Force Control of Surgical Robot with Time Delay using Model Predictive Control

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Abstract: Tele-surgical robotic systems are making our vision of "virtual open surgery" into reality by using minimum invasive techniques with laparoscopic vision technology. The commercial available minimally invasive robotic systems (MIRS) force the surgeons to forgo the ability to touch and feel the environment, unlike conventional open surgery. Surgeons rely on the visual feedback from the patient's side at the master console to get information about the operation site. The control gets even more difficult in the teleoperated surgical systems due to random network delays. The difference in the network delay in data and perception makes hand to eye coordination even more difficult. Force feedback can offer surgeon instant perception of the physical properties at the operating end. A novel approach is proposed to control the force of a surgical robot suffering from signal delays using model predictive control. The proposed MPC-scheme of force control in between the master and slave station shows compensation of the deterministic time delays.

1 INTRODUCTION

With the rapid advancement in technology, telerobotic concepts play a vital role in the world of robotic research (Tachi, Arai, and Maeda,1990),(Buss and Schmidt,1999). Telerobotic systems allowed a person to extend his intelligence and manipulation skills to the remote unknown environment. It was the leap towards the semi-intelligent systems, by providing semiautonomous capabilities to the system while having task controlled by humans. Remote surgery became possible by exploiting the capabilities of the teleoperated systems by overcoming the barriers such as temperature, scaling, and pressure. Force feedback is a much-esteemed feature required by the human operator to understand the characteristics of the unknown environment.

Minimum Invasive Surgery (MIS) is one of the areas where this field of telerobotics has led to massive advancements by enlarging the human possibilities (Ortmaier, Reintsema, Seibold, Hagan, and Hirzinger,2001). MIS has the following advantages over the open surgery (C. Preusche, T. Ortmaier and G. Hirzinder ,2002):

- Shorter rehabilitation time and fast recovery at the hospital.
- Pain reduced because of operating through incisions.
- Cosmetical advantages due to small incisions.

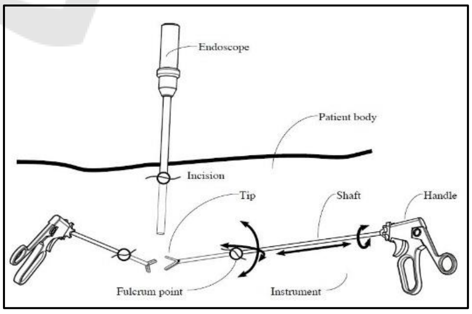

Figure 1: Conventional minimally invasive surgery (Hagn, 2011).

Figure 1 shows long slender instruments that are used to perform MIS. These long instruments are inserted into the patient's body through small cuts made on the body. The incision act as fulcrum point about which instruments rotates, this point restricts

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the motion of the body to 4 DOF (degrees of freedom).

MIS techniques also serve as disadvantages for the operators (C. Preusche, T. Ortmaier and G. Hirzinder ,2002) that are as following:

- Reduced or no tactile and force feedback because of long instruments.
- Reduced sight.
- Tremor gets amplified because of the giant lever arm.
- Pivot points restrict the motion.

New surgical systems have been developed such as ZEUS-Systems (ComputerMotion, 2003) and Da Vinci-Systems (Intuitive Systems, 2000) that are trying to overcome these handicaps.

Teleoperation is the ability to perform the surgery remotely, that will help the surgeon to practice it throughout the world. The Biorobotics lab at the University of Washington developed a RAVEN telerobotic system (B. H. et al., 2009) that focuses on carrying out remote surgeries. RAVEN is operated currently by using PHANTOM Omni controllers in which haptic feedback is yet not developed for the system.

Haptic feedback is a large area of interest when it comes to medical robotics. The traditional teleoperation one of the limitation is the lack of the force feedback to the surgeon such that surgeon only depends on the visual feedback to feel the force applied to the environment.

The Technical University of Eindhoven developed Surgeon's Operating Force Feedback Interface Eindhoven (SOFIE) robotic arm to improve the haptic feedback to the Da Vinci system. SOFIE was designed keeping following design requirements: easier set-up times; additional DOF at the tip of the instrument; haptic feedback and increased patient safety (Hannaford and Okamura, 2008).

