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# Nonlinear Prediction Control Design for Improving the Performance of a Three Degrees of Freedom Nonlinear Remote Operating System with the Limitation of Joints and Variable Delay in the Transmission Channel

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**Abstract**

In this paper, the nonlinear predictive controller is used to improve the performance of the remote operating system. In a remote operating system Master and Slave are considered which are also limited in the movement of their joints. In the same previous control methods, the remote operating system is assumed to be linear, or the controller is designed by linearizing the nonlinear system. In this paper, the control of the nonlinear remote operating system with three degrees of freedom is considered with the use of a nonlinear predictor controller. In this structure, applying the law of control must be such that the manipulator of the Slave accurately traces the position of the Master's manipulator. In order to allow comparison, the performance of the remote operating system in the presence of the predictive controller and PD controller based on the Lyapunov function has been investigated and evaluated. Considering the advantages of using predictive control methods, it seems logical to use these methods in remote operating systems and, as the simulation results confirm the accuracy of this claim, the Slave's position, tracks the Master's position well, with variable time delay in the transmission channel.

## 1. Introduction

The idea of predictive control methods was first introduced in the late 1970s and turned into highly acclaimed methods in systems control [1]. The model predictive control (MPC) method, also called Receding Horizon Control, is a control method that decides on how to apply control at the present time by explicitly using the process model and using the approximation of the future behaviors of the system. Basically, in the MPC method, the calculation of the control signal in the next steps is such that the cost function is minimized throughout the prediction horizon. In different predictive control methods, the cost function is expressed in different forms. The most common form of expression is the second-order function of the error between the future outputs of the system and the predictive reference path. Of course, in most cases, the cost function also includes the control signal. The general structure of the MPC controller is shown in figure 1 [2].

The MPC method is capable of applying to a variety of processes, from simple processes to complex processes with a high latency, as well as non-minimum phase or unstable processes. The MPC algorithm can be easily extended to the multivariate model. Because in each sample, the optimization problem is solved once and the control law is calculated, so the behavior of the controller will always be optimal.

The main advantage of the MPC method is the ability to consider the input and output constraints in the calculation and the ability to compensate for the system time delay. The MPC is the only method to overcome the incoming and outgoing constraints during the design and implementation of the controller, it is also an effective method for the stabilization of linear and nonlinear systems with constraints.

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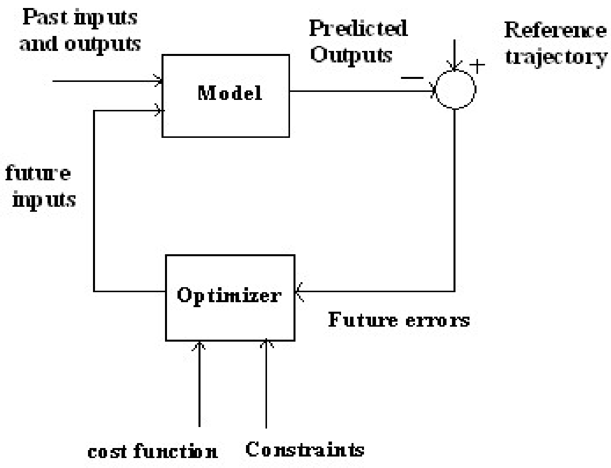


**Figure 1. The general structure of the MPC controller**

The technology of using remote operating systems has made great progress in the last two decades, and this has made it possible to do things such as working in distant environments, unknown or hazardous environments.

Over the past 50 years, extensive research has been conducted on remote operating systems. In the mid-1940s, for the first time, a remote operating system was constructed with Master-Slave structure [3].

In 1954, the position of servomechanism was reflected by electric force and thus the mechanical separation of the master and slave was provided [4]. Smith proposed a method called Smith predictor in 1957 and showed the effectiveness of this method to reduce the effect of delay time [5]. In the early 1960s, many studies were carried out to find out the effect of delay in remote operating systems [6]. In 1967 control methods were used to improve the performance of remote operating systems in the presence of delayed time [7].

