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Lagrangian Modeling and Optimal MIMO PID Control of a Manipulator Using Tabu Search Algorithm

Seyed Ehsan Aghakouchaki Hosseini[1*], Mohammad Dashti Javan[2]

[1]University of Mohaghegh Ardabili (UMA), Civil Engineering Department, Ardabil, Iran
[2]Amirkabir University of Technology (AUT), Electrical Engineering Department, Tehran, Iran

***Corresponding author:** Seyed Ehsan Aghakouchaki Hosseini, University of Mohaghegh Ardabili (UMA), Civil Engineering Department, Ardabil, Iran, E-mail: hosseini_civil@hotmail.com*

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Abstract

Robot manipulators, given their promising features and capabilities, have found a variety of applications in many fields including construction, nuclear, car, manufacturing and surgical industries, among others, which has turned them to a large and diffuse industry. In construction, use of robots has automated many tasks and risky jobs, including multitask road construction and maintenance processes based on ergonomic and economic analyses, surface finishing, concreting, excavating and backfilling, to name but a few. Hence, manipulators have progressively replaced human labor to meet strict health regulations, productivity gains, and control goals. Movement of an effector tool into a proper location and orientation required for a work object is the main role of a manipulator. In this research dynamic modeling and control of a 2-DOF planar robotic manipulator is presented using a PID controller to obtain optimal position of final operator of the manipulator. Considering nonlinearity of the system under consideration, to optimize final position of the manipulator, parameters of PID controller were tuned using Tabu Search (TS) algorithm as one of meta-heuristic optimization techniques. Numerical results obtained from simulations in this study demonstrated robustness and efficiency of the selected approach for optimizing the final position of the manipulator, minimizing oscillations and fast convergence of the error function to zero, compared to that of uncontrolled state as well as controlled system by PID controller with empirically adjusted factors. Efficiency of the proposed method was verified for different angular positions of joints in the manipulator.

Key Words: Lagrangian Modeling; Manipulator; MIMO PID Controller; Evolutionary Algorithms

Introduction

Manipulators are used in various fields including, construction industry, surgical wards in hospitals, exploration of mines and complex welds, nuclear technology, car and manufacturing industries, among others. In medical applications, utilization of manipulators in surgery has found many benefits and advantages like elimination of many difficulties such as breaking the bones and opening the chest, operation outside the hospital or even over large distances, reducing recovery period after surgery and post-operative pain and, hence less time for hospitalization,

There are many different operations in building construction as well as heavy construction including element placement, surface treatment, filling operations, excavation, and tunneling which can be conducted by robots. In addition, they can be employed for inspection, testing and operation control [1]. A considerable potential for robotization of building construction as the single largest industry of the time in US, was discussed by Warszawski [2] during the first conference on robotics in construction. As discussed by Warszawski, manipulator, effector, control unit, sensors and the locomotion mechanism are principle components of a robotic system that are to be studied for application in building construction industry. Warszawski [2] recommended four types of robots for implementation of building construction tasks which are: (a) robots for handling large building components, (b) robots for interior finishing and connecting works, (c) robots for finishing large horizontal surfaces, and (d) robots for finishing vertical exterior walls.

In construction industry, wood is considered a renewable and sustainable material used for structural elements. Automated technologies and manufacturing systems required for utilization of timber are currently the focus of attention to be adopted as an efficient alternative to conventional methodologies for production line. In the field of timber industry for construction, the assembly line for timber-based prefabricated panelized walls includes many repetitive processes through the production process which strongly requires automated solutions [3, 4, 5].

Road construction and maintenance tasks are extremely costly in the construction field. Moreover, work safety for laborers while using heavy vehicles and working machineries, and health regulations related to application of carcinogenic materials, are affecting factors that have turned automated road construction and maintenance equipment to an attractive alternative to execution of routine tasks, considering repetitiveness and moderate sensory requirements of many tasks in this field [6].

The proportional-integral-derivative (PID) controllers are widely used in industry and meet various requirements of complex industrial parts. A variety of applications including networked control of a large pressurized heavy water reactor (PHWR) [7], automatic voltage regulator (AVR) [8, 9], power plants [10], load frequency control (LFC) of power systems [11], temperature controllers such as temperature controllers used in tunable semiconductor laser modules for optical communication systems [12] or temperature controllers for a polymerase chain reaction (PCR) [13], compensation of an SVC load [14] and Variable-Speed Motor Drives [15] can be named for these controllers, among others. Capability of these controllers in utilization in numerous applications is their great advantage. In addition, in conditions where the mathematical model of the process is unknown, usually these controllers are applied.

Finding an efficient and optimal method of designing PID controllers which could be applied in variety of processes with a very low error rate, is highly challenging. Therefore, finding the most optimal method for adjusting these controllers' parameters is the focus of attention in literature. Methods used for setting these parameters can be divided into two general groups of classic and metaheuristic. Approaches proposed by Ziegler–Nichols [16] and Cohen-Coon [17] are among classical ones, based on approximation. Fuzzy inference [18, 19], fuzzy simulated annealing [20], simulated annealing [21], particle swarm optimization (PSO) [22], genetic algorithm (GA) [23] and ant colony neural network [24] can be mentioned as metaheuristic techniques utilized for adjustment of PID controllers in literature.

Tabu Search Algorithm is one of metaheuristic optimization methods developed by Glover [25, 26], for combinatorial optimization problems based on local search algorithms which attempt to overcome their imperfections. In fact, this method is a local search algorithm that uses flexible memory structures. Also, the convergence of this method to an optimal answer has recently been proven, in the case of increasing number of repetitions. In fact, Tabu algorithm works like a local search method, but it uses a *taboo* list to avoid local optimums.

In this research, dynamic analysis of a planar manipulator, using Lagrange equations is introduced, and formulation of a PID controller which has been widely utilized in industrial processes is presented to design a sample of this controller based on dynamic analysis of a planar manipulator. Tabu Search algorithm as one of meta-heuristic optimization tools [27] is introduced and would be applied as a robust tool for adjusting optimum parameters of PID controller for given nonlinear system. Finally, simulation results of analyzing the robotic manipulator in different states of uncontrolled, controlled by PID with empirically adjusted parameters and PID with parameters tuned by Tabu Search (TS) algorithm are presented and results thereof are examined and compared to show efficiency of the proposed method.

Manipulator-Based Systems

The work to be done on the environment is performed on robot Master by the operator. Robot Master executes commands received from operator as well as feedback from Robot Slave through the communication channel. The Slave robot will execute commands sent from operator to the Master through the channel or communication network and simulates behaviors. Controller system of robot has the task of producing appropriate stimulus signal to reach the optimal point, and the network or communication channel is responsible for communicating between Master and Slave robots. In fact, desirable task on the environment will actually be done by the Slave Robot. In Unilateral manipulators, position signal of the Master is sent to the Slave's via a communication channel to follow the same movements. In this way, there will be no feedback between two robots, hence making it unstable against environmental disturbances, easily.