In advanced telesurgery scenarios such as in orthopaedic surgeries, the surgeon and robot can share the tasks or can work on autonomous mode under the supervision of a surgeon like ROBODOC sold by Think Surgical Inc. (Netravali, Borner and Barger,2016). The robot uses Computed Tomography (CT) scans and fiducial markers to plan the motion using systems software.

PID controllers is widely spread in industries owing to its simplicity and effectiveness. MPC with the capability to predict the future enables it to cater the large time delayed processes unlike PID (Lennox and Lauri,2013).

In this paper, control of force using hybrid force/position control architecture suffering from time delay is discussed. The compensation of time delay using MPC is discussed that arises due to the wireless communication link in a surgical robot is proposed making the force control even more difficult.

In Summary, the significant contributions of this paper are: The robustness of the MPC controller over the PID as a force control in a teleoperated surgical system providing force feedback at the master end. Force feedback provides another dimension to the surgeon to feel the environment such as the tension of the surgical knot, the stiffness of the environment etc. The effectiveness of the MPC has been tested out in different constant delays. This study is limited to surgical arms capable of performing surgery in autonomous mode under the supervision of surgeon such that the reference is known to them before the operation starts.

Rest of the paper is organised as follows: The systems control architecture construction is discussed in section 2. MPC as a force controller along with its control synthesis is described in section 2.1 as a part of master end following the communication and slave end. Section 3 shows the simulation results of the force control using MPC and a comparison has been presented with PID. Section 4 discusses in detail the simulation results shown in section 3 of the paper In the end, Section 5 and 6 describes the conclusion along with the future work.

2 CONTROL ARCHITECTURE

Surgical robots are based on the principle of master and slave robot. A typical teleoperated robot has three major components: a master device (surgeon's end), a slave device and a communication channel (transmission) as shown in Figure 2. Slave side is extended affected by the tool-tissue interaction with the unknown environment inside the human body. It is vital to simulate a proper environment to study the behaviours of the system in those conditions. Systematic illustration of the operation is described as follows:

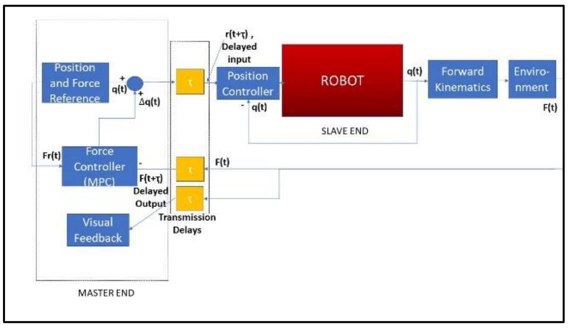

Figure 2: Position/force control architecture for telesurgical robot.

2.1 Communication System

The system responsible for the data transfer, coding and decoding signals and other tasks to have a communication between the two ends. A communication system comprises a transmitter, a receiver and a transmission medium. Latency and signal quality depends on the subcomponents of the system. Besides quality issues, in telesurgical systems, data loss is one of the most critical components to be taken care of which is best handled by User Datagram Protocol (UDP) (Arata, Jumpei, Takahashi, Pitakwatchara, Warisawa, Tanoue, Konishi and Ieiri et al., 2007). In the trans-Atlantic surgery carried in the past, the mean signal delay was around 155ms (Marescaux, Jacques, Leroy, Gagner, Rubino, Mutter, Vix, Butner, and Smith, 2001). 85ms of lag occurs in the data signals lag, but the 70ms lag occurs in the slave side in encoding and decoding of the visual cues. In telesurgery worked out between Japan and Thailand (Arata, Jumpei, Takahashi, Pitakwatchara, Warisawa, Tanoue, Konishi and Ieiri et al., 2007), the average time delay in data was observed around 122ms. When the average value of random delays changes, the effects of delay gets more pronounced.

In a study carried out (Smith and Chauhan, 2012) to investigate the effects of the distance on the latency. Da Vinci robotic mimic simulator was used to get the results for studying the impact of latency. This simulator was initialised with the actual delay parameters of the real-time scenario. Following observations were made:

1. The surgeons could not detect the lag time till 200ms.
2. From 300ms to 500ms, they could detect the lag time, but they were able to compensate for it by pausing their movements.
3. However, after 500ms it becomes insecure as the settling time increases for the system as shown in Table 1.

Table 1: Observations of the Da Vinci simulator.