The mid-1980s articles show the beginning of using advanced control methods, such as *Lyapunov* analysis and the internal virtual model [8, 9]. In the late 1980s and early 1990s, network discussions involved in research on remote operating systems [10]. In 1995, a method for scaling the force and speed of master and slave was used for control [11]. Lee Young and Francis introduced a method based on $H_\infty$ optimal control in 1995 and demonstrated that this method guarantees the stability of remote operating systems with certain amounts of delay time [12]. In 1998, frequency analyzes were carried out to investigate the sustainability of remote operating systems [13]. In 2001, adaptive control was used as a tool to reduce the uncertainty effect of master and slave robots [14]. In 1994, the sliding mode controller was designed for a remote operating system with a degree of freedom and without delay, and then in the continuation of research in 2001, the efficiency of this controller for systems with variable time delay in the transmission channel was proved [15, 16]. Due to the ability of the MPC algorithm to consider the constraints, the idea of using the model predictive control method in remote operating systems was introduced.

With the growth of technology, the need to use remote operating systems in the various industries has become more evident. In these systems, the ultimate goal is precise tracking with high confidence and creating a secure communication environment. Due to the characteristics of the predictive control algorithm, the use of this controller will greatly improve the performance of remote operating systems. The presented results also completely prove this.

Because of the extremely sensitive applications of remote operating systems, high-precision tracking should be done. There are also a number of constraints on these issues. Since the main advantage of the predictive control methods is the ability to consider the input and output constraints in the calculations and the ability to compensate for the system's time delay. Using these methods in remote operating systems seems logical [17]. In the previous research, the predictor controller for the remote operating system has been designed with the assumption of being linear, and it is obvious that this simplification will reduce the accuracy of performance in the highly sensitive applications of these systems. In the following article, the control of the nonlinear remote operating system, with three degrees of freedom, is considered using the predictive control method.

This article contains six sections. In the second section, the predictive control algorithm is briefly described. Remote operating systems, their performance and nonlinear Master and Slave robot models with three degrees of freedom in the third section are explained. In the fourth section, the nonlinear with the constrained predictive controller is applied to the remote operating systems and the simulation results are presented in the fifth section. Finally, in the sixth section, the conclusion is stated.

## 2. Predictive control method

The predictive control methods compute the control signal using the explicit system model and minimizing a cost function. All predictive control methods are common in the following two characteristics:

- Using an explicit system model to predict the output of the process in the future horizons
- Calculating the sequence of the control signal by minimizing a cost function

Different predictive control methods are only different in describing the system model, noise, and cost function. The MPC method is a discrete time technique that calculates the control law by solving a problem of open loop optimization in an iterative and online manner at each sampling interval time. Therefore, the behavior of the system at each stage will be optimal. The performance of the MPC controller is described in details:

The future output of the system is predicted by the process model at any sampling interval time, *t*. The expected output $\hat{y}(t + j/t)$ depends on the values of the previous input, the System output until *t*, as well as the value of the system's future control signals $k$=0,1,…, $N$-1, $u(t + k/t)$. N defined as a certain value, is called the Prediction Horizon.

All control signals of the system are calculated by optimizing a certain cost function, and performing optimization enable the system behavior to be optimal in each step. Also, with this action, we are trying to get the output of the process as close as possible to the reference path $w(t + k)$.

In various methods of predictive control, the cost function is considered in different forms. The most common form of the cost function is the second-order function of the error between the future output signal of the system and the predicted reference path. In most cases, the cost function of the control signal is also included. If the system is linear and unconditional, the answer can be explicitly calculated by considering the cost function to be in the second-order form. Otherwise, iterative optimization methods should be used.

From the control signal values calculated in each sample, only the first value $w(t/t)$ is applied to the process. The structure and general concepts of the MPC controller are shown in figure 1.

As shown in figure 1, the process model is used to predict the future output of the system. The prediction operation is performed using the past output and inputs of the system and the future input that is calculated through the optimization.

