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Design of a Fuzzy Type-2 Controller for 1-DOF Pitch Axis Twin Rotor System

Abdelrahman Sayed Sayed^{1,#}, Walid K. Shaker^{2,#}, Hossam Hassan Ammar³, Ahmad Taher Azar⁴, Chakib Ben Njima⁵

Abstract—This paper presents the design, manufacturing, modeling, and control of a novel 1-DOF pitch axis Twin Rotor system. An IMU sensor is used to precisely access the desired pitch angle of the system. A type-2 fuzzy controller is designed and implemented to achieve fast rise time and low overshoot, which are the desired response specifications for the system. In terms of overshoot and settling time, the performance of the type-2 fuzzy-PID controller is compared to that of the type-1 fuzzy-PID controller and the conventional PID controller. The type-2 fuzzy-PID controller's performance is promising when compared to that of the other controllers, proving that it is useful for taming the Twin Rotor system's non-linearities.

Index Terms—Fuzzy logic controller; Pitch Angle; Twin Rotor System; Type-2 Fuzzy Controller.

I. INTRODUCTION

Tandem rotor helicopters are frequently used for forest fire rescue, observation, and inspection missions [1]–[4]. In order to maneuver around the horizontal pitch and vertical yaw axes, a helicopter typically has two rotors that are the tail and main rotors. However, tandem rotor helicopters have two large horizontal rotors mounted in front of one another [5], as shown in Fig. 1. Tandem rotor helicopter benefits include a wide center of mass range and increased lift capacities with smaller rotors [6]. By extending the distance between the two rotor hubs and lifting one hub above the other, this loss can be reduced [7], [8].

In light of these benefits, a twin rotor system is being developed for laboratory investigation in order to gain a thorough understanding and enhance the performance of tandem rotor



Fig. 1. CH-47H Chinook DAFCS Tandem Rotor. Adopted from [13]

helicopters [9]. The majority of the characteristics of a helicopter, such as heavy cross-couplings, potent non-linearities, and counterweight, are particularly preserved in the twin rotor system, which is almost identical to a practical tandem rotor helicopter [10], [11]. However, the two main problems with the Twin Rotor system are its complex dynamic features, which increase the system's nonlinearity, and the near-impossibility of obtaining a proper dynamic representation of the system because of its complex physical fundamentals and various uncertainties [12].

Due to their ability to manage complicated and uncertain systems, type-1 fuzzy-PID controllers have been widely used to deal with nonlinear system behavior [14]–[17]. However, they are not always effective in handling highly complex systems with a high level of uncertainties. This is due to the inaccuracy of membership functions and knowledge base that can lead to poor control performance [5]. As a result, more advanced and sophisticated controllers have been developed to overcome these challenges.

One of such controllers is the type-2 fuzzy controller which offers a more advanced approach to deal with system uncertainties. Type-2 fuzzy controllers allow for uncertainty at different levels, which makes them more robust in handling highly complex systems [18]–[23]. This is accomplished through the use of an interval type-2 fuzzy set, which provides a more sophisticated method of handling system uncertainties than Type-1 fuzzy sets. The interval type-2 fuzzy set employs upper and lower membership functions to define the degree of a given value's membership to a particular fuzzy set. This approach results in a more robust and accurate control of highly complex and uncertain systems.

The efficiency of type-2 fuzzy controllers in managing complex systems has been the subject of numerous studies, including Type-2 fuzzy-PID controllers. For instance, in [24], the planned trajectory of the quadcopter UAV is stabilized

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and/or monitored by a fuzzy PID controller. In [25], a robust control strategy for the quadcopter system was presented using a Self-Regulating (SR) Fuzzy Proportional-Integral-Derivative (FPID) control system to improve system stability and disturbance rejection capabilities. In [26], a study on the use of a Type-2 fuzzy-PID controller for a quadcopter system showed its superiority over Type-1 fuzzy-PID controllers and conventional PID controllers in terms of system response and robustness. In [27], both the Ziegler-Nichols PID controller and the self-tuning fuzzy PID controller are used to control a quadcopter-style unmanned aerial vehicle with four rotors, four degrees of freedom, and vertical take-off and landing (VTOL) capability. In [28], a study on the control of a parallel robot using a Type-2 fuzzy controller, it was found that the Type-2 fuzzy controller performed better in terms of tracking performance and robustness than the traditional PID and Type-1 fuzzy controllers. To handle the position control problem of the Crazyflie 2.0 nano quadcopter in a real-world setting, a Fuzzy PID (FPID) controller structure is proposed in [29].

