Online Calculation of Time Varying Gain to Stabilize the Bilateral Teleoperation System

Tính toán trực tuyến hệ số bù thời gian trễ thay đổi để ổn định hệ thống vận hành từ xa song phương

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Tóm tắt
Các hệ thống vận hành song phương có nhiều ưu điểm và được ứng dụng rộng rãi trong nhiều lĩnh vực như sản xuất lắp ráp từ xa, bảo dưỡng từ xa, phẫu thuật từ xa, cứu hộ, v.v.... Tuy nhiên khi hệ thống vận hành song phương được thực hiện thông qua môi trường truyền thông có trễ, đặc biệt là với trễ biến thiên, các trễ truyền thông này làm cho hệ thống trở nên bất ổn định. Bài báo này sẽ đưa ra điều kiện ổn định hệ thống vận hành song phương dựa trên định lý hệ số khuếch đại nhỏ. Và sau đó, dựa vào điều kiện ổn định đã đưa ra, một phương pháp tính toán trực tuyến hệ số bù thời gian trễ thay đổi được đề xuất để ổn định hệ thống vận hành song phương sử dụng ma trận phát tán (scattering matrix). Các mô phỏng được thực hiện để chứng thực tính hiệu quả của tính toán được đề xuất.
Từ khóa: vận hành từ xa song phương, định lý hệ số nhỏ, ma trận phát tán

Abstract: Bilateral teleoperation has a wide field of applications such as tele-manufacturing, tele-maintenance, tele-sugery, rescue and so on. However, when teleoperation is performed via a time delay communication environment, especially time varying delay, this delay can destabilize a bilaterally controlled teleoperation. In this paper, the stability condition based on small gain theorem for time varying delay teleoperation is presented. Based on the stability condition, the online calculation of time varying gain is proposed for general teleoperation using scattering matrix. Simulation was done to verify the effectiveness of the proposed calculation.
Keywords: Bilateral teleoperation, small gain theorem, scattering matrix

1. Introduction

Teleoperation, where a human operator conducts a task in a remote environment via master and slave manipulators, has a wide field of applications such as tele-manufacturing, tele-maintenance, tele-sugery, rescue and so on. Bilateral teleoperation, in which contact force information is provided directly to the human operator, can improve task performance. However, when teleoperation is performed via a time delay communication environment, this delay can destabilize a bilaterally controlled teleoperator.

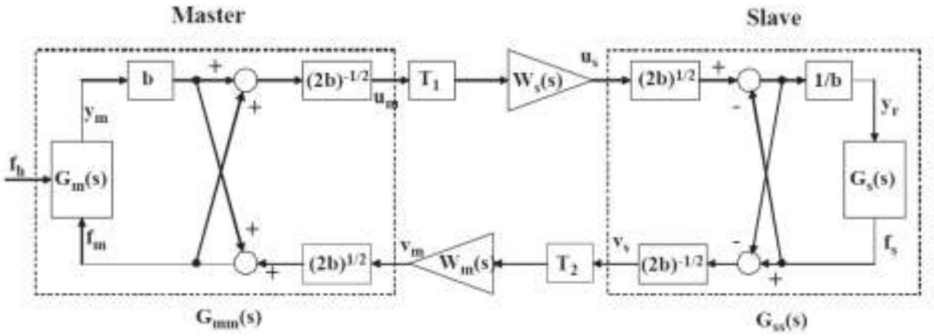
The instability problem of bilateral operation systems survived until 1989, when Anderson and Spong used passivity and the scattering theory to overcome this problem for arbitrary constant time delay [1]. In addition, Niemeyer and Slotine clarified the scattering matrix from the standpoint of the energy balance [2]. Although velocity-force architecture teleoperation systems could be stabilized based on the above researches, it has remained difficult to improve both the stability and transparency for teleoperation systems with time delay. The reason for this difficulty is that position-force architecture cannot be used, because of its non-passive property. Moreover, as long as the passivity concept is used, the human operator and the remote environment must be passive.

In order to overcome the non-passive problem of position-force architecture when using the scattering matrix, Miyoshi, et. al. proposed a design method utilizing wave filters to stabilize a non-passive operating system [3]. In this method, the scattering matrix is used, but it is considered with regard to its frequency characteristics rather than passivity concepts. Therefore, the position-force architecture can be adopted, and passivity of the operator and environment is not required. However, the system is proven to be stable only with constant time delay.

