Contact Prediction Control for a Teleoperation System with Time Delay

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In a teleoperation system with communication delay, the contact information on the slave side is transmitted to the master side with time delay. Hence, an operator may misunderstand that the slave has not contacted an object and may add more force. Eventually, excessive force by the slave may collapse the object. This paper proposes model predictive control with a variable dumping method to prevent collision on contact in a teleoperation system with time delay. The prediction method considers the distance to the object on slave side, and variable dumping is implemented on the master side. The proposed method is evaluated through numerical simulations and experiments.

Keywords: model predictive control, teleoperation system, time delay, network based control

1. Introduction

In recent years, rapid advances in network technology have resulted in a growing interest in research on control systems over networks. Researchers anticipate that teleoperation over networks will have applications in many fields, such as applying teleoperation to perform work tasks in dangerous environments including disaster zones, nuclear reactors, and space environments, and applying teleoperation to telesurgery. One type of teleoperation technology is master-slave teleoperation systems. master-slave teleoperation systems refer to systems that transmit the position and/or sense of force of a slave robot to a master robot through the use of cooperative control. Researchers have conducted much research on improving the transparency of the transmitted information on the sense of force and applying this system to various environments and work tasks in particular. In addition, researchers have also proposed many methods for designing systems while considering time delays. Time delays are a cause of performance degradation and cause phenomena such as instability, a decrease in transparency, and the occurrence of vibrations.

Related work includes research on switching control that assigns the optimal controller from amongst asset of multiple controllers that are predetermined according to the different operation environments to achieve both stability and operability for a wide range of environments (1). In situations in which there is a possibility that the system operability may be reduced, such as when the slave collides with the target object at high velocity or when vibrations arise due to the application of excess input upon contact, switching control is applied when the slave makes contact with the target. In addition, Hieno et al. proposed a method in which the control gain is set to be variable based on an estimate of the stiffness of the target (2). Proposed methods for implementation of bilateral teleoperation control include a 4-channel controller (Ch) in which the controller performs both position control and force control for both the master and the slave (3). Kambara et al. conducted research on 4-Ch controllers and proposed a method for reaction force estimation in which the reaction force is measured without using sensors (4). 4-Ch controllers send and receive information on the position and force over a network. Therefore, 4-Ch controllers are affected by communication delays. Systems using 4-Ch controllers are subject to problems such as degradation of performance and stability. In other research on 4-Ch controllers, researchers have proposed using low-pass filters to suppress vibrations (5). However, this method assumes that there is no delay in the system, and does not consider vibrations that arise as a result of collisions with the target due to time delays. On the other hand, Yoshida et al. proposed a method for compensating for the tracking error in the position and force by estimating the future reaction force using predictive control (6). Kozuki et al. considered the effect of a time delay and employed a method that handles only cases in which the manipulator is not in contact with the target (7). The authors also conducted research in which they considered contact between the target and the manipulator and proposed a master/slave tracking method in which a Kalman filter was used (8).

Researchers have been working on human tracking and collision force mitigation using model predictions for autonomous traveling robots that move around living areas of humans (9). This paper considers a teleoperation picking task (Fig. 1). The picking task considered in this paper consists of moving the tip of the manipulator close to the target and picking up the target object using suction force. In this task, it is necessary to control the manipulator so that it is placed at a distance from the target object at which an effective suction force can be applied to the object. However, due to the delay in the transmission of the contact information due to the time delay, there is a risk that the manipulator will overshoot the desired position and apply an excessive compression force to the target object.

Therefore, in this research, we propose a method for systems with communication time delays in which the controller mitigates the force of collision between the manipulator and target object by using model predictive control that considers...
the distance between the slave and the object it will come in contact with. We implemented contact preview control by using a variable damper on the master side to notify the operator of the proximity of the target object. In addition, we evaluate the effectiveness of the proposed method through simulations and experiments.