As a result, we suggest in this paper that a Type-2 fuzzy controller be used to control a Twin Rotor system with a single degree of freedom (DOF) pitch axis. The findings demonstrate that in terms of overshoot and settling time, the Type-2 fuzzy-PID controller performs better than the Type-1 fuzzy-PID controller and conventional PID controller. The proposed controller offers a more sophisticated and reliable method of handling system uncertainties, leading to more precise and effective control of extremely complex systems.

The paper is organized as follows. Section II presents the modeling and system description of the Twin Rotor system. In Section III, type-2 fuzzy PID controller design is discussed. In sections IV and V, results with discussion is given. Finally, conclusion is drawn in Section VI.

II. MODELING AND SYSTEM DESCRIPTION OF THE TWIN ROTOR SYSTEM

The paper discusses two essential Twin Rotor system-related issues. The transfer functions are established in accordance with the mathematical model of the system, which is derived using Euler-Lagrange equations [30], which is presented in the first section. The Twin Rotor system's design, including its components, actuators, drivers, and sensors, is covered in the second section.

A. Twin Rotor System Mathematical Model

Based on the free body diagram shown in Fig. 2, the mathematical model for the Twin Rotor system is developed. Two horizontal rotors are used in the proposed Twin Rotor system to account for the effects of propulsion, centrifugal, frictional, and disturbance torques on the motion of the propellers. A control input signal is delivered through the motors in order to counteract the effects of these forces [31].

The following dynamic equation describes the horizontal motion:

$$I_2 \ddot{\phi} = M_2 - M_{B\phi} - M_R \quad (1)$$

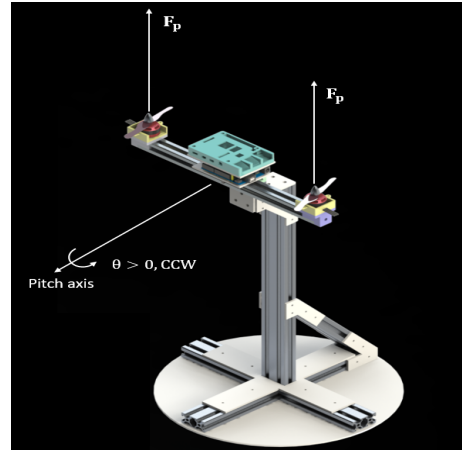


Fig. 2. Twin Rotor system free-body Diagram

where the two propellers' thrust is provided by:

$$M_1 = a_1 \tau_1^2 + b_1 \tau_1 \quad (2)$$

$$M_2 = a_2 \tau_2^2 + b_2 \tau_2 \quad (3)$$

The friction forces momentum is expressed as:

$$M_{B\phi} = B_{1\phi} \dot{\phi} \quad (4)$$

while the cross-reaction momentum can be obtained by:

$$M_R = K_c \left(\frac{T_o s + 1}{T_p s + 1} \right) M_1 \quad (5)$$

The two motors dynamics are given by:

$$\tau_1 = \left(\frac{K_1}{T_{11} s + T_{10}} \right) u_h \quad (6)$$

$$\tau_2 = \left(\frac{K_2}{T_{21} s + T_{20}} \right) u_h \quad (7)$$

The system can be linearized by converting the system dynamics represented by Eqs. 1 to 7 to state-space form.

The definitions of the A, B, and C matrices are:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ -3.61 & -0.09 & 0 & -0.12 & 2.06 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -5 & 0 & -0.54 & -50 \\ 0 & 0 & 0 & 0 & -0.91 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0.22 & 0 & -0.5 \end{bmatrix} \quad (8)$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 0.80 \\ -0.35 & 0 \end{bmatrix}, C = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (9)$$

Now, the system dynamics can be expressed as:

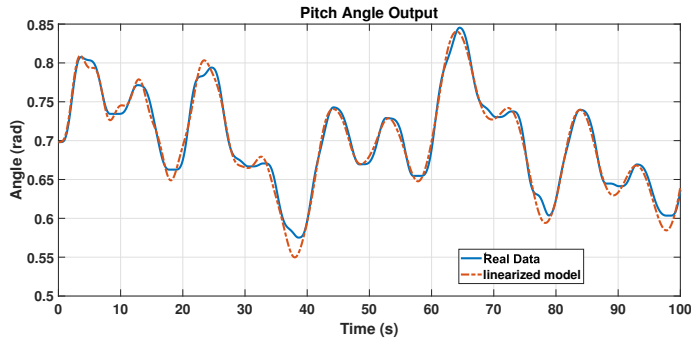


Fig. 3. Linearized Pitch angle

$$\dot{x} = Ax + Bu \quad (10)$$

$$y = Cx \quad (11)$$

where the system dynamics is captured at A matrix. B is the input matrix, while C is the output matrix. The state vector is given by x . The input and output vectors are represented by u , and y respectively. By using Eqs. 10 and 11, the system model is linearized and illustrated in Fig. 3.

Transfer functions are generated for the pitch axis at two different step inputs using the obtained linearized model. The two transfer functions expressing the output at each step output are expressed in Eqs. 12 and 13. When tuning the system, these two obtained transfer functions are used to determine the gain values that will enable the system to achieve balancing even when external loads and disturbances are applied.

At step input 1:

$$\frac{2.0612(s + 3.955)(s + 0.561)}{(s + 5)(s + 0.9091)(s^2 + 0.08824s + 3.605)} \quad (12)$$

At step input 2:

$$\frac{0.05003}{(s + 5)(s + 1)(s^2 + 0.08824s + 3.605)} \quad (13)$$

B. System Description

The primary goal of this study, as previously mentioned, is to validate the suggested controller using a real Twin Rotor system. Power consumption and weight, however, are significant elements that can impact performance in Twin Rotor systems. Therefore, it is always preferable to reduce the payload on the chassis and the power consumption of the electronic components. Low-power, light-weight, and inexpensive components were used to achieve real-time execution of the suggested setup while still meeting the necessary computational requirements.

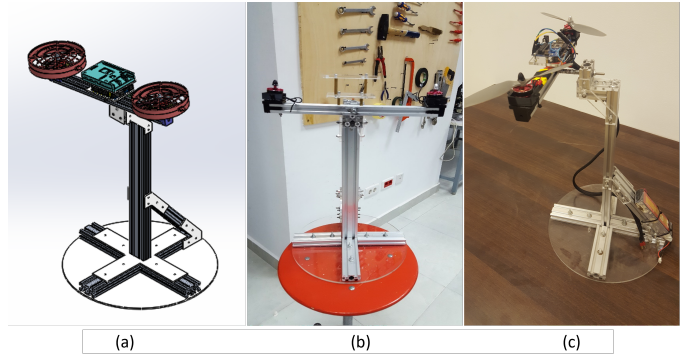


Fig. 4. Constructing the Twin Rotor process. (a): the system design phase, (b): the manufacturing phase, (c): assembling the electric components phase

1) **Mechanical Design:** The mechanical design for the Twin Rotor mechanism is created and modeled using SOLIDWORKS based on general engineering practices such as design for manufacturing (DFM) and design for assembly (DFA). The design consists of a base, a fixed vertical profile, and a rotating profile designed to hold the two brushless motors with their propellers, and the controllers' fixations plates. In the context of design, the material selection process resulted in using industrial Aluminum extrusion profile. It is a great framing material made of high-quality Aluminum Alloy. Besides its light weight, better corrosion resistance, it is characterized by clear anodize and surface finish. In addition, the profile is formed in a T-Slot shape which eases the assembly operation. The rotating bar is 2020 Aluminum extrusion profile, whereas all the other parts are in 2040 size. Moreover, 3D printed caps and motor holders are assembled to the rotating profile. The system construction process consists of 3 phases; design, manufacturing, and assembly as shown in Fig. 4.

2) **System Architecture:** An Arduino UNO board mounted on the Twin Rotor's chassis served as the subscriber to the master instructions, and a master PC served as the publisher. The Arduino board serves as a data acquisition device that detects changes in the Twin Rotor's angle from the IMU sensor and transmits this information to the master PC via Bluetooth module so that it can receive commands to control the brushless motors' speed as shown in Fig. 5.

