FPGA Based Modified Fuzzy PID Controller for Pitch Angle of Bench-top Helicopter

Ammar A. Aldair
Electrical Engineering Department
Engineering College
University of Basrah, Iraq
Emile: mmr.ali2@googlemail.com

Abstract— *Fuzzy PID controller design is still a complex task due to the involvement of a large number of parameters in defining the fuzzy rule base. To reduce the huge number of fuzzy rules required in the normal design for fuzzy PID controller, the fuzzy PID controller is represented as Proportional-Derivative Fuzzy (PDF) controller and Proportional-Integral Fuzzy (PIF) controller connected in parallel through a summer. The PIF controller design has been simplified by replacing the PIF controller by PDF controller with accumulating output. In this paper, the modified Fuzzy PID controller design for bench-top helicopter has been presented. The proposed Fuzzy PID controller has been described using Very High Speed Integrated Circuit Hardware Description Language (VHDL) and implemented using the Field Programmable Gate Array (FPGA) board. The bench-top helicopter has been used to test the proposed controller. The results have been compared with the conventional PID controller and Internal Model Control Tuned PID (IMC-PID) Controller. Simulation results show that the modified Fuzzy PID controller produces superior control performance than the other two controllers in handling the nonlinearity of the helicopter system. The output signal from the FPGA board is compared with the output of the modified Fuzzy PID controller to show that the FPGA board works like the Fuzzy PID controller. The result shows that the plant responses with the FPGA board are much similar to the plant responses when using simulation software based controller.*

Keywords: FPGA, Modified Fuzzy PID Controller, Bench-top Helicopter.

استخدام لوحة FPGA لتصميم منظومة سيطرة من نوع الكسب-التكاملي-التفاضلي المضبب المعدل للسيطرة على زاوية انقلاب الطائرة المروحية

عمار عبدالشهيد الدير
قسم الهندسة الكهربائية
كلية الهندسة
جامعة البصرة

الخلاصة: في هذا البحث تم تقليل عدد القواعد المستخدمة لبناء منظومة الكسب-التكاملي-التفاضلي المضبب وذلك من خلال بناء منظومة كسب-تفاضلي مضبب على حدة وبناء منظومة الكسب-التكاملي المضبب على حدة ثم ربط المنظومتيين معا. كما تم استبدال منظومة الكسب-التكاملي المضبب بكسب تفاضلي مضبب واضافة مركم عند الاخراج لتقليل تعقيد المنضومة الكلية. تم بناء المنظومة المقترحة باستخدام لوحة FPGA وتم اختبارها للسيطرة على زاوية انقلاب الطائرة المروحية. اثبتت النتائج المستحصلة ان استخدام منظومة السيطرة من نوع الكسب-التكاملي-التفاضلي المضبب المعدل يكون فعلا مقارنة مع اسنخدام الكسب=تاتكاملي-التفاضلي التقليدي. كما تم مقارنة النتائج المستحصلة عملا مع النتائج النضرية وقد اثبتت تطابقا ملحوظا في كلا الحالتين.

1. Introduction

Helicopter flight is a very difficult task due to the strong coupling of the various degrees of freedom of the helicopter. In addition, many mathematical models are unable to predict cross-coupling satisfactorily, thus making accurate modelling is difficult and controller design is challenging. The work of a helicopter pilot is thought to be significantly more difficult than any other pilot's due to the strong coupling of the various degrees of freedom. Helicopter is naturally non-stable system because of existence of great variations in system dynamics, the strong cross coupling composition and strict requirements on the system performance. Like aircraft control, helicopter control is accomplished primarily by producing moments about all three aircraft axes: roll, pitch and yaw.

Over the year, the problem of helicopter control design has received much attention. The researchers applied different design methodologies to design a control system for helicopters [1-7]. The helicopter parameters are very dependent on the operating point; therefore the controllers have to be very robust to meet the control objectives.

In the last four dcades, the fuzzy controller application becomes more familiar to propose as a robust controller for many industrial applications. In 1975, Mamdani and Assilian developed the first fuzzy logic controller (FLC), and it was successfully implemented to control a laboratory steam engine plant [8]. There are several types of control systems that use FLC as an essential system component. The majority of applications during the past decades belong to the class of fuzzy PID controllers [9-11]. Hu et al. described a new methodology for the systematic design of the fuzzy PID controllers based on theoretical fuzzy analysis and genetic based optimization [12]. These fuzzy controllers can be further classified into three types: the direct action (DA) type, the gain scheduling (GS) type and a combination of DA and GS types. The majority of fuzzy PID applications belong to the DA type; here the fuzzy PID controller is placed within the feedback control loop, and computes the PID actions through fuzzy inference. In GS type controllers, fuzzy inference is used to compute the individual PID gains and the inference is either error driven self-tuning or performance-based supervisory tuning.

