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## Control of master slave robotics system using optimal control schemes

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**Abstract.** This paper presents application of Proportional Integral Derivative (PID) and Non-linear PID (NPID) controllers to optimally operate the master slave robotic system. Teleoperation is widely used in different applications, such as surgical robots, underwater vehicles, power lines and even in space. However there are problems in teleoperation systems that may lead to degradation in system performance or even to system instability. This paper presents new and optimal control schemes that can satisfy the required performance, insure system stability and achieve zero tracking error in presence of constant time delay and model approximation. Optimal gains are obtained using the Genetic Algorithm in a systematic way that could be applied to other control schemes. The results proved the effectiveness of both control schemes than the previously applied scheme. The NPID control scheme has better performance, provided position tracking and achieved zero tracking error in less settling time than PID one. The results obtained by the presented control schemes are evaluated based on comparing the system performance using three different types of controllers which are P-like, Genetic PID and Genetic NPID. The study was carried out using MATLAB/SIMULINK 2017a.

**Keywords:** NPID, PID, Master Slave Robotics and Genetic Algorithm.

### Nomenclature

$B_i$	Damping Gain.
$C_i(\theta_i, \dot{\theta}_i)$	The Coriolis and Centrifugal Forces Matrix.
$g_i(\theta_i)$	The Gravitational Forces Matrix.
$i$	$i=M$ represents Master Manipulator and $i=S$ represents Slave Manipulator.
$K_p$	Proportional Gain.
$K_i$	Integral Gain.
$K_d$	Derivative Gain.
$J_i(\theta_i)$	Inertia Matrix of the Master or Slave Manipulator.
$\theta_M$	Joint Angle for Master Manipulator.
$\dot{\theta}_M$	Joint Velocity for Master Manipulator.



$\ddot{\theta}_M$	Joint Acceleration for Master Manipulator.
$\theta_S$	Joint Angle for Slave Manipulator.
$\dot{\theta}_S$	Joint Velocity for Slave Manipulator.
$\ddot{\theta}_S$	Joint Acceleration for Slave Manipulator.
$R$	Set of Real Numbers $(-\infty, \infty)$ .
$R^+$	Set of Real Positive Numbers $(0, \infty)$ .
$T_i(t)$	Time delay.
$\tilde{T}_i$	Time delay with upper bound.
$V(\theta, \dot{\theta}, t)$	Lyapunov-like Function.
$\lambda_e$	Minimum Eigen value.
$\lambda_E$	Maximum Eigen value.
$\tau_o$	Torque Exerted by the Human Operator
$\tau_e$	Torque Exerted by the Environment Interaction

## 1. Introduction

The master slave robotics system consists of a local robot which is manually controlled and a remote robot manipulator. The two robots communicate through a communication channel which may involve long distances or set limited data transfer between the master and the slave locations. In some circumstances a delay or inaccuracy may occur between the time a command is given by the human operator and the execution time of the command by the slave robot. Those two factors affect the overall stability of the system [1], [2],[3], [4].

The master slave robotics system is widely used nowadays in many applications; historically the system was presented for the first time in 1945 as a way to keep human safety in hazardous environments, to handle radioactive material from behind a shielded wall in a nuclear reactor. Afterwards the system found its way in e.g. telesurgery, power lines and even in space.

Chopra et al. (2006) achieved good system performance by sending the master position to the slave, and adding a proportional controller to the position error in the slave controller. Following this line, Namerikawa and Kawada (2006) proposed a symmetric scheme, by matching the impedances and adding the proportional error term to the master and slave robots, such that the resulting control laws turned into simple PD-like controllers.

The stability of the PD-like controller was proved to be better than the P controller only [5], [6],[7]. Emmanuel Nuño et al.[8] proposed three control schemes that can assure position tracking in the existence of variable time delay for non-linear teleoperators but in a long settling time. Additionally, using a Lyapunov-like function, they derived the conditions, under which the velocities and position error of the teleoperator are bounded for P-like, PD-like and scattering transformation based controllers.