In bilateral manipulator systems, a communication between Master's and Slave's positions is developed, through which, position signal from Master is sent to Slave and a feedback signal is sent from Slave to Master. In this type of manipulator, due to the presence of feedback, the system's instability can be reduced and therefore a more complex control system is required. Another type of Bilateral manipulator is by utilization of force in which Slave Robot's movements are recorded and Robot Master tries to follow them. In this model, a feedback from force of Slave's final operator is transmitted to robot Master. Indeed, in these manipulators, communication between two robots is done bilaterally.

Dynamic Equations of 2-Dof Planar Manipulator

The purpose of this section is to obtain the dynamic equations of a two-axis manipulator shown in Fig. 1, using Lagrange dynamical model. Lagrange's method is one of the common methods for calculating dynamical equations that has been widely used in research studies. The manipulator has two links, and the location and position equations in Cartesian space are as follows,

$$X_1 = L_1 \sin\theta_1 \quad (1)$$

$$Y_1 = L_1 \cos\theta_1 \quad (2)$$

$$X_2 = L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2) \quad (3)$$

$$Y_2 = L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) \quad (4)$$

Kinetic and potential energies of this manipulator in terms of angles of joints and links are as follows, respectively,

$$KE = \frac{1}{2}(M_1 + M_2)L_1^2\dot{\theta}_1^2 + \frac{1}{2}M_2L_2^2\dot{\theta}_1^2 + M_2L_2^2\dot{\theta}_1\dot{\theta}_2 + \frac{1}{2}M_2L_2^2\dot{\theta}_2^2 + M_2L_1L_2\cos\theta_2(\dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_1^2) \quad (5)$$

$$PE = M_1 gL_1 \cos\theta_1 + M_2 g(L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2)) \quad (6)$$

The Lagrangian is defined as the difference between the potential energy and the kinetic energy of the system, which based on above equations for kinetic and potential energies, would be as follows,

$$\mathrm{L} = \frac{1}{2}(M_1 + M_2)L_1^2\dot{\theta}_1^2 + \frac{1}{2}M_2L_2^2\dot{\theta}_1^2 + M_2L_2^2\dot{\theta}_1\dot{\theta}_2 + \frac{1}{2}M_2L_2^2\dot{\theta}_2^2 + M_2L_1L_2\cos\theta_2(\dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_1^2) - M_1gL_1\cos\theta_1 - M_2g(L_1\cos\theta_1 + L_2\cos(\theta_1 + \theta_2)) \quad (7)$$

Using the Lagrangian, the results obtained for the dynamical equations of 2-DOF planar manipulator is as follows,

$$B(q)\ddot{q} + C(\dot{q}, q) + g(q) = F \quad (8)$$

$$q = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} \quad (9)$$

$$B(q) = \begin{bmatrix} (M_1 + M_2)L_1^2 + M_2L_2^2 + 2M_2L_1L_2\cos\theta_2 & M_2L_2^2 + M_2L_1L_2\cos\theta_2 \\ M_2L_2^2 + M_2L_1L_2\cos\theta_2 & M_2L_2^2 \end{bmatrix} \quad (10)$$

$$\mathrm{C}(\dot{\mathrm{q}}, \mathrm{q}) = \begin{bmatrix} -M_2L_1L_2\sin\theta_2\left(2\dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_1^2\right) \\ -M_2L_1L_2\sin\theta_2\dot{\theta}_1\dot{\theta}_2 \end{bmatrix} \quad (11)$$

$$\mathrm{g}(q) = \begin{bmatrix} -(M_1 + M_2)\mathrm{g}L_1\sin\theta_1 - M_2\mathrm{g}L_2\sin(\theta_1 + \theta_2) \\ -M_2\mathrm{g}L_2\sin(\theta_1 + \theta_2) \end{bmatrix} \quad (12)$$

$$F = \begin{bmatrix} f_{\theta_1} \\ f_{\theta_2} \end{bmatrix} \quad (13)$$

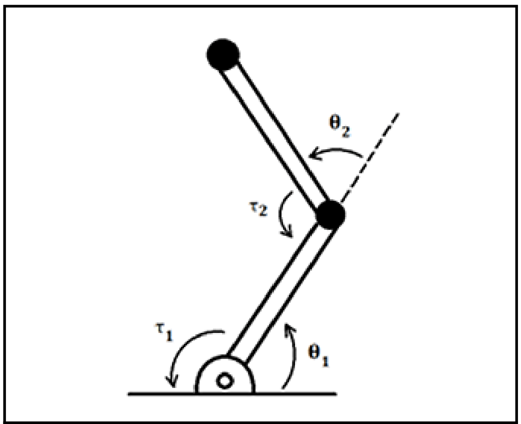

Figure 1: Model of Two Axis Robot

PID Controller

PID controllers are among the most functional industrial controllers. These controllers are based on proportional, integral and derivative control functions. The proportional operator multiplies a proportional interest in the error signal and outputs this controller. Integral and derivative operators also perform integral and derivative operations on an error signal and produce separate outputs for the controller. In PID controller, commands of these three functions are combined and the final form of control signal is generated as follows,

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (14)$$

In which, *u (t)* is the control signal, *e (t)* is the error signal, K_p is the proportional coefficient, K_i is the integral coefficient, and K_d is the derivative coefficient. There are a series of criteria for comparing performance and improving the quality of different controllers, among which the most reliable ones include integrated absolute error (IAE), integrated of time-weighted-absolute-error (ITAE), integral of squared-error (ISE), and integrated of time-weighted-squared-error (ITSE) which are defined as below,

$$IAE = \int_0^T |e| dt \quad (15)$$

$$ITAE = \int_0^T t|e| dt \quad (16)$$

$$ISE = \int_0^T e^2 dt \quad (17)$$

$$ITSE = \int_0^T te^2 dt \quad (18)$$

Designing PID Controller based on Dynamic Analysis of Manipulator

Regarding the relations obtained from dynamic analysis of two axis robotic manipulator in section III, the dynamic description of the manipulator would be as below,

$$\ddot{q} = B(q)^{-1}\left[-C(\dot{q},q)-g(q)\right]+\hat{F} \tag{19}$$

$$\hat{F} = B(q)^{-1}F \iff F = B(q)\hat{F} \tag{20}$$

Assuming separability, the input torque would be as follows,

$$\hat{F} = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} \tag{21}$$

$$\begin{bmatrix} f_{\theta_1} \\ f_{\theta_2} \end{bmatrix} = B(q)\begin{bmatrix} f_1 \\ f_2 \end{bmatrix} \tag{22}$$