Fuzzy PID controller is a fuzzy controller that takes error, summation of error and rate of change of error as inputs. A fuzzy controller with three inputs may not be preferred, because it needs large number of rules. The Fuzzy PID controller can be constructed as a parallel structure of a PDF controller and a PIF controller and the output of the fuzzy PID controller is formed by algebraically adding the outputs of the two fuzzy control blocks. This procedure will reduce number of rules needed significantly. It is difficult to formulate control rules with sum-of error variable input, as its steady-state value is unknown for most control problems. To overcome that problem, a PDF controller may be employed to serve as PIF controller in incremental form.

In the last two decades, many researchers focused on the development of a hardware implementation fuzzy logic controller. Some researchers used an analogue circuit to implement each part of fuzzy system (including: Fuzzification, Fuzzy Inference and Defuzzification) [13-15]. The structure of fuzzy system is complex, so that the analogue circuit has to be very complicated to implement the logic system. Therefore, many researchers proposed digital rather than analogue circuits to implement the fuzzy logic system. Microprocessors or microcontrollers are popular in being used to implement fuzzy logic system. Microprocessor based controllers are economical and flexible, but often face difficulties in dealing with control systems. Therefore, higher density programmable logic devices such as Programmable Logic Device (PLD) and Field Programmable Gate Array (FPGA) have been developed to overcome the problems of microprocessors. The FPGA is suitable for fast implementation and hardware verification. The control systems based on it are flexible and can be reprogrammed with unlimited number of times. Many papers have reported this technology to design Fuzzy Logic Controller (FLC) for different applications [16-19].

In this paper the modified fuzzy PID controller has been used as a control system for the pitch angle of bench-top helicopter. The results have been compared with the conventional PID controller and Internal Model Control Tuned PID (IMC-PID) Controller. Simulation results show that the proposed Fuzzy PID controller produces superior control performance than the other two controllers in handling the nonlinearity of the helicopter system. The fuzzy PID controller for the pitch angle of bench-top helicopter has been developed using Very High Speed Integrated Circuit Hardware Description Language (VHDL) and implemented by using the Field Programmable Gate Array (FPGA) board.

2. Bench-top Helicopter Mathematical Model

The physical model of bench-top helicopter is shown in Figure 1 [20]. The model was based on a 3-dof helicopter from Quanser. Two DC motors are mounted at the two ends of a rectangular frame and drive two propellers. The total force *F* caused by aerodynamic makes the total system turn around an angle measured by an encoder. The motors axes are parallel and the thrust vector is normal to the frame. The helicopter frame is suspended from an instrumented joint mounted at the end of a long arm and is free to pitch about its centre. The arm is gimballed on a 2-dof instrumented joint and is free to pitch and yaw. The other end of the arm carries a counterweight mass *M* such that the effective mass of the helicopter *m* is light enough for it to be lifted using the thrust from the motors. A positive voltage applied to the front motor causes a positive pitch while a positive voltage applied to the back motor causes a negative pitch. A positive voltage to either motor also causes an elevation of the body (pitch of the arm). If the body pitches, the thrust vectors result in a travel of the body (yaw of the arm) as well.

From Figure (1.a), the three body motions of the helicopter are represented by: pitch motion θ, roll motion φ and the yaw motion ψ. By applying Lagrange's equation, the dynamics of the pitch angle can be governed by the following nonlinear differential equation [21]:

$$\ddot{\theta} = -\frac{b_e}{J_e}\dot{\theta} - \frac{mg}{J_e}[(h+d)sin\theta + cos\theta] + \frac{Mg}{J_e}(l_2 + l_2 cos\alpha)cos\theta + \frac{Mg}{J_e}(l_3 sin\theta - h)sin\theta \;+\; Fl_1 \qquad (1)$$

where *m* is the total mass of the both motors; *M* is the mass of the counterweigh; b_e is the dynamic coefficient; *g* is the gravity acceleration, J_e is the initial moment of the whole system around the pitch angle θ; *h, d,* l_1, l_2 and l_3 are lengths (as shown in Figure (1.a)) ; and α is the fixed constriction angle.