Recently in 2017, some researchers focused on the development of master slave system for teleoperated ultrasonography by installing ultrasound probe inside of the platform and contacts with patients skin through the hole in the base frame to minimize the size of the robot [9].

Also there is another study presented a teleoperation system for remote control of mobile manipulators over the Internet, Using the time domain passivity concept and proposed a modified passivity controller to ensure enhanced transparency with bounded control actions in the existence of time-varying communication delay[10].

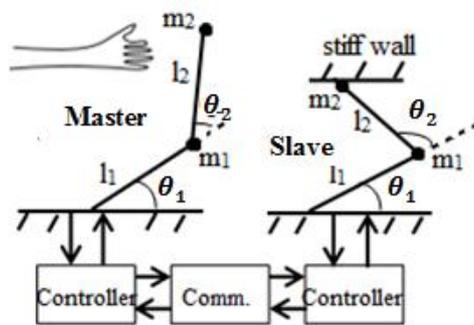
In this paper, the focus is on the optimal controller selection in terms of the type of the controller and the optimal controller parameter.

The most of real systems are nonlinear systems but, the nonlinearity percentage tolerances from system to another [11]. It is known that the mechanical systems contain a high percentage of nonlinearity. So, the traditional PID controller with linear parameters cannot achieve high performance for this type of systems. Also, the PID controller still has fixed gains which are not enough to deal with high complicated dynamic systems[12] . There's a new proposed nonlinear PID (NPID) controller which contains nonlinear gains incorporated with the fixed gains of PID controller [13]. These nonlinear gains enjoy the advantage of high initial gain to attain a fast dynamic response, followed by a low gain to

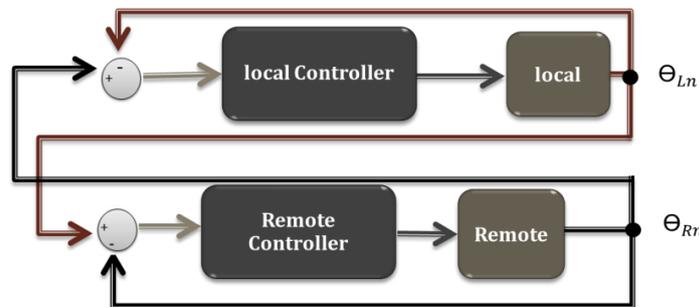
prevent an oscillatory behavior[14] . Many of studies provided that the harmony search optimization technique can reach the optimum solution for any problem compared to other optimization technique [15].

In this research (PID and NPID) controllers will be used to improve system performance compared to P-like controller which was used by[8] . The first one is the Proportional integral derivative controller (PID). PID is used in many industrial applications and generally if its parameters are optimally tuned, a better performance will be achieved. The second controller is a Non-linear Proportional integral derivative controller (NPID), this controller consists of four parameters which means high flexibility to improve the system performance. The two controllers will be designed by using Genetic Algorithm and their performances with the system will be compared.

**2. Modeling**



**Figure 1.** Tangential velocity across the cone region of the nozzle[6]



**Figure 2.** Master Slave controlled system [6].

The master and slave robots are modeled as a pair of coordination between the manipulators links with revolute joints. Their corresponding non-linear dynamics are described by equations (1) & (2).

$$J_M(\theta_M)\ddot{\theta}_M + C_M(\theta_M, \dot{\theta}_M)\dot{\theta}_M + g(\theta_M) = \tau_M^* - \tau_o \tag{1}$$

$$J_S(\theta_S)\ddot{\theta}_S + C_S(\theta_S, \dot{\theta}_S)\dot{\theta}_S + g(\theta_S) = \tau_e - \tau_s^* \tag{2}$$

where  $J_i(\theta_i)$  are the moment of inertia matrices for master and slave robots,  $C_i(\theta_i, \dot{\theta}_i)$  are the centrifugal damping for the robots,  $g(\theta_i)$  is the gravitational forces,  $\ddot{\theta}, \dot{\theta}, \theta$  are the acceleration, velocity and joint position respectively,  $\tau_o$  are the forces done by the operator,  $\tau_e$  is the force exerted by the environment interaction,  $\tau_i^*$  are the control signals. Where also  $i= M$  which is the master manipulator and  $i= s$  represents the slave manipulator [6]. The system is described by some properties which are shown in equations. (3)-(5).



