Research on the Wave-Variable Based Tele-operation with Force-Feedback

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Abstract. In this paper, we describe a wave variable based tele-operation system with force feedback. The wave variable is imported to the system, and the stabilization is discussed with passive theory. We calculated virtual force in VR environment and extrapolated it to achieve smooth force feedback to the human operator. The immersion is provided as well to help the operator finish the tele-operation task. At the end of the paper, an experiment was introduced.

Keywords: Tele-operation, wave-variable, force-feedback.

1 Introduction

The tele-operation system can drive the telerobot working under a dangerous environment or a place unreachable to human being. The working environments lead to distribution of the master-slave parts are in distance. And the time delay is also an important problem. The experiments indicate that when the time delay is larger than 0.25s, it will sharply decrease the system stability and affect the judgment of the operator in common bilateral control tele-operation system with force feedback. This will reduces efficiency and safety of tele-operation. Scientists suggested a lot to reduce the efficiency such as transparency, caused by time delay, such as tele-program, predictive control and event based supervisory control. Traditional method to reduce that efficiency is using VR based predictive display to simulate the working environment [1], [2], [3]. The operator interacted with the virtual reality environment continually, and the results can be showed in VR environment, then the telerobot would act as the one in the VR environment by time delay [4].

The network propagation delay can not be ignored when there is long distance between the master and slave .For example, the propagation delay between ground station and on-orbit telerobot reach 3~6s [5]. When only traditional methods are used in the tele-operation system, the system will become instability because of the time delay. Sometimes, the remote environment is changed by outside influence factors while the local VR environment is not updated in time, so working only with the graphic simulation in VR will limit the ability of the tele-operation system to deal with the external contingency. The force & video feed-back is delayed far behind the VR environment. It is not dependable to make real-time judgment only by the feed-back

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sensors, the tele-operation system will work as "move-wait" way. In this paper, virtual force is calculated in the VR environment to instead the real force feedback which is getting from the remote side to the operator. This will help the operator making real-time judgment. The delayed remote force sensor information is used to revise the virtual force. This will improve the immersion and the interaction and the transparency of tele-operation system. CyberGrasp is used as force feed-back equipment in this case.

Tele-operation is widely used in the maintenance of airspace equipment. German Aerospace Center (DLR) first operated the ROTEX(Robotic Technology Experiment) on "Columbia" (Space Shuttle) using tele-operation on the ground in 1993. Japan tele-operated the robot on ETS-VII (Engineering Test Satellite VII) to finish two extravehicular operation experiments, rendezvous of two on satellite robot systems and remote tele-operation in 1999.

Based on passive theory, focus on the energy transmission, a wave variable based technique is developed by Niemeyer and Slotine in 1991 [6]. And passive control arithmetic is developed. After that, wave variable becomes an important method to stable the tele-operation system under variable time-delay.

In this paper, we study a ground research system, which is used to simulate the ground-space tele-operation system. This system includes VR based tele-operation system with force-feedback and wave variable is used to make sure the system is stable. In chapter 3, stable analysis of the wave variable based tele-operation system is discussed. In chapter 4, force feed-back and the virtual force extrapolation is studied. The experiment set up and result analysis is in chapter 5.

2 System Descriptions

The structure of a tele-operation system is shown as fig.1:

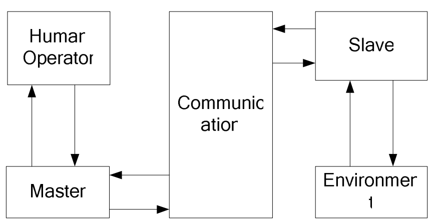


Fig. 1. A structure of tele-operation system

In a master-slave tele-operation system, the operator interacts with the master side. The master side sends the command to the slave side by the communication block. The tele-robot in slave side interacts with the environment, and sensor feedback is send back to the master side through the communication block. The time-delay of the tele-operation is mainly in the transmission process, which is in communication block.

In this paper, wave variable is imported in the transmission process of the tele-operation systems to make system stable under a time-vary delay. Wave variable based tele-operation is a method based on passive theory. It is considered in passive theory that the robustness control theory can be designed in a passive system, while a non-passive system can be converted to a passive system in a way.

The transmission block of a tele-operation system can be treated as a two port network [7-9] in fig2:

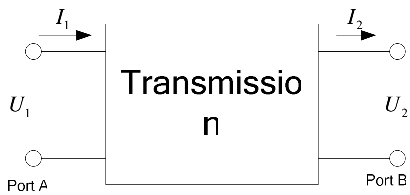


Fig. 2. Two port transmission network

The force F and the velocity v in tele-operation system is mapped with the voltage V and the current I in the circuit, that is $F \rightleftarrows V$, $v \rightleftarrows I$. The transmission delay T in the tele-operation system is mapped with l/v_0 in two port network. So a tele-operation system can be mapped as a two port network. And circuit theory can be used to analyze tele-operation system. It is considered that the transmission process should be passive to stabilize a system; otherwise there is no need to transmit energy from port A to port B.