The problem of general bilateral teleoperation using scattering matrix is the system instability caused by time varying delay. Lozano et. al. proposed a time varying gains inserted into communication block to stabilize the time varying teleoperation [4]. However, the online calculation of these gains is not considered yet. The network should be evaluated beforehand in order to choose the appropriate gain to stabilize the system.

In the present study, instead of using passivity concept to study about the stability of teleoperation system as in [4], we consider the system in the point of view of small gain theorem. And based on the established stability condition using small gain theorem, the online calculation of time varying gain is proposed for general teleoperation using scattering matrix. Simulation was done to verify the effectiveness of the proposed calculation.

The paper is organized as follows: the stability condition based on the small gain theorem of H_∞ norm is given in Section 2. In Section 3, the using of time varying gain to stabilize the system is considered. The online calculation of the gain is proposed in section 4. Section 5 presents the simulation results of the proposed system. To conclude, Section 6 provides a discussion of the results and some remarks.



H.1 *The bilateral teleoperation system with scaterring matrix*

2. Stability condition for teleoperation system with the scattering matrix

A fundamental block diagram of the bilateral teleoperation system with the scattering matrix is shown in Figure H.1. The human applies his force $f_h(t)$ to the master robot; the master robot also receives feedback force $f_m(t)$ from the slave site. The input force moves the master robot, and the movement information, $y_m(t)$, is sent to the slave site. At the slave site, the slave robot is moved according to the movement information $y_r(t)$. The contact force of the slave robot to the environment $f_s(t)$ is also transmitted back to the master site. The functions W_m and W_s in Figure H.1 are addition parts inserted into the communication block and will be explained later. $T_1(t)$ and $T_2(t)$ are the time delays with transfer function are $DT_1(s)$ and $DT_2(s)$ respectively. Coefficient b is a positive constant (matrix) known as the wave impedance or scattering coefficient. $G_m(s)$ and $G_s(s)$ are transfer functions of the master and the slave robot respectively.

$$G_m(s)=\frac{Y_m(s)}{-F_m(s)} \qquad G_s(s)=\frac{F_s(s)}{Y_r(s)} \tag{1}$$

The wave variables u_m, v_m, u_s, v_s given by

$$\begin{aligned} u_m &= \frac{1}{\sqrt{2b}}\left(f_m+by_m\right)\\ v_m &= \frac{1}{\sqrt{2b}}\left(f_m-by_m\right)\\ u_s &= \frac{1}{\sqrt{2b}}\left(f_s+by_r\right)\\ v_s &= \frac{1}{\sqrt{2b}}\left(f_s-by_r\right) \end{aligned} \tag{2}$$

while $G_{mm}(s)$ and $G_{ss}(s)$ are defined as follows:

$$G_{mm}(s)=\frac{U_m(s)}{V_m(s)} \qquad G_{ss}(s)=\frac{V_s(s)}{U_s(s)} \tag{3}$$

According to small gain theorem of H_∞ norm, the stability condition for the above teleoperation system is

$$J_\infty=\left\|W_mG_{mm}DT_1W_sG_{ss}DT_2\right\|_\infty\le 1 \tag{4}$$

Now, let's consider the conventional teleoperation system in [1]. The movement information is velocity, and the contact force that is transmitted back to the master site is the coordinating force (the output of the PI controller of the slave robot). In addition, the human operator and the environment suppose to be passive, then G_m and G_s are passive.

From equations (1) and (2), $G_{ss}(s)$ can be calculated as

$$G_{ss}(s)=\frac{G_s(s)-b}{G_s(s)+b} \tag{5}$$

Then

$$\begin{aligned}\left|G_{ss}(j\omega)\right|^2 &= G_{ss}(j\omega)G_{ss}(-j\omega)\\ &=\frac{\left(\mathrm{Re}\{G_s(j\omega)\}-b\right)^2+\mathrm{Im}\{G_s(j\omega)\}^2}{\left(\mathrm{Re}\{G_s(j\omega)\}+b\right)^2+\mathrm{Im}\{G_s(j\omega)\}^2}\end{aligned} \tag{6}$$

where Re$\{G_s(j\omega)\}$ and Im$\{G_s(j\omega)\}$ are real and image parts of $G_s(j\omega)$, respectively.