Time lag (milliseconds)	Effect on the system
0 – 200	Safe
200-500	Physically dependent on the surgeon
600 - more	Unsafe

The experiments were carried out in a virtual environment, rather than on live patients. The effectiveness of the proposed control scheme is tested under the deterministic time delays chosen in each of the three intervals in Table 1 and results are compared with the observation of the above study.

2.2 Master Model

The surgeon controls the slave end of the robot by using a master model that is capable of visual output from the slave end. The prime objective of this model is to provide a realistic and accurate surgical situation carried out in a remote site.

Figure 3 describes the principal components comprising the master's end. The master's inputs are designed like the inputs of the minimally invasive surgical tools. The surgeon also gets visual feedback from the slave robot that helps in effective decision making.

A position/force control approach is used to do the study such that the master end is responsible for controlling the end of effectors position and force. A hybrid approach for controlling position and force of the end of the effector is used as shown in figure 3 such that position and force is controlled independently. This architecture has two different loops one for controlling force and other for position control.

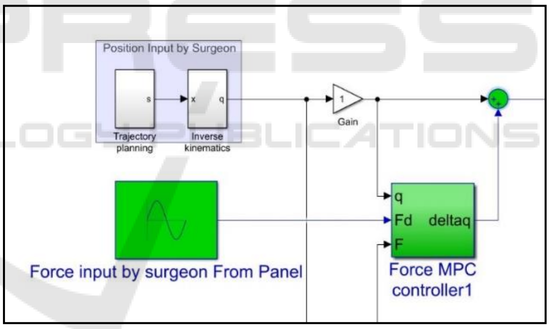

Figure 3: Design of master side.

The time delay can be controlled by a controller in a system only if the controller can predict the future. The feedback from the slave end suffers from transmission delay; the master controller must compensate for that. The proportional-integral-derivative (PID) can only predict one step, i.e. T_d (derivate time constant) such that the controller becomes unstable when the time delay is more than the time constant of the system (O' Dwyer, 2000). An adequate force controller should have the capability to compensate the time delay and reach the setpoint robustly by using prediction property. A model predictive controller is chosen for looking ahead and predicting the robot's behaviour in the future and control the force loop efficiently.

2.2.1 Model Predictive Control

MPC attracts researchers because of its unique advantages over other controllers. It is also known as Receding Horizon Control (RHC). The MPC performs the optimisation operation of the performance index concerning the future control sequences, using predictions of the output signal based on a systems model with constraints on the states, inputs and output. The difference in the primary methodology of both the type of controllers in which predicting the future is desirable while latter only has the property to react to the past behaviours.

Model predictive control solves an optimisation problem at each control interval to determine to manipulate variables (MV's) for the system until next control interval. A quadratic problem comprises a cost function, constraints and decisions. The cost function is a scalar quantity that must be minimised to at each interval to measure the controller's performance. Physical bounds in the form of constraints on mv's and plant output can be applied to keep a check on systems performance. MV is adjusted as per the applied constraints to satisfy the solution.

The Cost function (1) is given by:

$$J(z_k) = J_y(z_k) + J_u(z_k) + J_{du}(z_k) + J_e(z_k) \quad (1)$$

Where z_k is the Quadratic Problem (QP) decision. Default weights as shown in (2), (3), (4), (5) are applied on each term that can be varied to achieve the objectives of the system.

$$J_y(z_k) = \sum_{j=1}^{n_y}\sum_{i=1}^{p}\left\{\frac{w_{i,j}^{y}}{s_j^{y}}\left[r_j(k+i|k) - y_j(k+i|k)\right]\right\}^2 \quad (2)$$

$$J_{du}(z_k) = \sum_{j=1}^{n_u}\sum_{i=1}^{p-1}\left\{\frac{w_{i,j}^{du}}{s_j^{u}}\left[u_j(k+i|k) - u_j(k+i-1|k)\right]\right\}^2 \quad (3)$$

$$J_u(z_k) = \sum_{j=1}^{n_u}\sum_{i=0}^{p-1}\left\{\frac{w_{i,j}^{u}}{s_j^{u}}\left[u_j(k+i|k) - u_{j,target}(k+i|k)\right]\right\}^2 \quad (4)$$

$$J_e(z_k) = \rho_e\, e_k^2 \quad (5)$$

where:

k- Current control interval.
p- Prediction horizon (number of intervals)
n_y – Number of plant output variables.
z_k- QP decision, given by:
$z^T_k = [\, u(k|k)^T \; u(k+1|k)^T \; ..... \; u(k+p-1|k)^T \; e^k \,]$.
$y_j(k+i|k)$ – the Predicted value of j^{th} plant output at i^{th} step.
$r_j(k+i|k)$ – Reference value for j^{th} plant output at i^{th} step.
s^y_j – output scale factor.
$w^y_{i,j}$ – Tuning weights for the plant output.
s^u_j – input scale factor.
$w^u_{i,j}$ – tuning weight for plant input.
$w^{du}_{i,j}$ – tuning weight for the rate of change of input.
e^k- slack variable at control variable k.
ρ_e – Constraint violation penalty weight.

The discrete state space format for a time delayed is given in equations (6) and (7) (Wang, 2004):

$$x(k+1) = Ax(k) + B\Delta u(k-d) \quad (6)$$
$$y(k) = Cx(k-d) \quad (7)$$

Where:

x_i = i-th control variable
r_i = i-th reference variable
u_i = i-th manipulated variable
d = (total) time delay in the system

$$A = \begin{bmatrix} 0 & A_P 0_{n_{out}}^T \\ C_P A_P & I_{n_{out}} \end{bmatrix}$$

$$B = \begin{bmatrix} B_p \\ C_p B_p \end{bmatrix}$$

$$C = \begin{bmatrix} 0_{n_p} & I_{n_{out}} \end{bmatrix}$$

$$x(k)^T = \begin{bmatrix} \Delta x_p^T(k) & y(k)^T \end{bmatrix}$$

$$\Delta x_p(k) = x_p(k) - x_p(k-1)$$

At each control interval t, The process output is predicted p-steps into the future $y(t+l)$, where $l = 1,..,p$. The prediction output depends on the past results and planned m-steps. The planned move is evaluated by minimising a quadratic cost function. The cost function index incorporates the error and the actuation moves. Only u(t) is applied to the system, and the future vector is evaluated. Prediction value is evaluated at every step by comparing the current values to the predicted values through the filter as shown in Figure 4. The above-stated methods are repeated at every control interval, that is why it is called receding horizon control.

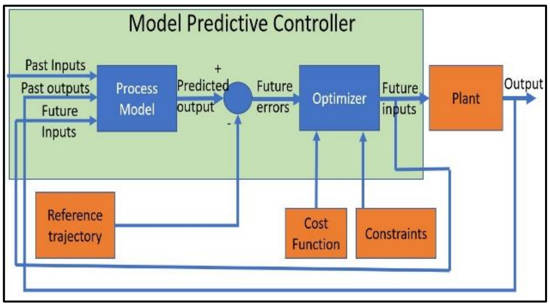

Figure 4: Model Predictive Controller.

MPC also has a "previewing" feature such that the past information helps to predict the future information of the system. This feature can be utilized for the systems with known reference trajectories such as surgical robots with the ability to perform autonomously to compensate for the time delay. Such information is useful because that makes the controller prepare few steps ahead of time.

2.3 Slave Model

Functionality and safety of the patient is the most crucial factor in the telesurgery. The accurate kinematic and dynamic models of the robot along with the appropriate image guidance and modelling widely contribute towards accuracy and safety of the system.

It is essential to know the accurate model of the slave robot and its behaviour when it encounters the environment. A 2 DOF dynamic model with first order flexible joints coupling is considered for our system.

The reaction force from the environment is calculated in the form of reaction torque and is used as feedforward compensation to the robot as shown in the Simulink™ model of slave model in figure 5.

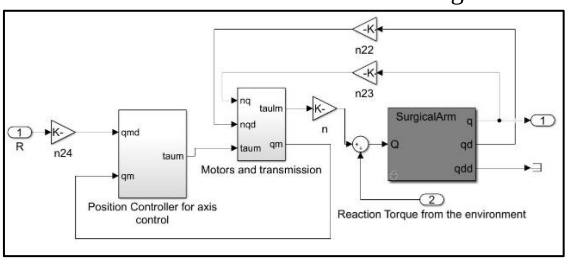

Figure 5: The dynamic model of the slave robot.