III. TYPE-2 FUZZY PID CONTROLLER DESIGN

The proposed control structure uses a Mamdani-type-2 fuzzy controller at the upper level and a conventional PID controller at the lower level. Generally, the PID controller is developed as

$$u(t) = k_p e(t) + k_i \int e(t) dt + k_d \frac{de(t)}{dt} \quad (14)$$

$$e(t) = y_r(t) - y_m(t)$$

where k_p , k_i , and k_d stand for proportional, the integral, and the derivative gains respectively. The operator modifies the values of k_p , k_i , and k_d in Eq. 14 in the classical PID

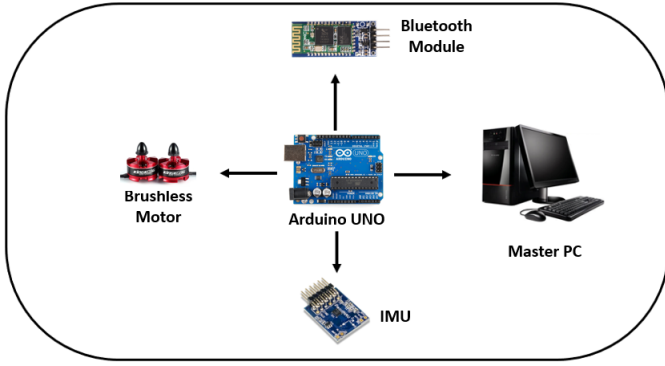


Fig. 5. Overall System architecture. Adopted from [32]

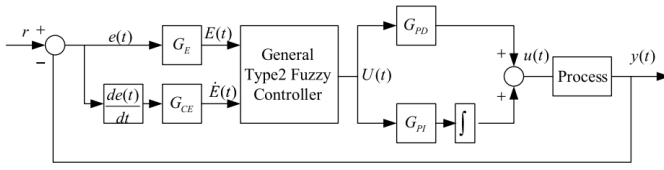


Fig. 6. Type-2 Fuzzy PID controller structure

controller in response to changes in the process condition. The letters u , y_m , and y_r correspondingly stand for the output from the controller, the output from the process, and the set point. The proposed type-2 fuzzy PID controller block diagram in Fig. 6 is a non-linear mapping; E and \dot{E} are its inputs, and U is the output.

The general type-2 fuzzy sets that are proposed in this study have a triangular membership function. For ease of understanding, Fig. 7 shows that error and its derivative share the same primary membership function.

There will be 9 fuzzy rules in this study, and as illustrated in Fig. 7, the membership functions are symmetric. The fuzzy rules are shown in Table I.

\tilde{A}_i and \tilde{A}_{i+1} in E or \tilde{B}_j and \tilde{B}_{j+1} in \dot{E} are the two membership functions that can fire at most concurrently. Fig. 8 shows that the total of the neighboring membership functions is 1. Thus, only 4 fuzzy rules are applied simultaneously, as

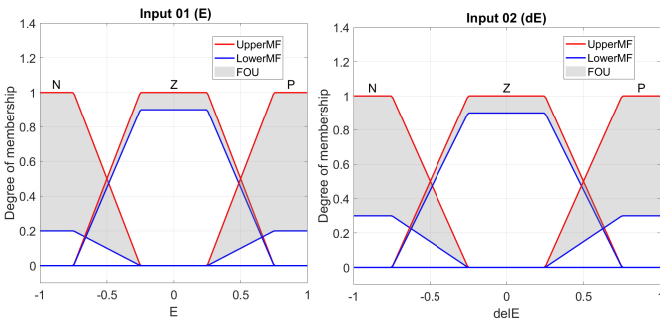


Fig. 7. Type-2 Fuzzy PID controller Membership functions

TABLE I
TYPE-2 FUZZY PID RULE BASE

E/dE	N	Z	P
N	NB	Z	Z
Z	NM	PM	PM
P	Z	Z	PB

shown below:

- If the input variable E is classified as \tilde{A}_i and the derivative of E , \dot{E} , is classified as \tilde{B}_j , then the output variable U takes on the value y_1 .
- If E is classified as \tilde{A}_i and \dot{E} is classified as \tilde{B}_{j+1} , then U takes on the value y_2 .
- If E is classified as \tilde{A}_{i+1} and \dot{E} is classified as \tilde{B}_j , then U takes on the value y_3 .
- If E is classified as \tilde{A}_{i+1} and \dot{E} is classified as \tilde{B}_{j+1} , then U takes on the value y_4 .