Since the MPC method provides the prediction of output by using a model, selecting a process model is very important. The process model should be selected in such a way as to be simple, as well as to describe the dynamic properties of the process. The error in modeling causes the error to repeat in each sample and the control performance to be inefficient with inappropriate accuracy. Depending on the selection of models with different structures, different formulas are created for the MPC method.

Another major part in the structure of the MPC controller is the optimization section for determining the control law. Defining a different cost function for obtaining the control law leads to different predictive control algorithms. In all of these algorithms, the goal is that the future output of the system follows a specific reference path. In the MPC method, the cost function is defined in various ways, such as norm 1, norm 2 or norm ∞. The most common form of the cost function is expressed as follows:

$$J\,(N_1, N_2, N_3)=\sum_{j=N_1}^{N_2}[\hat{y}(t + j/t) - w(t + j)]^2_{\delta(j)} + \sum_{j=1}^{N_u}[\Delta u(t + j - 1)]^2_{\lambda(j)} \quad (1)$$

In the above formula $\hat{y}(t + j/t)$, optimal output prediction of system *j* steps ahead according to time data *t*. $N_1$ And $N_2$ are the minima and maximum prediction horizons and $N_u$ is the control horizon.

$\delta(j)$ And $\lambda(j)$ are weights and $w(t + j)$ are the next steps of the reference path.

The selection of values $N_1$ and $N_2$ depends on the recognition level of the system and experience. If a large $N_1$ value is considered, it can be concluded that the error in the first samples is not important and this choice causes the response of the process to be very smooth.

In many applications, including robotics, batch processes, and servo systems, future changes to the reference path $r(t + k)$ are predefined.

One of the advantages of predictive control methods is that if the reference path is predefined, the system can react before an effective change occurs, and thus prevent delay in response time. The MPC method compensates for system latency intrinsically.

In practice, all processes have a constraint. Actuators have a limited and specific area of activity. Also, valves and sensors have features that causing constraint. The desirable characteristics of the response, including the rate of response, can cause to efficiency constraints on the process. Issues such as security or environmental factors impose a kind of limitation on the process. Limited sources of energy or limited material or economic profit consideration are those that cause of constraints exists in the systems.

The MPC is the only way to deal with the input and output constraints explicitly during calculations and performance of the controller. One of the most important features and benefits of the MPC method is that the constraints of the problem, whether they are input or output, are considered during the calculation.

## 3. Remote operating system (Master-Slave) nonlinear three degrees of freedom

Generally, the technology of controlling a system from a long distance and through mediator environment is referred to as a remote operation. In different applications, the distance can range from tens of centimeters (fine operations) to millions of kilometers (spatial applications). In remote operating systems, mediator environments have various forms, including the Internet network, computer, and interface circuits or robots. Considering the increasing growth of computer networks, recently, in major researches, the internet network is considered as a mediator environment. This tendency to use the internet as a mediator environment in remote operating systems is due to advantages such as flexibility, width, availability and low cost [18].

Figure 2 shows the overall structure of a bilateral remote operating system.

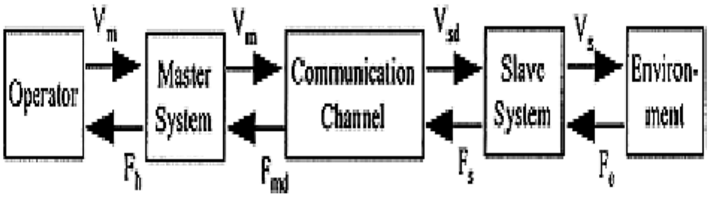


**Figure 2. The overall structure of a bilateral remote operation system**

In the structure of remote operating systems Master and Slave are connected through the transmission channel. The operator applies the command to the Master. This command is handed over to the Slave by the transmission channel, of course, delayed. The interaction between the Master and the environment also feedbacks to the Master system through the transmission channel.

In this research, the simulation was carried out using a three degrees of freedom nonlinear Master- Slave manipulator system in the remote operating system, which the dynamical model is presented below.

### 3.1. Two-way remote operating system considering the variable delay in the transmission channel

Figure 3 shows the overall design of the two-channel remote operating system, considering the variable time delay in the transmission channel. In remote operating systems, the controller can be used on the Master's side or at the Slave's or both sides.