Because G_s is passive, Re$\{G_s(j\omega)\}\ge 0$ (acoording to [5]). Therefore

$$\frac{\left(\mathrm{Re}\{G_s(j\omega)\}-b\right)^2+\mathrm{Im}\{G_s(j\omega)\}^2}{\left(\mathrm{Re}\{G_s(j\omega)\}+b\right)^2+\mathrm{Im}\{G_s(j\omega)\}^2}\le 1 \tag{7}$$

This leads to $\left\|G_{ss}(j\omega)\right\|_\infty\le 1$.

Similarly, we can get $\left\|G_{mm}(j\omega)\right\|_\infty\le 1$.

In the conventional system, $W_m=W_s=1$, in addition, $T_1(t)$ and $T_2(t)$ are constant, thus $\|DT1(s)\|_\infty= \|DT2(s)\|_\infty= 1$. Therefore

$$J_\infty\le\left\|G_{mm}\right\|_\infty\left\|DT_1\right\|_\infty\left\|G_{ss}\right\|_\infty\left\|DT_2\right\|_\infty\le 1 \tag{8}$$

The system is stable.

3. Time varying gain to stabilize the system

3.1. H∞ norm of time delay function

Suppose that the transfer function of time delay part is $DT(s) = Y_t(s)/U_t(s)$, with $y_t(t) = u_t(t-T(t))$. We have

$$\|y_t\|_2^2 = \int_0^\infty y_t^2(\tau)d\tau = \int_0^\infty u_t^2(\tau - T(\tau))d\tau \quad (9)$$

By changing the variable $\sigma = \tau - T(\tau)$ with supposing that $T(0) = 0$, we have $d\sigma = (1-T')d\tau$ where $T'=dT/dt$. Then equation (9) becomes (supposing that $T'<1$)

$$\|y_t\|_2^2 = \int_0^\infty \frac{1}{1-T'} u_t^2(\sigma)d\sigma \le \frac{1}{K_f^2}\int_0^\infty u_t^2(\sigma)d\sigma \quad (10)$$

or $\|y_t\|_2^2 \le \frac{1}{K_f^2}\|u_t\|_2^2$ (11)

where $K_f^2 = 1-T' \le 1$ in case $T'>0$, i.e. the time delay increase with time. Then

$$\|DT\|_\infty = \frac{\|y_t\|_2}{\|u_t\|_2} = \frac{1}{K_f} \ge 1 \quad (12)$$

Apply this result to time varying teleoperation system, it is obtained that $\|DT_1\|_\infty > 1$ and $\|DT_2\|_\infty > 1$. Thus if $W_m = W_s = 1$, the condition (8) is no more guaranteed, and the system may become unstable (in case the time delay increase with time).

3.2. Time varying gain to stabilize the system

Now if a gain W is added to communication block, i.e. $y_t(t) = W.u_t(t-T(t))$. Then

$$\|y_t\|_2^2 = \int_0^\infty \frac{W^2}{1-T'} u_t^2(\sigma)d\sigma \quad (13)$$

By choosing $W^2 \le 1-T'$, then

$$\|y_t\|_2^2 \le \int_0^\infty u_t^2(\sigma)d\sigma = \|u_t\|_2^2 \quad (14)$$

Thus, $\|W.DT\|_\infty = \frac{\|y_t\|_2}{\|u_t\|_2} \le 1$ (15)

Applying the above result to the teleoperation system with passive master and slave, we choose gain Wm and Ws such as $W_m^2 \le 1-T_1'$ and $W_s^2 \le 1-T_2'$. Then

$$J_\infty \le \|G_{mm}\|_\infty \|DT_1.W_s\|_\infty \|G_{ss}\|_\infty \|DT_2.W_m\|_\infty \le 1 \quad (16)$$

The system is stable.

The result is the same as in [4], however, the advantage of this approach is that the gain can be used to compensate the non-passivity of the master and slave sites [3].

