PSO Based PID Controller Design for Twin Rotor MIMO System

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***Abstract*—This paper presents particle swarm optimization (PSO) based design of proportional-integral-derivative (PID) controller for a twin rotor MIMO (multi-input multi-output) system (TRMS). The objective of the paper is to tune the gains of the PID controller automatically, by means of a global search method like PSO, so that the transient tracking error will be minimum. The modeling of TRMS exploiting the non-linear characteristics and cross-coupling phenomena and proper designing of PID control law for it, is being realized in simulation environment. The proposed design methodology is utilized to explore different mode of operations of TRMS under different reference trajectories. The results demonstrate that the proposed design of PID controller is capable of tracking different reference trajectories in satisfactory manner.**

Keywords—Integral absolute error (IAE), MIMO system, particle swarm optimization (PSO), PID Controller, twin rotor MIMO system (TRMS).

I. Introduction

In this paper, a control problem involving an experimental propeller setup called the TRMS [1] whose behavior is much similar to that of a helicopter, has been investigated. The TRMS can rotate freely both in the horizontal and vertical planes responding to yaw and pitch moments, respectively over a beam. At such end of the beam there are two rotors driven by DC motors. The main rotor produce a lifting force allowing the beam to raise vertically (pitch angle) and the tail rotor is used to control the beam to turn left or right (yaw angle). Both of the motors produce aerodynamic force through the blades and also provide the coupling effect. Thus, from the control engineering point of view, TRMS is a higher order non-linear system with prominent cross-couplings between the main rotor and the tail rotor [2], [3], [4]. The control objective is to make the beam of TRMS to follow the desired trajectory or to reach desired positions accurately and quickly and in this paper the objective is achieved by employing PID control scheme.

So many design techniques of PID controllers were presented in literature [5], [6], [7]. Although, the construction and operation of PID controller is very simple, but the problem is to tune the gains of it keeping the error minimum. The conventional Ziegler-Nichols method of designing PID controller is mostly incapable of tackling the non-linear characteristics and significant cross-coupling of the TRMS model. PSO is first introduced by Kennedy and Eberhart and is one of the modern heuristic algorithms [8] that can explore the solution space globally and automatically tune the PID controller to get an optimal / near optimal solution for the TRMS. Simulation results show the effectiveness of this optimization method in tuning the PID controller for different operational modes of TRMS, 1 degree-of-freedom (DOF) pitch control, 1 DOF yaw control, 2 DOF MIMO control and decoupled TRMS control, are performed with four types of reference trajectories.

The remainder of this paper is organized as follows: The TRMS model is introduced and described in section II. In section III, PSO is discussed. The PSO based PID controller is designed in section IV. Section V presents the simulation results and finally section VI concludes the paper.

II. Twin Rotor MIMO System Model

The TRMS experimental setup consists of mechanical and electrical units. Mechanical part consists of two rotors, main rotor (pitch) responsible for vertical movement and tail rotor (yaw) responsible for horizontal movement. They are pivoted on a vertical beam together with a counter balance. Electrical unit transfers measured signal to the PC and allows control signal application through an input-output port. The schematic diagram of TRMS is shown in Fig. 1. The system parameters of TRMS are taken from [1].

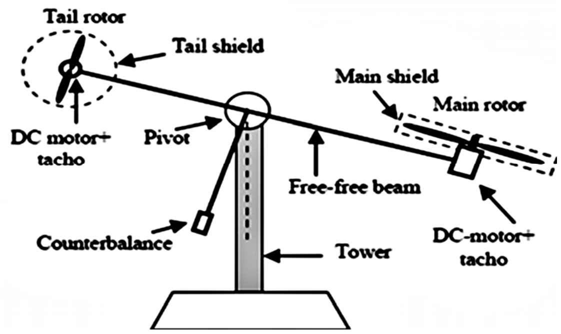

Fig. 1. The schematic diagram of the TRMS

In this present paper the TRMS model is controlled in three different modes as: a) 1DOF rotor control, where cross coupling dynamics is ignored and either of each rotor is controlled separately, b) 2DOF rotor control with both rotors can be controlled simultaneously and c) control with decoupled dynamics. This mode includes all coupling effects and both rotors can be controlled at the same time.