In fact, the output signal of the controller is of force type and can be written as below relations,

$$f = K_p\, e(t) + K_i \int e(t)\,dt + K_d \frac{de(t)}{dt} \tag{23}$$

$$e(\theta_1) = \theta_{1f} - \theta_1 \tag{24}$$

$$e(\theta_2) = \theta_{2f} - \theta_2 \tag{25}$$

$$f_1 = K_{p1}(\theta_{1f} - \theta_1) + K_{i1}\int e(\theta_1)\,dt - K_{d1}\dot{\theta}_1 \tag{26}$$

$$f_2 = K_{p2}(\theta_{2f} - \theta_2) + K_{i2}\int e(\theta_2)\,dt - K_{d2}\dot{\theta}_2 \tag{27}$$

$$\ddot{q} = B(q)^{-1}\left[-C(\dot{q},q)-g(q)\right]+\hat{F} \tag{28}$$

$$\hat{F} = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} = \begin{bmatrix} K_{p1}(\theta_{1f} - \theta_1) + K_{i1}\int e(\theta_1)\,dt - K_{d1}\dot{\theta}_1 \\ K_{p2}(\theta_{2f} - \theta_2) + K_{i2}\int e(\theta_2)\,dt - K_{d2}\dot{\theta}_2 \end{bmatrix} \tag{29}$$

$$\begin{bmatrix} f_{\theta_1} \\ f_{\theta_2} \end{bmatrix} = B(q)\begin{bmatrix} f_1 \\ f_2 \end{bmatrix} \tag{30}$$

To use the PID controller, a supplementary variable is defined and final equations would be of below forms,

$$x_1 = \int e(\theta_1)\,dt \iff \dot{x}_1 = \theta_{1f} - \theta_1 \tag{31}$$

$$x_2 = \int e(\theta_2)\,dt \iff \dot{x}_2 = \theta_{2f} - \theta_2 \tag{32}$$

$$\begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} = B(q)^{-1}\left[-C(\dot{q},q)-g(q)\right] + \begin{bmatrix} K_{p1}(\theta_{1f} - \theta_1) + K_{i1}x_1 - K_{d1}\dot{\theta}_1 \\ K_{p2}(\theta_{2f} - \theta_2) + K_{i2}x_2 - K_{d2}\dot{\theta}_2 \end{bmatrix} \tag{33}$$

Tabu Search Algorithm

Tabu Search (TS) Algorithm developed by Glover (Glover, 1989, 1990) is one of metaheuristic optimization methods for combinatorial optimization problems based on local search algorithms which attempt to overcome their imperfections. The risk in this algorithm to be avoided is being trapped in a local optimum and being faced with undesirable quantities. In fact, this method is a local search algorithm that uses flexible memory structures. Also, the convergence of this method to an optimal answer has recently been proven, in the case of increasing number of repetitions. In fact, TS algorithm works like a local search method, but it uses a *taboo* list to avoid local optimums. A local search can be considered as a repetitive algorithm that starts with an answer, and continues until it reaches a local optimum. However, these local optimums, are usually ordinary values but not desired ones. Thus, a TS algorithm can be considered as a combination of a short-term memory with a local search. In TS method, there is a list that holds out forbidden displacements and is known as *taboo* list, and its main application is to avoid converging to local optimum solutions. In other words, with aid of the *taboo* list, switching to the recently searched answers will be prohibited. Efficiency of a TS algorithm depends on the size of the neighborhood of a solution and on the number of iterations for which a step is kept as *taboo* [28, 29].

The general structure of TS technique is that, at first a possible initial answer is chosen and then for this answer, based on a specific criterion, a set of possible neighbor values is considered. In the next step, after evaluating neighbor values, the best one is selected, and the shift from the current answer to the selected neighbor answer takes place. This process is repeated in the same way as long as the termination condition is fulfilled. Shifting from the current answer to the neighbor value is permitted if and only if it is not in the *taboo* list. Otherwise, the next value in the neighborhood will be selected for evaluation. Prohibited solutions (*taboo*s) in TS are identified by referring to memory, are transferred from a social memory and are changed over time. The status of prohibitions is determined by reliance on a memory, in which the conditions, that are completely adaptable, can be changed over time according to given requirements. Adaptive memory of TS algorithm consists of short and long terms. In this research, short term aspect of this algorithm is given more focus. However, to achieve better computational results, the importance of long-term memory has been emphasized as well.

Moving from current value X_n to the next one will be done according to the best possible answer in the neighborhood V(X_n), even if no answer is better than the current answer X_n in V(X_n). If the neighboring structure is symmetric (that is, if X_n belongs to the neighborhood of V(X_n) then $X \in$V(X_n), there is a risk of falling into a loop. In fact, X_n may be the best answer in V(X_n), in which case, solution will fluctuate repeatedly between X and X_n. To avoid this state and other similar states which create such loops, a *taboo* list is provided which contains recent answers and is in the form of ($X_{(n-1)}$, $X_{(n-2)}$, ..., $X_{(n-l)}$). If X is in the *taboo* list, then movement from X_n to X is prohibited. Of course, this will also cause some issues, as registration and maintenance of all information about each candidate solution and evaluating them is a time-consuming process. So, instead of recording all information about these answers, only a specific feature of them is recorded. But, on the other hand, recording a feature of answers instead of them is more restrictive, because other answers other than recent ones may have the same feature. *Taboo* list, which includes features of these responses, may also not well avoid creation of a loop. The essential role of the *taboo* list is to create diversity in the search. Indeed, the purpose is to move from the current value to those in the search space that have not been looked up yet and specifically avoiding local minima. Deploying *taboo* lists which include solutions themselves, irrespective of high computational time, does not usually result in desired responses and does not perform diversification task very well. Thus, *taboo* lists often include one or more features of recent responses or moves. *Taboo* lists may be too much restrictive and prevent optimal movements, while there may be no risk of falling into the loop or these movements may even lead to a general improvement in searches. Therefore, it is necessary to use an algorithm which cancels out that particular avoidance and allows the corresponding variable to be entered into the search space. For this purpose, the *release criterion* is used to exit the *taboo* list.

Short Term Memory

Short-term memory in TS algorithm forms a kind of dynamic search to find the best answers, and it can be stated that the core of this method lies in this memory. As noted in previous section, answers obtained in this approach should satisfy specific conditions. These conditions are in the form of restrictions and prohibitions. These restrictions are intended to prevent backward movement or repetition of certain moves by assigning the *taboo* phrase to some of the features of these movements. The primary purpose of enforcing *taboo* restrictions is to avoid creation of a loop and to guide the algorithm to search for new spaces. Of course, it should be noted that these restrictions are not applied unilaterally, but in accordance with aspiration criteria.

