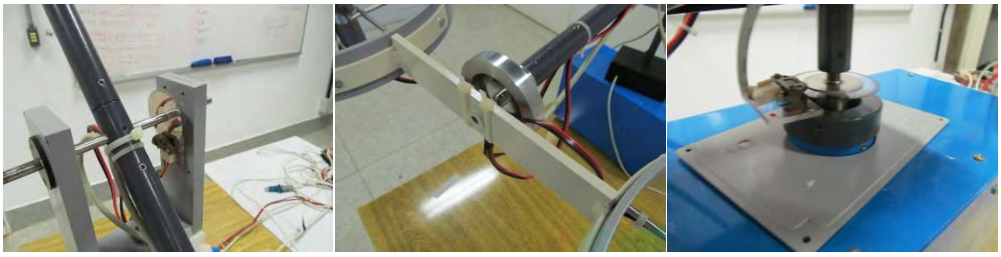

Figure 2. Encoders used for rotation angles' measurement

Due to systems dynamics, it is necessary to develop three controllers, each one acting in one degree of freedom. The controller referent to the rolling movement has as state variable the encoder number 3 measurement and its control action is the difference of engine power. The controller referent to the pitch movement has as state variable the encoder 2 measurement and its control action is the power of the two engines simultaneously. The controller referent to the last DOF, the yaw, has as state variable encoder 1 measurement and its control action is the set point of rolling movement. This coupling demonstrates the complexity of the system's dynamics.

3. PID CONTROLLER

Conventional (classical) proportional-integral-derivative (PID) controllers are perhaps the most well-known and most widely used controllers in modern industries: statistics has shown that more than 90% controllers used in Industries todays are PID or PID-type of controllers (Åström, 2002).

The structure of a PID controller is shown in Eq. (1).

$$u(t) = K_P e(t) + K_D \dot{e}(t) + K_I \int e(t) \tag{1}$$

where $e(t)$ is the tracking error, the difference between the set point reference $r(t)$ and the controlled system's output measured $y(t)$. The constants K_P, K_I and K_D are the P, I and D control gains.

However, the practical usage of the PID leads to a problem in dealing with the value of $\dot{e}(t)$. It occurs when the set point reference value need to be modified instantaneously, generating a discontinuity in the $e(t)$ function. This problem was solved using the controlled system's output in the derivative portion. This modified PID controller is often called PI+D controller (Chen and Pham, 2001). The control PI+D control law is show in Eq. (2).

$$u(t) = K_P e(t) + K_D \dot{y}(t) + K_I \int e(t) \tag{2}$$

The PI+D block diagram is show in Fig. 3.

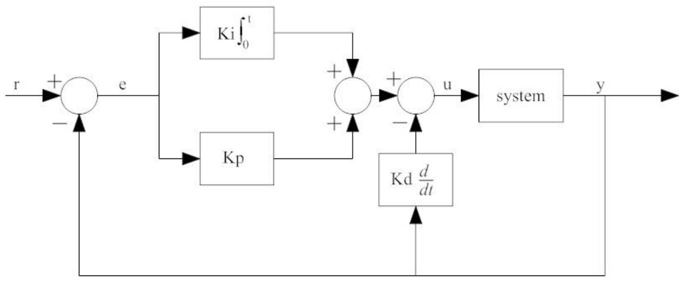

Figure 3. PI+D controller block diagram

The implementation of the PI+D controller in digital electronics circuits requires dealing with the equations in a discrete time space. Some considerations are made in order to implement the controller:

$$e(t=nT) \approx y(nT) - r(nT) \tag{3}$$

Where $n = 0,1,2,3...$ and $T > 0$ is the sampling period.

$$\dot{e}(t) \approx [y(nT) - y(nT-T)]/T \tag{4}$$

$$\int_0^{nT} e(t) \approx \sum_{i=0}^{n} e(iT)T \tag{5}$$

With these assumptions the PI+D equation in the discrete time space can be seen in Eq. (6).

$$u(nT) = K_P e(nT) + K_D \left[\frac{y(nT)-y(nT-T)}{T}\right] + K_I \sum_{i=0}^{n} [e(iT)T] \tag{6}$$

The final PI+D equation is so determined. This pure PI+D was implemented in the same parallel propeller system in order to compare the two controllers and evaluate the benefits of each one.