PID (Integral Proportional Derivative) controller is widely used to control various plants. It has a simple control structure that was understood and also was found that it is easy to be tuned by plant operators. It's shown in equation (8) the typical structure of PID, the proportional, integral and derivative actions is generated by the error signal  $e(t)$ , and the resulting signal is summed to form the control signal  $u(t)$  which is applied to plant.

$$u(t) = K_p e(t) + K_I \int e(t) dt + K_d \frac{de(t)}{dt} \quad (8)$$

The controlled system is described by the following equations using Lyapunov like function. Anderson and Spong (1989) established the basis for the wave variables. This transformation is described by [8].

$$\begin{aligned} u_M &= \frac{1}{\sqrt{2b}} (\tau_{Md} - b\dot{\theta}_{Md}), & u_S &= \frac{1}{\sqrt{2b}} (\tau_{Sd} - b\dot{\theta}_{Sd}), \\ V_M &= \frac{1}{\sqrt{2b}} (\tau_{Md} - b\dot{\theta}_{Md}), & V_S &= \frac{1}{\sqrt{2b}} (\tau_{Sd} - b\dot{\theta}_{Sd}), \end{aligned} \quad (9)$$

In a way that  $b$  represent virtual impedance of the transmission line and the subscript id, where  $i=M, S$ , means Master or Slave desired signals, respectively. Lozano et al. (2002) established the following equation to describe the master and slave interconnection.

$$u_S = \gamma_M u_M(t - T_M(t)), \quad V_M = \gamma_S V_S(t - T_S(t)), \quad (10)$$

By proposing the following Lyapunov function candidate  $V(\theta_i, \dot{\theta}_i, t)$  it given by

$$V = \frac{1}{2} \dot{\theta}_M^T J_M(\theta_M) \dot{\theta}_M + \frac{1}{2} \dot{\theta}_S^T J_S(\theta_S) \dot{\theta}_S + \frac{1}{2} K |\theta_M - \theta_S|^2 + \int_0^t (\dot{\theta}_M^T \tau_o - \dot{\theta}_S^T \tau_e) d\sigma + k_M + k_S + \int_0^t (\dot{\theta}_{Sd} \tau_{Sd} - \dot{\theta}_{Md} \tau_{Md}) d\sigma \quad (11)$$

Using equation (9) and equation (10), with  $\gamma_i^2 = 1 - \dot{T}_i(t)$

$$\therefore \int_0^t (\dot{\theta}_{Sd}^T \tau_{Sd} - \dot{\theta}_{Md}^T \tau_{Md}) d\sigma = \frac{1}{2} \int_{t-T_M(t)}^t |u_M|^2 d\sigma + \frac{1}{2} \int_{t-T_S(t)}^t |V_S|^2 d\sigma \geq 0 \quad (12)$$

$$\begin{aligned} \therefore \dot{V} &= -B_M |\dot{\theta}_M|^2 - B_S |\dot{\theta}_S|^2 - K_{dM} |\dot{\theta}_M - \dot{\theta}_{Md}|^2 - K_{dS} |\dot{\theta}_S - \dot{\theta}_{Sd}|^2 - K_{IM} \int (\theta_M - \theta_{Md}) d_t - \\ &K_{IS} \int (\theta_S - \theta_{Sd}) d_t - K \dot{\theta}_M^T \int_{-T_S(t)}^0 \dot{\theta}_S(t + \theta) d\theta - K \dot{\theta}_S^T \int_{-T_M(t)}^0 \dot{\theta}_M(t + \theta) d\theta \end{aligned} \quad (13)$$