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In all modes of operations the control objective is set the beam of the TRMS according to the desired or reference trajectory by controlling the pitch angle and yaw angle with minimum possible transient error. For details about TRMS please see [1].

III. PARTICLE SWARM OPTIMIZATION

PSO is a population based stochastic algorithm where the population dynamics replicate the school of fish or bird flock's activities, keeping the cognitive information sharing so that an individuals can profit from the discoveries and past experience of all the other companions during the search for food. Thus, each companion, called particle, in the population, called swarm, is assumed to fly over the search space to find the desired solution in terms of its position [8], [9].

In PSO algorithm a swarm of particles are placed into a *d*-dimensional search space with randomly selected velocities and positions knowing their best values so far (*pbest*) and the position. Best value among all of the particles in the swarm is known as global best (*gbest*). The past best position of the particle itself and the best overall position in the entire swarm are employed to obtain new position for the particle in quest to minimize (or maximize) the fitness. The PSO concept consists, in each time step, of changing the velocity of each particle flying towards its *pBest* and *gBest* location. The velocity is weighted by random terms, with separate random numbers being generated for velocities towards *pBest* and *gBest* locations respectively [8], [9].

Now the swarm size is given by s, each particle i $(1 \le i \le s)$ represent a trial solution with $j = 1, 2, \ldots, n$ parameters. Each particle, at t time, has a current position $\underline{x}_i(t) = \left(x_{i,1}(t), x_{i,2}(t), \ldots, x_{i,j}(t), \ldots, x_{i,n}(t)\right)$ in the search space, a current velocity $\underline{v}_i(t) = \left(v_{i,1}(t), v_{i,2}(t), \ldots, v_{i,j}(t), \ldots, v_{i,n}(t)\right)$ and a personal best position $\underline{p}_i(t) = \left(p_{i,1}(t), p_{i,2}(t), \ldots, p_{i,j}(t), \ldots, p_{i,n}(t)\right)$ in the search space. Let us assume that, to solve a given problem, a fitness function f need be minimized, and then all particles velocities in a swarm are updated, at each iteration, by [9]

$$v_{i,j}(t+1) = w(t)v_{i,j}(t) + c_1 r_1\left(p_{i,j}(t) - x_{i,j}(t)\right) + c_2 r_2\left(g(t) - x_{i,j}(t)\right) \quad (1)$$

where $g(t)$ denotes the global best particle, c_1 and c_2 are the 'trust' parameters and are usually set to 2, which control the velocity change of a particle in a single iteration, and $r_1 \to U(0,1)$ and $r_2 \to U(0,1)$ are elements from two uniform random sequences in the interval [0,1]. The term $w(t)$ is the inertia weight of the particle at iteration t, as introduced by Shi and Eberhart [9] and is given by:

$$w(t) = \frac{(iter_{\max} - t) * (w_{start} - w_{end})}{iter_{\max}} + w_{end} \quad (2)$$

Where $iter_{\max}$ is the maximum number of iterations of PSO. Normally $w(t)$ is reduced linearly from w_{start} = 0.9 to w_{end} = 0.4 throughout the PSO generation.

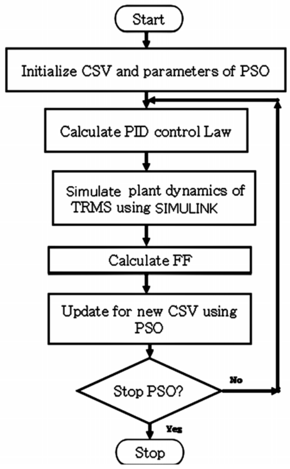

Fig. 2. Flowchart for tuning of PID controller using PSO

Now the update formulation of each particle's position vector is as follows [7]:

$$\underline{x}_i(t+1) = \underline{x}_i(t) + \underline{v}_i(t+1) \quad (3)$$

The personal best particle position $\underline{p}_i$ and the global best particle swarm position g are updated by the following equations respectively:

