FUZZY CONTROL DESIGN FOR A TWIN ROTOR MULTI-INPUT MULTI-OUTPUT SYSTEM (TRMS)

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مُسْتَخْلَص

تقدم هذه الورقة تصميماً لمتحكم غامض لنظام دوار توأم متعدد المداخل والمخارج. الهدف من ذلك جعل عمود الدوار التوأم يتحرك للوضع المطلوب (الزاوية الأفقية والزاوية الرأسية) بسرعة ودقة عالية. من المتميز جداً إيجاد متحكم لهذا النوع من الأنظمة بسبب الخصائص اللاخطية العالية وتأثير الترابط بين المحورين الرأسي والأفقي. في هذا البحث تم إيجاد النموذج الرياضي الدقيق لكل من الجزء الرأسي والجزء الأفقي للنظام، من أجل الحصول على استجابة مشابهة للنظام الحقيقي. وتم استخدام النماذج كأساس اختبار لإيجاد مجموعة المتحكمات الغامضة. وكان أداء هذه المتحكمات مرضياً من حيث قدرتها على دفع النظام لتتبع الحركة في كلا المحورين. تقدم هذه الورقة أيضا مقارنة في الأداء بين المتحكمات الغامضة المقترحة والمتحكم التناسبي-التكاملي-التفاضلي التقليدي.

ABSTRACT

This paper presents the designing of fuzzy logic controller for a twin rotor multi-input-multi-output system (TRMS). The control objective is to make the beam of the TRMS move quickly and accurately to the desired positions, i.e., the pitch and the travel angles. Developing controller for this type of system is challenging due to the coupling effects between two axes and also due to its highly nonlinear characteristics. In this investigation accurate dynamic models of the system for both vertical and horizontal movements are developed so as to get very similar responses to that of the real plant. These models are then used as test-beds to develop a set of fuzzy controllers. The performance of the controllers in tracking movements in both vertical and horizontal planes is found to be very satisfactory. A comparative performance study of this fuzzy control approach with respect to a single PID approach is also presented in this study

Keywords: *MIMO, TRMS Model, PID Control, Fuzzy Control.*

1. INTRODUCTION

Many researchers have recently studied intelligent control in order to solve problems with classical methods of control, and what is remarkable of all is Fuzzy Control using expert's knowledge or experience and Neural Network Control with learning ability [1].

Modem control which proved to be invaluable for providing solutions to well-structured aerospace problems, has not been as successful in process control applications, where the conventional controllers are still used.

However, conventional controllers do not perform optimally for complex problems [2]. One such problem is the TRMS problem discussed in this paper.

Recent work showed that conventional PID tuning turned out to be inadequate for this complex system, resulting in a poor performance. Thus, the objective was to design an intelligent control scheme to overcome the limitations of conventional control. It has been shown that Fuzzy Logic Controller (FLC) could improve the response of TRMS in terms of tracking and transient response [3].

In this paper we discuss the design of a fuzzy logic controller to control the pitch and travel of the TRMS problem. This controller has been designed and simulated in MATLAB.

2 INTELLIGENT CONTROL SYSTEMS

Intelligent control system techniques have been utilized effectively to solve control problems for the past few years. Among them fuzzy systems, neural networks, neuro-fuzzy, and genetic algorithms are the most used methods. In 1974, Mamdani [4] pioneered the investigation of feasibility of using compositional rule of inference that had been proposed by Zadeh [5], for controlling a dynamic system. Later, Mamdani and Assilian [6] developed the first fuzzy logic controller, in a sense; the first fuzzy controller was equivalent to two input fuzzy PD controllers, where error and change of error were used as inputs to the inference engine. Takagi and Sugeno [7] introduced a different linguistic description of the output fuzzy set, and a numerical optimization approach to design fuzzy controller structure. All fuzzy controllers design is based on experience or knowledge. Fuzzy control is characterized by the use of linguistic rules to manipulate and implement human knowledge in control systems so as to handle the uncertainty present in the environment.

