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DESIGNING ROBUST CONTROLLER FOR TWIN ROTOR MIMO SYSTEM

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Abstract. *This paper proposed a robust controller for the Twin Rotor MIMO System (TRMS) to achieve stability and robustness performance for the system during operation. In particular, the μ_Synthesis method was utilized to define the parameters of the robust controller that can deal with a change in parameters, disturbances, and noise acting on the system. The weighting functions were obtained by theory and experiments to have a balance between the stability and robustness of the system. The experimental results for the TRMS were shown to verify the effectiveness of the proposed controller for the high nonlinear complex systems.*
Keywords: High nonlinear system, Robust controller, Twin Rotor MIMO System (TRMS), Uncertainties, Disturbances, μ_Synthesis

1. **Introduction.** The Twin Rotor MIMO System (TRMS) is one of the valuable models for investigation in the adaptive, optimal and robustness control areas. Due to highly cross-coupling between pitch and yaw axes, changes in parameters during operation, the TRMS is the high nonlinear system and its dynamic equation is crucially difficult to obtain in the practical applications [1,2], and the performance of the model-based controllers will get worse [3,4]. To deal with these high nonlinear systems, many advanced controllers have been developed in recent years to achieve high performance during operation [5-9]. In particular, the fuzzy controllers were proposed for the TRMS, inverted pendulum resulting in good tracking responses for control systems, but these results were only shown in the simulation [5,6]. The improved adaptive neural and sliding mode controllers were also recommended to utilize the strong points of sliding mode control and learning capability of the neural network to overcome the harshness of nonlinear systems which in turn obtained good results in simulation and real time [7-9]. Besides, an innovative recurrent cerebellar articulation controller was suggested to enhance the learning capability of the neural network and adapt to dynamic systems [10].

Although the above proposers had good tracking responses in controlling high nonlinear systems, the robustness of the systems in the presence of the uncertainties, disturbance, and change in parameters was not mentioned completely.

In this paper, the robust μ_Synthesis method is utilized to build the robust controller for the TRMS to achieve a balance between the stability and robustness performance under effects of change in parameters, disturbance, and noise during operation in reality.

The rest of this paper is organized as follows. Section 2 describes the dynamic system of the TRMS and the proposed controller. Section 3 is about designing the robust controller

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using the μ_Synthesis method. The experimental results for the TRMS are provided in Section 4, along with a conclusion and future research in Section 5.

2. **System Dynamic Description.** The TRMS is depicted in Figure 1. It consists of a free-beam affixed to the top of a tower so that it can turn and twist freely both in the vertical and horizontal planes. At both ends of the free-beam, the main and tail rotors are driven by DC motors. A counterbalance arm with a weight at its end is fixed to the free-beam at top of the tower. The vertical and horizontal angles are measured by encoders. The aerodynamic force acting on the free-beam is controlled by varying the speed of rotors. These rotors are controlled by Pulse Wide Modulation (PWM) signals from the STMicroelectronics STM32.