$$\underline{p}_i(t+1) = \begin{cases} \underline{p}_i(t) & \text{if } f(\underline{x}_i(t+1)) \ge f(\underline{p}_i(t)) \\ \underline{x}_i(t+1) & \text{otherwise} \end{cases} \quad (4)$$

$$g(t+1) = \arg\min\left(f\left(\underline{p}_i(t+1)\right)\right) \quad (5)$$

The values of each component in every $\underline{v}_i$ vector can be clamped to the range [$-v_{\max}$; $v_{\max}$] in order to reduce the likelihood of particles leaving the search space. This mechanism does not restrict the values of $\underline{x}_i$ in the range of $\underline{v}_i$, it only limits the maximum distance that a particle will move during each iteration [7], [8].

IV. PSO BASED PID CONTROLLER DESIGN

In this new era of modern control applications still the most popular type of controller used in industry is PID controller. A basic PID control action consists of proportional error signal supplemented with derivative and integral of the error signal. Thus, the PID control law can be written as

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (6)$$

Where, $u(t)$=input, $e(t)$=error, K_p=proportional gain, K_i=integral gain and K_d=derivative gain.

In this paper PSO based tuning of gains of the PID controller is proposed. A candidate solution vector (CSV) in search space is a vector containing all required information to construct a PID controller, e.g. i) proportional gain, ii) integral gain and iii) derivative gain. This vector is formed as [11]:

$$x = [K_p \mid K_i \mid K_d] \quad (7)$$

To design a PID controller utilizing a stochastic algorithm, like PSO, first the population of CSV is chosen. Each CSV is then implemented for calculating the fitness function (FF), the integral absolute error (IAE), which can be defined as IAE = $\sum_{n=0}^{PST} e(n)\Delta t_c$, where PST = plant simulation time and Δt_c = step size or sampling time. Then, according to the value of the fitness function (IAE) of each CSV in each iteration, the best solution is achieved using the global version of PSO [10], [11]. PSO algorithm will stop searching the solution space when the number of iterations specified is reached or a pre specified error is attained by the controller. The flowchart of proposed PSO based PID design is shown in Fig. 2.

V. Simulation Study

To demonstrate the effectiveness of the proposed PSO based scheme of PID controller design for TRMS, a benchmark MIMO system previously utilized in several research works, is considered. The plant model is simulated using a fixed step 4th order Runge-Kutta method with sampling time Δt_c = 100 ms. IAE between the reference trajectory and the rotor output is taken as the attribute to evaluate the control strategy.

As PSO is a stochastic search algorithm, so it is customary to perform the search technique several times and take the best result out of that. Also to estimate the variations in the results standard deviation is calculated. In this paper PSO is run for ten times each for 1DOF (pitch and yaw), 2DOF and decoupled TRMS model. Again each model is tested for four different reference trajectories, namely fixed step, variable step, pure sine wave and a mixed sine wave. After optimizing the PID gains each plant model is evaluated for 100 s.

Table I contains the result of 1DOF pitch control for four different reference trajectories and responses and corresponding control signals are shown in Fig. 3 to Fig. 6 respectively. It has been seen from the responses that the design objective of tracking the reference trajectories is satisfactory, that proves the justification of PSO based tuning of PID controller.

Table II, Table III and Table IV tabulated the results of 1DOF yaw control, 2DOF control and decoupled TRMS control respectively for four different reference trajectories and their responses and corresponding control signals are shown in Fig. 7 to Fig. 18 respectively.

TABLE I. Simulation results for 1DOF pitch control (Simulation time=100 s)

Reference Trajectories	Best IAE	Ave. IAE	Std. Dev.
Fixed step	1.0304	1.4228	0.3161
Variable step	2.9960	3.5766	0.5345
Pure sine wave	2.1017	4.4512	1.4427
Mixed sine wave	1.8250	2.3856	0.2644

TABLE II. Simulation results for 1DOF yaw control (Simulation time=100 s)

Reference Trajectories	Best IAE	Ave. IAE	Std. Dev.
Fixed step	0.5591	0.6563	0.0815
Variable step	1.6888	2.3244	0.4696
Pure sine wave	5.9603	7.1792	0.8420
Mixed sine wave	6.4719	8.2388	0.8163