Recency-Based Memory

The most common form of short-term memory that detects characteristics of responses that have changed recently (recent repetitions) is called recency-based memory. To use this memory, characteristics of values that have changed in recent repetitions are entitled as *Taboo*-Active and solutions containing either these elements or certain combinations of them are avoided. This approach causes recently obtained answers to be excluded from the neighborhood and not be re-launched again.

Aspiration Criteria

A. First Criterion

Should any response, based on the value of objective function, be better than all previously obtained responses, have to be excluded from *taboo* list; No such a response has been obtained before.

B. Second Criterion

If the structures of taboo lists in one of iterations do not allow any movement, then the last move in the exit queue in the list is selected and the ban will be lifted. In TS method, after each move, *taboo* list is updated, so that each new move is added to the list and the movement which has been in the list, up to the *n*th iteration, is removed. The basic concept of the TS algorithm is to allow responses which even though do not improve the objective function, may lead the search to the absolute optimum.

Proposed Method

Using equations obtained in section III, the manipulator is modeled as Master and Slave robots by programming in MATLAB to control output of the system, which are torques of joints, based on changes in inputs. PID controller introduced in section IV is used to control this robot while the TS algorithm is employed to adjust coefficients of this controller. Based on the error values defined in (24) and (25), and using the *ISE* performance criterion, the proposed controller coefficients are determined and the stability of the system is examined with respect to its specific values. In the proposed method, it is not necessary to analyze the model of the system but is considered as a black box in each step. Indeed, decision-making process in metaheuristic algorithms is affected by inputs and outputs of the system.

Communication channel between Master and Slave robots is modeled with a delay. Robot Slave is modeled with same dynamic equations as Robot Master and desired parameters of controller are searched for, to minimize the objective functions. Flowchart of a Tabu Search Algorithm is as shown in Fig. 2.

Dynamic equations of Master and Slave robots are developed by programming in MATLAB so that each iteration, by accessing error values, search algorithm can change the controller's coefficients to find the best ones in terms of the value of error. Constant values required for Master and Slave robots, along with values of TS optimization algorithm, are listed in Table 1. In this simulation, initial and final position values are considered as ($-\pi/2$, $\pi/2$) and ($\pi/2$, $-\pi/2$), respectively.

Table 1: Constant values of Master and Slave robots

Variables	Constant Values	Variables	Constant Values
L1_Master	1		
L2_Master	1		
M1_Master	5		
M2_Master	5		
L1_Slave	2		
L2_Slave	2	Communication Delay	5%
M1_Slave	4	M2_Slave	17

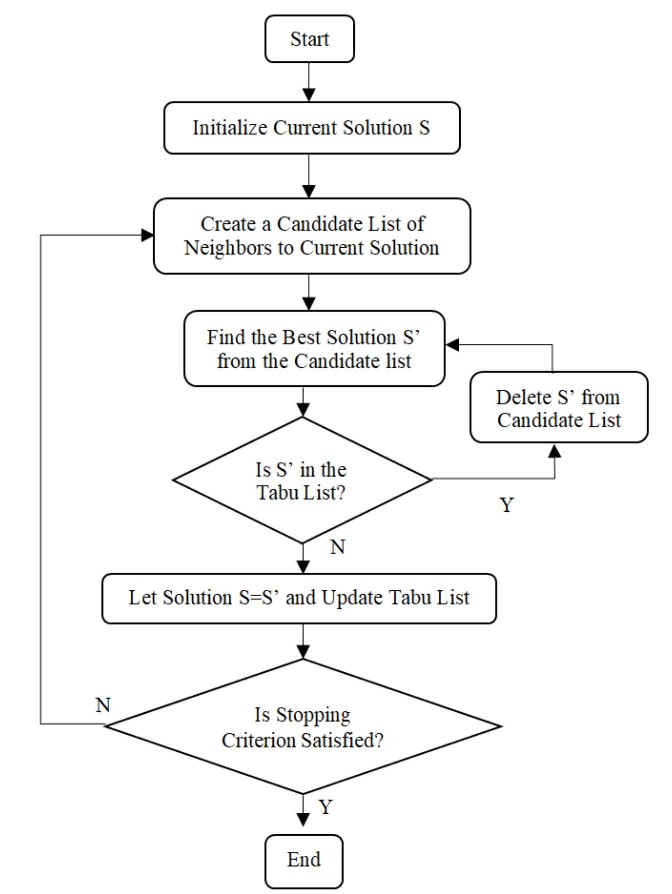

Figure 2: Tabu Search (TS) Algorithm Flowchart

Simulation Results

The manipulator with two degrees of freedom (2-DOF) with specifications mentioned in the section III was analyzed which results thereof are discussed in this section. The objective is to transfer the final operator of manipulator from position (-π/2, π/2) to (π/2, -π/2). For this purpose, the system requires a proper torque to reach the desired position while not passing it. Fig. 3 shows the value of the error θ_1, which first has been fluctuating and then after experiencing a series of sever changes, has not reached zero. Fig. 4 shows values of error θ_2, which after initial fluctuations and then a sudden change has not reached zero. Therefore, since error values for angular positions of joints do not reach zero, the system faces variations and never reaches the desirable point. Figs. 5 and 6 illustrate values of τ_1 and τ_2, which are angular torques of joints 1 and 2. These figures demonstrate that angular torques has encountered considerable fluctuations and never has reached desired values.

Considering the fact that the system is non-linear, it is impossible to use the conventional methods such as Ziegler-Nichols. Thus, PID controllers whose coefficients have been determined by empirical methods were applied which numerical results thereof are discussed herein. Figs. 7 and 8 display error values θ_1 and θ_2 of joint angles which show an improvement compared to uncontrolled system. It should be noted that when the non-linear robotic model is uncontrolled, the error values face oscillations and do not converge to zero.

As shown in Fig. 7, error values in the first joint after some variations converge to zero. However, since in 2-DOF robotic model, positions of the system variables depended on each other, and error in the second joint does not approach zero, hence the whole system has not properly been controlled. Torques' values in joints are shown in Figs. 9 and 10, which demonstrate they have not reached desired values.

The proposed method for adjusting PID controller's parameters using TS technique was implemented and obtained results are presented in this section. In Figs. 11 and 12, error values related to positions of first and second joint show no oscillations and gradually reach the desired value, i.e. zero. As both joints have reached zero error values, the position of the final operator has reached its desired value. Figs. 13 and 14 show torques applied to the joints, which represent acceptable amounts without becoming infinite. In TS-PID controlled case, as shown in Figs. 15 and 16, error values of angular positions for both first and second joint, without any fluctuations, has reached zero which demonstrate the final operator of manipulator has achieved its desired value.

