A Novel Control Scheme Combining Wave Variable and Generalized Predictive Control for Teleoperation

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Abstract. A control scheme for teleoperation system is developed in this paper, which combines wave variables and predictive control methods to reduce the impact of time delay between local and remote. Wave variable transmission technology is adopted to ensure the passivity of the communication and the stability of the teleoperation system under any time delay. The velocity information transmitted by the wave variable is used to generate the predicted trajectory. Then a novel predictive control structure and generalized controller (GPC) is proposed. Unlike traditional method, the proportional and derivative terms were added to the dynamic compensation to facilitate the design of predictive controllers, which allow the control system has better tracking ability. Finally, the superiority of the proposed control scheme is proved by comparing the traditional predictive control simulation.

Keywords: Wave variables technology, Generalized predictive control, Dynamic compensation

1.INTRODUCTION

The teleoperation system mainly includes the operator, the master device, the slave device, the environment and the communication. In the bilateral teleoperation system, the force from the slave is fed back to the master, allowing the operator to perceive the environmental forces. It help the operator improve the quality and efficiency of the task [1]. According to the force feedback from the slave side, the operator regulation status of the master device. The information from the master side change the slave device via the communication. The whole process above is a closed loop system. The long time delay of communication easily lead to system instability [2].

In order to study the effects of time delay, Raju et al. used the two-port network to describe the teleoperation system for the first time, and indicated that time delay cause the activeness of the communication, which eventually lead to system instability [3]. On the basis of scattering theory, Spong used passive control algorithm to solve the active problem of communication [4]. Most of the subsequent researches on the time delay of teleoperation communication are based on the passivity theorem of the two-port network. Niemeyer et al. introduced the notation of wave variable [5], and derived the wave variable transformation formula based on the passivity theory and the scattering theorem [6]. So far, as the most classic passive control method, the wave variable method realized the function of ensuring system stability under any time delay. It provides a simple and robust method of analyzing stability for input and output systems such as communication.

In order to improve the stability of remote operation control, a local controller will be designed at the slave end to eliminate the influence of some rapid disturbances. For the teleoperation system, the reference signal of the local controller is generated according to human wishes, which is unknown [7]. For the slave local controller, the robot arm as the control object is equivalent to the servo system. In this case, the traditional motion control cannot meet the system's rapid response performance requirements, and even becomes unstable under the long time delay. The predictive control is widely used in the control of teleoperation robots because of its characteristics such as predicting the future state and compensating for time delay [8]. Chen proposed an event-based predictive control strategy which use the path regulator (PG) on the master side to generate the predicted trajectory online [9]. They designed a GPC to deal with time delay of communication. Slama proposed a teleoperation bilateral GPC with time delay [1]. They predicted the future position of the master based on the dynamic model, and then designed the GPC based on the dynamic model of the slave robot.

This paper mainly combines multi-degree-of-freedom wave variable technology and GPC. Under the premise of ensuring that the teleoperation system with any delay is passive, the multi-degree-of-freedom wave variable technology is adopted to transmit joint information. The predictive control trajectory is generated by the speed information transmitted to the slave, which is used as the reference trajectory of GPC for rolling optimization. A novel predictive control structure was designed, which dynamically compensate the non-linear model of the manipulator and add proportional and derivative terms to improve the predictive control effect.

The article structure is arranged as follows. In section 2, it mainly introduces the structure of the GPC and the generation of the expected signal of the slave controller. In section 3, the multi-degree-of-freedom wave variable method is introduced to solve the problem of time delay. In section 4, a two-degree-of-freedom robotic arm simulation is carried out on SIMLINK of MATLAB. Finally, in section 5, it is the summary and the study focus of future work.

2. PREDICTIVE CONTROL STRUCTURE

2.1. Predictive Model

The dynamic equations of the master and slave multi degrees of freedom manipulator are as follows:

$$M_m(q_m)\ddot{q}_m + C_m(\dot{q}_m, q_m)\dot{q}_m + G_m(q_m) = \tau_m \quad (1)$$

$$M_s(q_s)\ddot{q}_s + C_s(\dot{q}_s, q_s)\dot{q}_s + G_s(q_s) = \tau_s \quad (2)$$

where the subscript m, s represents the master and slave respectively. Omit subscripts in the subsequent explanations and formulas. $q, \dot{q}, \ddot{q}$ are angle, angular velocity and angular acceleration respectively. $M(q)$ and $G(q)$ are the inertia matrix and the equivalent gravity matrix respectively, which are only related to the joint angle. $C(\dot{q}, q)$ is the centripetal and Coriolis force coefficient matrix, which is related to the joint angle and angular velocity. τ is the resultant torque of joint input.