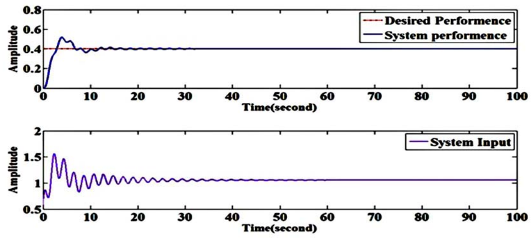

Fig. 3. Evaluation period response and control signal for fixed step trajectory for 1DOF pitch control

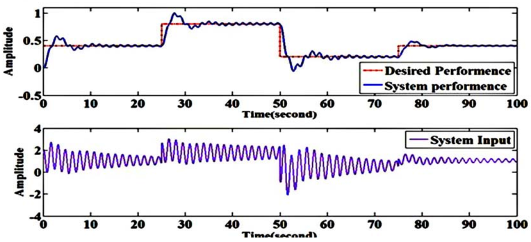

Fig. 4. Evaluation period response and control signal for variable step trajectory for 1DOF pitch control

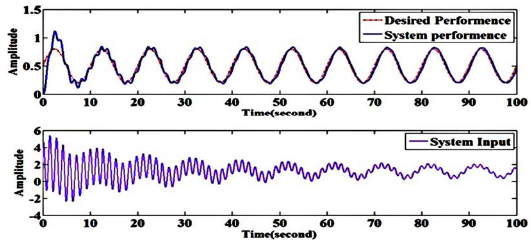

Fig. 5. Evaluation period response and control signal for pure sine wave trajectory for 1DOF pitch control

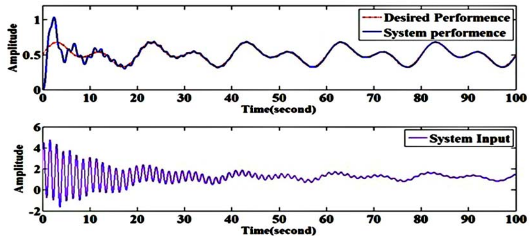

Fig. 6. Evaluation period response and control signal for mixed sine wave trajectory for 1DOF pitch control

TABLE III. SIMULATION RESULTS FOR 2DOF CONTROL (SIMULATION TIME=100 S)

Reference Trajectories	Best IAE	Ave. IAE	Std. Dev.
Fixed step	0.9687	1.3618	0.2793
Variable step	4.0103	5.1256	1.1769
Pure sine wave	4.9811	5.3771	0.5059
Mixed sine wave	4.7647	4.9520	0.1477

TABLE IV. SIMULATION RESULTS FOR DECOUPLED TRMS CONTROL (SIMULATION TIME=100 S)

Reference Trajectories	Best IAE	Ave. IAE	Std. Dev.
Fixed step	1.5343	1.8461	0.1559
Variable step	4.0454	4.6461	0.5189
Pure sine wave	4.6845	7.2992	1.3638
Mixed sine wave	4.6703	5.0881	0.2414

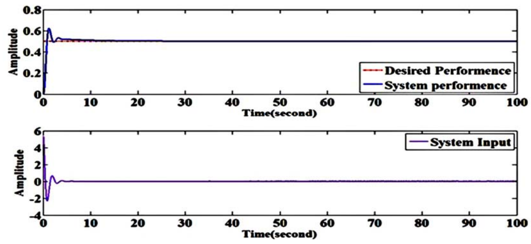

Fig. 7. Evaluation period response and control signal for fixed step trajectory for 1DOF yaw control

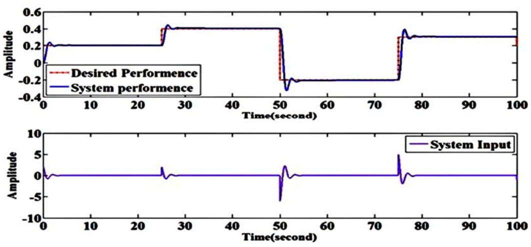

Fig. 8. Evaluation period response and control signal for variable step trajectory for 1DOF yaw control