In this paper, three control systems have been designed to control the pitch angle of the bench-top helicopter

- Conventional PID controller
- Internal Model Control Tuned PID (IMC-PID) Controller
- Fuzzy PID Controller

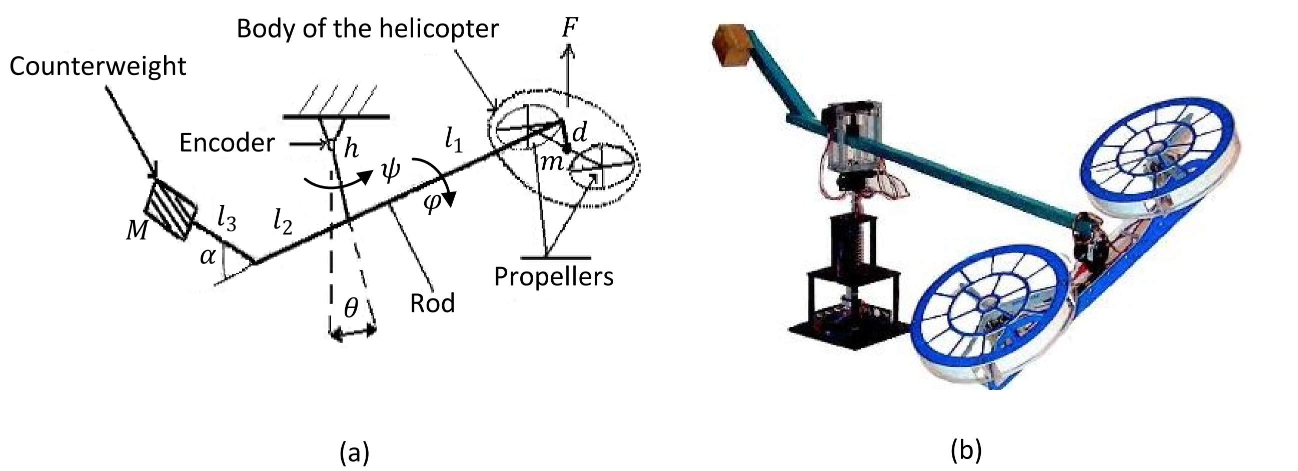

Figure 1 Physical Model of Bench-Top Helicopter

The Ziegler-Nichols closed loop tuning method has been used to tune the parameters of the conventional PID controller. The structures of the next two control systems that have been used in this paper are discussed in section 3 and section 4 respectively.

3. The Structure of the IMC-PID Controller

Many researchers used the IMC-PID controller to design the control system for different applications [22, 23]. The internal model control scheme has been widely applied in the field of process control. This is due to its simple and straightforward controller design procedure as well as its good disturbance rejection capabilities and robustness properties.

Figure 2 shows the structure of the IMC-PID controller. Where *P(s)* is the actual process object being controlled; $G(s)$ is the controller, $\breve{G}(s)$ is the internal model of the process; $G_c(s)$ is the controller which can get the result of internal model controlling structure after varying equivalently.

The IMC primary controller C(s) is given in the following equation

$$C(s) = G^{-1}(s)F(s) \qquad (2)$$

where $F(s) = \frac{1}{\lambda s+1}$ is the realizable factor [22].

The equivalent controller transfer function $G_c(s)$ is given as

$$G_c(s) = \frac{C(s)}{1-C(s)\breve{G}(s)} \qquad (3)$$

From equation 3, the equivalent controller transfer function depends on the structure model of the *C(s)* and $\breve{G}(s)$.

4. The Structure of Fuzzy PID controller

Fuzzy logic control technique has found many successful industrial applications and demonstrated significant performance improvement. The PDF controller is a fuzzy logic controller has two inputs where the error and error change are used as the inputs for the inference. PIF controller can be produced by replacing the error change input of the PDF by the sum of the error. The fuzzy PID controller contains three inputs to design a fuzzy inference system where the inputs are: the error, error change and sum of the error. Figure 3 shows the structure of fuzzy PID controller.

A fuzzy controller with three inputs may not be preferred, because it needs large number of rules. The total number of the rules in fuzzy inference system can be calculated from the following equation:

$$N_r = \prod_{i=1}^{n} N_{mi} \qquad (4)$$

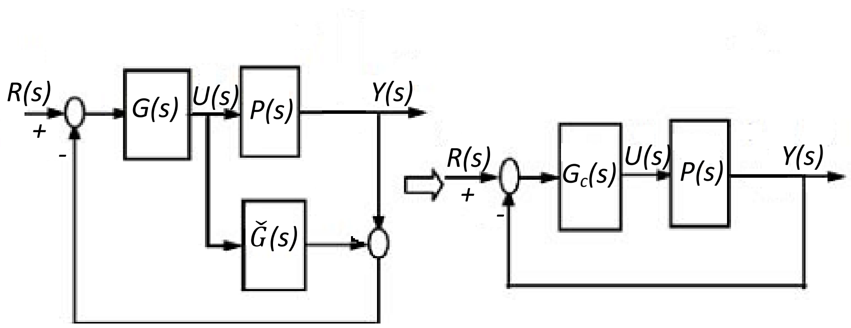

Figure 2 Equivalent the IMC-PID to General Control Structure

where N_r is the total numbers of the rules in fuzzy inference system; n is the number of inputs for the fuzzy inference system; and N_{mi} is number of the membership function of i^{th} input signal. For example, if each input is described with five membership function then the total number of the rules of the fuzzy PID controller is $5 \times 5 \times 5 = 125$ rules. The number of the rules can be reduced by construction of the fuzzy PID controller as a parallel structure of a PDF controller and a PIF controller as shown in Figure 4.