4. FUZZY THEORY

The fuzzy logic theory, created by Zadeh (1965), leads to the creation a logic that deals with non-absolute variables and imprecise data. Among the rise of the fuzzy logic emerges its usage in dealing with control problems. Lee (1990) described the usage of the fuzzy theory in control problems.

The fuzzy controller typical diagram can be seen in Fig. 4.

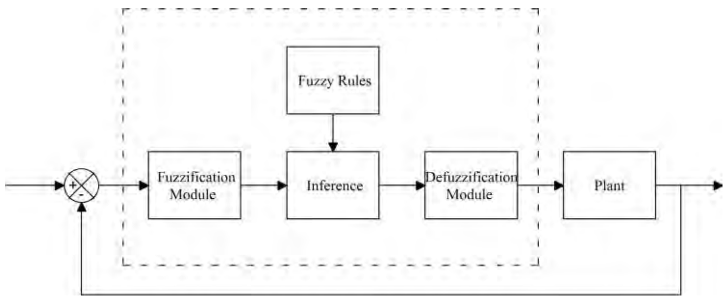

Figure 4. – Fuzzy controller block diagram

The input variables in a fuzzy controller are mapped using membership functions in a process called fuzzification. These membership functions take crisp values of the variables and divide them into ranges of fuzzy values. Typical membership functions have the form of triangles and trapezoids. One of the big advantages of using fuzzy techniques is that the same crisp value can represent two or more fuzzy values. An example of a trapezoidal membership function is shown in Fig. 5.

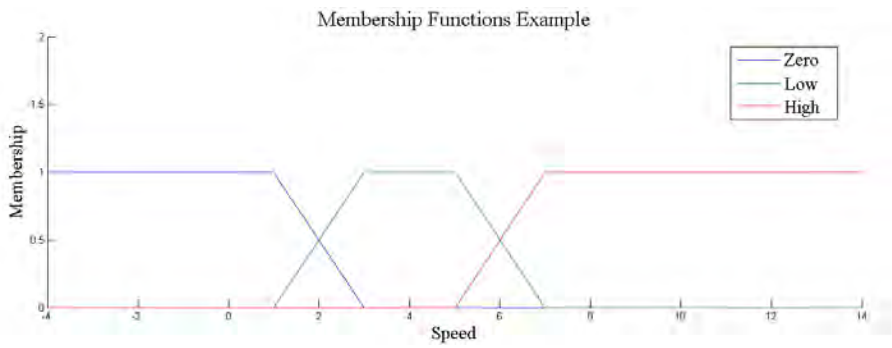

Figure 5. Example of a membership functions example

This way, one value of speed is fuzzified to three values according to each fuzzy variable membership value. As the crisp values are now converted to fuzzy variables, the next step is evaluating them based on a set of rules. The rules are compounded of fuzzy statements that are linked with *"if-then"* sentences and express a control command. As an example of a fuzzy rule we have:

IF *speed is* ***high***, THEN *engine power is* ***low***

After the decision rules step is done, the output variables are achieved by a process called defuzzification. In this process, the output variables are divided in ranges that represent fuzzy values. According to the rules, the input fuzzy values generate output fuzzy values. To reach the final crisp value of the variable, there are many defuzzification methods. The one that will be adopted in this study is the center of gravity defuzzification method. In this method, after all evaluations of the rules, the values of the membership functions are transferred to the final variables map and the final crisp value is calculated pondering the values by the areas of the trapezoids that represents the output variables. An example of this method's application is shown in Fig. 6.