4. Online calculation of time varying gain

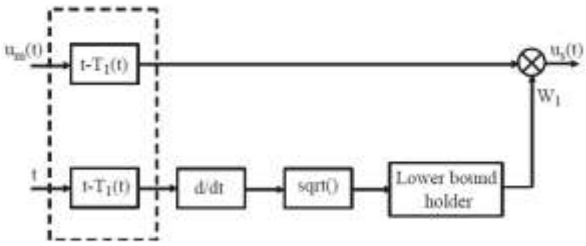
From the calculation of H_∞ norm of communication with time delay in the previous section, it is possible to stabilize the system by using time varying gain $W \le \sqrt{1-T'}$. In order to determine the value of this gain, the derivative of communication time delay must be measured online or the lower bound of $1-T'$ must be known beforehand. Some hints was mentioned in [4] such as developing realistic models of network delays and utilizing these models together with network statistics to develop switching control strategies for adjusting the communication gains on-line. The reason that the gain should be adjusted is a constant gain to account for the worst-case rate of change of the delay leads to overly conservative performance. However, the realistic network delay model is difficult to determined because network delay varies randomly and depends on many unpredicted elements such as network traffic, quality of service (QoS).

In this paper, instead of trying to develope the model of network model, the online calculation of the gain W is developed by trying to determine the network delay online. Determining the time delay value is difficult, because the time synchronization between master and slave site is quite complicated. However, the exact value of time delay is not required, but its derivative value. Thus, it is not necessary to synchronise two sites to determine time delay derivative. Instead, time information is sent from one site to the other, in addition to force and motion data. Then the delay derivatie can be calculated as follows.

If $u(t) = t$ is sent, then $y(t) = t - T(t)$ is received. By making the derivative of $y(t)$, we get $y'(t) = 1 - T'$. The value of $(1-T')$ is calculated without synchronization the sending the receiving sites. The gain now can be chosen to be $W = \sqrt{1-T'}$.

When the teleoperation system is implemented via public communication environment such as Internet, the communication time delay is a random value. Therefore, if we use the above calculation for the gain W, this gain includes so much noise of communication channel that makes the performance is very bad.

In order to avoid noise and improve the performance, the gain should be chosen to be the smallest constant value among an interval of time (for example, some seconds) so that the noise is eliminated while still can update the changing of communication time delay. Figure H.2 shows the block diagram of calculating the gain. The calculation of gain W is done by Lower bound holder block.



H.2 *Calculating of wave gain to stabilize the system*

The algorithm of lower boud holder function is as pseudo codes in H.3.

Begin
Lower_bound = input at the beginning of the internal of time;
Output = Lowe_bound;
While (*in the interval of time*) **do**
If input *is less than or equal* Lower_bound
Lower_bound = input;
EndIf
Output = Lowe_bound;
EndWhile
End

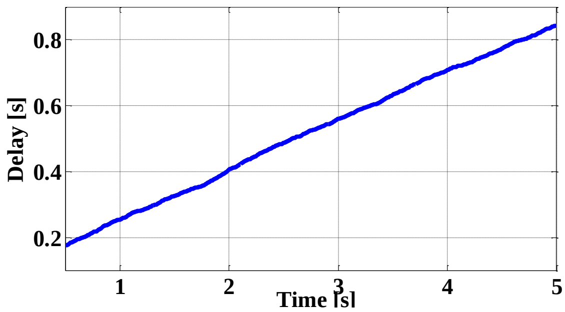
H.3 *Lower bound holder algorithm*

This algorithm guarantees the gain W always satisfies the inequality $W \leq \sqrt{1-T'}$ that make the system stabe. Moreover, the gain always tracks the variation of time delay that improve the system performance when the communication quality is improved.

5. Simulation results

5.1 Online calculation of the gain

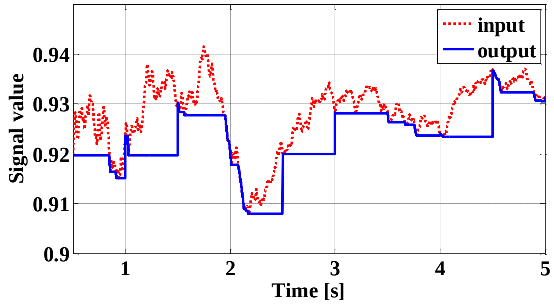
In order to verify the effectiveness of the proposed gain calculation algorithm, simulation is done. H.4 shows the time delay values that is varied with time (increasing).



H.4 *Simulated time delay*

A time signal is sent from one site to the other site, and then the calculation is done according to Figure H.2. The input and output values of the lower bound holder block are shown in Figure H.5. The gain is the output value of this block.

It can be seen that with the time delay T as in figure H. 3, the value of $\sqrt{1-T'}$ (the input signal- dotted line in figure H.5) varied randomly, and if this value is chosen to be gain value, it will add much noise to the teleoperation system. Thus makes the system peformace becomes very bad.