A 1-DOF spring damping system in the form of Proportional-Derivative (PD) control is used as an artificial flexible coupling for our system. Actuators provide localised feedback to the controller. The position controller founds the necessary driving torque required to minimise the error.

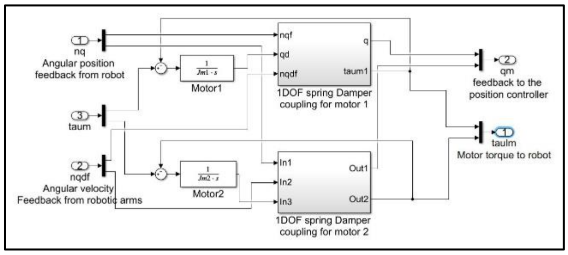

Figure 6: Block diagram of the motor attached with artificial coupling.

We have assumed that the slave is operating in a known environment with a point contact interaction model as depicted in figure 7. The robot is in free motion initially until meets the environment. The detachment block outputs zero value when the robot is not in contact with the environment and gives a nonzero value when in contact.

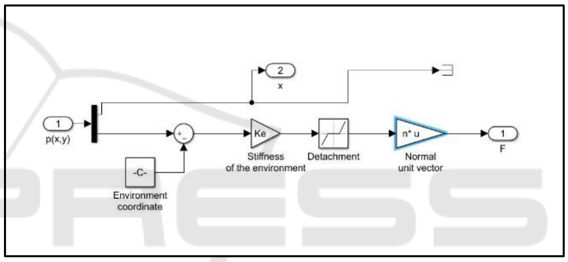

Figure 7: Known environment model.

A simple spring model of the environment reaction force is given in equation (8) :

$$F_e = K_e*(x - x_e) \quad (8)$$

Where:

K_e = Stiffness of the environment.

Y = EOF position.

y_e = Environment position.

The following values were chosen for simulation:

K_e =1. e+7 [N/m], for hard tissue

y_e = 2.82.e-5 [m]

2.3.1 Robot Specifications

A 2-R (Revolute) degree planar robot as shown in figure 8 is considered for the study. The dynamic parameters of the robot as follows:

L_1 = 1 m is the length of the link 1.
L_2 = 1 m is the length of the link 2.
M_1 = 50 kg, the mass of the link 1.

M_2 = 50 kg, the mass of the link 2.
θ_1 is the rotational angle of the joint 1.
θ_2 is the rotational angle of the joint 2.
$Lc_1 = Lc_2$ = 0.5m is the length to the mass centre of the link.

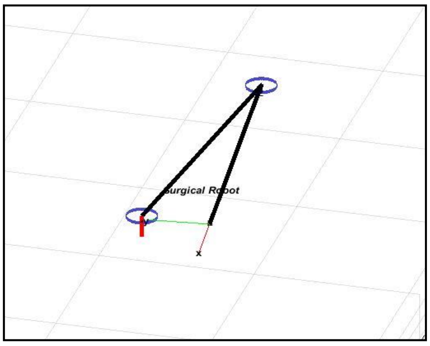

Figure 8: Surgical arm with 2 DOF.

2.3.2 Robot Kinematics

Denavit - Hartenburg representation for the 2-R robot is shown in table 2 below:

Table 2: D-H parameters of the 2-R robot.

Joint no.	a_i	α_i	d_i	θ_i
1.	L_1	0	0	θ_1
2.	L_2	0	0	θ_2

2.3.3 Robot Dynamics

Forward kinematic equations (9), (10), (11), (12) of the 2-R robot are described as follows:

$$x_1 = L_1 \sin\theta_1 \quad (9)$$

$$y_1 = L_1 \cos\theta_1 \quad (10)$$

$$x_2 = L_1 \sin\theta_1 + L_2 \sin(\theta_1+\theta_2) \quad (11)$$

$$y_2 = L_1 \cos\theta_1 + L_2 \cos(\theta_1+\theta_2) \quad (12)$$

The general form of the equation of robot is described in (13):

$$H(\ddot{q}) + C(\dot{q}, q) + g(q) = M + J^T.F \quad (13)$$

Where:

$H(\ddot{q})$: is the inertia matrix of the system
$C(\dot{q}, q)$: Coriolis and Centrifugal forces
$G(q)$: gravitational components
M: Torque of the system
J^T: transpose of the Jacobian
F: Force at the EOF

Table 3 shows the dynamic parameters of the system simulation (Rocco, Paolo, Gianni Ferretti, and Magnani, 1996)

Table 3: Dynamic parameters of the system.