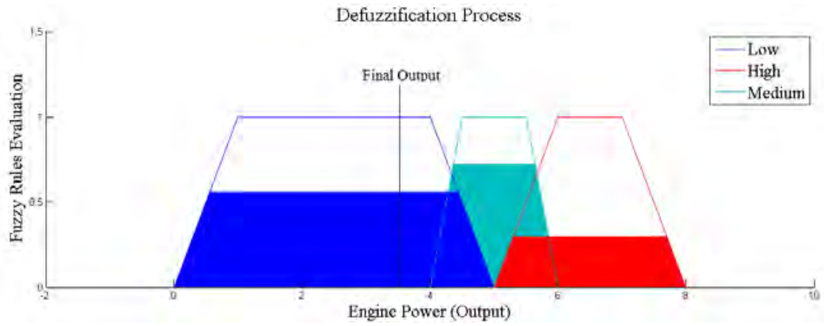

Figure 6. Example of defuzzification

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5. PROPOSED CONTROL SYSTEM

The proposed control system consists in setting the values of the gains of the PID's controllers in the parallel propeller system using fuzzy sets theory.

The controller diagram is shown in Fig 7.

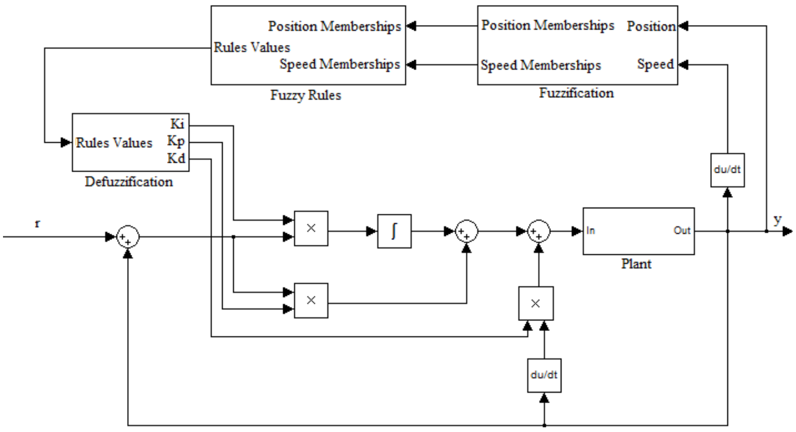

Figure 7. Fuzzy-PID controller diagram

Six membership functions were defined for each DOF of the plant, being three defined over speed and three defined over error. The three values that these variables can perform are Negative, Zero and Positive. The graphic representation of these membership functions are shown in Fig 8.

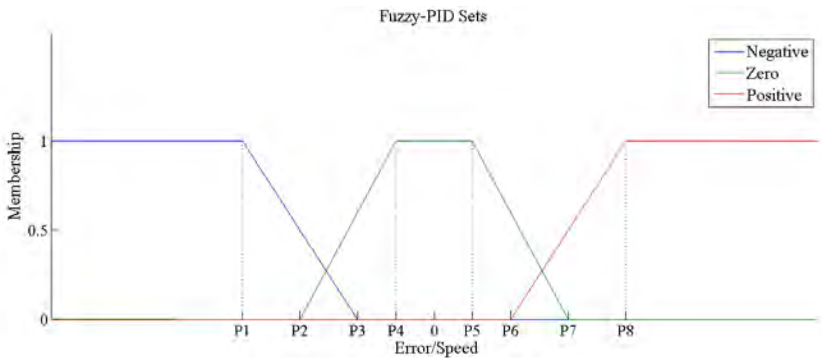

Figure 8. Fuzzy-PID general membership functions

Considering that the variables have been already fuzzified, it is necessary to establish the fuzzy rules that will govern the system. The rules should be established in order to provide the desired performance to the controller. The rules are created aiming a specific behavior of the system; it should follow the reference as fast as possible while the error is high and should decrease speed when it is near the reference and too fast. The steady-state error is corrected only when error is low, in this case, the K_I is high only when the system is near the reference.