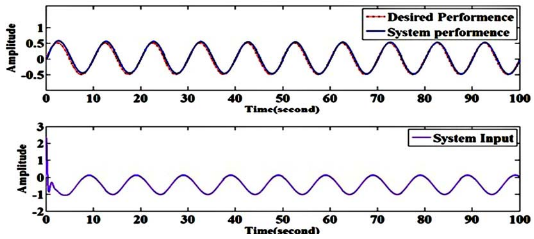

Fig. 9. Evaluation period response and control signal for pure sine wave trajectory for 1DOF yaw control

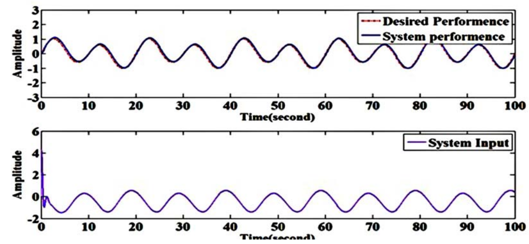

Fig. 10. Evaluation period response and control signal for mixed sine wave trajectory for 1DOF yaw control

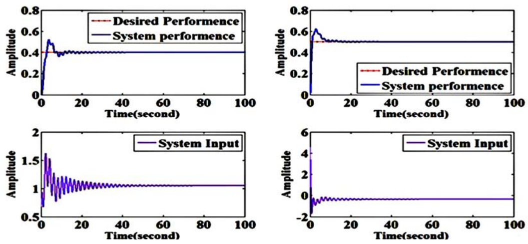

Fig. 11. Evaluation period response and control signal for fixed step trajectory for 2DOF control

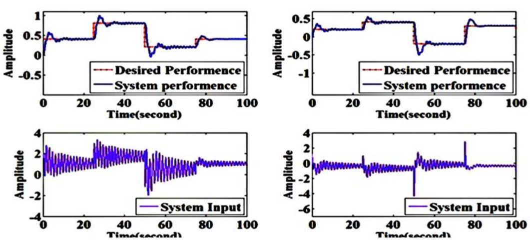

Fig. 12. Evaluation period response and control signal for variable step trajectory for 2DOF control

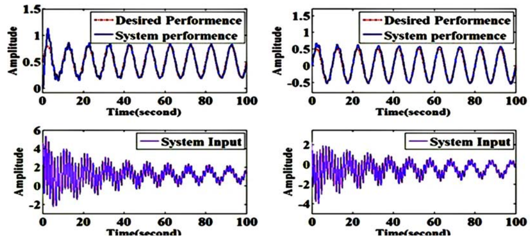

Fig. 13. Evaluation period response and control signal for pure sine wave trajectory for 2DOF control

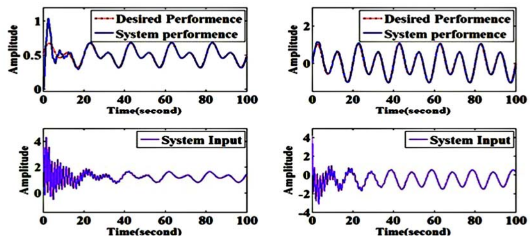

Fig. 14. Evaluation period response and control signal for mixed sine wave trajectory for 2DOF control

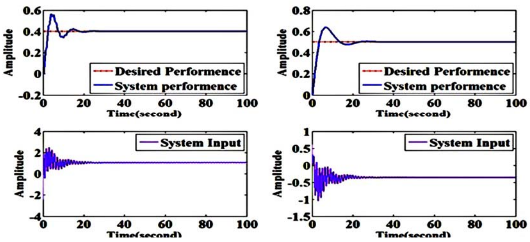

Fig. 15. Evaluation period response and control signal for fixed step trajectory for decoupled TRMS control

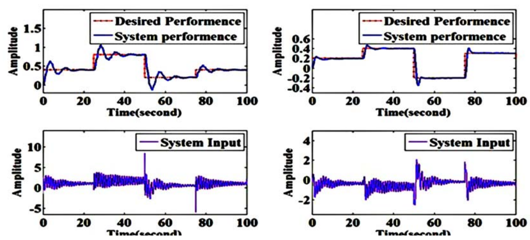

Fig. 16. Evaluation period response and control signal for variable step trajectory for decoupled TRMS control