To verify the proposed method, values of the initial and desired position were changed, and results of changes of positions from (-π/4, π/4) to (π/4, -π/4) have been presented in Figs. 17 and 18. Torques of joints is also within acceptable ranges and control signal has not become infinite. Numerical results obtained from analyzing the manipulator controlled with the PID controller tuned by TS algorithm, considering optimal positions specified in the previous section, were examined for new parameters of 2-DOF robotic system. In this case, mass values as well as lengths of two links were considered as per Table 2, based on which, responses were obtained as follows. As shown in Figs. 19 to 22, error values have approached zero, but values of torques have increased. In other words, despite changes in some coefficients of manipulator's equations, the controller can still optimally control the system and only amount of control signal, i.e. input torque to the 2-DOF manipulator, due to more mass, has increased, which is mathematically reasonable.

Table 2: Parameters of 2-DOF manipulator

G	M2	M1	L2	L1
9.8	3.4	5.2	2	1

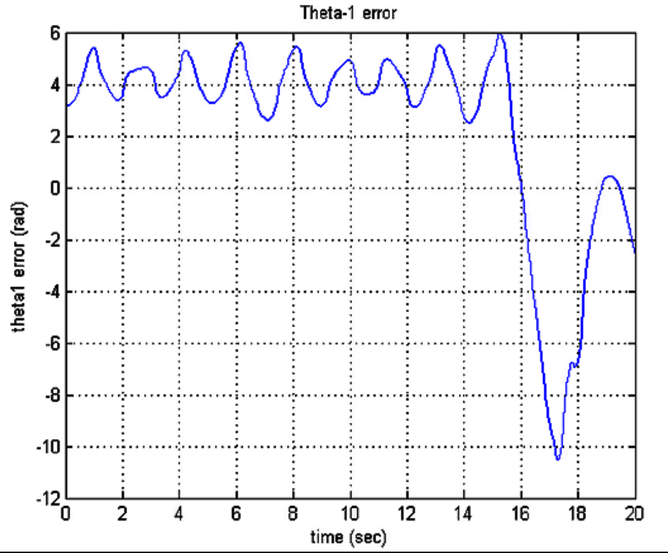

Figure 3: Error values of angular position for first joint without controller

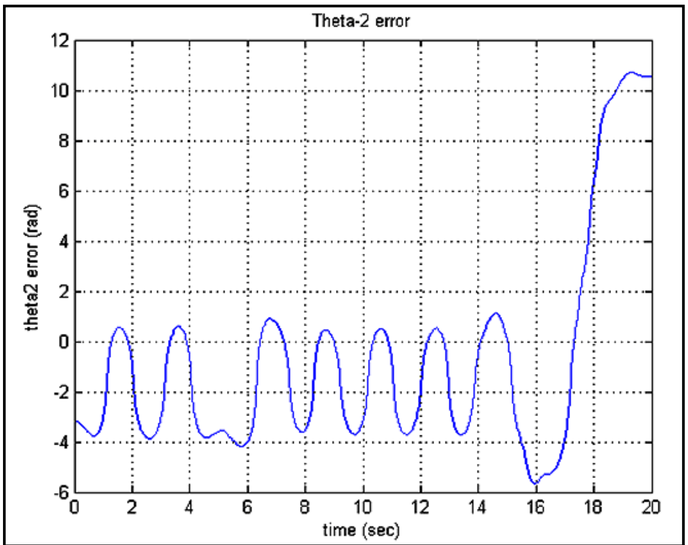

Figure 4: Error values of angular position n for second joint without controller

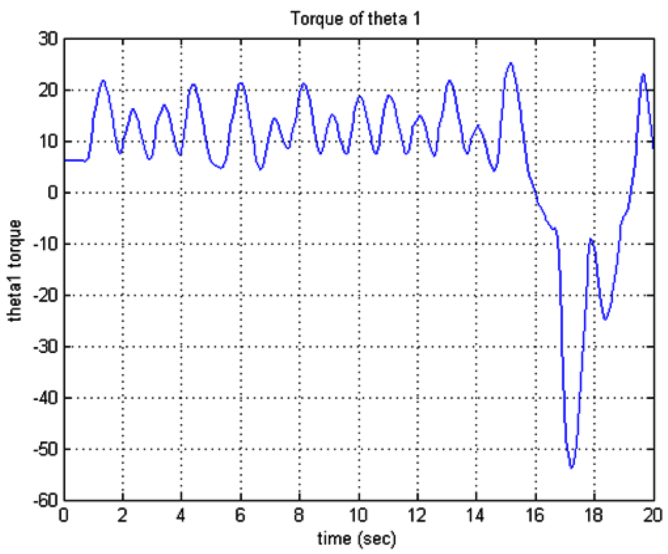

Figure 5: Torque in first joint without controller

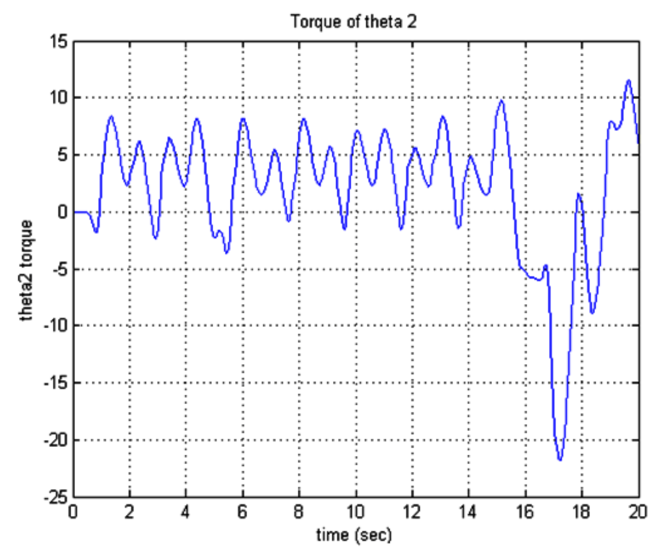

Figure 6: Torque in second joint without controller

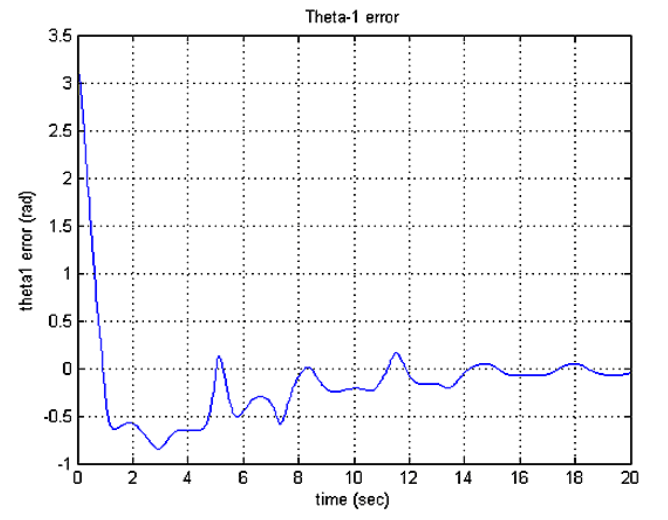

Figure 7: Error values of angular position for first joint with empirically adjusted PID controller