With the desired controller's behavior established, we have the nine fuzzy rules listed below:

(R1) IF $e(nT)$ ∈ **Positive** AND $\dot{y}(nT)$ ∈ **Positive** , THEN K_P ∈ **High**, K_D ∈ **High**, K_I ∈ **Low**
(R2) IF $e(nT)$ ∈ **Positive** AND $\dot{y}(nT)$ ∈ **Zero** , THEN K_P ∈ **High**, K_D ∈ **Low**, K_I ∈ **Low**
(R3) IF $e(nT)$ ∈ **Positive** AND $\dot{y}(nT)$ ∈ **Negative** , THEN K_P ∈ **High**, K_D ∈ **Low**, K_I ∈ **Low**
(R4) IF $e(nT)$ ∈ **Zero** AND $\dot{y}(nT)$ ∈ **Positive** , THEN K_P ∈ **Low**, K_D ∈ **High**, K_I ∈ **High**
(R5) IF $e(nT)$ ∈ **Zero** AND $\dot{y}(nT)$ ∈ **Zero** , THEN K_P ∈ **Low**, K_D ∈ **Low**, K_I ∈ **High**
(R6) IF $e(nT)$ ∈ **Zero** AND $\dot{y}(nT)$ ∈ **Negative** , THEN K_P ∈ **Low**, K_D ∈ **High**, K_I ∈ **High**
(R7) IF $e(nT)$ ∈ **Negative** AND $\dot{y}(nT)$ ∈ **Positive** , THEN K_P ∈ **High**, K_D ∈ **Low**, K_I ∈ **Low**
(R8) IF $e(nT)$ ∈ **Negative** AND $\dot{y}(nT)$ ∈ **Zero** , THEN K_P ∈ **High**, K_D ∈ **Low**, K_I ∈ **Low**
(R9) IF $e(nT)$ ∈ **Negative** AND $\dot{y}(nT)$ ∈ **Negative** , THEN K_P ∈ **High**, K_D ∈ **High**, K_I ∈ **Low**

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To proceed to the next step, the defuzzification, the outputs K_P, K_I and K_D are divided in two ranges, “High” and “Low” and their defuzzification functions can be seen in Fig. 9.

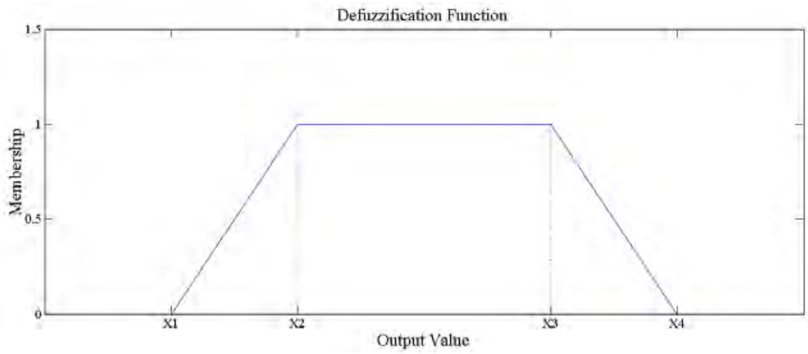

Figure 9. Fuzzy-PID deffuzification functions

Using the center of gravity defuzzification method, the final values of K_P, K_D e K_I can be calculated considering the error ($\dot{e}$) and derivative of the output ($\dot{y}$) for each DOF. The final controller is the traditional PI+D’s with these fuzzy controlled gains.

6. EXPERIMENT METHOD

In order to evaluate the controllers acting in the plant it was necessary to develop a platform capable of performing data acquisition and implementing the different control systems. The platform scheme can be seen in Fig. 10.

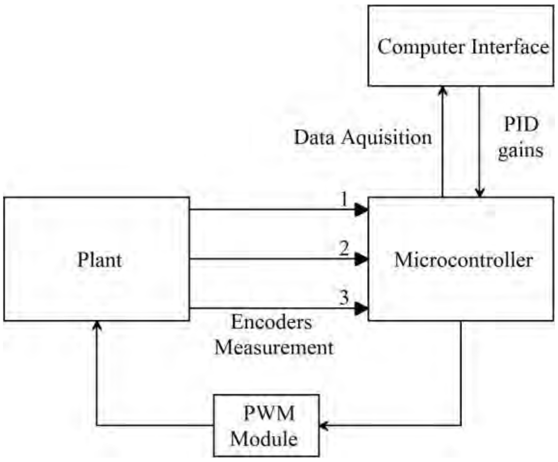

Figure 10. Platform scheme

It was implemented the three PI+D’s in a microcontroller. The measure of the parallel propeller state was also implemented using the digital signal received from the optical encoders. It was used a Pulse-Width Modulation (PWM) Module to produce the control action, the engine power. The microcontroller was linked to a microcomputer by a serial interface in order to permit the data acquisition from the plant and to set the PI+D gains according to the required experiment. It was also possible to change the set points for the yaw and pitch DOF’s through the computer interface.