3 Stabilization Analysis of a Wave Variable Based Tele-operation System

An ideal non-dissipation transmission system is shown in fig 3. The operator is non-passive in a tele-operation system, but operator is adaptable with the system. So the operator is able to adapt the passive system.

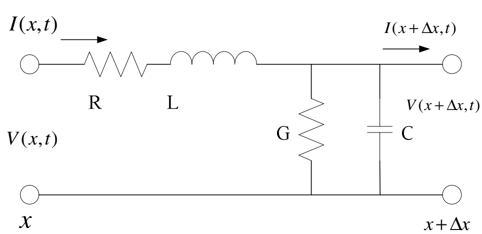


Fig. 3. An ideal non-dissipation transmission circuit

There are typical inductances and capacitors in the circuit. The voltage is referred as V , the current is referred as I , the capacitor is referred as C and the inductance is referred as L .

$$\frac{\partial V(x,t)}{\partial x} = -L\frac{\partial I(x,t)}{\partial t}$$
$$\frac{\partial I(x,t)}{\partial x} = -C\frac{\partial V(x,t)}{\partial t} \tag{1}$$

After Laplace transform, using impedance matrix to separate the voltage V and the current I .

$$\begin{bmatrix} V_1(s) \\ V_2(s) \end{bmatrix} = \begin{bmatrix} Z_0 \coth \frac{sl}{v_0} & Z_0 \cos ech \frac{sl}{v_0} \\ Z_0 \cos ec\text{h} \frac{sl}{v_0} & Z_0 \coth \frac{sl}{v_0} \end{bmatrix} \begin{bmatrix} I_1(s) \\ -I_2(s) \end{bmatrix} \tag{2}$$

Z_0 is impedance characteristic of transmission process, v_0 is transmission velocity, the lower mark 1&2 is referred as master & slave side.

Because of the time-delay:

$$V_1(t) = V_2(t-T)$$
$$I_2(t) = I_1(t-T) \tag{3}$$

In tele-operation system it means :

$$F_1(t) = F_2(t-T)$$
$$\dot{x}_2(t) = \dot{x}\ (t-T) \tag{4}$$

Consider about the pure time-delay statement, at time t, force at the master side equals to the force at the slave side but T delay ago, while the velocity at the slave side equals to the one at master side but T delay ago.

Import wave variables U, V:

$$u_l = \frac{b\dot{x}_l + F_l}{\sqrt{2b}}, w_l = \frac{b\dot{x}_l - F_l}{\sqrt{2b}} \tag{5}$$

The two port network is changed as shown in fig 4:

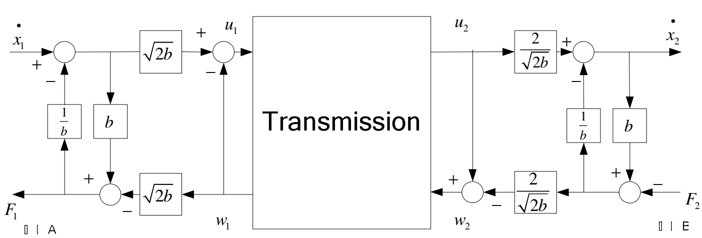


Fig. 4. The framework of the transmission process imported with the wave variable

By calculating the energy flow of the two port network, it can be proved that energy flow into the network is larger than the flow out, which means the network is passive, so that the system is stable.

The proof is as follow (assume there is no energy in the network at first):

$$\underline{F} = \begin{bmatrix} F_1 \\ F_2 \end{bmatrix}, \quad \underline{\dot{x}} = \begin{bmatrix} \dot{x}_1 \\ -\dot{x}_2 \end{bmatrix} \tag{6}$$

At time t, the energy in the transmission process is:

$$E_{net}(t) = \int_0^t \left(\underline{F}^T \underline{\dot{x}} \right) d\tau = \int_0^t \left(F_1 \dot{x}_1 - F_2 \dot{x}_2 \right) d\tau \tag{7}$$

If the network is passive, the flow in energy is larger than the flow out. Means:

$$\int_0^\infty \left(F_1 \dot{x}_1 - F_2 \dot{x}_2 \right) d\tau \geq 0 \tag{8}$$