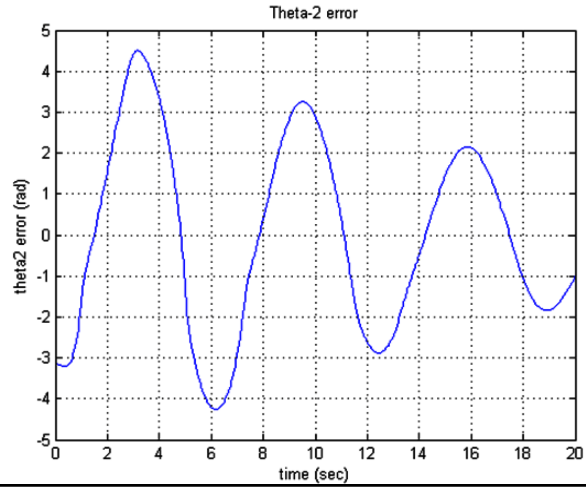

Figure 8: Error values of angular position for second joint with empirically adjusted PID controller

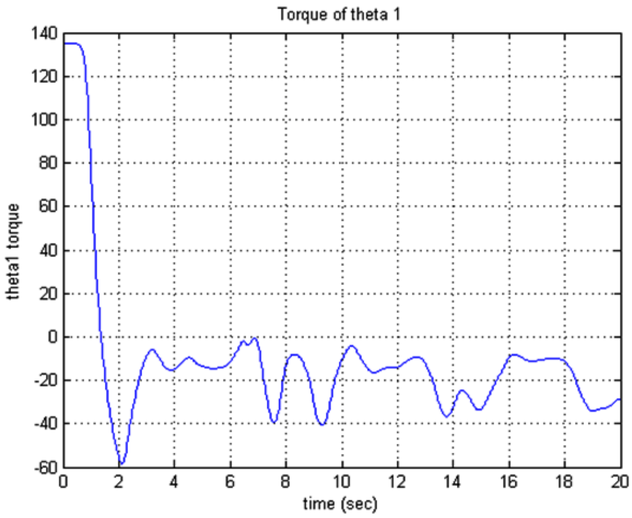

Figure 9: torque values of first joint with empirically adjusted PID controller

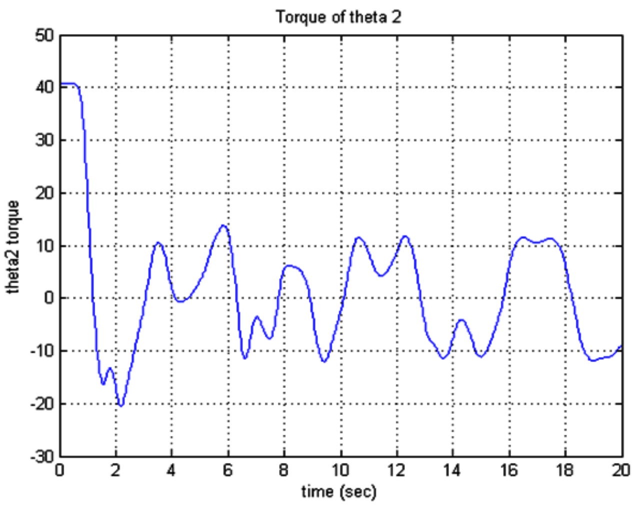

Figure 10: Torque values of second joint with empirically adjusted PID controller

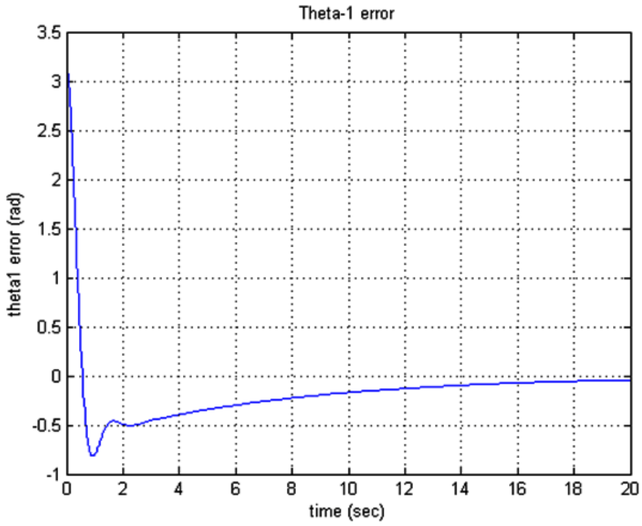

Figure 11: Error values of angular position for first joint with PID controller set by TS algorithm for movement from (-π/2, π/2) to (π/2, -π/2)

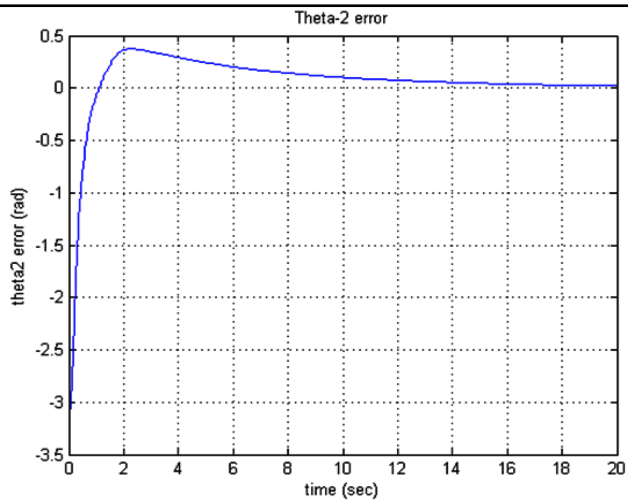

Figure 12: Error values of angular position for second joint with PID controller set by TS algorithm for movement from (-π/2, π/2) to (π/2, -π/2)