From Figure 4, the output of the fuzzy PID controller u_{PID} is formed by algebraically adding the output of the PDF controller u_{PD} and the output of PID controller u_{PI}. This procedure will reduce the total numbers of rules needed to $5 \times 5 + 5 \times 5 = 50$ rules only.

It is difficult to formulate control rules with the input variable sum of error Σe, as its steady state value is unknown for most control problem [24].

To overcome the problem, a PDF controller may be employed to serve as PIF controller in incremental form.

The following equation represents the FPD controller in the position form

$$u(n) = K_p e(n) + K_d\, r(n) \qquad (5)$$

where $e(n)$ is sampled error signal, $r(n)$ rate of change of sampled error signal $(r(n) = e(n) - e(n-1))$.

The PIF controller is written in incremental form as

$$\Delta u(n) = K_p r\,(n) + K_i e(n) \qquad (6)$$

Now by comparing equation (5) with equation (6), the FPD controller in position form becomes the FPI controller in incremental form if:

- $e(n)$ and $r(n)$ exchange positions,
- K_d is replaced by K_i and
- $u(n)$ is replaced by $\Delta u(n)$.

From above, the structure of fuzzy PID controller in Figure 4 can be modified as shown in Figure 5, where PIF controller is replaced by PDF controller with summation at its output is used.

5. Implementation of Fuzzy PID Controller Using FPGA Board

5.1 Field Programmable Gate Arrays (FPGA) Architecture

During the last years, consumer digital devices have been built using either application specific hardware modules (ASICs) or general purpose software programmed microprocessors, or a combination of them. Hardware implementations offer high speed and efficiency but they are tailored for a specific set of computations. Software implementations can be modified freely during the life-cycle of a device, through patches and updates. However, they are much more inefficient in terms of speed and area. Field-Programmable Gate Arrays (FPGAs) is intended to fill the gap between hardware and software, achieving potentially much higher performance than software, while maintaining a higher level of flexibility than hardware. The FPGA is suitable for fast implementation and quick hardware verification. The systems based on it are flexible and can be reprogrammed with unlimited number of times. The rapid evaluation of silicon technologies has helped to reduce the size of FPGA integrated circuits and cost, therefore, the FPGAs can be used