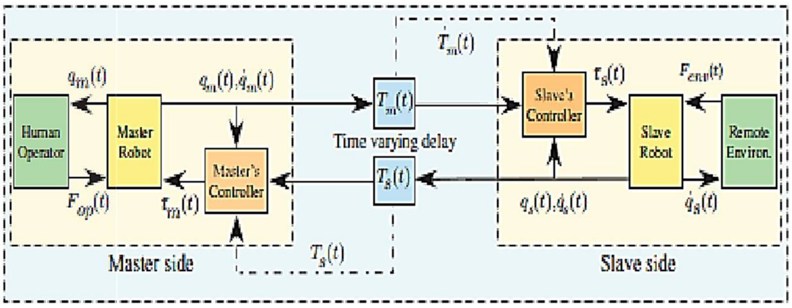


**Figure 3. Two-channel remote operating system**

Remote operating systems should be designed in such a way that the Slave can track the position of the Master's manipulator. Also, since the Slave is directly assumed to be in contact with the external environment, the reaction force on the Slave must be transmitted to the Master exactly.

### 3.2. Kinematics of master and slave robots

In this article, Master and Slave, two robots with three degrees of freedom and nonlinearity are considered.

The desired robot is a robot with three degrees of freedom. All joints of this robot are revolute. To get the kinematic model of the robot, we put a coordinate system on each link with the Z axis of this system on the rotary axis of the robot.

By placing the coordinate system, the transformation matrixes are obtained as follows:

$$ {}^{0}T_1=\begin{bmatrix} c_1 & 0 & s_1 & 0 \\ s_1 & 0 & -c_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^{1}T_2=\begin{bmatrix} c_2 & 0 & s_2 & 0 \\ s_2 & 0 & -c_2 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^{2}T_3=\begin{bmatrix} c_3 & -s_3 & 0 & 0 \\ s_1 & c_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2} $$

With the values of the transformation matrixes, calculating the Jacobian matrix and finding the kinematics of the problem will be possible.

### 3.3. Dynamics of master and slave robots

The dynamic model of a robot with N degrees of freedom is as follows:

$$ \tau=\mathrm{M}(q)\ddot{q}+\mathrm{C}(q,\dot{q})\dot{q}+\mathrm{g}(q) \tag{3} $$

Using Lagrange's terms, robot dynamics will be achieved. Details of robot dynamics are described in the appendix.

## 4. Using the non-linear predictive controller

Figure 3 shows the the9 structure of the remote operating system, considering the variable time delay in the transmission channel. In this structure, the control law must be such that the manipulator of the Slave accurately traces the position of the Master's manipulator. In order to allow comparison, the performance of the remote operating system in the presence of the predictive controller and PD controller based on the Lyapunov function has been investigated and evaluated.

The position of the Master with the time delay of the transfer channel is applied to the controller. The controller, as described in detail, compares the Slave's position $y_s$, with the Master's position (assumed as reference input), calculates and applies the appropriate control law.

### 4.1. Applying the non-linear constrained predictive control method to the remote operating system

The basis of the predictive control methods is explained in details in section 2. In this section, we will briefly review non-linear predictive control. The overall system dynamics is defined in the following form and the constraints can be considered on system states or the input.

$$ \begin{gathered} x(k+1) = f(x(k), u(k)) \\ x(k) \in X \, , u(k) \in U \end{gathered} \tag{4} $$

$f$ is generally assumed to be twice continuously differentiable in general. The cost function in the nonlinear predictive control method is usually defined in the two-order form of the following:

$$ \textstyle\sum_{i=0}^{N-1} (\| \, x(k+i/k) \, \|_Q^2 + \, \| \, u(k+i/k) \|_R^2) + \| \, x(k+N/k) \|_Q^2 \tag{5} $$