H.5 *Input and output values of lower bound holder block*

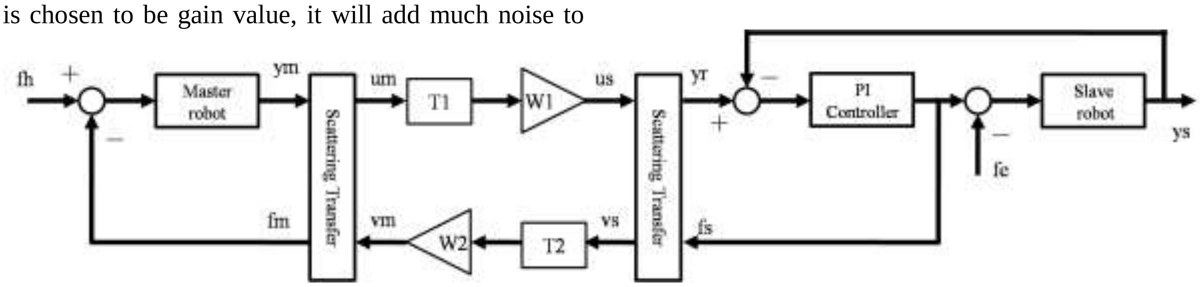
By using the proposed online calculation algorithm, the gain value now becomes smoother (solid line in figure H.4). Time interval to update the gain value in this simulation here is 0.5 second. It can be seen that the gain value is updated at the beginning of a interval, and then this value is updated immediately when the incoming signal is smaller than the present gain value. In addtion, the variation of the gain value in a time interval is much smaller than that of the input, that minimizes the bad affect to the system performance significantly. This affect can be adjusted by adjust the time interval.

5.2 Bilateral teleoperation via varying time delay communication

The next simulation is done with bilateral teleoperation sytem with time varying delay of communication environment. The simulation structure is described as follows:

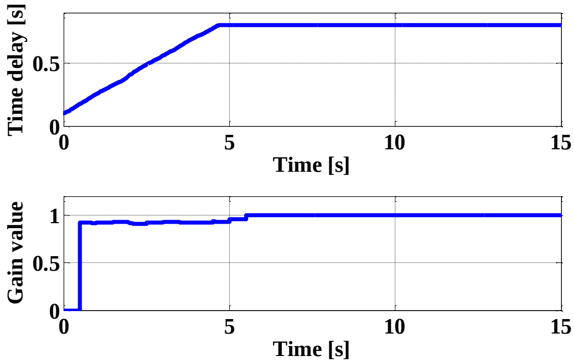
- Master and slave robots are similar with the transfer function from force to velocity is a first-order system.
- Master velocity information is sent to the slave site, the slave robot uses the received velocity to be reference signal.
- Slave robot use PI controller to track the the master velocity.
- The output of PI controller, not the enviroments force, is fed back to the master site (according to [1]).
- The communication environment is with time varying delay.
- The bilateral teleoperation system uses scattering matrix with time varying gain.
- The time varying gain is calculated using the proposed algorithm with time interval is 0.5 second

Figure H.6 shows the simulation diagram of bilateral teleoperation system.



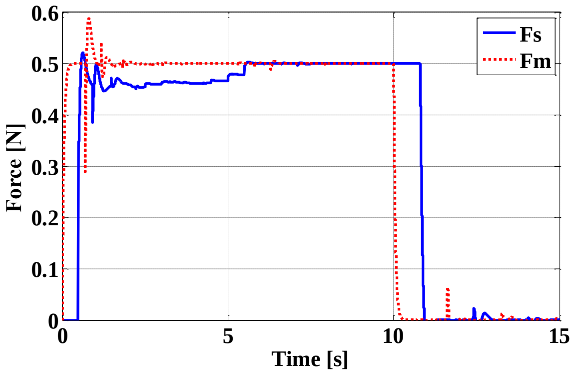
H.6 *Simulation diagram of bilateral teleoperation system*

Simulation is done in two cases: slave robot moves freely and slave robot contacts with environment.In both cases the time delay and time varying gain in both two communication channels are as in figure H.7.