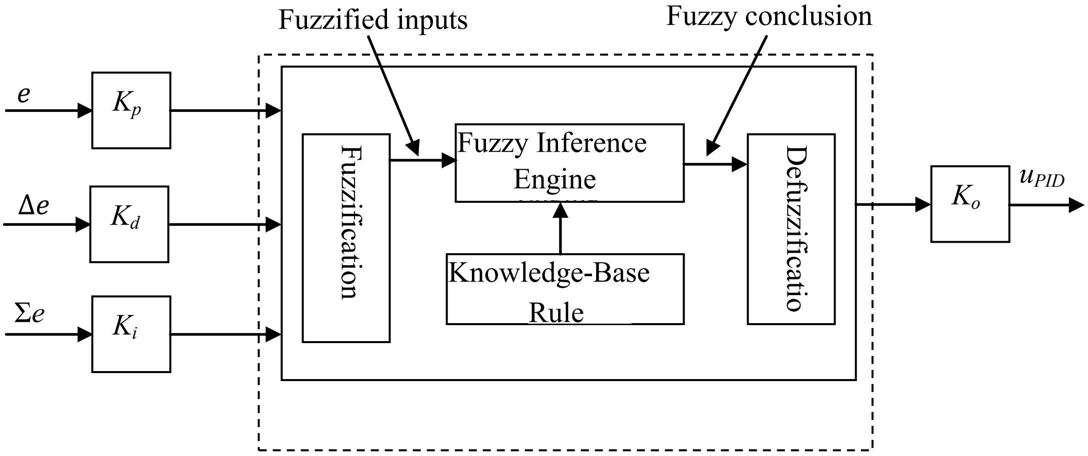

Figure 3 Structure of Fuzzy PID Controller

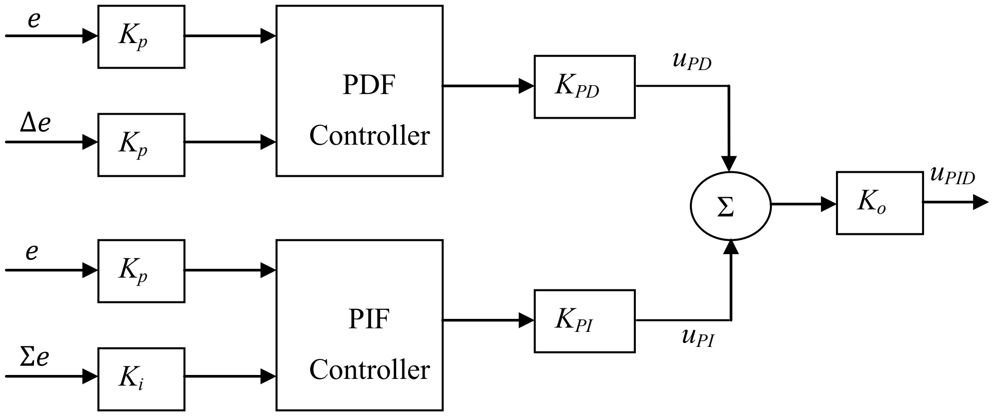

Figure 4 Modified Structure of Fuzzy PID Controller

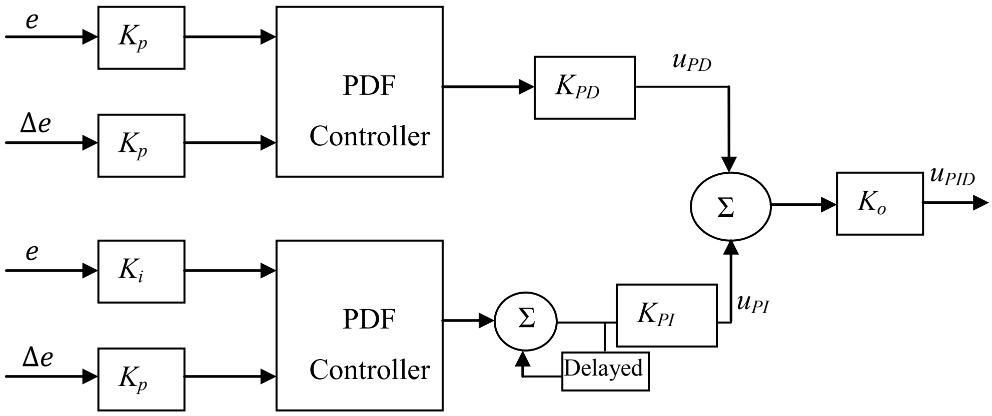

Figure 5 Modified Structure of Fuzzy PID Controller
Using Two PDF Controller

as final solutions to implement many control systems like fuzzy PID controller.

A field programmable gate array (FPGA) is a logic device that contains a two-dimensional array of generic logic cells and programmable switch that can realize any digital system with low cost and reduced time. The FPGA consists of three major configurable elements [25].

1. Configurable Logic Block (CLBs) arranged in an array that provides the functional elements and implements most of the logic in an FPGA. Each logic block has two flip flop and can realize any 5-input combination logic function.
2. Programmable interconnect resource that provide routing path to connect between the rows and columns of CLBs, and between CLBs and input-output blocks.
3. Input-Output Blocks (IOBs) that provide the interface between the package pins and internal signal lines. It can be configured as input, output or bidirectional port.

The CLBs, IOBs and their interconnectors are controlled by a configuration program stored in a chip memory.

The conceptual structural of FPGA device is shown in Figure 6. A custom design can be implemented by specifying the function of each logic cell and selectively setting the connection of each programmable switch. FPGAs are programmed using support software and a download cable connected to a host computer. Once they are programmed, they can be disconnected from the computer and will retain their functionality until the power is removed from the chip. Since this process can be done by the user rather than by the fabrication facility, the device is known as field programmable.