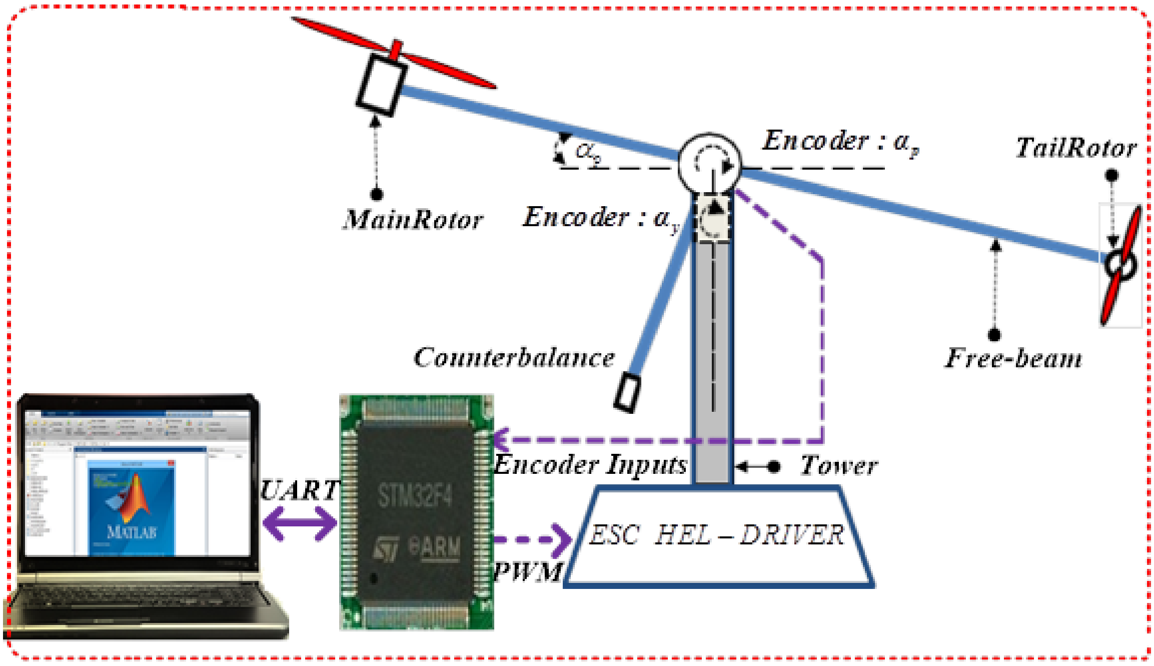


FIGURE 1. The twin rotors MIMO control system

A change in the voltage value results in a variation of the rotation speed of the propeller which changes the position of the free-beam in the vertical and horizontal axes. The outputs of the TRMS are the corresponding position of the free-beam, which are the pitch angle, α_p and yaw angle, α_y.

The dynamic of the TRMS was described by Newton or Euler-Lagrange methods and was represented in detail in [11]. Notation, nominal value, and perturbations on the coefficients of the TRMS are described in Table 1. Some of these coefficients were taken from the research of Petkov et al. [12], and the others were measured on the practical model. To evaluate the effectiveness of the proposed robust controller in the presence of the uncertainties, disturbances, and change in the parameters, it was assumed that the coefficients have 10% variations over the nominal coefficients.

Based on the dynamic equation [8], a block complete diagram of the TRMS is depicted in Figure 2. The output variables of the system are pitch and yaw angles, corresponding to α_p and α_y, respectively. The input signals $\mathrm{u_p}$ and $\mathrm{u_y}$ are the voltage of the main and tail rotors. The disturbance moments acting on the pitch and yaw axes are $\mathrm{d_p}$ and $\mathrm{d_y}$. The stability and robustness performance of the TRMS in reality under the effects of change in parameters, disturbance, and measurement sensor noise during operation is guaranteed by the μ_Synthesis method-based robust controller.

Table 1. Nominal coefficients and purturbation

Coefficient	Description	Nominal value	Unit	Perturbation
K_{fy}	Friction constant respect to horizontal	5.88×10^{-3}	Nms/rad	10%
K_{fp}	Friction constant respect to vertical	1.27×10^{-2}	Nms/rad	10%
K_{yp}	Moment constant from the tail rotor to the main rotor	4.17×10^{-3}	Nm	10%
K_{py}	Moment constant from the main rotor to tail rotor	-1.78×10^{-2}	Nm	10%
K_y	Speed constant of tail rotor	9.83×10^{3}	rad/s	10%
K_{Fy}	Elevation force constant of tail rotor	2.12×10^{-5}	Ns/rad	10%
K_p	Speed constant of main rotor	4.87×10^{3}	rad/s	10%
K_{Fp}	Elevation force constant of main rotor	3.07×10^{-4}	Ns/rad	10%
J_y	Initial moment respect to horizontal	-4×10^{-2}	Nm	10%
R_p	Force reflect of gravity	1.2×10^{-2}	Kgm^2	10%
I_p	Moment of inertia of the main rotor	1.6×10^{-5}	Kgm^2	–
I_y	Moment of inertia of the tail rotor	2.7×10^{-5}	Kgm^2	–