Integrating from zero to  $t$ , and based on (Nuño et al. 2008, Lemma 1)

$$V(t) - V(0) \leq - \left[ B_M - \frac{K}{2} \left( \alpha_M + \frac{T_M^2}{\alpha_S} \right) \right] \|\dot{\theta}_M\|_2^2 - K_{dM} \|\dot{\theta}_M - \dot{\theta}_{Md}\|_2^2 - K_I \int \theta_M - \theta_{Md} d_t - \left[ B_S - \frac{K}{2} \left( \alpha_S + \frac{T_S^2}{\alpha_M} \right) \right] \|\dot{\theta}_S\|_2^2 - K_{dS} \|\dot{\theta}_S - \dot{\theta}_{Sd}\|_2^2 \quad (14)$$

By substituting on the following equation

$$\begin{aligned} \tau_M &= \tau_{Md} + K [\theta_S(t - T_S(t)) - \theta_M] - B_M \dot{\theta}_M, \\ \tau_S &= \tau_{Sd} + K [\theta_S - \theta_M(t - T_M(t))] - B_S \dot{\theta}_S \end{aligned} \quad (15)$$

where,

$$\begin{aligned}\tau_{Md} &= -K_{dM}[\dot{\theta}_M - \dot{\theta}_{Md}], \\ \tau_{Sd} &= -K_{dS}[\dot{\theta}_S - \dot{\theta}_{Sd}]\end{aligned}\quad (16)$$

The result is

$$\tau_M = \frac{K_{dM}}{2}[\gamma_S \dot{\theta}_S(t - T_S(t)) - \dot{\theta}_S] + K[\theta_S(t - T_S(t)) - \theta_M] + \frac{K_{IM}}{2}[\gamma_M \int \theta_S(t - T_S(t)) - \theta_S] + B_M \theta_M \quad (17)$$

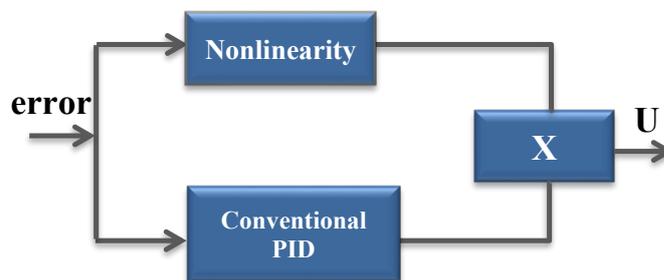
$$\tau_S = \frac{K_{dS}}{2}[\dot{\theta}_S - \gamma_M \dot{\theta}_M(t - T_M(t))] + K[\theta_S - \theta_M(t - T_M(t))] + \frac{K_{IS}}{2}[\gamma_S \int M(t - T_M(t)) - \theta_M] \quad (18)$$

By substituting in equation (7) the PID controller parameters margins are calculated as in table 1.

### 3.3 NPID Controller

It has been noticed in the recent years that the modifications on PID controllers may reach to better system performance than the conventional ones. One of those modifications is the nonlinear PID (NPID). The concept behind NPID is to create continuous dynamic nonlinear function instead of gain-scheduling by creating a nonlinear gain function with combination of error, integration of error and error derivative to achieve a reference point.

The configuration of the nonlinear PID is shown in figure 4[16], and the NPID transfer function is shown in equation (19).



**Figure 4.** Nonlinear PID configuration.

$$U = \frac{e^{(Gxerror)} + e^{-(Gxerror)}}{2} (K_P + \frac{K_I}{S} + K_D S) error \quad (19)$$