2. Issues in Teleoperation Systems with Time Delays

Consider a master-slave type teleoperation system as shown in Fig. 2. If there is delay in the information transmission between the master and the slave, then this will result in a delay to transmit the fact that the slave has contacted the target object, and the master will fail to recognize that the slave has already made contact with the target object. In this case, the operator controlling the master would tell the system to continue approaching the object (Fig. 2(c)). This would result in an excessive force being applied to the target object, which may damage the target object (Fig. 2(d)). On the slave side, it is difficult to make the slave suddenly stop at the surface of the target object due to the inertia of the slave in the direction of the target object. Therefore, it is necessary to make the slave decelerate based on its distance from the target object. However, it is difficult to determine the motion of the slave based on the distance between the slave and the target object alone. For example, even if the slave is near the target object, if the slave is moving away from the target object as shown on the left side of Fig. 3, it is not necessary to make the slave decelerate. Therefore, in order to avoid collisions between the slave and the target object, it is necessary to use information related to the velocity and acceleration of the slave as well as its distance from the target object to predict the position of the slave in relation to the target object. Below, we describe the details of this prediction method.

3. Design of a Contact Preview Control for a System with Time Delay

A block diagram of the model predictive control system proposed in this paper containing a variable damper is shown in Fig. 4. In the figure, $J_m$ and $J_s$ represent the moments of inertia of the master and slave robots, $C_m$ represents the damping coefficient of the variable damper, $x_i$ represents the position of the target object, $e^{-ds_i}$ represents a delay element with a delay of $d$ seconds, and $x_i, v_i, a_i, \{i = m, s\}$ represent the position, velocity, and acceleration of the master and slave. We assume that this system includes a sensor placed on the slave to measure the distance between the manipulator and the target object in order to predict contact with the target object. We introduce new constraints in the model predictive control based on the distance information obtained from the sensor. We also apply variable damping based on the distance between the slave and the target object to the master controller.

3.1 Motion Prediction Model

The dynamic model of the proposed system is shown below. For simplicity, the models for the master and slave will be explained in 1 dimension only. However, the models can be expanded to 2 dimensions.

3.1.1 Dynamic Model of the Master

The master is modeled with an acceleration dynamic model. The model can be expressed as a discrete-time system as shown in Equation (1).

$$x_m[k + 1] = x_m[k] + v_m[k] T_s + \frac{1}{2} a_m[k] T_s^2, \ldots, (1)$$

Let $x_m$ represent the position of the master, $v_m$ the velocity, $a_m$ the acceleration, and $T_s$ the sampling time per step. The prediction horizon is represented by $N_p$. The matrix $X_M[k]$ which contains the predicted positions $x_m$ from step $k + 1$ to step $k + N_p$ at time $k$ is shown in Equation (2).

$$X_M[k] = \begin{bmatrix} x_m[k + 1] \\ x_m[k + 2] \\ \vdots \\ x_m[k + N_p] \end{bmatrix}$$

$$= \Sigma_{x_m} x_m[k] + \Gamma_{x_m} v_m[k] + \Theta_{x_m} a_m[k] \ldots, (2)$$

Here,

$$a_m[k] = a_m[k + 1] = \ldots = a_m[k + N_p] \ldots, (3)$$

and $\Sigma_{x_m} \in \mathbb{R}^{N_p \times 1}, \Gamma_{x_m} \in \mathbb{R}^{N_p \times 1}, \Theta_{x_m} \in \mathbb{R}^{N_p \times 1}$ are given as follows.
Here, the control input $u^{\text{ref}}[k]$ is calculated based on the control input $u[k-1]$ from one step ago and the amount of change $\Delta u^{\text{ref}}[k]$ in the input in the current step that was obtained through the model prediction calculations, and is given by Equation (6).

$$u^{\text{ref}}[k] = u[k-1] + \Delta u^{\text{ref}}[k]$$

$$u^{\text{ref}}[k+1] = u[k-1] + \Delta u^{\text{ref}}[k] + \Delta u^{\text{ref}}[k+1]$$

$$
\vdots
$$

$$u^{\text{ref}}[k+N_p-1] = u[k-1] + \sum_{i=1}^{N_p} \Delta u^{\text{ref}}[k+N_p-i]$$