The membership degree of a fuzzy rule that is fired as a result of fuzzy inference by an interval type-2 fuzzy logic system is an interval. Eq. 15 utilises the 'product' operator to show the intervals for the four fuzzy rules.

$$\begin{aligned}
 [f_{-1}, \bar{f}_1] &= [\underline{u}_{\tilde{A}_i}(E) \times \underline{u}_{\tilde{B}_j}(\dot{E}), \bar{u}_{\tilde{A}_i}(E) \times \bar{u}_{\tilde{B}_j}(\dot{E})] \\
 [f_{-2}, \bar{f}_2] &= [\underline{u}_{\tilde{A}_i}(E) \times \underline{u}_{\tilde{B}_{j+1}}(\dot{E}), \bar{u}_{\tilde{A}_i}(E) \times \bar{u}_{\tilde{B}_{j+1}}(\dot{E})] \\
 [f_{-3}, \bar{f}_3] &= [\underline{u}_{\tilde{A}_{i+1}}(E) \times \underline{u}_{\tilde{B}_j}(\dot{E}), \bar{u}_{\tilde{A}_{i+1}}(E) \times \bar{u}_{\tilde{B}_j}(\dot{E})]
 \end{aligned} \tag{15}$$

Eq. 15 shows three sets of vector cross-products. The first set involves \tilde{A}_i and \tilde{B}_j , the second set involves \tilde{A}_i and \tilde{B}_{j+1} , and the third set involves \tilde{A}_{i+1} and \tilde{B}_j . The resulting vectors are denoted as f_{-1} , \bar{f}_1 , f_{-2} , \bar{f}_2 , f_{-3} , and \bar{f}_3 .

Where $NB = -1$, $NM = -0.8$, $Z = 0$, $PM = 0.8$, $PB = 1$ ^[49] are the consequent parameters.

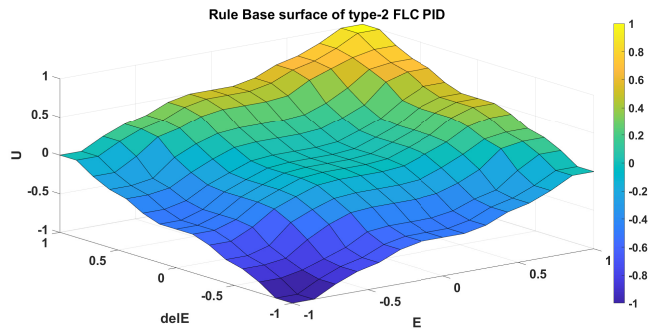


Fig. 8. Type-2 Fuzzy PID Rule base surface

IV. RESULTS

The Ziegler-Nichols tuning method is used to fine-tune the PID controller, with proportional gain $K_p = 10.2$, integral time $T_i = 0.045$, and derivative time $T_d = 0.004$. As

the system under consideration is a multi-input single-output (MISO) system, two controllers had to be designed for each input/output model, as was described in section II.

Fig. 9 illustrates the PID, Type-1 fuzzy-PID, and Type-2 fuzzy-PID controllers' combined transient response for (input1/output). The type-2 fuzzy controller performs better than the PID and Type-1 fuzzy controller in terms of overshoot and settling time, but PID performs better in terms of rising time. Fig. 10 also illustrates the combined transient response of PID, Type-1 fuzzy-PID, and Type-2 fuzzy-PID controllers for (input2/output), but PID performs better in terms of rising time.

Table II for (input1/output) and Table III for (input 2/output) show the comparison of transient responses for the different controllers, including overshoot ($OS\%$), settling time, rise time, and Integral Absolute Error (ISE). The tables show that in terms of percentage overshoot and settling time, the Type-2 fuzzy-PID controller performs better than the Type-1 fuzzy PID controller and the conventional PID controller.

