Design of MIMO Controller for a Manipulator Using Tabu Search Algorithm

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***Abstract* - In this paper, we present an optimum approach to design a MIMO controller for a manipulator using discrete Tabu Search (TS) algorithm. In the first step, the TS algorithm is reviewed and then we employ the proposed method in order to assign efficiently the optimal PID controller parameters. The design goal is to minimize the integral absolute error and reduce transient response by minimizing overshoot, settling time and rise time of the system. A 5-bar-linkage is considered as a case study. We define an objective function including these indexes. Then by minimizing this function using discrete TS algorithm, controller parameters design is performed efficiently and quickly.**

Superior features of this algorithm are fast tuning of PID parameters, rapid convergence, less computational burden and capability to avoid from local minima. Simulation results demonstrate that our proposed TS method compared with other heuristic method, i.e., the Genetic Algorithm (GA) is more efficient in terms of improving the step response of the robot.

Keywords: Discrete Tabu Search (TS) algorithm, Genetic algorithm, dynamic equations, MIMO controller, robotics, 5-bar-linkage manipulator.

I. INTRODUCTION

Proportional-Integral-Derivative (PID) controller is the most common type of control method for industrial control processes. This is due to its simple structure and powerful performance in a wide range of operating conditions. The design of such a controller requires specification of three parameters; proportional gain K_p, integral gain K_i, and derivative gain K_d. Almost for MIMO systems which compose of nonlinear and coupled terms, the problem of tuning these parameters has been accomplished by a trial and error method. This way takes considerable time and it is hard to determine optimal or near optimal PID controller parameters for MIMO systems with high complexity and nonlinearities [1]. To decrease the complexity and difficulty of tuning PID parameters using traditional methods, several heuristic methods such as GA [2], Particle Swarm Optimization (PSO) [3], Fuzzy Logic [4], Simulated Annealing [5], Ant Colony Optimization [6] and Pattern Recognition [7] have been developed, but these methods have some disadvantages in designing of PID controller such as high computational time, low rate of successful optimization and high usage of memory. In order to overcome these difficulties, a new approach is proposed which employing new optimization method called Tabu Search. In this paper, we formulate the problem of designing PID controller as an optimization problem. Our goal is to design a controller that has a well performance with adjusting four performance indexes, the maximum overshoot, the settling time, the rise time and the steady state error of step response. Although it has been applied for a robot manipulator, it should be a promising way for broad range of MIMO systems. The paper is organized as follows: section 2 contains a description of the system and presents dynamic equations of the robot. In section 3 we present an overview of TS algorithm and section 4 presents the problem formulation. Section 5 illustrates implementation of both TS and GA algorithms on the plant as well as performance comparison between them followed by conclusion in section 6.

II. DYNAMIC EQUATIONS DESCRIPTION

The 5-bar-linkage manipulator robot is frequently used an appropriate configuration in many industrial robotic applications such as spray-painting, arc welding and adhesive or sealant applications. Figure 1 shows the typical one built in robotics research lab in our department. Also, figure 2 depicts schematic diagram of the robot where the links form a parallelogram [10]. Let q_i, T_i and I_i^h be the joint variable, torque and hub inertia of the i^{th} motor, respectively. Also, let I_i, l_i, l_{ci} and m_i be the inertia matrix, length, distance to the center of gravity and mass of the i^{th} link, correspondingly.

Fig. 1. Planar presentation of robot

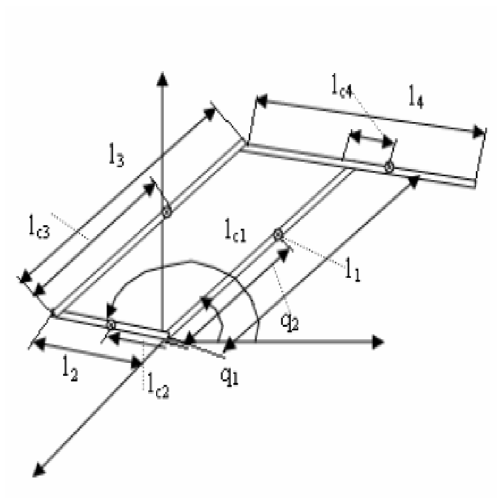

Fig. 2. Schematic diagram of robot

The dynamic equations of this manipulator are [10-11]:

$$T_1 = (M_{11} + I_h^1)\ddot{q}_1 + M_{12}\ddot{q}_2 + \frac{\partial M_{12}}{\partial q_2}\ddot{q}_2^2 + g\,(m_1 l_{c1} + m_3 l_{c3} + m_4 l_1)\cos q_1 \qquad (1)$$

$$T_2 = (M_{22} + I_h^2)\ddot{q}_2 + M_{12}\ddot{q}_1 + \frac{\partial M_{12}}{\partial q_1}\ddot{q}_2^2 + g\,(m_2 l_{c2} + m_3 l_2 + m_4 l_{c4})\cos q_2 \qquad (2)$$

where g is the gravitational constant and

$$M_{11} = I_{11}^1 + I_{11}^3 + m_1 l_{c1}^2 + m_3 l_{c3}^2 + m_4 l_1^2 \qquad (3)$$

$$M_{22} = I_{11}^2 + I_{11}^4 + m_2 l_{c2}^2 + m_3 l_2^2 + m_4 l_{c4}^2 \qquad (4)$$

$$M_{12} = M_{21} = (m_3 l_{c2} l_2 - m_4 l_{c4} l_1)\cos(q_1 - q_2)\,. \qquad (5)$$

Equation (5) demonstrates that M_{12} and M_{21} depend on both q_1 and q_2, consequently motor torques affect on both angles. In other words system variables are intensively coupled. Using the above equations, the 5-bar-linkage manipulator robot is simulated employing Simulink® and Matlab® packages. Our proposed method is that to apply controller parameters generated by TS algorithm to the bocks in simulink model of the system, and then calculate the cost function in the manner that has been presented later in section 4.

III. OVERVIEW OF THE DISCRETE TABU SEARCH ALGORITHM

Tabu Search (TS) algorithm first was introduced by Glover (1975-1986). The TS method is a local search approach with a flexible memory structure and it can be applied directly to various problems, without requiring the plant models. This approach is a combination of optimization and search methods based on converging to the best available neighborhood solution point. In the other words, the principle idea is to move to the best point from the viewpoint of cost function in neighborhood, even if it is worse than the current solution point. In this controller design method based on discrete TS algorithm, each solution point is a binary string including *N* bits related to 3 variables, (K_p, K_i, K_d), hence the number of bits for each variable is *N*/3.

For instance, a sample solution point with 12-bits and three variables (K_p, K_i, K_d), is shown as follows, which assigned 4 bits for each variable.

$$\overbrace{1\quad 0\quad 1\quad 1}^{K_p}\ \overbrace{0\quad 0\quad 0\quad 1}^{K_i}\ \overbrace{1\quad 0\quad 0\quad 1}^{K_d}$$

To calculate the cost function of solution points, they must be decoded at first. In the following, decoded form of the mentioned string is calculated.

$$\begin{cases} K_p \rightarrow 1\times 2^3 + 0 + 1\times 2^1 + 1\times 2^0 = 11 \\ K_i \rightarrow 0+0+0+1\times 2^0 = 1 \\ K_d \rightarrow 1\times 2^3 + 0 + 0 + 1\times 2^0 = 9 \end{cases} \Rightarrow Cost(K_p, K_i, K_d) = Cost(11,1,9)$$

Neighbors of a solution point are obtained by converting one and only one bit of the string to inverse state. Consequently, each string with ***N***-bits has ***N*** neighbors.