Sr. No	Parameters	Values
1.	Moment of inertia of the motors(Jm_1)	5.e-3 kg.m^2
2.	Moment of inertia of the motors(Jm_2)	2.e-3 kg.m^2
3.	Stiffness for coupling (Kel_1)	70 Nm^{-1}
4.	Stiffness for coupling (Kel_2)	70 Nm^{-1}
5.	Viscous damping (del_1)	0.05 Nsm^{-1}
6.	Viscous damping (del_2)	0.05 Nsm^{-1}
7.	Reduction ratio	100

3 SIMULATION RESULTS

Let's consider the robot initially at a steady state with the initial conditions described in Table 4, in a lower elbow posture. The environment is supposed to be known and frictionless such that robot will apply force on the negative y-direction while moving parallel to the x-axis (for 30 cm) with a trapezoidal velocity profile with a maximum velocity of 3 mm/s in 15 seconds.

Table 4 shows the initial conditions of the arm for the simulation.

Table 4: Initial conditions of the arm.

Sr. No	Parameter	Initial condition
1.	Initial motor position (qm0)	[-147.06,294.12] rad
2.	End of effector position	[0.2,0] m
3.	Initial link position (q0)	[-1.47,2.94] rad

The robot was tested with different constant time delays as suggested (Smith and Chauhan, 2012), in Table 1.

Figure 9 illustrates that with the increase in the dead time, oscillations in the system increases that is controlled by tuning the weights of MPC to get an overshoot free system. The response of the system gets slower as the weights are made less aggressive with the increase of time delay. Overshoot of less than 10% was observed with the time delay of 100ms when using MPC for specific tuning weights of MPC with no time delay are used.

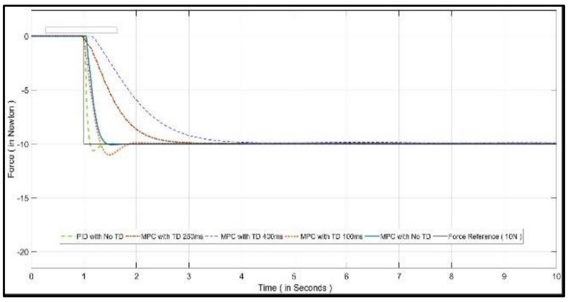

Figure 9: MPC (with previewing) with a different time delay with 10^7 N/m stiffness.

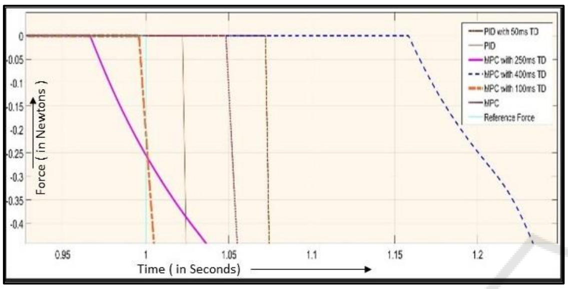

Figure 10: Panned view of Figure 8 around time stamp 1 second when force starts acting on the system.

Figure 10 shows that previewing can help to compensate for the effect of dead time in the system as we can see that MPC is prepared for the dead time ahead of its time. All the responses with different time delays are tuned for previewing in such a way that makes their response close to the reference of the system showing no or minimal dead time effect on the reaction of the force control. Previewing could be used for the case of surgical robots capable to operate in autonomous mode since the reference is known to them. MPC previews the reference to make the system closed to delayed free system when the time delay is deterministic as shown.

Figure 11 presents a comparison of PID controller vs MPC with time delay. PID results in a highly oscillatory response with the time delay of 100ms and hence making the system unstable. Therefore, the time delay of 50ms is considered for PID to compare with MPC with dead time 100ms. The system's response with PID is oscillatory and cannot be damped by changing the tuning parameters. MPC has shown its robustness as compared to PID with double the time delay.