In this paper a fuzzy control system has been developed for a TRMS. For such a complicated system the conventional model-based (PID) controller shows poor performance. However, due to its nonlinearity fuzzy logic based control approach looks promising. The applications of fuzzy logic to control these types of systems, with high nonlinearity, have widely been used. Tanaka et al. [8] has implemented a Takagi-Sugeno fuzzy model for stabilization of a 3-DOF RC helicopter. Combined fuzzy and PID control approach for an unmanned helicopter has been reported in [9]. Fuzzy behavior navigation has been implemented on an unmanned helicopter in unknown environment [10]. Shim et al. [11] have performed a comprehensive study of control design for an autonomous helicopter some investigations are reported to have addressed the modeling and control of a TRMS using various model-based and artificial intelligence (AI)-based approaches. For instance, dynamic modeling and optimal control of a TRMS has been presented in [12]. Performance analysis of 4 types of conjugate gradient algorithms in the nonlinear dynamic modeling of a TRMS using feed-forward neural networks has been reported in [13]. Dynamic modeling of a TRMS has been presented in [14], which has investigated the utilization of neural networks. It is noted that some intelligent control schemes based on fuzzy logic have been applied to TRMS [15, 16]. Those controllers have been developed on the basis of a crude and simple supplied model of the TRMS by feedback. The model has not taken all the acting forces into consideration and therefore does not represent the TRMS accurately. The developed fuzzy controllers, therefore, do not show good performance to various inputs. Most importantly, those controllers cannot be implemented on the real plant. In this investigation the fuzzy controller has been developed on the basis of an accurate dynamic model of the plant and therefore can be implemented on the real TRMS easily.

3 TWIN ROTOR MIMO SYSTEMS

3.1 TRMS Control Structure

The TRMS, shown in Figure 1, is a laboratory set-up designed by Feedback Instruments Limited [16] for control experiments. The TRMS is characterized by its complex and highly nonlinear dynamics. In certain aspects it behaves like a helicopter. However, the TRMS is different from a helicopter in many ways. (Table 1) lists the main differences between a helicopter and a TRMS. The TRMS consists of a beam pivoted on its base in such a way that it can rotate freely both in the horizontal and vertical planes responding to yaw and pitch moments, respectively. At such end of the beam there are two rotors driven by DC motors. The main rotor produces a lifting force allowing the beam to raise vertically (pitch angle), while the tail rotor is used to control the beam turn the left or right (yaw). Both of motors produce aerodynamic force through the blades and also provide the coupling effect. From the control point of view this exemplifies a high order non-linear system with significant cross-coupling.

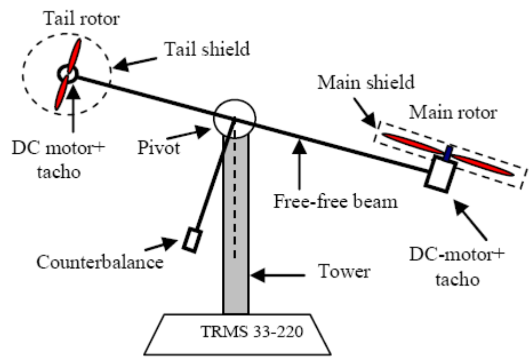

Figure 1: Schematic diagram of the TRMS

Table 1: Main difference between a helicopter and a TRMS

	TRMS	Helicopter
Location of pivot point	Midway between two rotors	Main rotor head
Lift generation of vertical axis	Speed control of main rotor	Collective pitch control
Yaw is controlled by	Tail rotor speed	Pitch angle of tail rotor blades