Since the manipulator is a multi-degree-of-freedom strongly coupled nonlinear system, its kinematics model is difficult to apply to predictive control. The dynamic compensation method is used to transform it into a prediction model with a new structure.

Introduce a new control structure:

$$\tau = \hat{C}(q, \dot{q})\dot{q} + \hat{G}(q) + \hat{M}(q)(K_1\dot{u} + K_2u), \quad (3)$$

where $\hat{M}(q), \hat{C}(q, \dot{q}), \hat{G}(q)$ are the estimation items of the corresponding matrix, respectively. K_1, K_2 is the input differential and proportional coefficient matrix.

After the above-mentioned compensation, the robot dynamics equation is simplified to the following form:

$$\ddot{q} + f(q) = K_1\dot{u} + K_2u, \quad (4)$$

$$f(q) = \hat{M}^{-1}(\tilde{M}\ddot{q} + \tilde{C}\dot{q} + \tilde{G} + d) \quad (5)$$

where $\tilde{M}, \tilde{C}, \tilde{G}$ are the estimation errors of the corresponding matrix, respectively. d is the interference term of the robotic arm. $f(q)$ is the system disturbance term after dynamic compensation.

After discretization, the Controlled Auto-Regressive Integrated Moving Average (CARIMA) model is obtained:

$$A(z^{-1})q(k) = B(z^{-1})u(k-1) + \frac{C(z^{-1})\xi(k)}{\Delta} \quad (6)$$

where $\xi(k)$ is Gaussian white noise, instead of interference $f(q)$ in dynamic models. $A(z^{-1}), B(z^{-1})$ are the input and output coefficient terms respectively. z^{-1} is the displacement operator representing the previous moment. $\Delta = 1 - z^{-1}$ is the difference operator.

2.2. Desired Trajectory

In the teleoperation system, the control signals transmitted from the master side are priori unknown for the slave controller. In predictive control, the selection of the desired trajectory is very important, and it will affect the tracking performance of the system. Therefore, the signals received from the master need to be processed. There are generally three kinds of signals from the master side, position, speed and force. This article combines the information transmitted by the wave variable, and then uses the velocity signals to generate the desired trajectory.

First integrate the speed signals to find the angle:

$$q(t) = \int_0^t \dot{q}(\tau)\mathrm{d}\tau \quad (7)$$

where $q(t)$ and $\dot{q}(t)$ are the angle and angular velocity at time t.

Assuming that the energy changes little in the short-term control and the acceleration is approximately zero, then the expected control trajectory in the predicted time domain is expressed in discrete time as:

$$q_r(k+i) = q(k) + \dot{q}(k)Ti \quad (8)$$

where T is the sampling time; $q_r(k+i)$ represents the angle at time $(k+i)T$. $i = 1, 2 \cdots P$; P is prediction horizon. The above algorithm calculates the desired angle for subsequent rolling optimization calculations of the predictive control.

3. WAVE VARIABLE COMMUNICATION

3.1. Wave Variable Structure

In order to solve the instability problem caused by the time delay in the bilateral teleoperation with multiple degrees of freedom, this paper adopts the traditional wave variable method. The power variables are converted into the wave variables in advance at the master side, and transmitted to the slave via the communication channel. Then the wave variable is converted into the original power variable at the slave side. The multi-degree-of-freedom wave variable transformation formula is as follows:

$$\begin{aligned} u_m(t) &= A_w\dot{x}_m(t) + B_w f_{md}(t) \\ v_m(t) &= C_w\dot{x}_m(t) - D_w f_{md}(t) \end{aligned} \quad (9)$$

and

$$\begin{aligned} u_s(t) &= A_w\dot{x}_{sd}(t) + B_w f_c(t) \\ v_s(t) &= C_w\dot{x}_{sd}(t) - D_w f_c(t) \end{aligned} \quad (10)$$

where u is the forward moving wave from master to slave; v is the backward moving wave from slave to master. $A_w, B_w, C_w, D_w \in R^{n\times n}$ are the wave impedance matrices. $\dot{x}_m$ is the reference speed from the master. $\dot{x}_{sd}$ is the desired speed received at the slave side. f_{md} is the feedback force received by the master. f_c is the control force from the slave side. The master and slave are symmetrical, so the impedance matrix of the master and slave is the same.

Let T be the time delay, then the communication can be described as:

$$\begin{aligned} u_s(t) &= u_m(t-T) \\ v_m(t) &= v_s(t-T) \end{aligned} . \quad (11)$$

The multi-degree-of-freedom wave variable structure is shown in Fig. 1.