Here,

$$\Delta u^{\text{ref}}[k+N_p-i] = u^{\text{ref}}[k+N_p-i] - u^{\text{ref}}[k+N_p-i-1]$$

Here, $[k+N_p-i]$ refers to the predicted value for step $k+N_p-1$ that was made at step $k$. The matrix $X_S[k]$ of predicted values of $x_i$ from step $k+1$ to step $k+N_p$ that was made at step $k$ is given by:

$$X_S[k] = C_X \begin{bmatrix} x_{S1}[k+1] \\ x_{S1}[k+2] \\ \vdots \\ x_{S1}[k+N_p] \end{bmatrix}$$

Substituting Equation (6) into Equation (7), Equation (9) can be obtained.

$$X_S[k] = C_X \begin{bmatrix} \Delta u^{\text{ref}}[k] \\ \vdots \\ \Delta u^{\text{ref}}[k+1] \\ \Delta u^{\text{ref}}[k+2] \\ \vdots \\ \Delta u^{\text{ref}}[k+N_p-1] \end{bmatrix}$$
Here, the slave manipulators relative to the target object are shown receiving the commands from the master. The slave has already contacted the target object caused by delays in the slave. However, in the proposed method, we added a function and the constraints for deriving the input to the slave.

The cost function in Equation (13) uses the variance of the relative position between the master and slave and the norm of the control input at each step as the metric. The model predictive controller calculates the control input that minimizes the cost function in Equation (13) for each step and applies this control input to the slave.

As shown in Fig. 4, the model predictive controller is implemented on the slave side. Since the information from the master is transmitted to the slave with a time delay \(d\), the variance of the relative position between the master and slave is given by \(X_{\text{M}}[k-d] - X_{\text{S}}[k]\). We define the weighting matrices \(Q_1\) and \(Q_2\) to be diagonal matrices with diagonal elements \(q_1\) and \(q_2\) as follows.

\[
Q_1 = \begin{bmatrix} q_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & q_1 \end{bmatrix}, \quad Q_2 = \begin{bmatrix} q_2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & q_2 \end{bmatrix}
\]

The matrix of constraints \(L_\Sigma\) in Equation (14) gathers the predictions equations for the distances \(l_i\) between the slave and the target object from step \(k\) to step \(k+N_p\).

\[
l_i[k+1] = l_i[k] - (x_i[k+1] - x_i[k])
\]

\[
l_i[k+2] = l_i[k] - (x_i[k+2] - x_i[k])
\]

\[
l_i[k+3] = l_i[k] - (x_i[k+3] - x_i[k])
\]

Therefore, the structure of matrix \(L_\Sigma[k]\) is as follows.

\[
L_\Sigma[k] = \begin{bmatrix} l_i[k+1] \\ l_i[k+2] \\ \vdots \\ l_i[k+N_p] \end{bmatrix}
\]

Furthermore, the matrix can be rewritten as follows by partitioning the matrix into separate terms.

\[
L_\Sigma[k] = \begin{bmatrix} \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{bmatrix}
\]

In other words, Equation (14) shows that the distance \(l_i\) between the slave and the target object is greater than 0 at each prediction step in the slave model. This constraint has the effect of limiting the input of the model predictive control so that the slave does not overshoot the position of the target object. Therefore, large forces are not applied to the target object. By using the matrices \(\Sigma_{\text{rel}}\) and \(X_{\text{S}}[k]\) described above,
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the equation can be rewritten as follows.

\[ L_x[k] = \Sigma_{mx} + l_m[k] - X_3[k] + \Sigma_{sx} x_s[k] \]  

(18)

Using the above setup, the model prediction equations can be solved to obtain the value of \( \Delta u^c[k] \) that is needed for calculating the input \( u[k] \) to the slave.