3.2 TRMS Mathematical Models

A block diagram of the TRMS model is shown in Figure 2, where $\boldsymbol{M_v}$ is the vertical tuning moment, $\boldsymbol{J_v}$ is the moment of inertia with respect to horizontal axis, $\boldsymbol{\alpha_v}$ is the vertical position (pitch angle) of TRMS beam, $\boldsymbol{l_m}$ is the arm of aerodynamic force from main rotor, $\boldsymbol{l_t}$ is the effective arm of aerodynamic force from tail rotor, g is the acceleration of gravity, $\boldsymbol{\omega_m}$ is the rotational speed of main rotor, $\boldsymbol{F_v(\omega_m)}$ is the nonlinear function of aerodynamic force from main rotor, $\boldsymbol{k_v}$ is the moment of friction force in horizontal axis, $\boldsymbol{\Omega_v}$ is angular velocity (pith velocity) of TRMS beam, $\boldsymbol{\Omega_h}$ is the angular velocity (azimuth velocity) of TRMS beam $\boldsymbol{\alpha_h}$ is horizontal position (azimuth position) of TRMS beam, $\boldsymbol{M_h}$ is the horizontal tuning torque, $\boldsymbol{J_h}$ is the nonlinear function of moment of inertia with respect to vertical axis, $\boldsymbol{\omega_t}$ is the rotational speed of tail rotor, $\boldsymbol{F_h(\omega_t)}$ is the nonlinear function of aerodynamic force from tail rotor, $\boldsymbol{k_h}$ is the moment of friction force in the horizontal axis, $\boldsymbol{J_{tr}}$ is the vertical angular momentum from tail rotor, $\boldsymbol{J_{mr}}$ is the vertical angular momentum from main rotor, $\boldsymbol{S_v}$ is the vertical tuning moment, $\boldsymbol{S_h}$ is the horizontal tuning moment, $\boldsymbol{S_f}$ is the balance factor, $\boldsymbol{U_v}$ and $\boldsymbol{U_h}$ are the DC- motor control inputs, in order to control TRMS in the vertical and horizontal separately.

The main rotor and the tail rotor are decoupled, the mathematical models of main rotor is as follows:

$$\frac{dS_V}{dt} = I_m\, S_f\;\; F_V\,(\omega_m) - \Omega_V\,\mathrm{kv} + \mathrm{g}\big((\mathrm{A}-\mathrm{B})cos\alpha_V - \mathrm{C}\sin 2\alpha_V\big) - \frac{1}{2}\,\Omega^2(\mathrm{A}+\mathrm{B}+\mathrm{C})\,\sin 2\alpha_V \qquad (1)$$

$$\frac{d\alpha_V}{dt} = \Omega_V \qquad (2)$$

$$\mathrm{S_V}=\frac{S_V+J_{tr}\omega_t}{\mathrm{Jv}} \qquad (3)$$

$$\frac{dU_{VV}}{dt} = \frac{1}{T_{mr}}(-U_{VV}+U_V) \qquad (4)$$

$$\omega_m = P_V\,(U_{VV}) \qquad (5)$$

$\boldsymbol{m_{mr}}$ is the mass of the main DC motor with main propeller, $\boldsymbol{m_m}$ is the mass of main part of the beam, $\boldsymbol{m_{tr}}$ is the mass of tail motor with tail propeller, $\boldsymbol{m_t}$ is the mass of tail part of the beam, $\boldsymbol{m_{cb}}$ is the mass of the counter –weight, $\boldsymbol{m_b}$ is the mass of the counter-weight beam, $\boldsymbol{m_{ms}}$ is the mass of the main shield, $\boldsymbol{m_{ts}}$ is the mass of the tail shield, $\boldsymbol{l_b}$ is the length of counter-weight beam, $\boldsymbol{l_{cb}}$ is the distance between the counter-weight and the joint.

Assume that the main rotor is an independent part:

$$\frac{dS_V}{dt} = I_m\, S_f\ \ F_V(\omega_m) - \Omega_V\, k_V + \mathrm{g}((\mathrm{A}-\mathrm{B})\ \cos\alpha\mathrm{v} - \sin\alpha_V \qquad (6)$$

$$\Omega_r = \ 9.1 S_V \qquad (7)$$

The block diagram of the main rotor is shown in Figure 3.