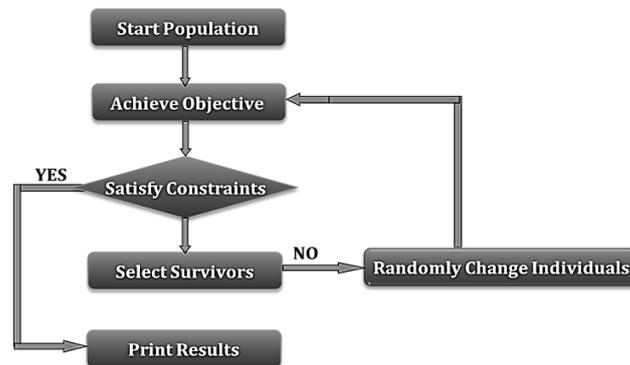
The term G indicates to the nonlinearity when G=0, the NPID controller turns to conventional PID controller. In this paper, the aim of the nonlinearity term is to enable better tracking of the slave to the master robots.

## 4. Genetic algorithm

GA is widely known for its optimization capability results, it includes three main stages which are: reproduction, crossover and mutation. GA in each stage produces a new generation from the old one by selecting individuals. The convergence speed is varied by using different probabilities for applying these operators. Crossover and mutation operators must be designed carefully, because their selection highly contributes to the evaluation of genetic algorithm.

In the reproduction stage, the performance of individuals is measured by the fitness function, and it also directs the selection process. Individuals which cope will have been increasing opportunities to transfer genetically important material to successive generations. Through this route, GA searches in the

search space from many points simultaneously, and the search focus is constantly narrowed to the observed performance areas[17]. The reproduction is responsible for selecting a novel form of chromosomes, and cross-over mix exchanging partitions of two chromosomes. With the cross-over operation, more chromosomes are generated. Reproduction is a clear characteristic of existing species with significant reproductive potential that their population size will increase exponentially if individuals of this species proliferate successfully. Reproduction can progeny by the transfer of the individual's genetic program. The search space is widened to all possible groups of the parameter values of the controller to minimize the values of the fitness function, which is the error criterion. The error criteria of PID controller are minimized by GA in each iteration. In this paper integral of square error is selected to be minimized as a fitness function for the design of optimal controllers[17].



**Figure 5.** Genetic Algorithm flow chart [17].

The objective function to get optimal PID and NPID parameters is described by equation (20)

$$\min \int_0^t e^2 dt \quad (20)$$

where  $e$  is the error between master and slave positions.

Variables: (12 variable for PID) and (16 variable for NPID)

Constraints: lyapunov limits.

Based on equations (17), (18) and (19), and considering the limits of the nonlinearity factor ( $G$ ); The controllers parameters ( $K_p$ ,  $K_I$ ,  $K_d$ ,  $G$ ) are bounded and the limits of PID and NPID are illustrated as shown in table 1.

Table 1. Upper and lower boundaries of PID and NPID Gains

	Master Robot Joints (1&2)		Slave Robot Joints (1&2)	
	Lower limit	Upper limit	Lower limit	Upper limit
<b>K<sub>p</sub></b>	0	2	0	2.8
<b>K<sub>I</sub></b>	0	1	0	1.4
<b>K<sub>d</sub></b>	0	0.6	0	0.84
<b>G</b>	0	1	0	1