Where $x(k+i/k)$ and $u(k+i/k)$ are the predicted values of system and control modes at $K$ time. By defining the vector of states and predicted inputs we have:

$$ X(k) = [x(k+1/k)^{T} \dots \, x(k+N/k)^{T}]^{T} \tag{6} $$

$$ U(k) = [u(k/k)^{T} \dots \, u(k+N-1/k)^{T}]^{T} \tag{7} $$

Thence, the control law is calculated for each sample of the following optimization problem.

$$ \begin{gathered} \min_{x(k).u(k)} J(x(k).u(k)) \\ s.t.x(k+i/k) \in X \, , u(k+i/k) \in U \\ x(k+i+1/k) = f(x(k+i/k)) \, , u(k+i/k) \end{gathered} \tag{8} $$

$x = 1.2. \cdots . N-1$

$x(k + N/k) \in \Omega_T$

$\Omega_T$ is the appropriate space form stability constraints view.

Different algorithms have been proposed to solve this optimization problem, of these methods, SQP, HJB, interior point method, recurrent neural networks, …can be mentioned.

In this paper, the SQP method is used to solve the optimization problem. The problem constraints are the limitation of the movement of the joints of the robot. The dynamic model of the robot in the Master-Slave systems is described in Section 2-3. The cost function is considered to be the customary two-order form.

### 4.2. Controller design by using Lyapunov's law

In this section, we examine the two-way control of a remote operating system with variable communication delay with time. The method studied in this section is a PD model whose P and D terms are variable with time. Using the Lyapunov-Krasovskii functions of stability, dependent on delay for origin is obtained for a range of interests.

Consider the remote operating system of figure 3. As seen, the position and speed of the Master robot are transferred to the Slave robot, and the position and speed of the Master robot are also transferred to the Slave robot.

The proposed control is as follows:

$$\tau_m(t) = K_{md}(t)\{\dot{q}_s(t - T_m(t)) - \dot{q}_m(t)\} - \{D_{md}(t) + D_P\}\dot{q}_m(t) + K_P\{q_s(t - T_m(t)) - q_m(t)\} \quad (9)$$

$$\tau_s(t) = K_{sd}(t)\{\dot{q}_m(t - T_m(t)) - \dot{q}_s(t)\} - \{D_{sd}(t) + D_P\}\dot{q}_s(t) + K_P\{q_m(t - T_m(t)) - q_s(t)\} \quad (10)$$

Where in:

$$\begin{cases} K_{md}(t) = \left(1 - \dot{T}_s(t)\right) K_d \\ K_{sd}(t) = \left(1 - \dot{T}_m(t)\right) K_d \end{cases} \quad (11)$$

$$\begin{cases} D_{md}(t) = \dfrac{\dot{T}_s(t)}{2} K_d \\ D_{sd}(t) = \dfrac{\dot{T}_m(t)}{2} K_d \end{cases} \quad (12)$$

And $D_p . K_p . K_d \in R^{n\times n}$ are constant positive-definite matrixes.

To prove this, we consider the Lyapunov function as follows:

$$V_1(x) = \dot{q}_m^T(t)M_m(q_m)\dot{q}_m(t) + \dot{q}_s^T(t)M_s(q_s)\dot{q}_s(t) + \{\tilde{q}_m(t) - \tilde{q}_s(t)\}^T K_p \{\tilde{q}_m(t) - \tilde{q}_s(t)\} + \tilde{q}_s^T(t) K_e \tilde{q}_s(t) + \int_{t-T_m(t)}^{t} \dot{q}_m^T(\xi)K_d\dot{q}_m(\xi)d\xi + \int_{t-T_m(t)}^{t} \dot{q}_s^T(\xi)K_d\dot{q}_s(\xi)d\xi \quad (13)$$

According to the above Lyapunov function, the *Kp* range for stability of the desired system is as follows:

$$K_p < \frac{2}{T_{ms}^+} D_p \quad (14)$$

## 5. Simulation and evaluation of results

In this article, in the structure of the remote operating system, the predictive controller is located on the Master's side and on the Slave's side. In this structure, the performance of the predictive controller and PD controller based on the Lyapunov function are compared and the results of the two methods are analyzed.