### 3.3 Control of Master and Variable Damper

Meanwhile the input to the slave is calculated using model predictive control, the control system for the master is switched over when the slave makes contact with the target object so that the position of the master tracks the slave, as shown in Fig.4. In systems with time delays, the operator may mistakenly believe that the manipulator has not yet contacted the target object since there is a delay in this information being sent to the master. The operator may continue the operation, resulting in the possibility that a large force could be applied to the target object. Therefore, the position of the target object is calculated from the distance between the slave and target object that is measured by the slave, and is sent to the master beforehand. When the master approaches the position of the target object, the controller prevents the master from greatly overshooting the position of contact by damping the motion of the master. In this control method, we introduce the variable damping coefficient \( C_m(l_m) \) which depends on the distance \( l_m = x_r - x_m \) between the slave and the target object based on the measurement results. When the master approaches the target object, the damping force increases and suppresses overshoot of the target object. The damping coefficient \( C_m \) of the variable damper is given by Equation (19).

\[ C_m(l_m) = C_0 e^{-\gamma l_m} \]  

(19)

Here, \( C_0 \in \mathbb{R} \) and \( \gamma \in \mathbb{R} \). The value of the damping coefficient \( C_m(l_m) \) increases exponentially as the value of \( l_m \) approaches zero. When \( l_m = 0 \), the value of \( (l_m) \) is at its maximum.

### 4. Evaluation through Simulation

#### 4.1 Comparison of the Proposed Method with a 4-Channel Controller

In order to evaluate the proposed method, we conducted numerical simulations. We compared the proposed method with a 4-channel controller to verify the effectiveness of the proposed method. For the purpose of comparison, we implemented the 4ch controller assuming that the distance from the target object was known. Specifically, we implemented position control so that the master stops at the position of the target object (reference is the position of the target object) when the master reaches the position of the target object.

The parameters used in the simulation are shown in Table 1. The position control for the 4ch controller was a PID controller with a transfer function of \( K(s) = 100 + 4/s + 30s \). The gain for the force control was \( K_f = 100 \). In the proposed method, choosing a long prediction horizon would result in an increase in computation time. Therefore, the value of \( N_p \) was chosen considering the effect of the sampling time. The values of the weighting matrices were adjusted considering the tradeoff between responsiveness and stability. The value of the gain in the position controller \( K(s) \) for the master was chosen to be the same as the position feedback gain \( K(s) \) in the 4ch controller. We assume that the position of the target object is fixed, and that the position that was measured by the slave was sent to the master beforehand.

#### 4.2 Simulation Results

The results of simulations using the 4ch controller and the proposed method are shown in Fig. 6, Fig. 7, Fig. 8, and Fig. 9. The vertical axes of the

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**Table 1. Parameters for simulations**

<table>
<thead>
<tr>
<th>Values</th>
<th>Position of the object</th>
<th>Time delay</th>
<th>Length of horizon</th>
<th>Weight matrix</th>
<th>Controller (master)</th>
<th>Variable damper parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness of the object</td>
<td>1.0 ( \times ) 10^5 N/m</td>
<td>0.05 m</td>
<td>1.0 s</td>
<td>( q_1 = 2.0 \times 10^2 ), ( q_2 = 5 )</td>
<td>( K(s) = 100 + 4/s + 30s )</td>
<td>( C_0 = 150 ), ( \gamma = 80 )</td>
</tr>
</tbody>
</table>

**Table 2. Specification of the experimental device**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working space</td>
<td>4( \times ) 4( \times ) 4”</td>
</tr>
<tr>
<td>Allowable load</td>
<td>8.9 N</td>
</tr>
<tr>
<td>Resolution of position</td>
<td>400 dpi</td>
</tr>
<tr>
<td>Programming language</td>
<td>Visual studio C++</td>
</tr>
<tr>
<td>Operating System</td>
<td>Windows 7</td>
</tr>
</tbody>
</table>

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**Fig. 6. Simulation results in the conventional 4-ch controller (Position)**