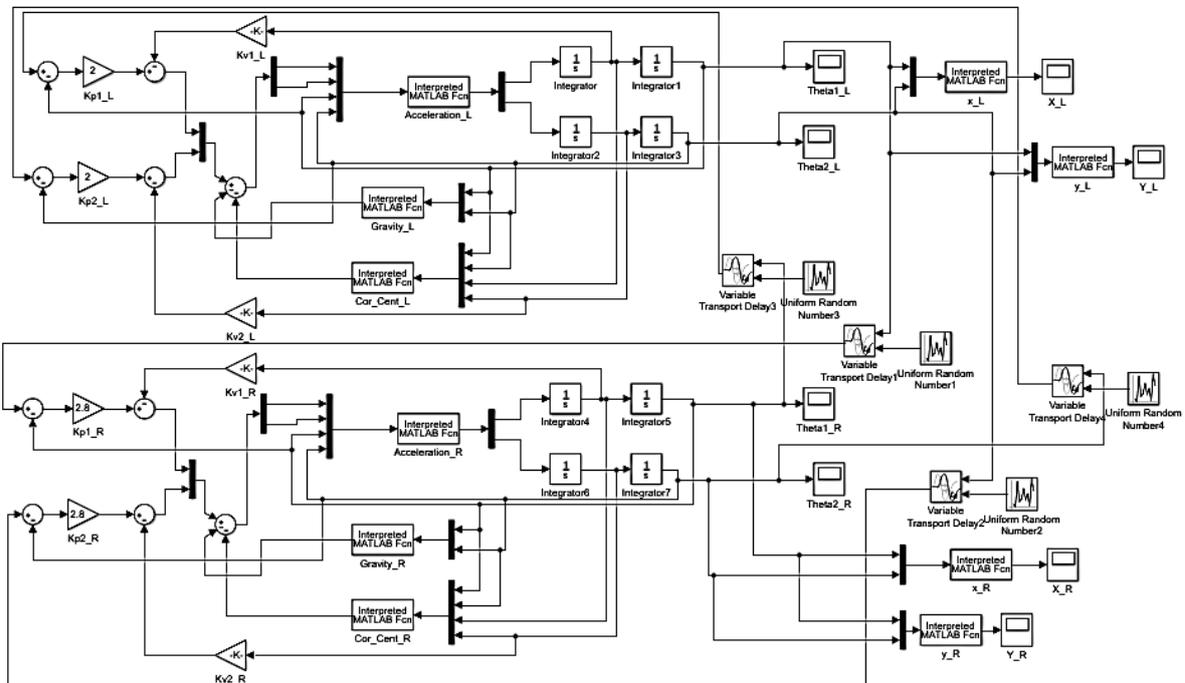


Figure 6. Master Slave Robotics System Simulink Model [2].

**5. Simulations and Results**

Figure 6 shows P controlled Master slave robotics system Simulink model as illustrated in [2]. The model includes two joints in master robot and also two joints in slave robot. The system is controlled first by P- like, then controlled by Genetic PID and finally by Genetic NPID. The controllers in the master robot controlled by P-like as in figure 6 are Kp1\_L, Kp2\_L for arm 1 and arm 2 respectively. while the controllers in slave robot are Kp1\_R, Kp2\_R, and the feedback of master are Kv1\_L, Kv2\_L for arm 1 and arm 2 respectively, while the feedback in slave robot are Kv1\_R, Kv2\_R.

*5.1. System controlled by optimal genetic PID and NPID compared to P-like responses for joint 1*