The first experiment was done by setting fixed PI+D gains and submitting the plant to step inputs in pitch and yaw DOF’s. To perform the second experiment, fuzzy laws were implemented in the computer interface. This way, according to the state of the plant, acquired by the microcomputer, the PI+D gains were calculated and sent to the microcontroller. This strategy allowed dealing with more complex calculation in the microcomputer and using the experiment platform without the necessity of reprograming the microcontroller in each test.

7. COMPARISON PID X FUZZY PID

It is very important having consistent parameters to evaluate a controller performance. In this study, it was decided to realize the comparison between a simple PI+D and the proposed fuzzy-PI+D controller. Considering that the

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principal advantage of the fuzzy-PI+D system is in dealing with high-order non-linear systems, this comparison is very pertinent.

The PI+D was first implemented in the form of the Eq. (6). The gains in respect to each DOF are shown in the table 1.

Table 1. Pure PI+D gains

DOF	Kp	Ki	Kd
Yaw (1)	0.7	0.002	4
Pitch (2)	0.6	0.0005	0.6
Roll (3)	0.13	0.001	0.2

In the implementation of the fuzzy-PID controller it was necessary to set the parameters of the fuzzification membership functions and the defuzzification function to each DOF. The calibration of these values was done by varying the values around the PID gains, in order to increase the system performance. The final calibration values are plotted in Tab. 2 and Tab. 3, respectively, in respect with the shape of the functions previously described in Fig. 8 and Fig. 9.

Table 2. Fuzzification membership function characteristics

	P1	P2	P3	P4	P5	P6	P7	P8
Error Pitch	-20	-20	-10	-10	10	10	20	20
Speed Pitch	-10	-10	-1	-1	1	1	13	13
Error Roll	-10	-10	0	0	0	0	10	10
Speed Roll	-13	-13	-4	-4	4	4	13	13
Error Yaw	-10	-10	0	0	0	0	10	10
Speed Yaw	-2.5	-2.5	0	0	0	0	2.5	2.5

Table 3. Deffuzification functions characteristics

	X1	X2	X3	X4
Pitch - Kp High	0.58000	0.59000	0.61000	0.62000
Pitch - Kp Low	0.38000	0.39000	0.41000	0.42000
Pitch - Ki High	0.00140	0.00145	0.00155	0.00160
Pitch - Ki Low	-0.00010	-0.00005	0.00005	0.00010
Pitch - Kd High	0.70000	0.75000	0.85000	0.90000
Pitch - Kd Low	0.52500	0.55000	0.65000	0.67500
Roll - Kp High	-0.86000	-0.36000	0.64000	1.14000
Roll - Kp Low	-0.88000	-0.38000	0.62000	1.12000
Roll - Ki High	-0.99800	-0.49800	0.50200	1.00200
Roll - Ki Low	-1.00000	-0.50000	0.50000	1.00000
Roll - Kd High	-0.79000	-0.29000	0.71000	1.21000
Roll - Kd Low	-0.81000	-0.31000	0.69000	1.19000
Yaw - Kp High	-0.25000	0.25000	1.25000	1.75000
Yaw - Kp Low	-0.35000	0.15000	1.15000	1.65000
Yaw - Ki High	-0.99750	-0.49750	0.50250	1.00250
Yaw - Ki Low	-0.99800	-0.49800	0.50200	1.00200
Yaw - Kd High	4.50000	5.00000	6.00000	6.50000
Yaw - Kd Low	3.00000	3.50000	4.50000	5.00000

The time responses for a 25° step input in the pitch DOF was obtained by the data provided by the encoder 2. In Fig. 11 the time responses are plotted for the two controllers, allowing the comparison of the characteristics of its responses.