3.2. Passivity Analysis

The teleoperation system is composed of five parts: the human operator, the master joystick, the communication channel, the slave robot and the environment. The master and slave robot mechanisms are generally considered to be passive inertial. This article assumes that the robot only

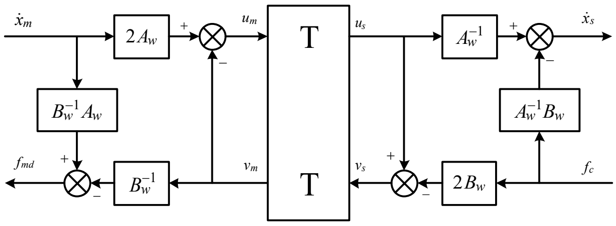

Fig. 1 Wave variable structure

interacts with the environment, and most environments are passive [3]. The whole system composed of passive systems in series or in parallel is still passive [4]. Combining the above conditions, using Lyapunov function can prove the stability of the system. The next step is to prove that communication with the wave variable is passive.

In order to simplify the calculation [10], let

$$A_w = C_w, B_w = D_w . \tag{12}$$

Incorporate (12) into (9) and (10), and obtain that

$$\begin{aligned} \dot{x}_m(t) &= A_w^{-1}[u_m(t)+v_m(t)] \\ f_{md}(t) &= B_w^{-1}[u_m(t)-v_m(t)] \end{aligned} \tag{13}$$

and

$$\begin{aligned} \dot{x}_{sd}(t) &= A_w^{-1}[u_s(t)+v_s(t)] \\ f_c(t) &= B_w^{-1}[u_s(t)-v_s(t)] \end{aligned} . \tag{14}$$

The input power of the communication is as follows:

$$\begin{aligned} \int_0^t P_{in} \mathrm{d}\tau &= \int_0^t (\dot{x}_m^{\mathrm{T}} f_{md} - \dot{x}_{sd}^{\mathrm{T}} f_c) \mathrm{d}\tau \\ &= \int_0^t [u_m + v_m]^{\mathrm{T}} A_w^{-\mathrm{T}} B_w^{-1} [u_m - v_m] \mathrm{d}\tau \\ &\quad - \int_0^t [u_s + v_s]^{\mathrm{T}} A_w^{-\mathrm{T}} B_w^{-1} [u_s - v_s] \mathrm{d}\tau \end{aligned} \tag{15}$$

Let

$$B_w = \frac{1}{2} A_w^{-\mathrm{T}} , \tag{16}$$

and put (11) into (15), then we can get

$$\int_0^t P_{in} \mathrm{d}\tau = \frac{1}{2}\int_0^t (u_m^{\mathrm{T}} u_m - u_s^{\mathrm{T}} u_s) \mathrm{d}\tau + \frac{1}{2}\int_0^t (v_s^{\mathrm{T}} v_s - v_m^{\mathrm{T}} v_m) \mathrm{d}\tau$$

$$= \frac{1}{2}\int_{t-T}^t (u_m^{\mathrm{T}} u_m + v_s^{\mathrm{T}} v_s) \mathrm{d}\tau \ge 0 \ge -E_{store}(0) . \tag{17}$$

According to the definition of passivity, the communication is passive, and the energy consumed by the system is zero, and the communication is lossless.

4. SIMULATION EXPERIMENT

In order to verify the effectiveness of the proposed method, a two-link manipulator model was simulated on MATLAB/ SIMULINK software. The PID control was used to simulate the operator behavior at the master side. Then, comparing with traditional predictive control methods, the tracking effects of the teleoperation were observed. The generalized predictive control frequency is 100Hz. The control horizon and prediction optimization weighting coefficients are 5 and 10, respectively.

The parameters of the proposed control method are shown in Table. 1. In the table, $I(n)$ represents the n dimensional identity matrix; m_i, l_i are the weight and length of the robot arm joint respectively, and the subscript $i = 1,2$ represents joint number. Other symbols have been explained in the previous article.

Table. 1 Control parameter settings

Parameters	Value
m_1, m_2	1kg, 1kg
l_1, l_2	1m, 1m
K_1, K_2	$I(n), I(n)$
A_w	$6 \times I(n)$
B_w	$1/12 \times I(n)$
T	100ms
P	10