For example one of the 12 neighbors of the previous sample that is obtained by converting 6th bit from 0 to 1, is as follows:

$$\overbrace{1\quad 0\quad 1\quad 1}^{K_p}\ \overbrace{0\quad 1\quad 0\quad 1}^{K_i}\ \overbrace{1\quad 0\quad 0\quad 1}^{K_d}$$

$$\begin{cases} K_p \rightarrow 1\times 2^3 + 0 + 1\times 2^1 + 1\times 2^0 = 11 \\ K_i \rightarrow 0+1\times 2^2 + 0 + 1\times 2^0 = 5 \\ K_d \rightarrow 1\times 2^3 + 0 + 0 + 1\times 2^0 = 9 \end{cases} \Rightarrow Cost(K_p, K_i, K_d) = Cost(11,5,9)$$

TS procedure is utilized with features that lead to escape from local minima. Important features consist of Short-Term Memory, Long-Term (Frequency–Based) Memory and Aspiration Criteria. In the Short-term Memory (Tabu List) we maintain a list of solution points that have been visited recently and must be avoided. We update the tabu list in each iteration based on solution points.
In the Long-Term Memory we register the number of occasions that the solution point has been visited. The updating period of this memory is very longer than short-term memory. We use this memory while all of the non-tabu points in the neighborhood lead to increase the cost function and aspiration criterion is not satisfied.
Aspiration Criteria implies that if some tabu moves lead to promising solutions, these moves are accepted.

Stages of the algorithm:

In this part we summarize the discrete TS algorithm in five steps. Assume that X is a total search space and x is a solution point sample and $f(x)$ is cost function:

1- Choose $x \in X$ to start the process.
2- Create a candidate list of non-Tabu moves in neighborhood. $(x_i, i = 1, 2, ..., N)$
3- Decode all solution points that are obtained in step 2.
4-Find $x_{winner} \in N(x)$ such that $f(x_{winner}) < f(x_i), i \neq winner$.
5- Check the stopping criterion. If satisfied, exit the algorithm. If not, $x = x_{winner}$, update Tabu List and then go to step 2.

Remark:
In order to exit from algorithm, there are several criterions:
1- Determining a threshold T_0: If the value of cost function is less than T_0, stop algorithm.
2- Determine specific number of iterations.
3- If the value of the cost is remained invariable or negligible change for several iterations, exit the algorithm.
Flow chart of the algorithm is shown in figure 3.

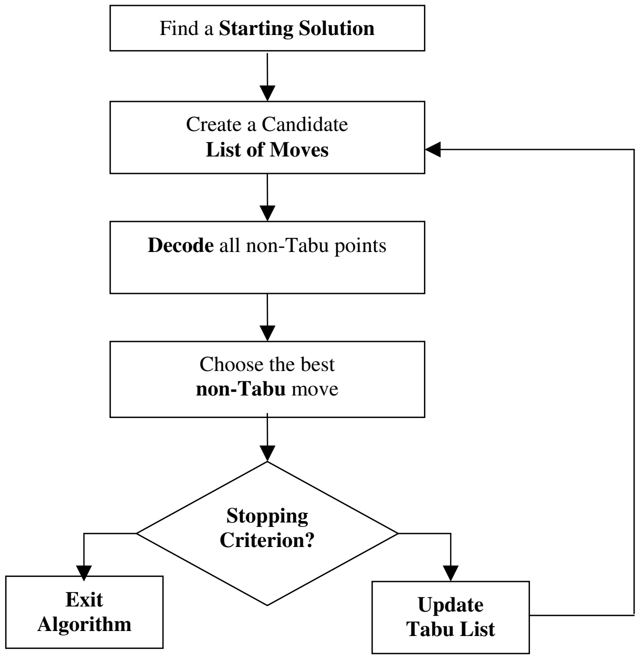

Fig. 3. Flow chart of the TS algorithm

IV. MIMO CONTROLLER DESIGN AND PROBLEM FORMULATION

The PID controller is used to improve the dynamic response and reduce the steady-state error. The transfer function of a PID controller is described as follows:

$$G_c(s) = k_p + \frac{k_i}{s} + k_d s \tag{6}$$

where
, k_i and k_d are the proportional, integral and derivative gains, respectively. A Performance criterion in the time domain includes the overshoot M_p, rise time t_r, settling time t_s, and steady-state error E_{ss}. We find the optimal MIMO controller parameters minimizing the performance indexes on the load disturbance and transient responses. The proposed cost function is:

$$f(k) = (1 - e^{-\beta})(M_p + E_{ss}) + e^{-\beta}(t_s - t_r) \tag{7}$$

where K is [k_d , k_p , k_i] and β is the weighing factor [3]. If β is set to be smaller than 0.7 the rise time and settling time are reduced and if it is set to be larger than 0.7 the overshoot and steady state error are reduced [3]. The discrete TS algorithm for searching optimal PID controller parameters is as follows:
First of all specify the lower and upper bounds of controller parameters and find the initial solution point randomly. Each

solution point is a 24-bits string and divided to three sections, each section related to a variable, k_d, k_p, k_i. Tabu list length and neighborhood size are selected 10 and 24, respectively.

Each solution, i.e., K has the neighbor points. We select the non-Tabu neighbors and send them to blocks in simulink model of the system. On the other hand the values of four performance criteria in the time domain namely M_p, E_{ss}, t_r and t_s are calculated iteratively in 20 generations. Then, cost function is evaluated for each point according to these performance criteria. Comparing the cost values of all solutions (all available neighborhood points), the best point is selected as the next search point. At the end of each iteration, the program checks the stop criterion. If the number of iterations reaches the maximum or the stopping criterion is satisfied, records the latest global best solution and stop the algorithm.

GA method utilizes its solution pool as a mechanism for introducing diversity into reproduction process. TS, on the other hand, employs memory for additional purpose, precisely to prevent the search from returning to a previous explored solution points rapidly. Also, TS contains a mechanism for controlling the search using Tabu list. This ensures that some solutions will be unsatisfactory. However, the constraints complied with Tabu list may cause the algorithm get trapped at local optima.

To compare TS with GA results, parameters of GA are derived using trial and error method. Population size of chromosomes and number of generation are 10 and 20, respectively. Mutation rate is selected 0.01 and crossover rate is 0.5.

V. SIMULATION RESULTS

The lower and upper bounds of the three controller parameters are as shown in Table I. The simulink block diagram of 5-bar-linkage manipulator robot with PID controller is shown in Figure 4 which shows drastically nonlinear and coupled systems. Figure 5 illustrates the step response without controllers indicating the system is in the boundary stability state.

TABLE I
RANGE OF THREE CONTROLLER PARAMETERS

Controller Parameters	*Lower Bounds*	*Upper Bounds*
k_d	0	30
k_p	0	30
k_i	0	30

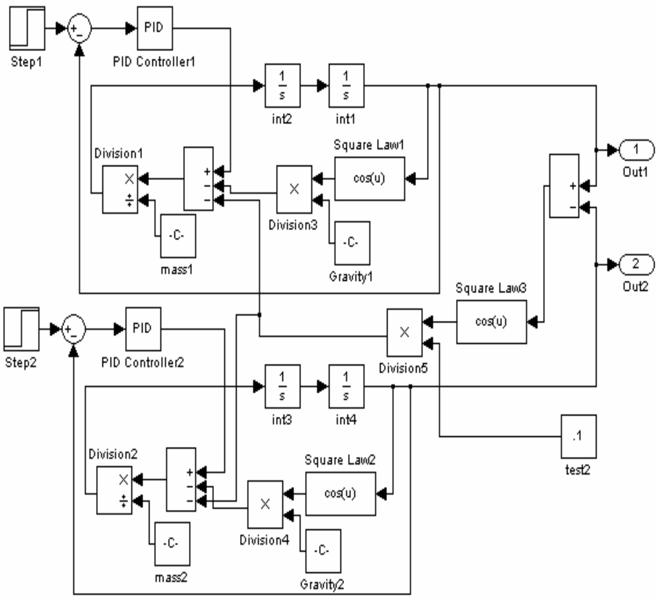

Fig. 4. Block diagram of two motors with PID controllers. (motor 1and motor 2 are coupled)