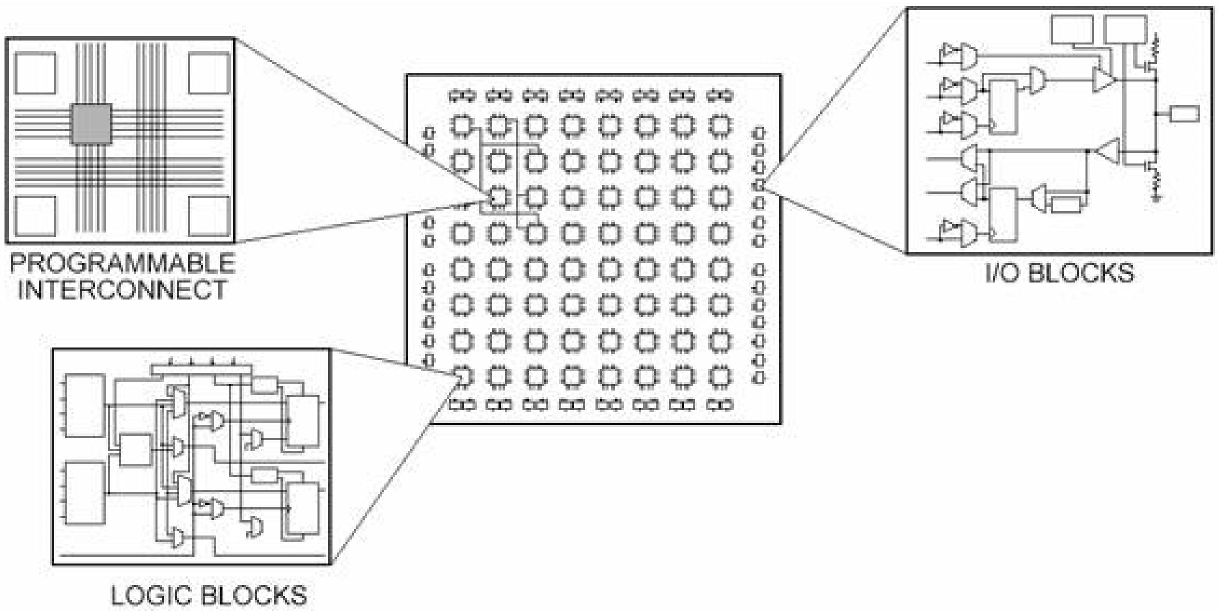

Figure 6 Overall Schematic of a traditional FPGA

5.2 Design a FPGA board for Fuzzy PID controller

In this paragraph, the hardware implementation of fuzzy PID controller using FPGA will be explained. A Very High speed integrated circuit Hardware Description Language (VHDL) codes have been used to describe the operation of the modified fuzzy PID controller that has been designed in section 4. The Xilinx Integrated Software Environment (Xilinx ISE 10.1) has been used as an environment to type the VHDL codes. Xilinx ISE 10.1 allows taking designs through several steps: Analysis and Synthesis, Fitter (Place and Route), Assembler (Generated Programming Files), Classic timing Analysis and EDA net list Writer. After successfully compiling the design, the generated programming files (Configuration files) will be downloaded using USB port to program the FPGA boars. The response of the plant with FPGA board are compared with the simulation response of the plant with fuzzy PID controller to make sure the FPGA board works like fuzzy PID controllers.

6. Simulation and Results

To investigate the effect of the modified Fuzzy PID controller on the pitch angle of bench-top helicopter, the results of the proposed controller are compared with the conventional PID controller and internal model control PID tuned controller through MATLAB simulation software.

The helicopter parameters used in this simulation are shown in Table 1.

Three types of control systems have been designed to control the pitch angle of the bench-top helicopter

- Conventional PID controller
- Internal Model Control Tuned PID (IMC-PID) Controller
- Fuzzy PID Controller

Table 1 The helicopter parameters

Variable	Value	Unit
l_1	20	cm
l_2	6	cm
l_3	18.5	cm
M	1.426	kg
m	1.87	kg
d	7	cm
h	2	cm
g	9.81	m/s^2
J_e	1.2	Nms^2

To find the parameters of the conventional PID controller, the Ziegler-Nichols closed loop tuning method is used. The parameters of the conventional PID controller that are used in this simulation are: *P= -20.3, I=13.5* and *D=84.3*. The transfer function of IMC-PID controller is given as $G_c(s) = K\left(\frac{a+bs+cs^2}{s(ds+1)}\right)$, where the coefficients of $G_c(s)$ that are used in this simulation are obtained using the Control System Toolbox in MATLAB (*a=1; b=0.36; c=3.24; d=1.7* and *K=14.333)*.

To design the fuzzy PID controller, the triangular membership functions have been used for input and output variables shown in Figure 7. Table 2 shows the rule table of 64 fuzzy rules.

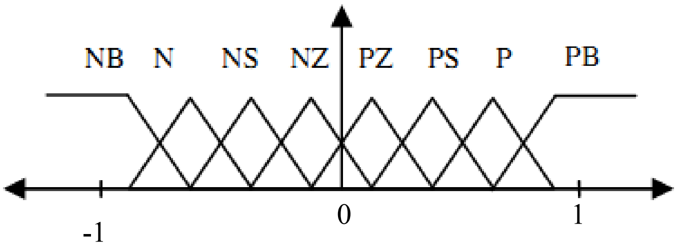

Figure 7 Triangular membership function

Table 2 Fuzzy rules

		ė							
		NB	NM	NS	NZ	PZ	PS	PM	PB
e	NB	NB	NB	NB	NM	NM	NS	NZ	PZ
	NM	NB	NB	NM	NM	NS	NZ	PZ	PZ
	NS	NB	NM	NM	NS	NZ	PZ	PZ	PS
	NZ	NM	NS	NS	NZ	PZ	PZ	PS	PM
	PZ	NM	NS	NZ	NZ	NZ	PZ	PS	PM
	PS	NS	NZ	NZ	PZ	PS	PM	PM	PB
	PM	NZ	NZ	PZ	PS	PM	PM	PB	PB
	PS	NZ	PZ	PS	PM	PM	PB	PB	PB

For any fuzzy logic controller design, it is necessary to check the surfaces between the proposed membership function and the control action in order to make sure of the rounding process inside the fuzzy system. Figure 8 shows the control surface between inputs/output variables using the proposed membership functions.