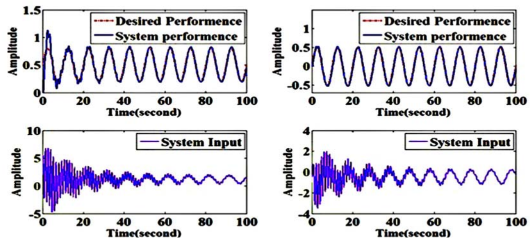

Fig. 17. Evaluation period response and control signal for pure sine wave trajectory for decoupled TRMS control

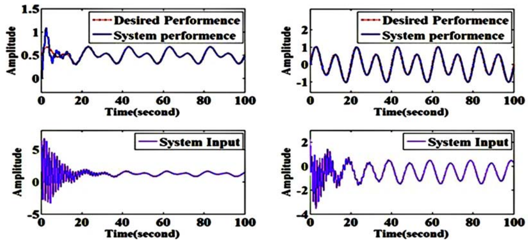

Fig. 18. Evaluation period response and control signal for mixed sine wave trajectory for decoupled TRMS control

VI. CONCLUSION

In this paper a design methodology of PID controller for MIMO system employing PSO, a global search method, is proposed. The proposed design scheme is implemented for simulation case studies for the benchmark TRMS model. The proposed PID design scheme for TRMS model is tested for different mode of its operation with different reference trajectories. The proposed method successfully demonstrated that it can simultaneously provide good tracking performance with high degree of automation in the design process.

REFERENCES

[1] TRMS 33-220 User Manual, 3-000M5, Feedback Company, E. Sussex, U.K. 1998.

[2] J. P. Su, C. Y. Liang, and H. M. Chen, “Robust control of a class of nonlinear systems and its application to a TRMS,” in Proc. IEEE Int. Conf. Ind. Technol., Bangkok, Thailand, 2002, pp. 1272–1277.

[3] C. Y. Tsai, M. T. Huang, and J. G. Juang, “Application of real-type GA to TRMS position control,” in Proc. Autom. Control Conf., Jung-Li, Taiwan, 2003, pp. 1267–1273.

[4] P. Wen and T. W. Lu, “Decoupling control of a twin rotor MIMO system using robust deadbeat control technique,” IET Control Theory Appl., vol. 2, no. 11, pp. 999–1007, 2008.

[5] A. Odwyer, Handbook of PI and PID Controller Tuning Rules. London, U.K.: Imperial College Press, 2003.

[6] R. A. Krohling, H. Jaschek, and J. P. Rey, “Designing PI/PID controllers for a motion control system based on genetic algorithms,” in Proc. 12th IEEE Int. Symp. Intell. Control, Istanbul, Turkey, 1997, pp. 125–130.

[7] R. A. Krohling and J. P. Rey, “Design of optimal disturbance rejection PID controllers using genetic algorithms,” IEEE Trans. Evol., vol. 5, no. 1, pp. 78–82, Feb. 2001.

[8] J. Kennedy and R. Eberhart, “Particle swarm optimization,” in Proc. IEEE Int. Conf. Neural Networks, vol. IV, Perth, Australia, 1995, pp. 1942-1948.

[9] R. C. Eberhart and Y. Shi, “Comparison between genetic algorithms and particle swarm optimization,” in Proc. IEEE Int. Conf. Evol. Comput., Anchorage, AK, May 1998, pp. 611–616.

[10] Z.-L. Gaing, “A particle swarm optimization approach for optimum design of PID controller in AVR system,” IEEE Trans. Energy Conversion, vol. 19, pp. 384-391, June 2004.

[11] Kaushik Das Sharma, Amitava Chatterjee, and Anjan Rakshit, “A hybrid approach for design of stable adaptive fuzzy controllers employing Lyapunov theory and Particle swarm optimization”, IEEE Trans. Fuzzy Syst., vol. 17, no. 2, April 2009.