TABLE II
5-BAR-LINKAGE MANIPULATOR DATA

Link	*Mass (Kg)*	*Length (m)*	*C of G (m)*
1	0.288	0.33	0.166
2	0.0324	0.12	0.06
3	0.3702	0.33	0.166
4	0.2981	0.45	0.075

The manipulator specification consisting of mass, length and center of gravity of links are given in Table II. Figures 6 and 7 show the convergence characteristics of the controller for motor 1 with two values of β using TS method compared with the Genetic Algorithm. Figures 8,9,10 and 11 show the corresponding step response of motor angles, i.e., motors 1 and 2 respectively. As it can be observed, TS method can prompt convergence and achieve a good evaluation value less than 10 iterations for all situations. It confirms the rapid convergence property of TS algorithm. Furthermore, TS-PID controller introduces a perfect step response for the robot, indicating the superiority of proposed controller with regard to GA-PID controller. The simulation results of the best solution for various values of β are summarized in Table III. These results also verifies that TS-PID controller can give more appropriate controller parameters for MIMO system quickly and efficiently rather to GA-PID.

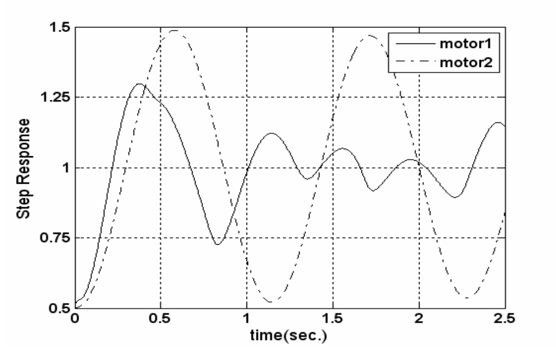

Fig. 5. Step response of the motors without PID controller.

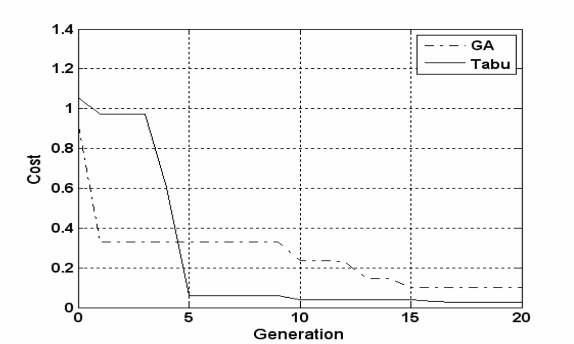

Fig. 6 The evolution of the cost function with β=0.5 for motor 1.

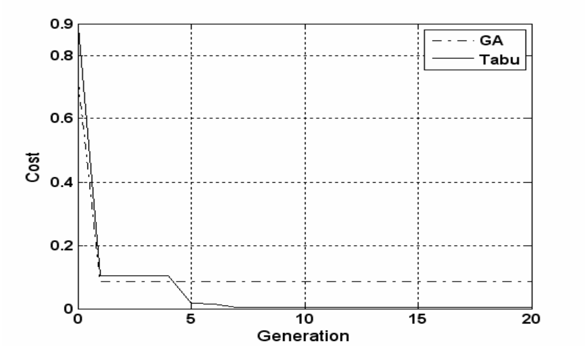

Fig. 7. The evolution of the cost function with β=1.5 for motor 1 .