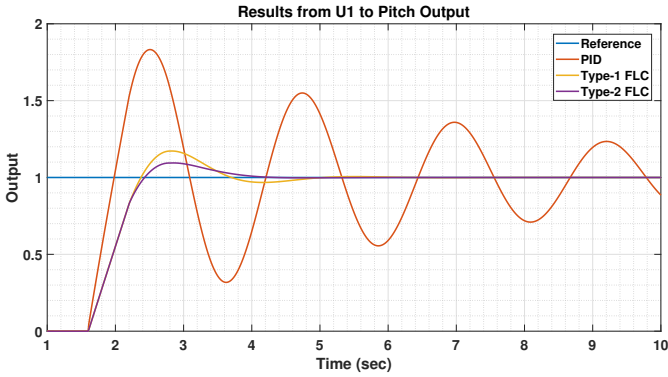


Fig. 9. Time response results of input 1 (U1) to Pitch angle

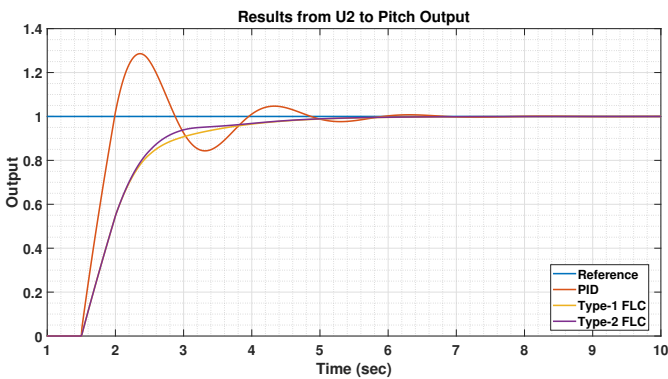


Fig. 10. Time response results of input 2 (U2) to Pitch angle

The fuzzy-PID controller has an average of 92.3% less than PID controller and 73.2% less than Type-1 fuzzy PID controller in terms of overshoot. Similarly, the settling time is also 3.6% and 21.6% less than that of PID and fuzzy controller.

TABLE II
RESPONSE RESULTS OF INPUT 1 (U1) TO PITCH ANGLE

Controller	Rise Time (sec)	OS (%)	Settling Time (sec)	ISE
PID	0.3106	83.5128	21.5817	3.8748
Type-1 FLC	0.5919	17.2242	4.5639	1.1337
Type-2 FLC	0.6045	9.4580	3.7753	1.0600

TABLE III
RESPONSE RESULTS OF INPUT 2 (U2) TO PITCH ANGLE

Controller	Rise Time (sec)	OS (%)	Settling Time (sec)	ISE
PID	0.2965	7.7990	2.6153	0.4523
Type-1 FLC	1.1345	0	3.2874	0.7622
Type-2 FLC	0.9874	0	3.1522	0.7297

V. DISCUSSION

The study's results show that the Type-2 fuzzy-PID controller has a significant advantage over Type-1 fuzzy-PID controllers in terms of overshoot and settling time when it comes to controlling the MISO system. The PID controller was tuned using Ziegler-Nichols tuning method. Two controllers were created for each input/output model because the system is a MISO system, as was mentioned in section II.

The Type-2 fuzzy-PID controller appears to be a promising option for controlling MISO systems, especially when overshoot and settling time are important considerations, according to these results. Further study is necessary to examine the controller's performance in various scenarios and for various kinds of systems, though. In particular, it would be intriguing to look into how resilient the controller is to system dynamics disturbances and uncertainties, such as those brought on by outside forces or measurement noise.

VI. CONCLUSION

The control of a 1-DOF Pitch Axis Twin Rotor using PID, Type-1 Fuzzy-PID, and Type-2 Fuzzy-PID is demonstrated in this paper. The type-2 fuzzy-PID controller has more advantages than both the type-1 fuzzy-PID controller and the conventional PID, according to numerical simulation. The type-2 fuzzy-PID controller has low settling time, strong robustness, and minimal overshoot. It also possesses a significant capacity for adapting to changes in the system's characteristics, anti-disturbance performance, and capacity for handling uncertainty. The controller complies to the set point precisely. The type-2 fuzzy-PID controller performs better in terms of error index ISE. For the future work, implementing other controllers such as Fractional-Order PID (FOPID) to optimize the performance of the Twin Rotor would be interesting as FOPID flexibility may allow to achieve better results, particularly for highly nonlinear systems where classical PID controllers may struggle.

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