The mathematical model of tail rotor is as follows:

$$\frac{dS_h}{dt} = I_t\, S_f\ \ F_h\ (\omega_t)\cos\alpha_r - \Omega_h\, k_h \qquad (8)$$

$$\frac{d\alpha_h}{dt} = \ \Omega_h \qquad (9)$$

$$\Omega_h = \frac{S_h + J_{mr}\omega_m \cos\alpha_V}{J_h} = \ \frac{S_h + J_{mr}\omega_m \cos\alpha_V}{\mathrm{D}sin\ ^2\alpha_V + \mathrm{E}cos\ ^2\alpha_V + \mathrm{F}} \qquad (10)$$

$$\frac{dU_{hh}}{dt} = \frac{1}{Tmr}(-U_{hh} + U_h) \qquad (11)$$

$$\omega_t = P_h\ (U_{hh}) \qquad (12)$$

Assume the tail rotor is an independent system, then:

$$\frac{dS_h}{dt} = I_t\, S_f\ \ F_h\ (\omega_t) - \Omega_h\, k_h \qquad (13)$$

$$\Omega_h = \ 90 S_h \qquad (14)$$

The block diagram of TRMS system is shown in Figure 2.

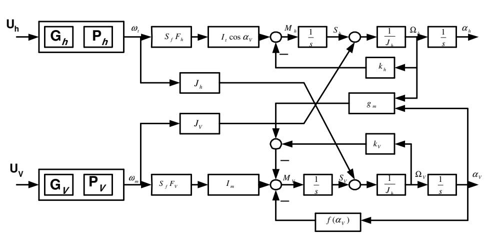

Figure 2: Block diagram of TRMS model

The block diagram of tail and main rotor systems are shown in Figure 3, and Figure 4, respectively.

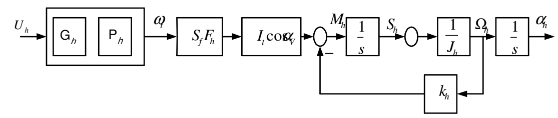

Figure 3: Block diagram of Horizontal Part of TRMS model

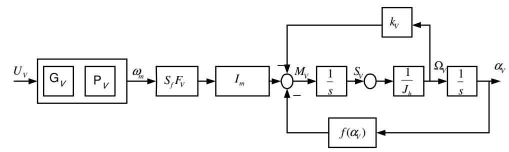

Figure 4: Block diagram of Vertical Part of TRMS model

4 PID CONTROL DESIGN

A PID controller with its basic form shown in equation 15 is proposed for the control design of TRMS; the control theory can be realized for obtaining the proportional, integral and derivative gains of the PID controller. Adjustment may be required for control purposes and to reduce the error from the model. The TRMS has two degrees of freedom, travel and pitch. Results show that conventional PID tuning turned out to be inadequate for this complex system, which resulting in **a** poor performance.

$$u(t) = K_p(t) + K_i \int e(t)dt + K_d \frac{d}{dt}\ e(t) \ (15)$$

5 FUZZY LOGIC

5.1 Fuzzy Fundamental

A conventional fuzzy controller consists of four subsystems, as shown in Figure 6, in which two parts have the duty of transformation; fuzzifier (first transformation), fuzzy rule base, inference engine and defuzzifier (second transformation). The fuzzifier changes the input variables (crisp signals) into fuzzy values. The fuzzy rule base consists of basic data and linguistic rules. The inference engine is the brain of a fuzzy controller which has the ability to simulate the human decision based on fuzzy idea. Finally, the second transformation converts the fuzzy values into the real values.