Using the scatter operator S

$$S(s) = \begin{bmatrix} -\tanh(sT) & \sec h(sT) \\ \sec h(sT) & \tanh(sT) \end{bmatrix} \tag{9}$$

$$\underline{F}(s) - \underline{\dot{x}}(s) = S(s)\left[\underline{F}(s) + \underline{\dot{x}}(s) \right] \tag{10}$$

$$\left\| \underline{F}(s) + \underline{\dot{x}}(s) \right\|^2 - \left\| \underline{F}(s) - \underline{\dot{x}}(s) \right\|^2 \geq 0 \tag{11}$$

$$\int_0^\infty \left[\left(\underline{F} + \underline{\dot{x}} \right)^T \left(\underline{F} + \underline{\dot{x}} \right) - \left(\underline{F} - \underline{\dot{x}} \right)^T \left(\underline{F} - \underline{\dot{x}} \right) \right] d\tau = 4 \int_0^\infty \left(\underline{F}^T \underline{\dot{x}} \right) d\tau \geq 0 \tag{12}$$

Means the energy flow into the two port network is larger than the flow out, the transmission network is passive, and the tele-operation system is stable.

4 Tele-operation System with Force Feedback

According to the research, force feedback can enhance the immersion of the tele-operation system, and improve the efficiency and veracity of the operation. If people operate the master side only depends on the VR graphic simulation without force feedback, the modeling error will lead to the failure. And it is not safe and reliable. Force feedback provides huge agility and high efficiency to the tele-operation system [10]. Some scientists studied on the master-slave tele-operation system with and without force feedback, the research indicate that force feedback can reduce 40% time to accomplish the task.

Human can feel force variations about 300~1000HZ. The lower frequency will lead intermission to human's haptic feelings. Direct sensor force feedback frequency from remote is low. The force feedback depends on the calculating speed of the virtual force. In this paper, two methods are combined to calculate the virtual force in VR environment, and feedback to the human operator in time.

Based on the mapping relationship of the robot hand and the VR environment, using the angle displacement of fingers on robot hand to instead of the move of the robot hand, and calculate the virtual force by Hooke's law. Then update the force feedback to the operator.

Use the insert-value method to extrapolate the virtual force based on time sequence, disperse the force value which is gotten in experiment and save to a database. Calculate the virtual force in VR environment as a symbol, and query from the database to extrapolate and feedback to the human operator. This will achieve smooth force feedback and conquer the impulse of the force feedback.

The force changes because of the move of the robot hand which made the distortion of face-contacted of the object. Considered the characteristics of the robot hand, the angle displacement of fingers R is referred to the position changes P of the fingers. While the angle displacement is easier to get than the position change, the angle displacement is used to instead the distortion of the face-contacted in virtual force calculation. This approximation will reduce the calculation of virtual force. The t time virtual force $F(t)$ changes from

$$F(t) = \begin{cases} f(P_n) & t = n \\ f(a_{n+i}) & n < t < n+1 \end{cases} \tag{13}$$

$$F(t) = \begin{cases} f(R_n) & t = n \\ f(a_{n+i}) & n < t < n+1 \end{cases} \tag{14}$$

Function f is referred to the mapping of the angle displacement and it can be query in the database, P_n referred to the position of the finger, R_n referred to the angle displacement of the finger, $f(a_{n+i})$ referred to the extrapolation of the virtual force.

4.1 Virtual Force Extrapolation Based on Material Characteristics

Calculating speed of the virtual force is not fast enough to catch up human operator's feeling. An extrapolation of virtual force based on material characteristics by testing in experiment is studied in this paper. The approaches are:

1. Operate the HIT/DLR robot hand to grasp object and save the force value and draw a curve.
2. Disperse the force value and save to the database
3. Using the calculated virtual force in the VR environment as a symbol, extrapolate the virtual force.

An angle displacement R_n is gotten in every refresh of the VR environment. The virtual force is calculated by function $F(t) = f(R_n)$. Query the most near force value $f(a_n)$ in database, feedback $f(a_n) \ldots f(a_{n+i})$ to human operator until next update of VR. The calculation should judge the grasp and release action to decide the orientation of the extrapolation. The extrapolation of $F(t_n)$ is

$$F(t) = \begin{cases} F(t_n) & t = t_n \\ F(a_{n+i}) & t_n < t < t_{n+1} \\ F(t_{n+1}) & t = t_{n+1} \end{cases} \tag{15}$$

The process is shown as fig5

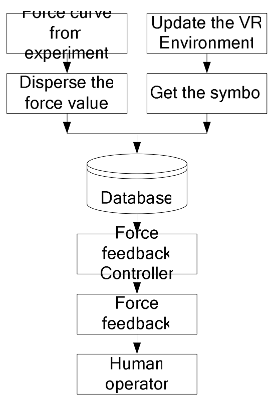


Fig. 5. The approach of virtual force extrapolate

This extrapolation of virtual force is based on material characteristics, so the extrapolation is very close to the real force feedback. The next update and re-query will avoid the accumulative errors.