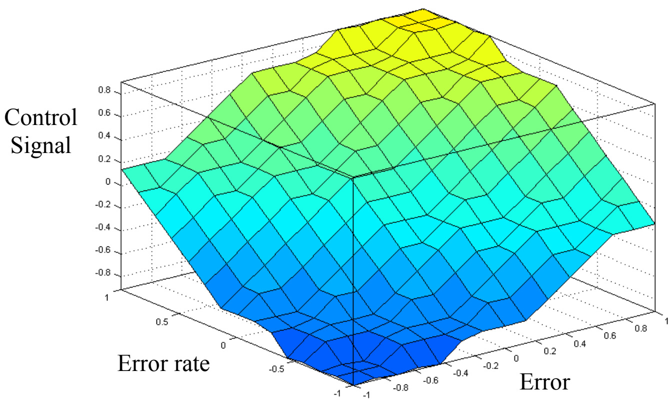

Figure 8 Control surface between inputs and output variable

Figure 9 shows the time response of the pitch angle for the three control types. In the simulation, the desired pitch angle is assumed 4°. Figure 10 shows the comparison of the control signal generated from each control type.

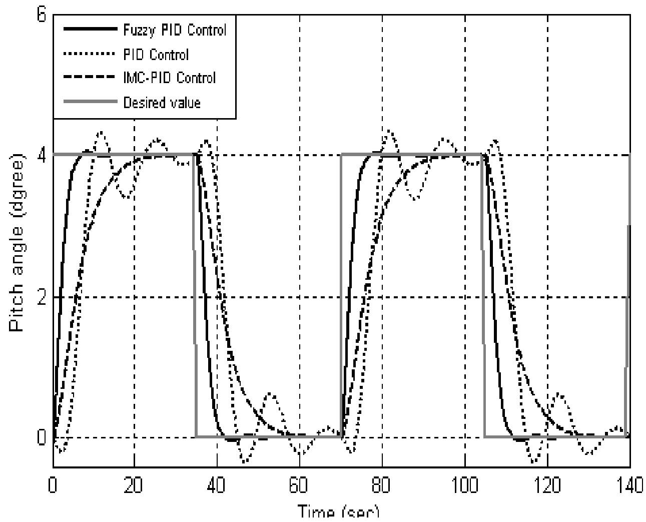

Figure 9 Time response of the pitch angle for the different control types

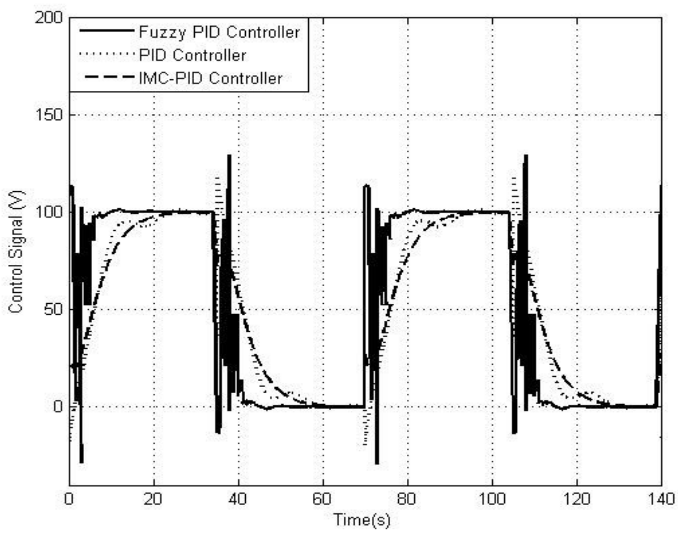

Figure 10 Control signal generated from different control types

From Figure 9, when the proposed fuzzy controller is applied as a control system, the pitch angle reaches the desired value in a very short time and without overshot. While, when the PID controller applied, the time response of the pitch angle oscillates around the desired value. Even the time response of the pitch angle is without overshoot, when the IMC-PID controller is used, but it takes more time to reach the desired value. Simulation results have shown, without doubt, that the proposed fuzzy PID controller is more effective and robust than the other control types.