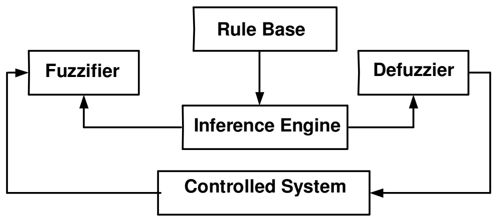

Figure 5: Fuzzy controller and controlled system

5.2 Fuzzy Controller Design

In this paper two fuzzy controllers have been developed, one for horizontal and the other for vertical 1 DOF TRMS. They work simultaneously to give the desired output. One controller controls and keeps track **of** travel while the other of pitch. Both these controllers are Mamdani Inference [2, 4] and designed in MATLAB. Each controller has two inputs and generates one output for its respective rotor.

The inputs of both fuzzy controllers are beam angle error and the derivative of beam angle error. Figs. 6 to 8 illustrate the membership functions of the inputs and outputs. The most important part of fuzzy controller design is the determination of fuzzy rule base.

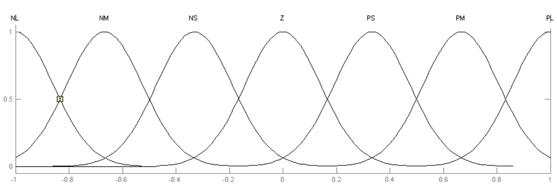

Figure 6: Membership functions of beam angle error

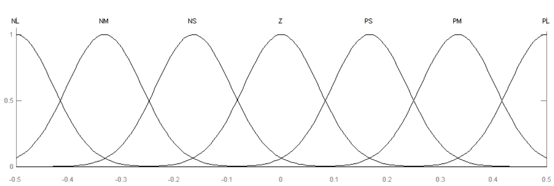

Figure 7: Membership functions of beam angle error change

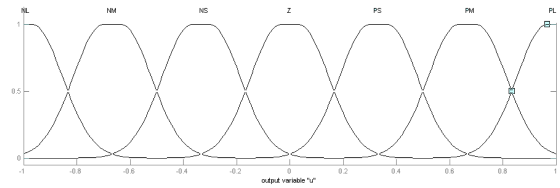

Figure 8: Membership functions of controller output

The fuzzy rule bases for these two controllers have been determined in accordance with the system behavior in both vertical and horizontal planes. The identical rule bases have been used for vertical and horizontal fuzzy controllers. Table 1 lists the rule base of both the fuzzy controllers.

Table 1: Rule Base of Fuzzy Controllers

	CE_V or CE_h							
E_v or E_h		NL	NM	NS	Z	PS	PM	PL
	NL	NL	NL	NL	NL	NM	NS	Z
	NM	NL	NL	NL	NM	NS	Z	PS
	NS	NL	NL	NM	NS	Z	PS	PM
	Z	NL	NM	NS	Z	PS	PM	PL
	PS	NM	NS	Z	PS	PM	PL	PL
	PM	NS	Z	PS	PM	PL	PL	PL
	PL	Z	PS	PM	PL	PL	PL	PL

6 SIMULATION RESULTS

The TRMS system is decoupled to horizontal part and vertical part. Each part is controlled by a fuzzy controller as shown in Figure 9 and Figure 10. In order to force the TRMS to track the specified trajectory quickly and accurately, the parameters of fuzzy controller g0, g1, and h, are tuned by using genetic algorithms in the MATLAB. The response of the system with PID controller is shown in Figure 11 and Figure 13.

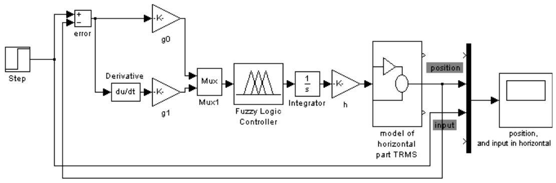

Figure 9: Fuzzy control of the TRMS horizontal part

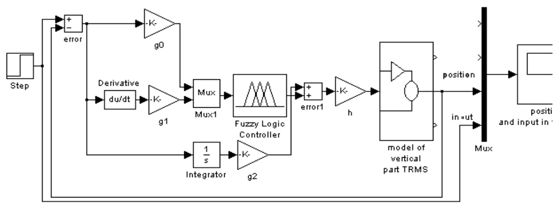

Figure 10: Fuzzy control of the TRMS vertical part

It can be seen that the actual beam angle varies quite a lot from the desired angle. Hence**,** it can be clearly deduced that the PID controller is not a good solution to the TRMS problem. The response of the system to unit step input with fuzzy control is shown in Figure 12 and Figure 14. Simulations show that the FLC controls the pitch and travel simultaneously such that the system is stable and the response of the system is better than PID controller.