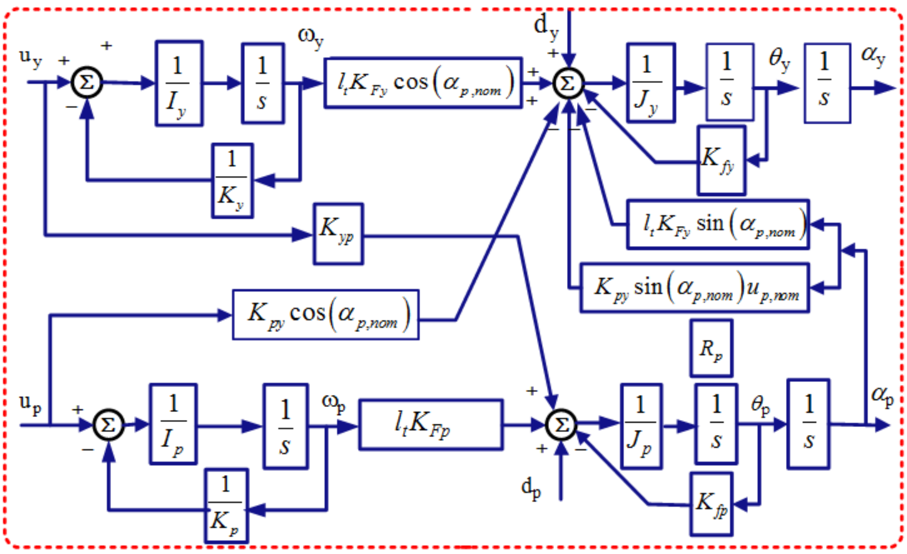


Figure 2. A block complete diagram of the TRMS

3. **Designing the Robust Controller Using μ_Synthesis Method.** According to the representation of the uncertainties, the Upper Linear Fractional Transformation (UL FT) model was used to describe the TRMS model in this study [11]. A perturbed plant model in form of the ULFT $\mathrm{F_U}(\mathbf{G}_{\mathrm{nom}}, \Delta)$ with a 10×10 matrix, Δ that contains ten uncertain coefficients and closed-loop robust control system of the TRMS including perturbation in the parameters, the elements relating to the performance requirements were depicted in Figure 3. Therein, $\Delta = diag\left(\delta_{J_y}, \delta_{R_p}, \delta_{k_{Fy}}, \delta_{k_{Fp}}, \delta_{k_{Hy}}, \delta_{k_{Hp}}, \delta_{k_{fy}}, \delta_{k_{fp}}, \delta_{k_{yp}}, \delta_{k_{py}}\right)$, $\Delta \in R^{10\times10}$ is the matrix representing the variation in the coefficients.