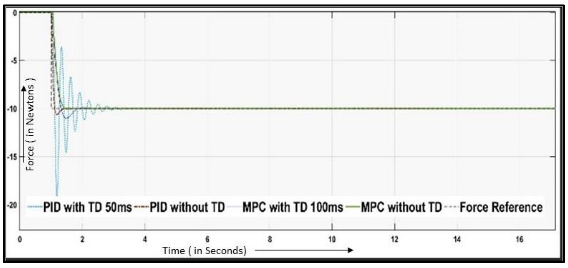

Figure 11: Comparison of MPC vs PID with time delay.

Figure 12 shows the position of the surgical arm in Y plane versus time. It compares the type of contact robot is making in the presence of time delays with MPC and PID controllers. PID with the time delay shows oscillatory contact with the environment versus stable contact by MPC under different time delays.

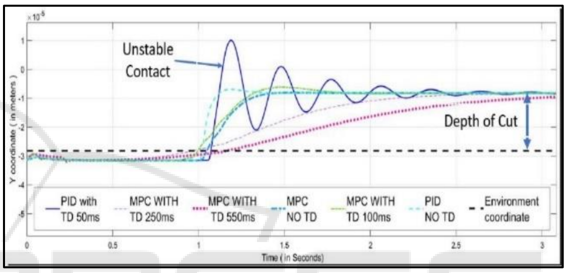

Figure 12: Position of the robot vs time.

In the situation when no previewing is available, the dead time cannot be compensated by using MPC. The effects of dead time are neutralised by the MPC unlike PID as shown in figure 13 but a time lag exists in the system unlike with previewing. The simulation results show that the system is stable under the control of MPC.

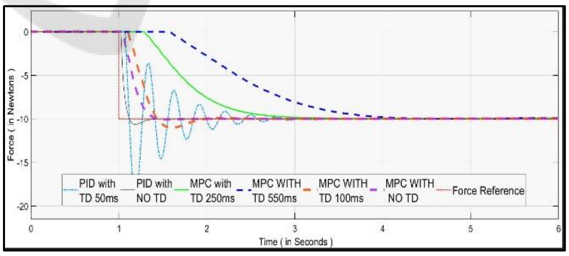

Figure 13: MPC vs PID with different time delays with no previewing.

Figure 14 shows the frequency analysis of the system with different time delays by using bode plot. The phase lag increases with the increase of the time delay as described in the above figure with an increase in frequency. The time delays considered in the system are approximated by using Padé approximation technique. Increasing the frequency of the system increases the computational load on the system increases demanding for more computation power. Since the system gets the linearised system is controllable even when the frequency is increased.

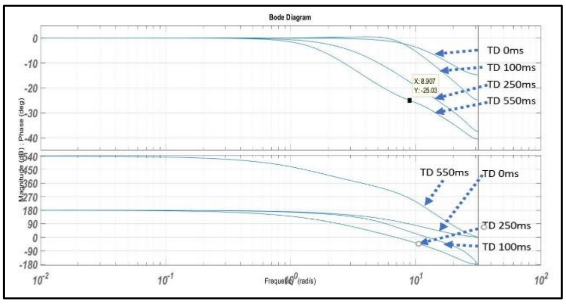

Figure 14: Bode plot for the system under different time delays.

4 DISCUSSIONS

- MPC as a force controller can be used to develop haptic feedback in a surgical system suffering from time delays.
- The approach's effectiveness was tested in different scenarios and results were compared with the observations of the previous work by researchers. MPC shows a stable response in all the scenarios.
- MPC can be used even when the time delay is more significant than 500ms and shows the system is robust enough to carry out the surgery. The response of the system gets slower when time delay goes beyond 500ms increasing total time to carry out the operation.
- Previewing can be used to compensate for the dead time using MPC when reference is known. The response of the system is closer to a delay-free system in that case. This feature can be used in surgical robots with the capability of performing in autonomous mode.

5 FUTURE WORK

Introducing impact and velocity model into the system to have a zero-impact velocity during the contact is the proposed future work. Such work will also show the more considerable difference in the performance of MPC over PID. Gain scheduling using MPC can help to handle the system with random delays.

6 CONCLUSIONS

In this paper, force feedback by using Model Predictive Control (MPC) for surgical robots was developed and discussed that will give an extra dimension to the existing surgical systems. MPC can compensate the time delays when the delays are known by previewing. The goal is to design control signal at each sampling time k such that state feedback law minimises the cost function to constraints of control input. The benefit of using the previewing in case of known references helps controller to predict the delayed free future. Simulation experiments show the effectiveness of the concept.

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