For the feasibility of comparing the performance of a remote operating system in the presence of the predictive controller and PD controller based on the Lyapunov function, in these structures, the remote operating system is considered the same and the values of the parameters are assumed equally.

In this modeling, the interactions between the operator, the Master, the Slave and the environment are considered.

The simulation results show the better performance of the MPC controller compared to the PD controller based on the Lyapunov function.

**5.1. Controller application using the Lyapunov law**

In this simulation, the variable time delay of the following is used:

$$T_m(t) = 0.1sin\,4t + 0.3 \tag{15}$$

$$T_s(t) = 0.2sin\,4t + 0.3 \tag{16}$$

Due to the used latency, the maximum reciprocating delay is 0.9 second and the maximum delay variation is 0.8 second. We also select the controller parameters according to the condition of the case, as follows:

$$K_d=\begin{bmatrix}3 & 0 & 0\\0 & 1.5 & 0\\0 & 0 & 1\end{bmatrix}\ ;\ K_p=\begin{bmatrix}20 & 0 & 0\\0 & 25 & 0\\0 & 0 & 21\end{bmatrix}\ ;K_d=\begin{bmatrix}9 & 0 & 0\\0 & 12 & 0\\0 & 0 & 10\end{bmatrix} \tag{17}$$

Figures (4) and (5) and (6) show the position of the joints of Master and Slave robots in the presence of the PD controller based on the Lyapunov function.

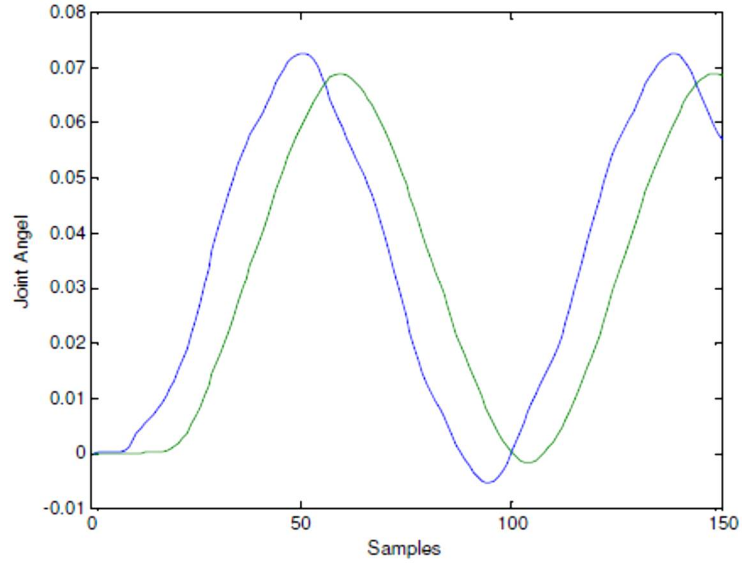


**Figure 4. Comparison of the position of First Joints of Master and Slave with PD Controller with Time Variables Parameters**

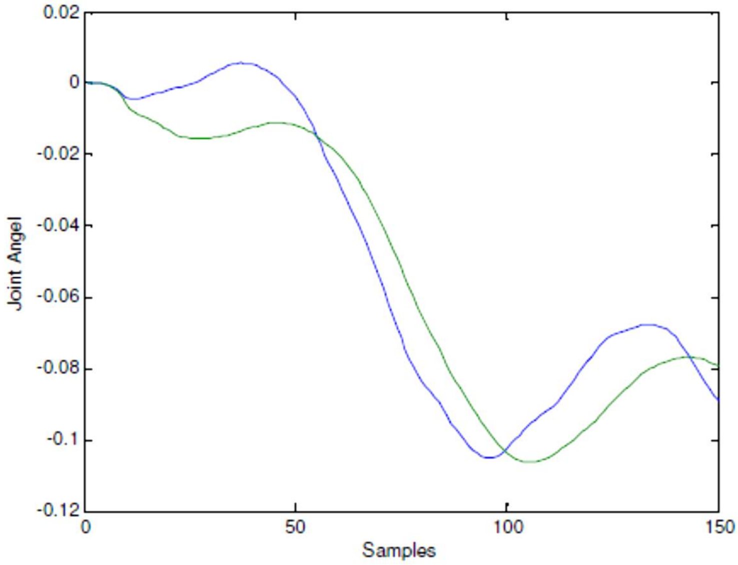


**Figure 5. Comparison of the position of second Joints of Master and Slave with PD Controller with Time Variables Parameters**