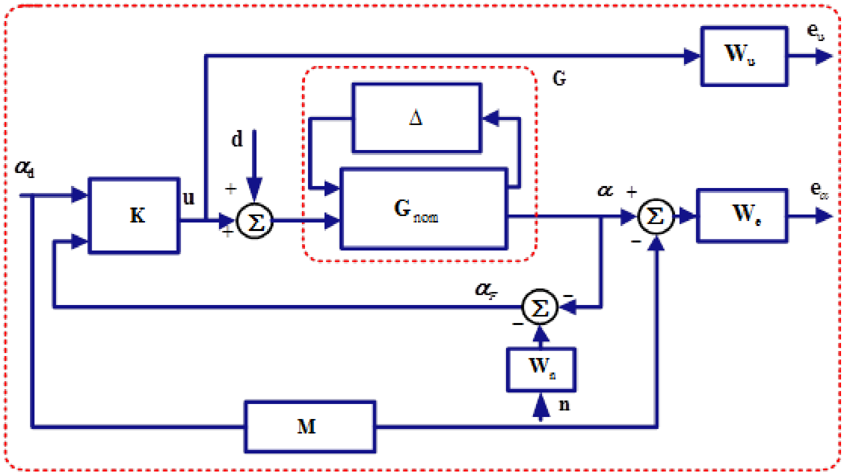


FIGURE 3. Block-diagram of the closed-loop system with performance requirements

$\mathbf{G}_{\text{nom}}$, $\mathbf{G}$ are the nominal matrix, and the actual, perturbed matrix of the TRMS, respectively. The system has reference inputs: $\boldsymbol{\alpha}_{\mathbf{d}}$; input disturbances, $\mathbf{d}$ and sensor noise, $\mathbf{n}$ due to the measurement of angles, $\boldsymbol{\alpha}$ in the pitch and yaw axes. The outputs of the system are the pitch and yaw angles, $\boldsymbol{\alpha}$ and two weighted outputs of the system are $\mathbf{e}_{\boldsymbol{\alpha}}$ and $\mathbf{e}_{\mathbf{u}}$. The block $\mathbf{M}$ is the ideal dynamic model that the designed closed-loop system should follow. The angle $\boldsymbol{\alpha}_F = -\boldsymbol{\alpha} - \mathbf{W}_{\text{n}}\mathbf{n}$ is the full feedback of the system.

To meet performance requirements of the robust controller, the frequency-dependent weighting functions, $\mathbf{W}_{\text{u}}$, $\mathbf{W}_{\text{e}}$ and $\mathbf{W}_{\text{n}}$ were utilized to tune the controller's performance and robustness characteristics such as a small inputs control action, convergence small error, attenuation disturbances, and noise rejection. The selection of weighted functions is the most crucial and difficult task of designing robust controllers, especially for the high non-linear system. In this study, the selection of weight functions in [13-15] was reused with some modifications during experiments.

The μ_Synthesis method was used to find out the parameters of the robust controller, $\mathbf{K}$. To achieve a balance between the controller's performance and robustness, the algorithm was performed for several different weighting functions by the Robust Control Toolbox of Matlab to obtain desired results. Figure 4 represents a complete block diagram of the inputs, output signals, and commands used to build the robust controller.

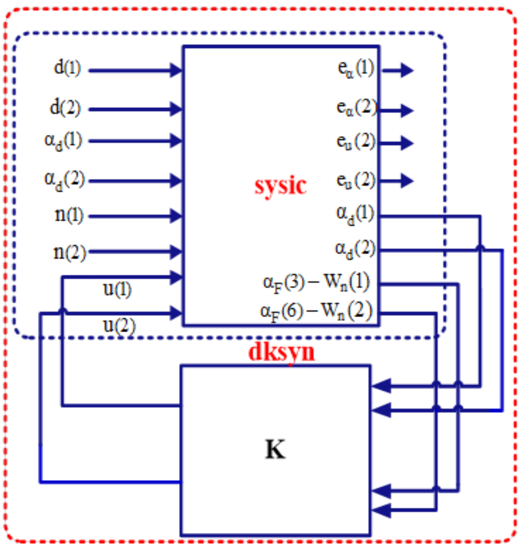


FIGURE 4. Defining the robust controller using Robust Control Toolbox

With the coefficients and parameters given in Table 1, after six iterations were performed, the maximum value of μ was decreased to 0.718 as Table 2. This value satisfies the robust performance of the closed-loop system; thus, the robust stability of the system is guaranteed as well.

Table 2. Number of iterations and values of μ

Iteration Summary

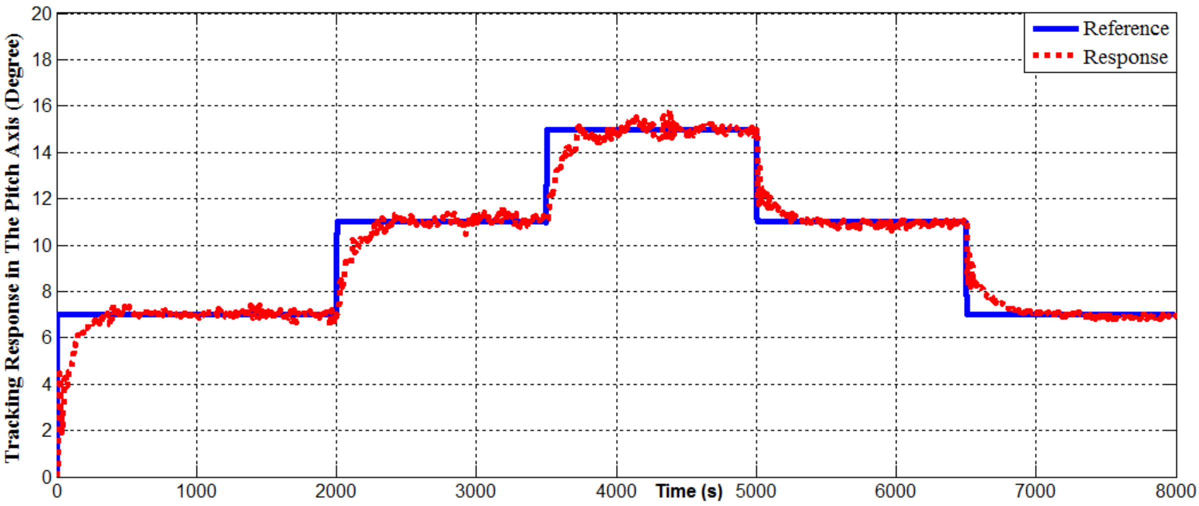
Iteration #	2	3	4	5	6
Controller Order	18	18	32	34	30
Total D-Scale Order	2	2	16	18	14
Gamma Achieved	7.320	1.254	0.789	0.726	0.722
Peak μ-Value	4.848	1.024	0.785	0.724	0.718