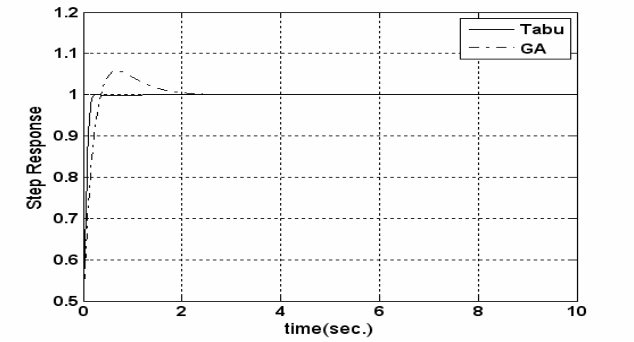

Fig. 8. Step response of motor1angles with β=.5

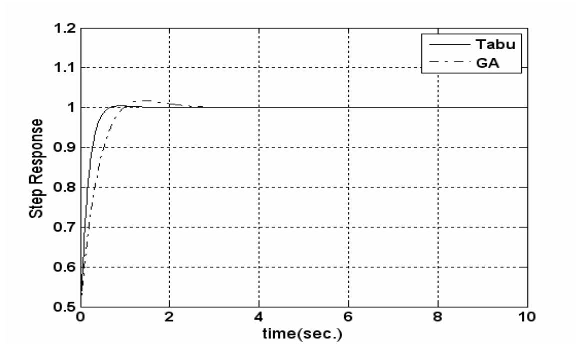

Fig. 9. Step response of motor2anles with β=0.5

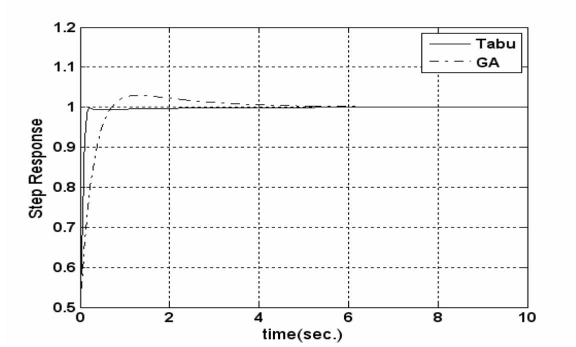

Fig. 10. Step response of motor1angles with β=1.5

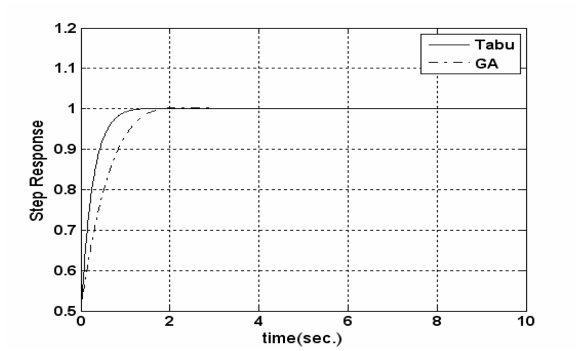

Fig. 11. Step response of motor2anles with β=1.5

TABLE III
BEST PID CONTROLLERS WITH DIFFERENT β VALUES GAINED BY TS AND GA ALGORITHMS FOR MOTOR 1 AND MOTOR 2

		β	Iteration	k_d	k_p	k_i	$M_p(\%)$	E_{ss}	$t_r(s)$	$t_s(s)$	Min Cost
Motor 1	**TS**	0.5	20	1.2549	9.8431	2.8235	0.12	0	0.11	0.15	0.028
		1.5	20	1.2507	8.9020	2.9020	0	0	0.16	0.20	0.083
	GA	0.5	20	0.7451	3.3725	1.6471	5.79	0	0.23	1.39	0.133
		1.5	20	1.2941	9.4510	2.3529	2.98	0.0001	0.38	2.21	0.096
Motor 2	**TS**	0.5	20	1.9216	8.3922	7.3333	0.40	0	0.28	0.47	0.311
		1.5	20	2.4314	8.1569	4.5882	0.08	0	0.45	0.83	0.466
	GA	0.5	20	3.2157	7.8039	4.3529	1.73	0	0.53	0.81	0.545
		1.5	20	1.8824	5.2549	2.4706	0.32	0	0.84	1.37	0.686

VI. CONCLUSION

In this paper we present modified Tabu search algorithm for determining the MIMO controller parameters of the 5-bar-linkage manipulator robot. Through the simulation results, the proposed controller can perform an efficient search for optimum PID parameters. This paper demonstrates that the TS method can solve searching and tuning PID controller parameters more efficiently and quickly than GA method. The topic of our future researches is to employ other heuristic methods in order to achieve better results of designing controller parameters and improving its performance in real time and decreasing delays. Also, implementation of mentioned algorithm should be a challenging task.

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