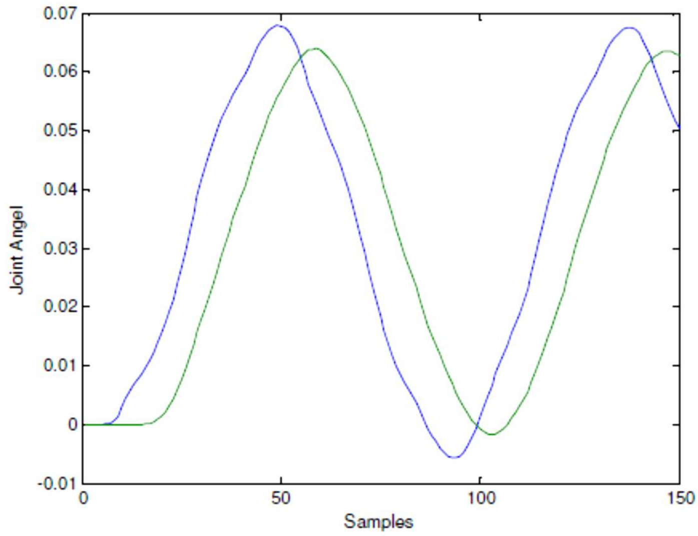


**Figure 6. Comparison of the position of third Joints of Master and Slave with PD Controller with Time Variables Parameters**

As can be seen, the Slave follows the Master's position well.

### 5.2. Applying the nonlinear constrained predictive controller

Figures (7) and (8) and (9) show the position of the Master and Slave robot joints using a nonlinear constrained predictive controller despite the variable time delay.

The control horizon ($N_u$) is considered 5, the prediction horizon ($N$) is considered 0.2, the sampling time ($t_s$) is considered 0.01 and the weight values in the cost function δ and λ are considered equal to 1 and 0.01, respectively.

The first and third joints of the robots are assumed to have movement restrictions as follows:

$$-\pi \leq q \leq \pi \tag{18}$$

As noted earlier, today in most remote operating systems, the Internet is considered as an interface environment. Since the time lag of the Internet varies from time to time, for evaluating MPC controller performance in these conditions, the variable time delay is considered in the simulation.