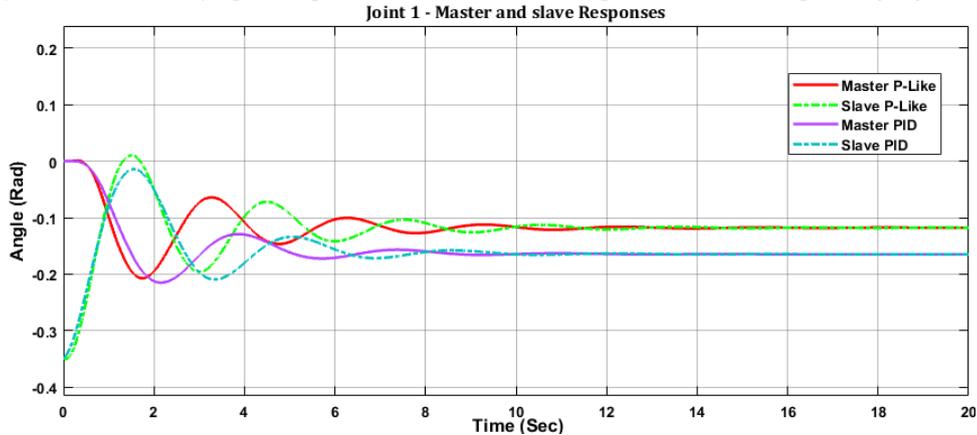
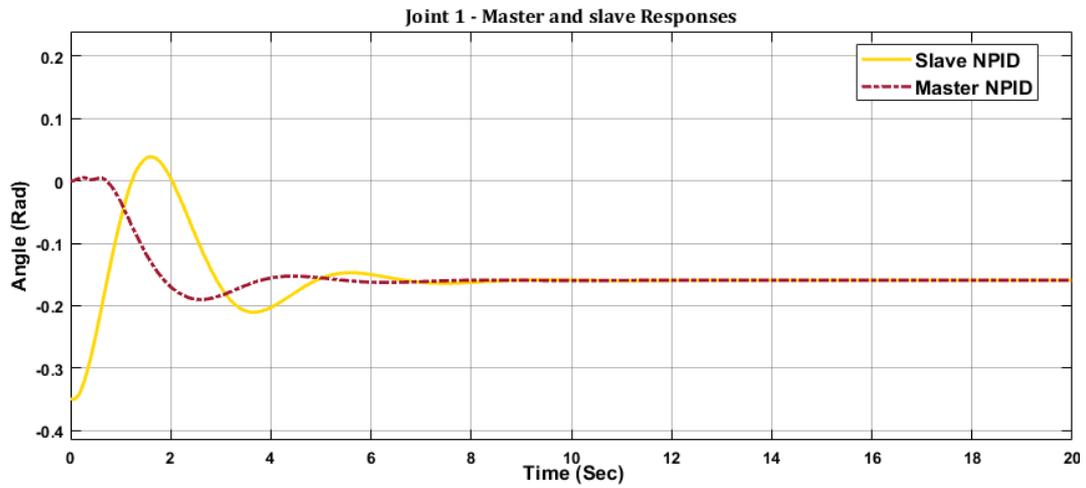
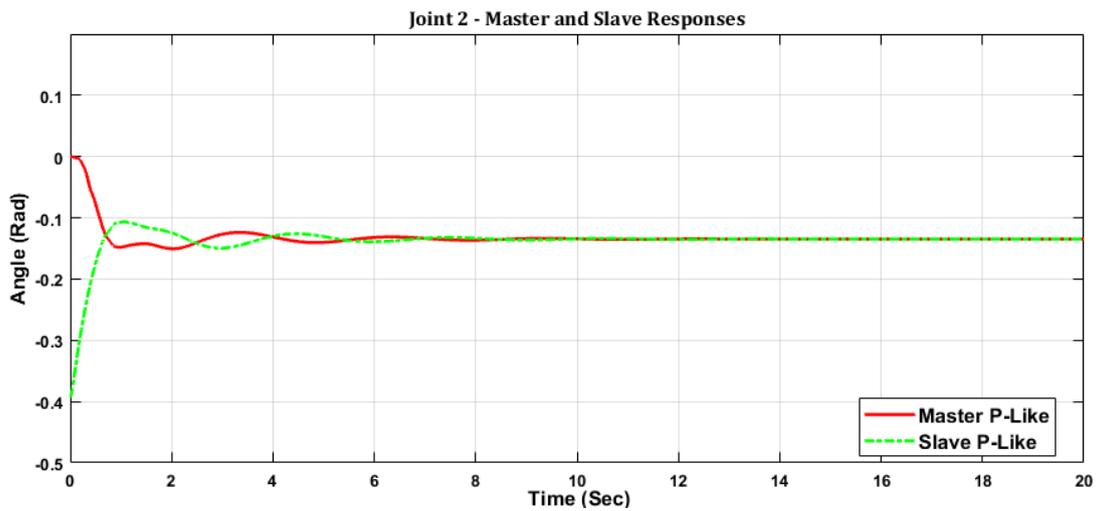


Figure 7. Master and slave angles joint 1 responses using PID compared to P-like.