4. **Experimental Results.** An image of the experimental equipment of the TRMS is shown in Figure 5. To illustrate the superiority of the proposed controller, the tracking responses of the TRMS in the pitch and yaw axes were simultaneously performed. The coefficients and parameters of the TRMS including perturbation are represented in Table 1. The experimental results of the system in the real time are shown in Figure 6.

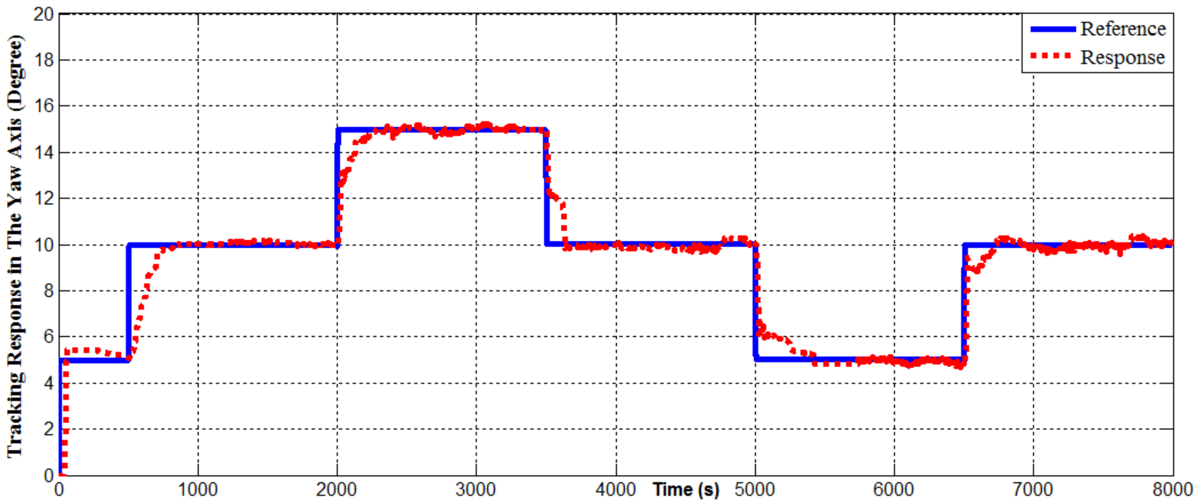
Figure 5. Image of the practical control system of the TRMS

The experimental results of the TRMS due to periodic step commands showed that the robust controller has good trajectory tracking in the presence of the uncertainties and noise in the real time. The superior results of the robust controller such as fast response time, small convergence error, and stability were guaranteed for a long time. These results once again confirm the effectiveness of the proposed controller.

5. **Conclusion and Future Research.** In this research, the μ_Synthesis method was used to build the robust controller for the TRMS in reality. The system had good command following in the pitch and yaw axes in the complex aerodynamics conditions. Furthermore, although the coefficients have a large variation (10%) over the nominal values, the robustness of the system was guaranteed during operation for a long time. This is the main contribution of this research. However, the robust controller should be combined with other adaptive controllers to improve convergence error.



(a)



(b)

FIGURE 6. Tracking response of the TRMS in the pitch and yaw axes

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