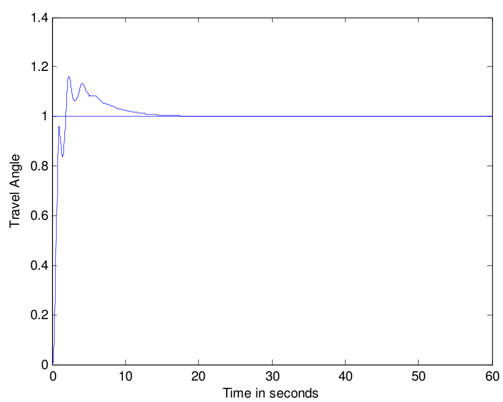

Figure 11: PID response for travel control of TRMS

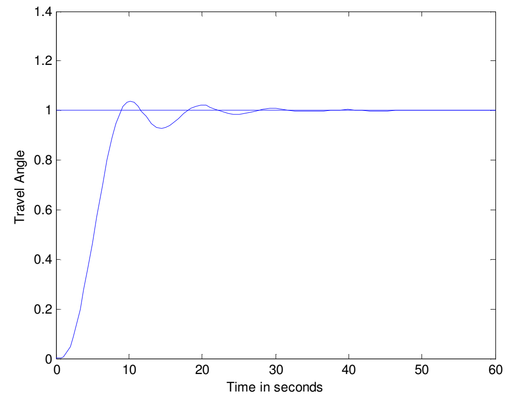

Figure 12: Fuzzy response for travel control of TRMS

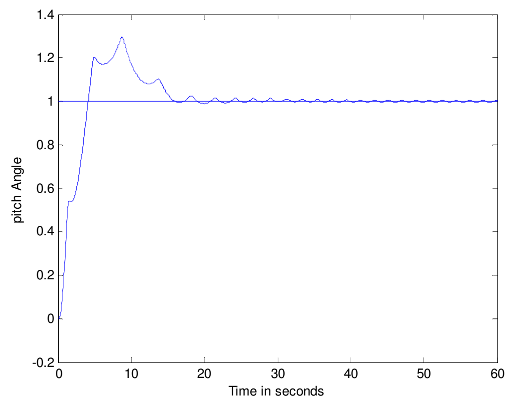

Figure 13: PID response for pitch control of TRMS

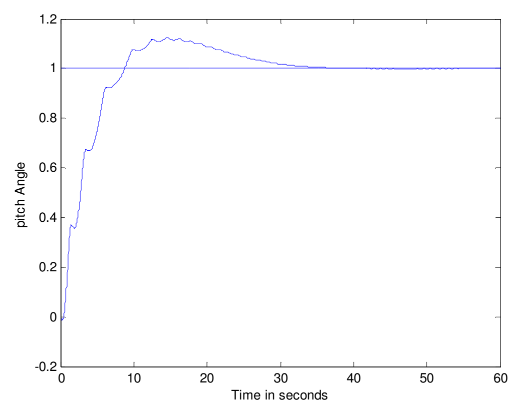

Figure 14: Fuzzy response for pitch control of TRMS

7 CONCOLUSION

In this paper, a control problem of the twin rotor multi input multi output system (TRMS) has been studied. The study combines the conventional PID and fuzzy controllers. The fuzzy controller proposed in this paper meets the objective of controlling the TRMS system to achieve stable tracking of inputs, and it is superior in performance compared to conventional controller.

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