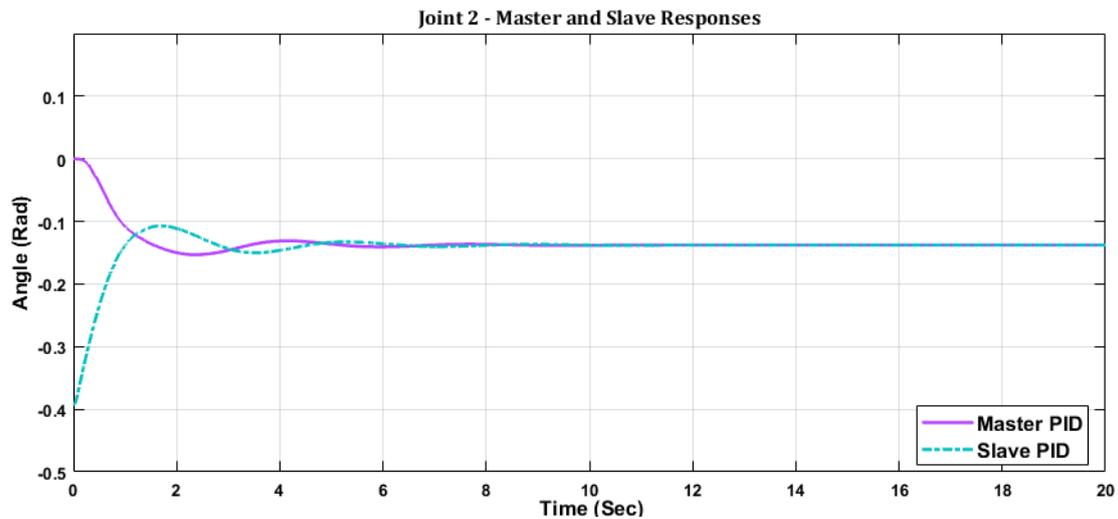


**Figure 8.** Master and slave Joint 1 responses using NPID.

5.2 System controlled by optimal genetic PID and NPID compared to P-like responses for joint 2



**Figure 9.** Master and slave angles joint 2 responses using P-like.



**Figure 10.** Master and slave joint 2 responses using PID.



**Figure 11.** Master and slave joint 2 responses using NPID.

### 5.3 Results summary

From figure 7 and figure 8, it can be seen that for joint 1, the position tracking is perfectly achieved and the error reached zero by Genetic NPID that has the minimum settling time between master and slave followed by Genetic PID and finally by the P- like controller. The settling is done after 8 sec with NPID while in terms of PID it is done after 11 seconds and finally it takes near 16 seconds in terms of P controller.

From figure 9, figure 10 and figure 11, it can be seen that for joint 2, the position tracking is perfectly achieved and the error reached zero by Genetic NPID that has the minimum settling time between master and slave followed by Genetic PID and finally by the P- like controller. The settling is done after 5 sec with NPID while in terms of PID it is done after 8 seconds and finally it takes near 11 seconds in terms of P controller.

## 6. Conclusion

Modeling and simulation of the master slave robots give the chance for better improvement in system performance. As mentioned before that in many applications such as telesurgery where master slave system is used to improve human accuracy; Some problems such as high overshoot, long time delay, long settling time and position tracking error shouldn't exist to avoid any serious consequences. Therefore, the proposed and optimal control schemes were used in this research to improve the system performance and achieve position tracking in minimum settling time. The tracking conditions for PID and NPID controllers are derived using Lyapunov like function based on the previous work that was done in [8]. It is proved that PID and NPID controllers can stabilize the teleoperator under constant time delays and, moreover, they provide position tracking and achieved zero tracking error in minimum settling time. Using PID controller to control the system achieved better performance at about 31% time earlier than P-like controller at joint 1 and about 20% time earlier at joint 2. The NPID closed loop system gives more flexibility due to the presence of four variables to achieve better performance than PID and P-like controllers. It achieved better performance at about 19% time earlier than PID controller at joint 1 and about 13% time earlier at joint 2. And comparing to P-like controller it is 44% at joint 1 and 30% at joint 2. The genetic algorithm gives the chance for optimal tuning of both the PID and NPID parameters.

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