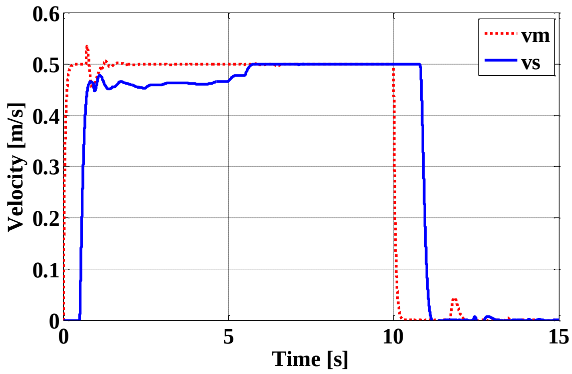


H.7 *Time delay and time varying gain*

In case the slave robot moves freely and does not contact with environment, the simulation results are shown in Figure H.8 for force information and in Figure H.9 for velocity information of both master and slave sites.



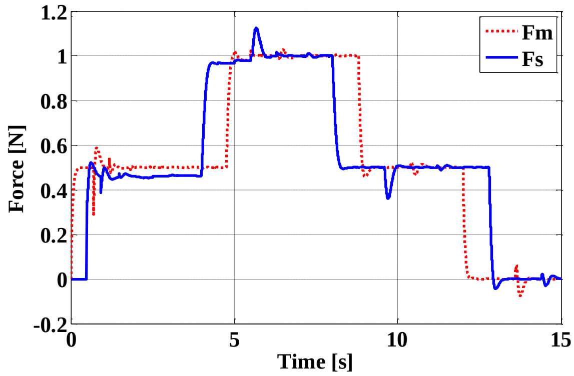
H.8 *Reflected forces at master and slave sites in non-contact case*



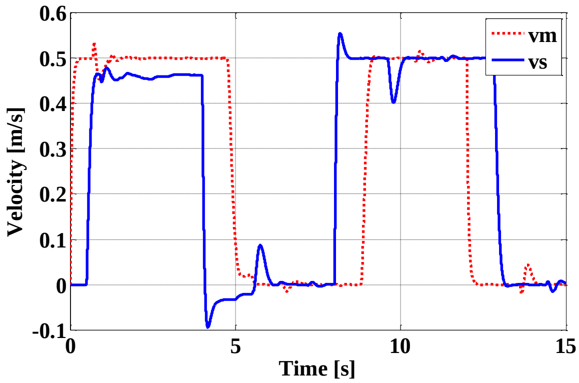
H.9 *Master and slave velocities in non-contact case*

It can be seen that the system is stable, even with time varying delay. The slave robot velocity tracks the master robot velocity, the tracking of reflected force is also obtained. When the time delay is varied with time (from 0 to 6 seconds), the gain is not equal to 1. That makes the force and velocity differences between master and slave sites. However, when the network quality is improved, the time delay is constant, the good tracking is obtained.

In case the slave robot contacts with environment, the simulation results are shown in Figure H.10 for force information and in Figure H.11 for velocity information of both master and slave sites.



H.10 *Reflected forces at master and slave sites in with-contact case*



H.11 *Master and slave velocities in with-contact case*

The slave robot contacts with environment from 4 to 8 second. It can be seen that the system remains stable, even with time varying delay and in-contact with environment. The slave robot velocity tracks the master robot velocity, the tracking of reflected force is also obtained, even when the slave robot contact with the environment. When the time delay is varied with time (from 0 to 6 second), the gain is not equal to 1. That makes the force and velocity differences between master and slave sites. However, when the network quality is improved, the time delay is constant, the good tracking is obtained.

Moreover, when the slave robot contact with the environment, the reflected force also increases, in comparison to non-contact period. That makes the operator in the master site recognize the contact situation by feeling the force difference between non-contact and in-contact periods. And that is the purpose of the bilateral teleoperation system where the operator can improve his task by obtaining the reflection force.

6. Conclusions

In this paper, the stability of the teleoperation system with scattering matrix via time varying delay communication is considered. The stability condition is established based on small gain theorem. By calculating the H_∞ norm of time varying delay part, the gain can be added to stabilize the general teleoperation system with scattering matrix, and online calculation of the gain is proposed. Simulation was done to verify the effectiveness of the proposed calculation. The teleoperation system is stable with time varying delay.

However, there still has some problems. At first, the system performance is reduced if the gain is not equal to 1. Second, the gain only can solve the problem of communication part, not whole the system, where some part may be non-passive. Third, the position tracking is not considerd yet. These problems will be our future works.

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