After the design of Fuzzy PID controller has been completed, the FPGA board has been used to implement the proposed control system. Figure 11 shows the connection of the FPGA board with chip. The digital control signal is sent to the D/A convertor to generate an analogy control signal which is applied as input to the helicopter model. Figure 12 shows the output signal of the D/A converter (control signal). By comparing Figure 12 and the simulation output signal of Fuzzy PID controller (which is shown in Figure 10), it can be seen that, the two output signals are identical.

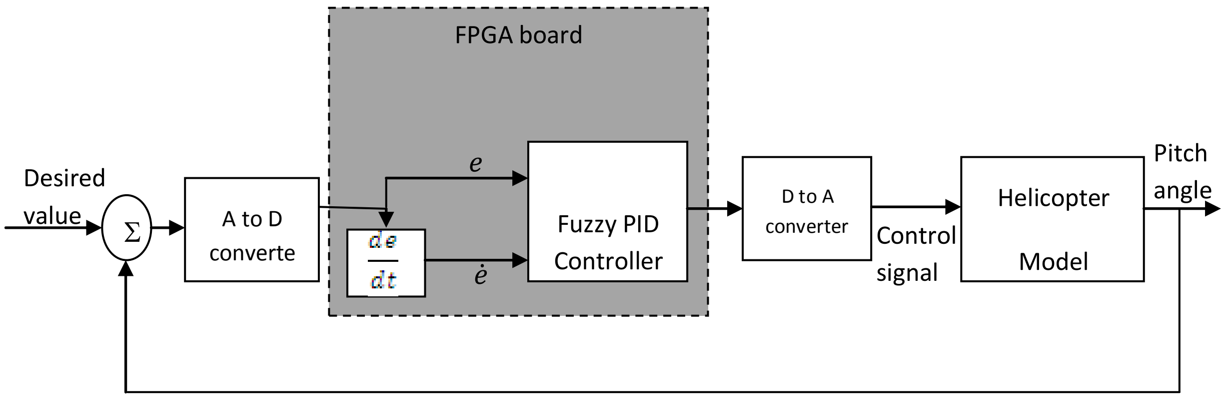

Figure 11 Layout of FPGA board with helicopter model

process system. First, a VHDL codes are downloaded into the FPGA chip (XILINX Spartan XC3S700AN) by using USB cable. Then, the Hirose 100-pin FX2 Edge connector (one port of the FPGA board) is used to connect the FPGA board with the helicopter system. The error between the reference input and the system output has been applied as input to the A/D converter. The digital output of the A/D converter has been applied as input data to the FPGA boards. The FPGA board generates digital inputs to the Fuzzy PID controller (error and error rate). The Fuzzy PID controller generates a suitable digital control signal based on the rules that store in the FPGA

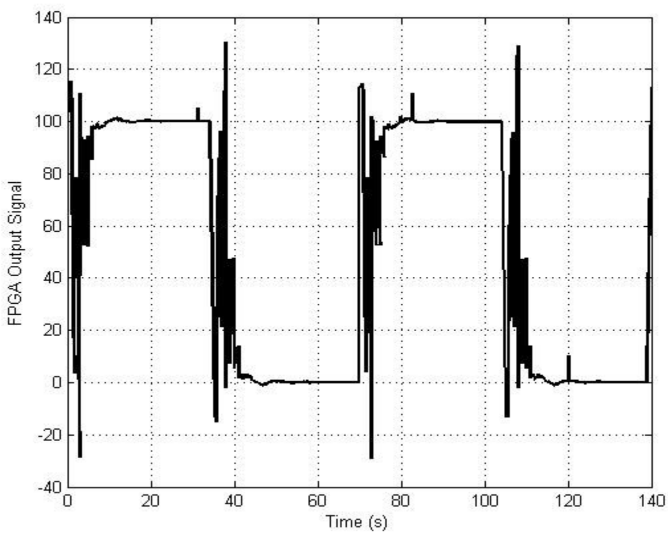

Figure 12 Control signal generated from FPGA board

7. Conclusion:

A modified Fuzzy PID controller is proposed to reduce the huge number of the fuzzy rules required in the normal fuzzy PID controller. The fuzzy PID controller is represented as Proportional-Derivative Fuzzy (PDF) controller and Proportional-Integral Fuzzy (PIF) controller connected in parallel through a summer. The PIF controller design has been simplified by replacing the PIF controller by PDF controller with accumulating output. The modified Fuzzy PID controller is used to design a robust controller for pitch angle of bench-top helicopter. The response of the plant with the modified Fuzzy PID controller is compared with the response of the plant with conventional PID controller and Internal Model Control Tuned PID (IMC-PID) Controller. Simulation results show that the proposed Fuzzy PID controller produces superior control performance than the other two controllers in handling the nonlinearity of the helicopter system. The FPGA board is used to implement the modified Fuzzy PID controller. The VHDL codes are written to describe the operation of proposed controller. The results show that response of designed FPGA board work like the proposed controller.

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