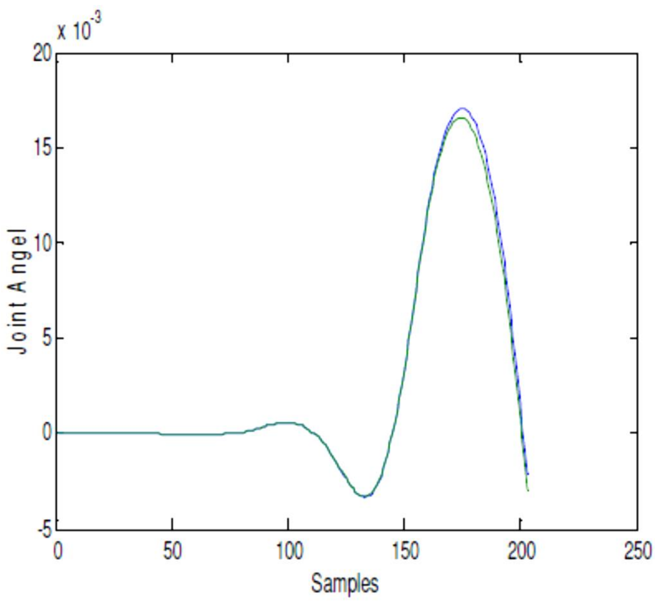


**Figure 7. Position of first joints of Master and Slave using a predictive controller**

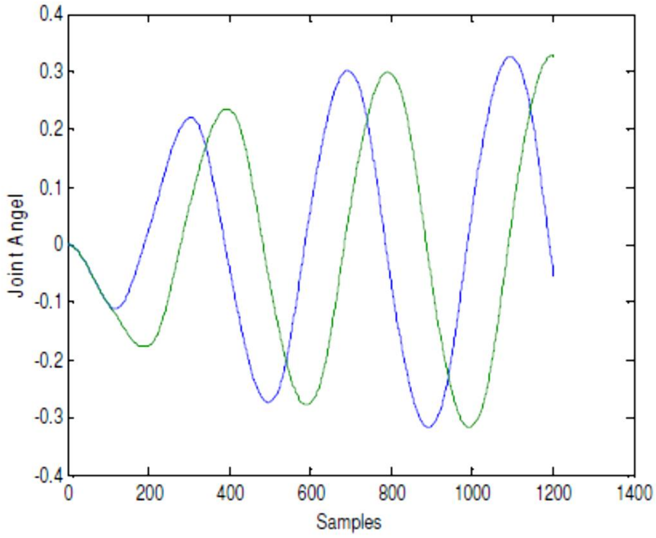


**Figure 8. Position of second joints of Master and Slave using a predictive controller**

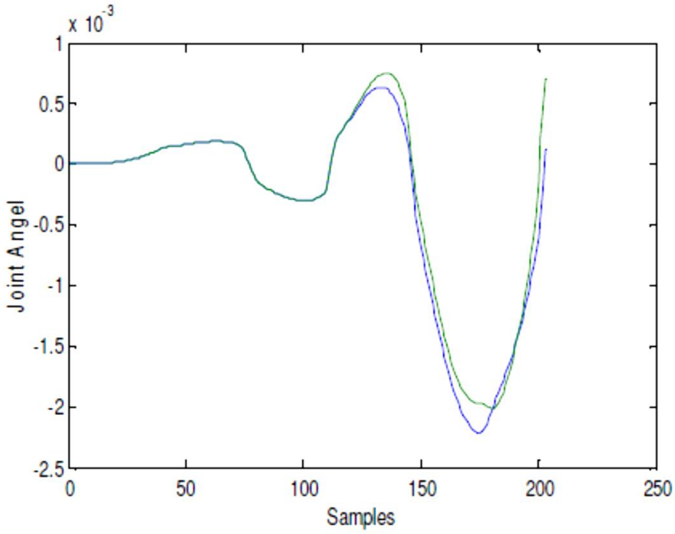


**Figure 9. Position of third joints of Master and Slave using a predictive controller**

As can be seen, the Slave's position accurately tracks the position of the Master, despite the variable time delay in the transmission channel.

Of course, such desirable responses were not far from expected due to the features of the MPC controller. Because the MPC controller predicts the output in the next steps and calculates the control law based on it. The $\delta$ and $\lambda$ parameters determine the amount of input energy and the response speed. By changing these parameters, different results can be obtained.

Increasing the prediction horizon also improves tracking, as the number of next steps of the output that will be predicted and the controller decides based on them will increase.

## 6. Conclusions

In this paper, the goal was to control the remote operating system with a non-linear three degrees of freedom model. According to the advantages of using predictive control methods that some of them were mentioned, and the broad application of these methods in robotics, the use of these methods in remote operating systems to improve performance seems logical. The simulation results in this paper show the correctness of this claim.

The performance of the remote operating system in the presence of the predictive controller and the PD controller based on the Lyapunov function was investigated and evaluated.

Due to the efficiency of remote operating systems in various industries and with significant advances in systems control discussions, it seems that controlling such systems in the future will be one of the most effective and attractive topics of control discussions.

Despite the many advantages of MPC, one of the most important limitations of this method is the high volume of computations.

As a future research topic in remote operating systems, if speed is also important and the design of a fast predictive controller is necessary, available ideas can be used to increase the speed of this controller [19, 20]. Methods of simplifying the model methods or methods for solving the problem of rapid optimization, such as Newton-Raphson, Interior point method, the method based on single values of the system or the use of recurrent neural networks can be mentioned.

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