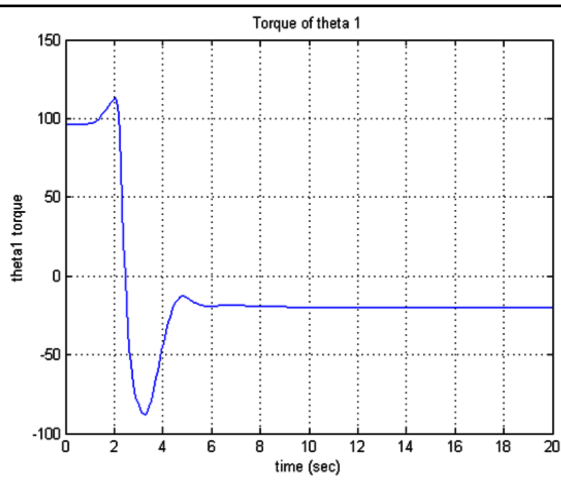

Figure 13: Torque in first joint with PID controller set by TS algorithm in displacement from (-π/2, π/2) to (π/2, -π/2)

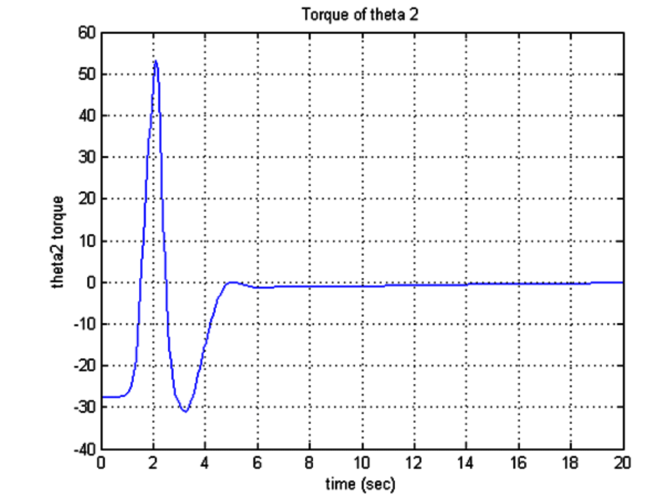

Figure 14: Torque in second joint with PID controller set by TS algorithm in displacement from (-π/2, π/2) to (π/2, -π/2)

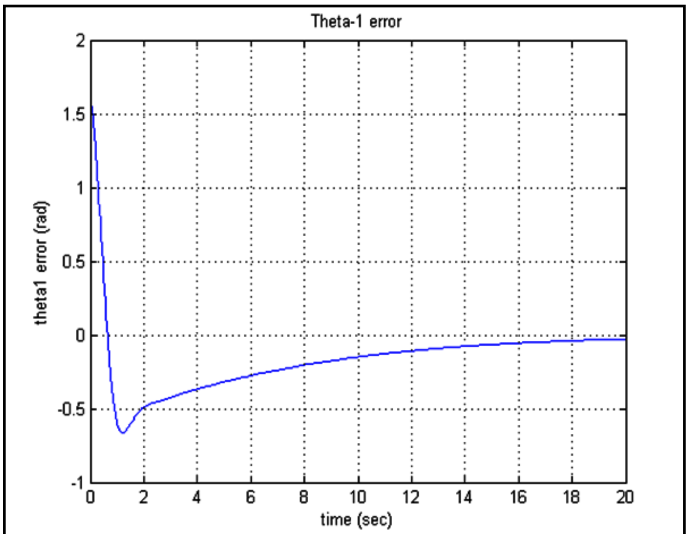

Figure 15: Error values of angular position for first joint with PID controller set by TS algorithm for displacement from (-π/4, π/4) to (π/4, -π/4)

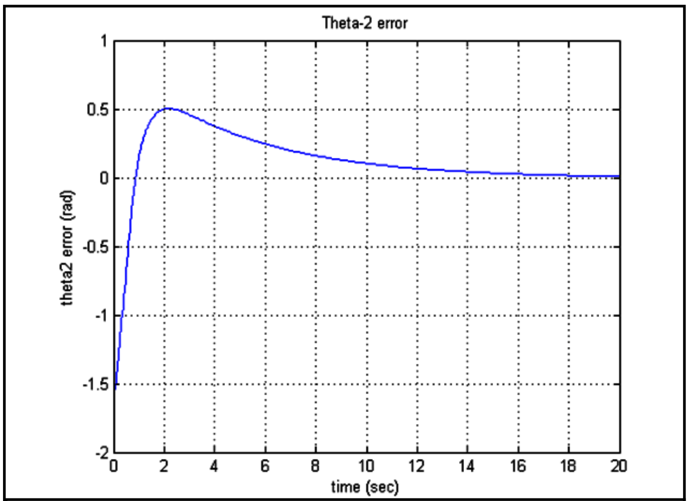

Figure 16: Error values of angular position for second joint with PID controller set by TS algorithm for displacement from (-π/4, π/4) to (π/4, -π/4)

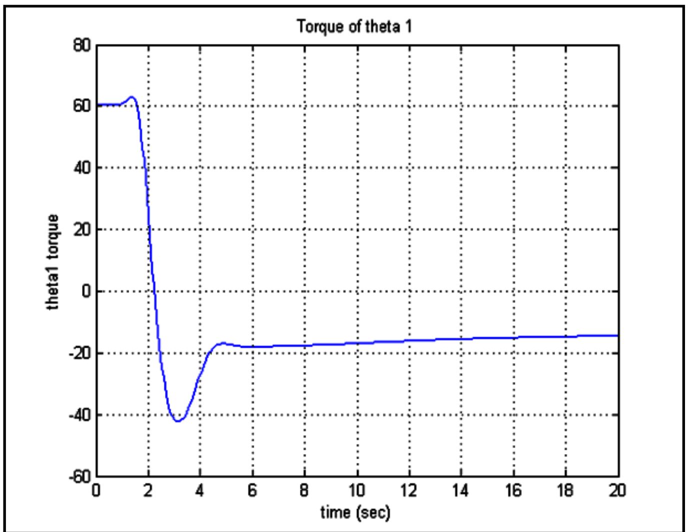

Figure 17: Torque in first joint with PID controller set by TS algorithm in displacement from (-π/4, π/4) to (π/4, -π/4)

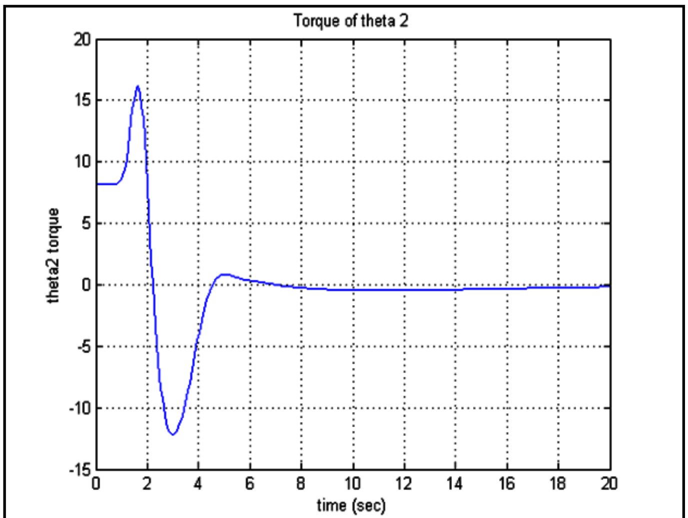

Figure 18: Torque in second joint with PID controller set by TS algorithm in displacement from (-π/4, π/4) to (π/4, -π/4)