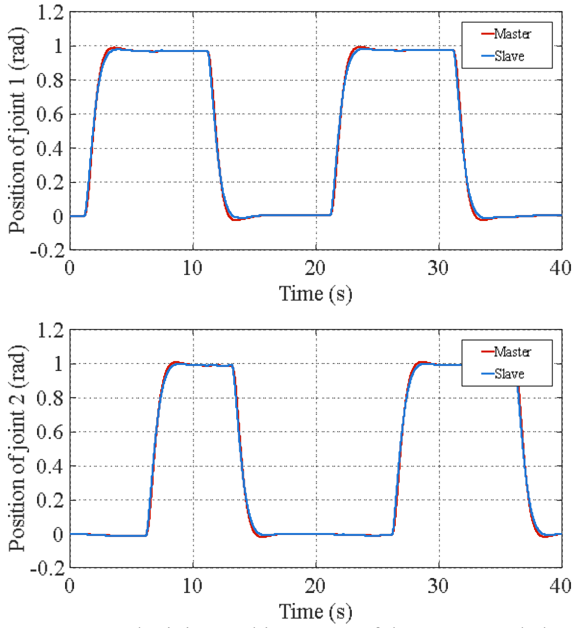

Fig. 2 The joint tracking curve of the master and slave

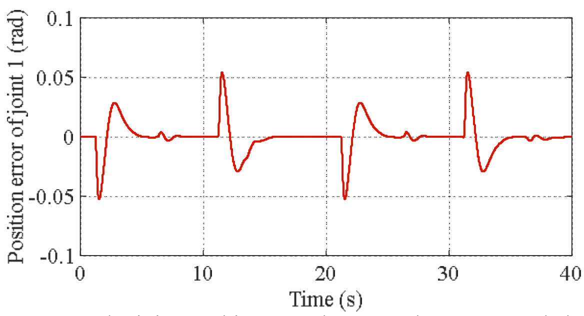

Fig. 3 The joint tracking error between the master and slave

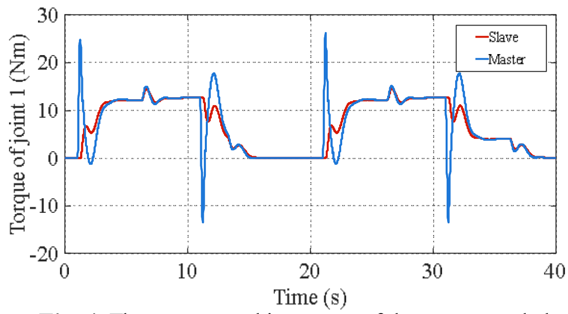

Fig. 4 The torque tracking curve of the master and slave

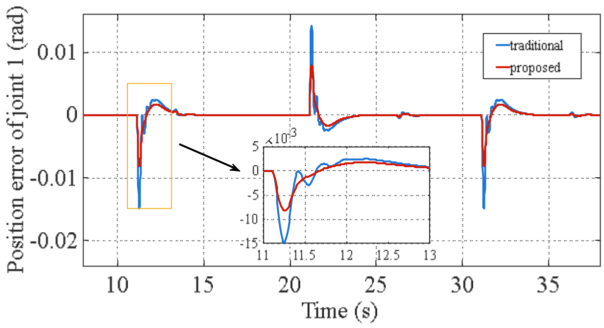

Fig. 5 The comparison curve of the angle tracking error at the slave side

The signals expected by the operator consist of a series of rectangular waves. After the human operate the joystick, the reference signals will be outputted from the master side. And the master joystick is dynamically compensated to facilitate operator control. The teleoperation tracking curve is shown in the figures below.

It should to be noted that the master signals had delayed the communication time in the comparison of the trajectory and torque. It can be seen from Figure 2 that the joint tracking performance of the teleoperation is excellent, and the error is within a small range. The tracking effects of joint 1 and joint 2 are similar. In order to reduce repetition, only joint 1 is shown in the following figure.

Figure 3 shows the master-slave joint tracking error. Figure 4 shows that the master-slave force tracking error is relatively small except the error at the beginning of the movement. When the system is stable, the force no longer changes, and the torque is the equivalent gravity of the robotic arm joint. Whether it is force tracking or trajectory tracking, there will be a large error at the beginning of the movement. This is due to the bias problem in the wave variable transmission method which sacrifices transparency to meet the stability of the system. Figure 5 shows the errors between the actual values of the slave manipulator and the signals received from the master, which are much smaller than the master-slave errors. The figure shows that the tracking error of the proposed predictive control method is smaller than that of the traditional method. The most important thing is that the proposed method eliminates the shock before the system reaches stability, and its tracking curve is smoother.

In addition, in all the graphs of joint 1, there are slight fluctuations in the curve at 6s, 13s, 26s, and 36s. This is because when the joint 1 is stable, the violent movement of the joint 2 interferes with the torque of the joint 1.

5. CONCLUSION

The main content of this paper is to seamlessly combine the multi-degree-of-freedom wave variable method and predictive control technology to ensure the stability of the teleoperation system under any time delay. When the reference trajectory at the slave side is priori unknown, the velocity information transmitted by the wave variable was used to generate the predictive trajectory. Combining with the proposed method, the predictive controller is designed. While ensuring the stability of the system, it improves the tracking effect of the system. Compared with traditional predictive control, the main contribution is that the proposed method has a significant improvement in tracking performance. In the future work, we will mainly solve the problem of stability in the case of variable time delay and reduce transparency caused by wave variables.

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