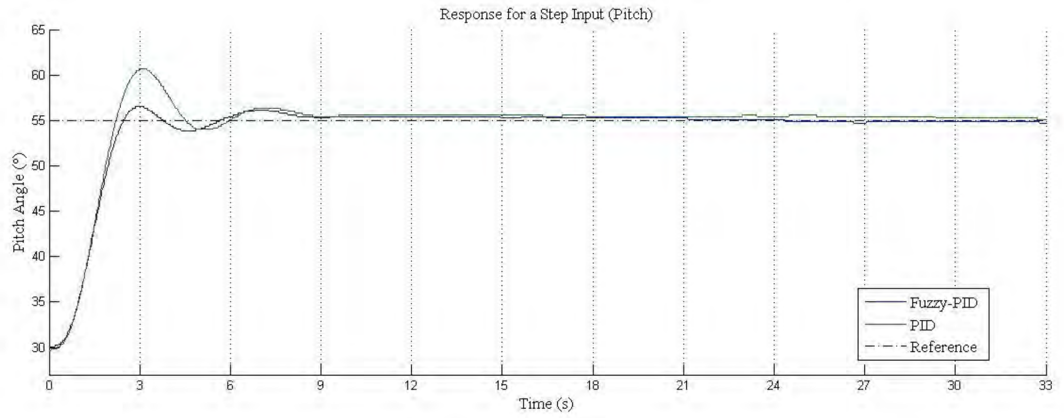

Figure 11. Diagram of the pitch response for a step input.

Analyzing the responses it is possible to note that the fuzzy-PID controller achieved a significant smaller overshoot and reached the steady-state earlier than the pure PID controller.

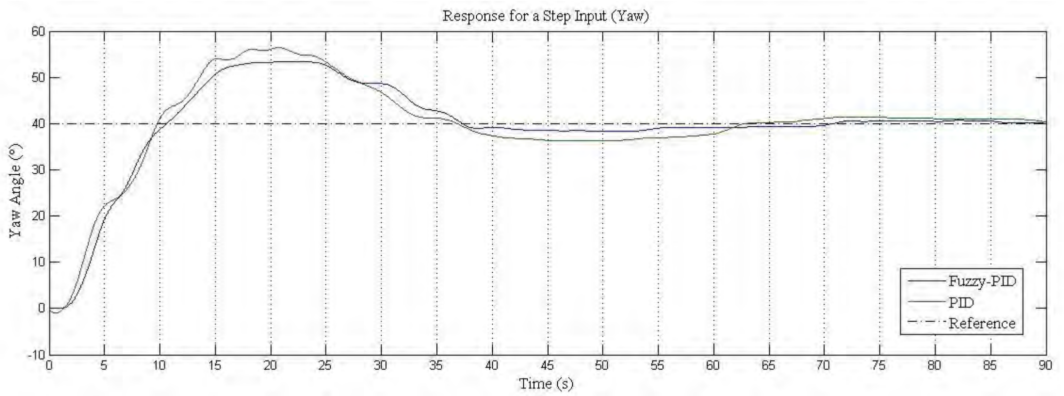

Figure 12. Diagram of the yaw response for a step input

The yaw DOF represents a particularly complex control problem. It occurs because it is a fourth order DOF coupled with the roll movement. The complexity of its response can be seen in Fig. 12. The fuzzy-PID controller improved the performance of the system in comparison with the pure PID. It can be noted in the diagram that the overshoot of the system decreased among the oscillations and the system reached the steady-state previously.

8. CONCLUSION

The fuzzy-PID controller proved to be a good and simple solution to complex dynamics systems. Furthermore, the use of this controller can represent a better performance in unmanned aerial vehicles' control, especially in rotorcrafts, that are relatively more complex systems.

Future works can be done to increase the performance of the fuzzy-PID controller. Establishing more detailed fuzzification membership functions and improved defuzzification methods could increase the performance of the system; however it would increase the complexity of the system.

Another performance limitation of the fuzzy-PID is the absence of an effective method to set the parameters relative to the fuzzification and defuzzification methods.

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10. RESPONSIBILITY NOTICE

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