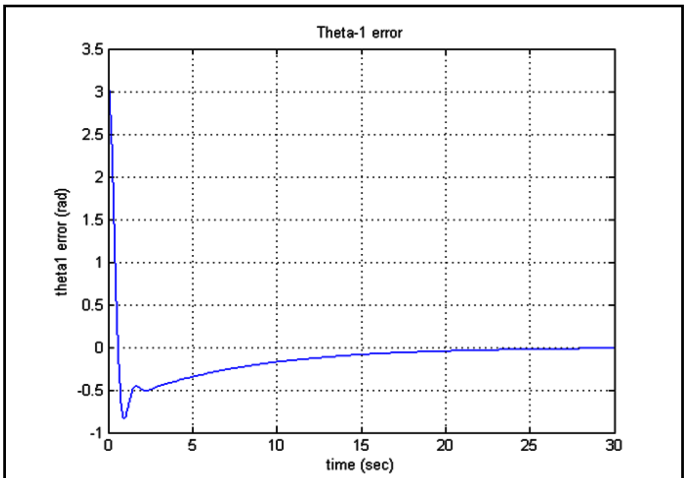

Figure 19: First position angular position error with new parameters

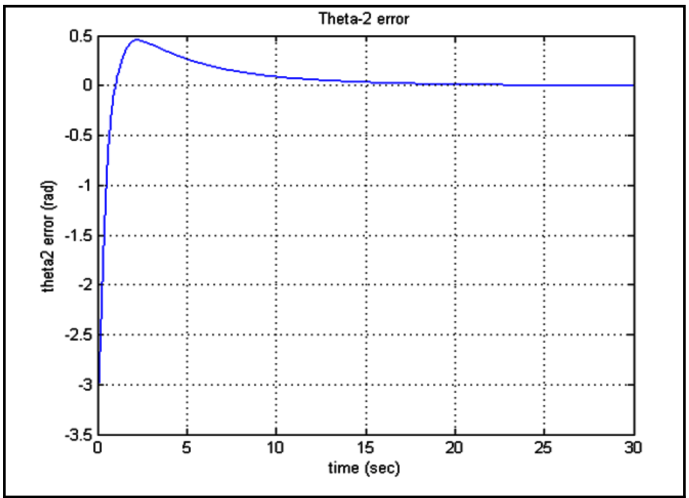

Figure 20: Second position angular position error with new parameters

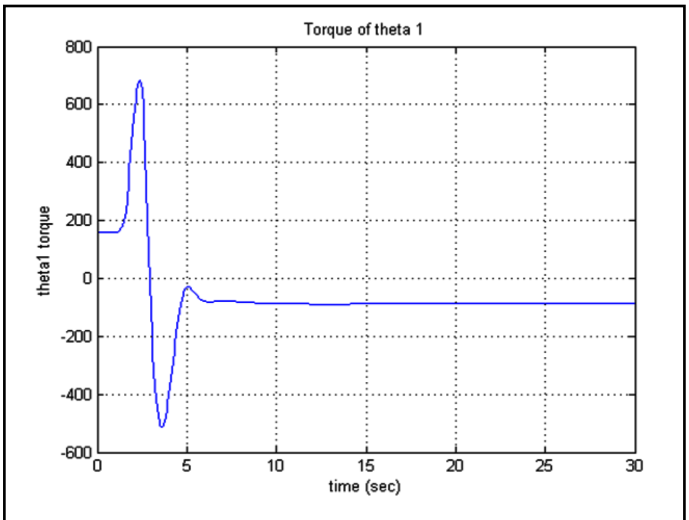

Figure 21: First joint torque with new parameters

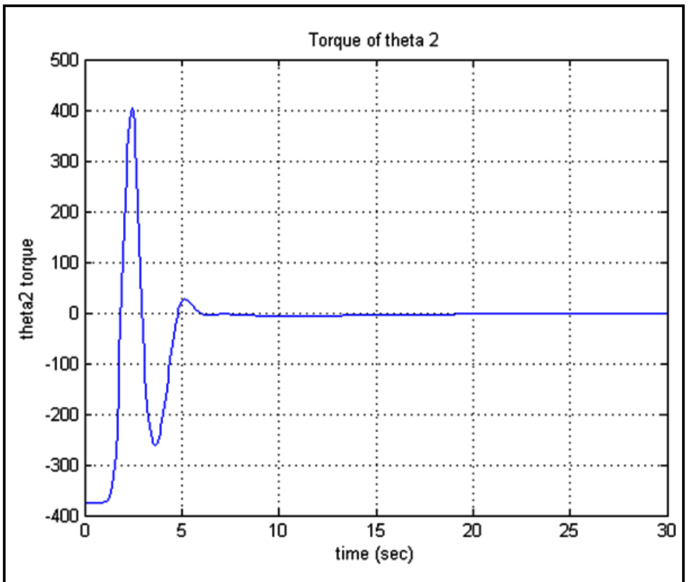

Figure 22: Second joint torque with new parameters

Conclusion

Regarding the considerable utilization of manipulators in a wide range of modern technology applications including aeronautics, explorations, operating destructive materials, surgical operations and specifically construction technology, controlling these manipulators in order to obtain the desired position of final operator in minimum time are of crucial importance. In this paper two-axis manipulator, also known as two-degrees-of-freedom (2-DOF) manipulator was analyzed in both states of uncontrolled and controlled with PID controller. Due to their robust performance and simple structure, PID controllers have been used widely in industrial applications. These controllers were deployed in this study to acquire the desired position of final operator of the manipulator. However, given the nonlinearity of the system under consideration as a challenge, a meta-heuristic search algorithm known as Tabu Search (TS) was employed to optimally adjust PID parameters. Simulation results of uncontrolled system, controlled by PID controller with empirically adjusted parameters, and PID controller with its parameters tuned by TS algorithm, were compared. Analysis results showed that in uncontrolled state, desired final position is not achieved. Also controlling the system with PID controller while its parameters are empirically adjusted would not give the desired solution while deployment of TS approach as one of metaheuristic search methods demonstrated robustness in delivering optimum parameters of the PID controller and consequently the final position of robotic manipulator in minimum time.

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