**Fig. 7. Simulation results in the conventional 4-ch controller (Force)**

**Fig. 8. Simulation results in the proposed method (Position response)**
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graphs plot the positions $x_i$[m] [i = m, s], and the horizontal axes plot the time $t$ in seconds. The solid line (red) shows the response of the master, and the dashed line (blue) shows the response of the slave. In the case of the 4ch controller, the slave tracks the master with a time delay of 1 second, as shown in Fig. 6. The master reached the position of the target object after approximately 0.7 seconds. The controller for the master was switched over at this instant in order to cause the master to come to a stop at the position of the target object. However, the master could not be brought to a stop suddenly. It can be seen that the master slightly overshooted the position of the target object. As a result, the slave collided with the target object as shown in Fig. 7. 3.1 N of force was applied to the target object.

On the other hand, in the case of the proposed method, the velocity of the master began to decrease after 0.2 seconds due to the increase in the damping coefficient of the variable damper, as shown in Fig. 8. The master approached the position of contact gradually. The slave contacted the target object after 3.6 seconds. This information was transmitted to the master with a 1 second delay. The control system for the master was switched after 4.6 seconds. It can be seen that the position of the master converged to the position of the slave. On the other hand, the slave tracked the master and contacted the target object while beginning to decelerate before reaching the target object according to the model predictive control Equations (13) and (14). From Fig. 9, it can be seen that almost no force was applied to the target object. These results show that the proposed method is able to make the slave contact the target object while mitigating the collision that occurs when the slave contacts the target object, even for systems with time delays.

5. Evaluation through Experiment

5.1 Experimental Setups Based on the results of the simulation, we performed experiments using 2 parallel link manipulators (Falcon, manufactured by Novint Technologies, Inc.) as shown in Fig. 10, in which an experimenter operated the master-side manipulator. The parameters used in this experiment are shown in Table 3. The experiment was conducted with the sampling time including the calculation time for the predictive control set to 8 ms.

5.2 Experiment Results We performed experiments using the conditions shown in Table 3. The results of experiments using the proposed method are shown in Fig. 11. The positions $x_i$[mm] [i = m, s] are plotted on the vertical axis, and the time $t$ in seconds is plotted on the horizontal axis, the same as in the graphs for the simulation results. The red solid line shows the response of the master, and the blue dashed line shows the response of the slave.

Figure 11 shows that the slave tracked the master with a 1 second delay until the slave contacted the target object. It can be seen that the master began to decelerate due to the effect of the variable damper after 1.3 seconds when the master was located in the vicinity of the target object. The slave contacted the target object after 4.2 seconds. This information was transmitted to the master with a 1 second delay. Therefore, the master began to track the slave after 5.2 seconds. On the other hand, the slave satisfied the constraints of the model predictive control, and decelerated while approaching the target object. These experimental results show that the model predictive control and variable damper in the proposed method are effective.

6. Conclusion

In this paper, we proposed a teleoperation system with a control system consisting of model predictive control and a variable damper for the purpose of mitigating the force of collision during contact in teleoperation systems with time delays. We verified the effectiveness of the proposed method through simulations and experiments. We expect that this method can be applied to improve the safety of remote operations in systems with time delays.
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References


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Appendix

1. Discussion of Measurement Error

Here, we discuss the effect of error in the measurement of the position of the slave and the target object. Let 2ε represent the allowable distance for picking up the target object using suction in the task shown in Fig. 1. In this case, if the distance between the slave and the target object is between 0 and 2ε, then the suction force will be able to retain the target object. Therefore, in the case in which the range of the measurement error lerror satisfies

\[ |l_{\text{error}}| \leq \epsilon \] \hspace{1cm} (A1)

then if the constraint in Equation (14) satisfies

\[ L_S[k] \geq \sum_{m=1}^{\infty} \epsilon \] \hspace{1cm} (A2)

then the suction device will be able to retain the target object, even if there is error in the measurement obtained by the sensor.

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