5 Experiment Setup

The operator interacts with the virtual slave in the master side. The virtual slave provides VR environment to simulate the real slave side and graphic feedback to the operator. The tele-operation commands are examined in virtual slave to be inerrant before send to the robot in slave side by transmission network. At the same time, the slave side feedback remote sensor to master side. The master side updates the VR environment of virtual slave and provides force feedback to the operator by Cyber-Grasp equipment. Operator makes decision by those feedback information and step on the next operation (fig7).

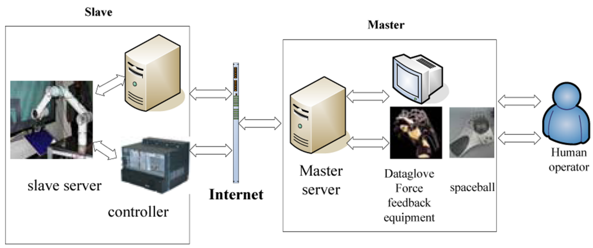


Fig. 6. Force feedback tele-operation based on VR

A 4DOF robot arm and a 4-finger robot hand (13DOF) are used as the slave robot system in this tele-operation experiment. Spaceball 5000 (6DOF) is used as a input equipment to operate the robot arm and CyberGlove dataglove is used to operate the robot hand, while CyberGrasp is used as the force feedback equipment. Through the internet, a tele-operation experiment between Wuhan and Harbin was held to push to unfolding the invalid sun panels and to wipe the polluted camera lens on the satellite. A time-vary delay was added in the transmission network to simulate the maintenance on the of airspace equipment.

When the tele-operation started, the contact was established between the master & slave side, initialized by the remote sensor feedback.

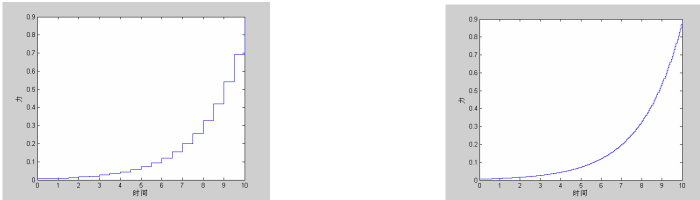
- With the help of local VR environment, the operator use the Spaceball to move remote robot system (including robot arm & hand) to approach the sun panel
- When reaches the panel, adjust the pose of robot arm and initialize the robot hand to grasp
- Grasp the handle on the sun panel with robot hand by using CyberGlove dataglove, the force feedback is provided by Cybergrasp equipment so that the operator could confirm a stable grasp to the handle
- Program a path and push the sun panel to a correct position
- Release the handle and take back the robot system in the slave side

Wave variable method is used in tele-operation system to reduce the impact of time-delay. The experiment shows that the force feedback becomes smooth by extrapolating virtual force (fig7).

Obviously, the force feedback is smoother when virtual force extrapolation is used. The disadvantage of this method is the material characteristics should be tested beforehand.

Because of the transmission delay, the force sensor and the position statement information are delayed in the master side. The impact of time delay is reduced by importing wave variable. The command from the master side and the sensor feedback from slave side of the robot's first joint are shown in fig8.

The tele-operation system is stable during the experiment.



(a) (b)

Fig. 7. The Force-feedback results with & without virtual force extrapolate, (a) is virtual force feedback without extrapolation, (b) is virtual force feedback with extrapolation

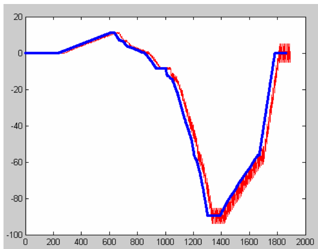


Fig. 8. The command from the master side and the sensor feedback. The blue curve is the command and the red curve is the sensor feedback.

6 Conclusion and Future Work

A wave variable based tele-operation system with force feedback is analyzed in this paper. The stabilization of the tele-operation system imported wave variable is discussed by using passive theory. By calculating virtual force and extrapolation, a smooth force feedback is provided to human operator, and an immersion is provided as well. In future, the stabilization of tele-operation system needed to be studied under time-vary delay. A new virtual force algorithm is required to reduce the reliance to the material characteristics.

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