Position Controller Based on State Observer for Teleoperation Robot
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Abstract: The detection system of electro-hydraulic servo control tele-robot slave side is simplification and credibility, which is needed by work environment and test signal remote transfers. The displacement of slave side is only measured signal in this research and designs state observer for restructure velocity and acceleration state variables. Consider the influence of restructure error to position control and random disturbance of slave side, apply lower order output variable to make up of a output linear feedback system, design optimal controller based on quadratic control to accomplish master-slave position tracking control and force feedback of bilateral servo control. Simulation and Experimental results are given to demonstrate the developed controller is availability and robustness to existence of outside random disturbance.

Keywords: tele-operation, position control, state observer, quadratic control

1. INTRODUCTION

The tele-presence of tele-operation system can be achieved through many sensing information such as force sense, visual sense and auditory. As to those unknown or changing operation tasks and environment, operators can accomplish the operation tasks precisely only if they obtain the exact position information of the slave side \[ 1^{9}. \]

The slave-side position controller based on state space for tele-operation system is a full-state feedback controller \[ 8^{12}. \] The detection system of electro-hydraulic servo control tele-robot slave side is simplification and credibility, which is needed by work environment and test signal remote transfers. As a result, it's impractical and infeasible to construct the detection system of the full-state variables. This paper aims to measure slave-side displacement only by using the displacement sensor, then make use of the output variables to constitute control variables, that is to say, make use of the low-dimension output variables to form a linear output system with feedback. In addition, reconstruction error and random disturbance on the slave side need to be considered. This paper designs an optimized controller based on quadratic control \[ 1^{13} \] to realize the master-slave side position following and the bilateral servo control with force feedback. The results of simulation and experiments show that the proposed controller is effective and has a strong robustness against random disturbance.

2. DESIGN OF STATE OBSERVER

The master-slave tele-operation system is based on a 6-DOF (Degree of Freedom) parallel-mechanism Stewart platform. The master side manipulator can be shown in Fig.1. Through operating the master side manipulator, the operator can control the slave side, the isomorphic hydraulic-servo parallel mechanism, which is of the same structure but of the different sizes.

![Fig.1. 6-DOF tele-operation master-side manipulator](image)

This paper aims to measure slave-side displacement only by using displacement sensors and design a dimension-reduced state observer to construct the state variables of velocity and acceleration. Suppose the piston's displacement is \( X \), define state variables \( X_1 = X \), \( X_2 = \dot{X} \), \( X_3 = \ddot{X} \), then the state-space equation of the hydraulic cylinder is shown as \[ 1^{14}. \]

\[
\begin{bmatrix}
X_1 \\
X_2 \\
X_3
\end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 \\
0 & 0 & 1 \\
0 & 444440 & 1056
\end{bmatrix}
\begin{bmatrix}
X_1 \\
X_2 \\
X_3
\end{bmatrix} +
\begin{bmatrix}
0 \\
0 \\
555560
\end{bmatrix}U
\]

(1)

Suppose the system \( \Sigma = (A, B, C) \), \( \dot{x} = Ax + Bu \), \( y = Cx \) are observable, then linear transformation \( x = TX \) exists surely,

\[
\bar{X} = T^4 AT = \begin{bmatrix} A_1 & A_2 \\ A_3 & A_4 \end{bmatrix}, \quad \bar{B} = T^3 B = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix}
\]

\[
\bar{C} = CT = \begin{bmatrix} 1 \\ 0 \end{bmatrix}
\]

With a view to generality and linear transformation, the state variables can be decomposed into \( \bar{X}_1 \) and \( \bar{X}_2 \) based on
the observability analysis, $x_i$ needs reconstruction and $\hat{x}_i$ can be obtained through measure. Define a three-order identity matrix $T$, then the state space of the system shown in Equation (1) will be,

$$
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{bmatrix} =
\begin{bmatrix}
A_{11} & A_{12} \\
A_{21} & A_{22}
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2
\end{bmatrix} +
\begin{bmatrix}
B_1 \\
B_2
\end{bmatrix} u
$$

(2)

where, $A_{11} = 0$, $A_{12} = [1 \ 0]$, $A_{21} = [0 \ 0]^T$, $A_{22} = \begin{bmatrix} 0 & 1 \\ -444440 & -1056 \end{bmatrix}$, $B_1 = 0$, $B_2 = \begin{bmatrix} 0 & 555560 \end{bmatrix}^T$.

Because the system $\Sigma = (A,B,C)$ is observable, then the system $\Sigma = (\hat{A},\hat{B},\hat{C})$ can be observed, too. In the coordinate system $\bar{x}$, the state element $\bar{x}_1$ can be obtained by measuring and another state element $\bar{x}_2$ can be estimated after constructing the state observer. The structure of the transformed system can be shown in Fig.2, where the subsystem inside the dotted lines presents the state variable to be reconstructed. We can draw from the equation (2) that,

$$
\hat{x}_2 = (\hat{A}_{22} - \hat{G}\hat{A}_{12})\hat{x}_2 + \hat{M} + \hat{G}z
$$

(3)

where, $z = \bar{x}_{12} x_2$, $u$ is known, $\hat{y}$ can be obtained after measure, $M = \bar{A}_{12} x_2 + \bar{B}_2 u$ and $z = \bar{x}_1 - \bar{A}_{11} x_2 - \bar{B}_2 u$ can be regarded as the input and output variables for the observed subsystem respectively. $\bar{A}_{12}$ is equivalent to the output matrix. The equation of the state observer can be shown as,

$$
\dot{\hat{x}}_2 = (\hat{A}_{22} - \hat{G}\hat{A}_{12})\hat{x}_2 + \hat{M} + \hat{G}z
$$

(4)

Fig.2 Decomposition structure of transform system

After substituting equation (4) to equation (2) and (3), we can conclude,

$$
\dot{\hat{x}}_2 = (\hat{A}_{22} - \hat{G}\hat{A}_{12})\hat{x}_2 + (\hat{A}_{21} - \hat{G}\hat{A}_{11})\hat{y} + (\hat{B}_2 - \hat{G}\hat{B}_1)u + \hat{G}\hat{y}
$$

(5)

By means of choosing matrixes, the eigenvalues of $\hat{A}_{21} - \hat{G}\hat{A}_{11}$ can be assigned to the desired positions. The variable, $\hat{W} = \hat{x}_2 - \hat{G}\hat{y}$, is introduced to eliminate $\hat{y}$ and substitute $\hat{x}_2$ to the variable. The equation of state observer can be shown as,

$$
\dot{\hat{W}} = (\hat{A}_{22} - \hat{G}\hat{A}_{12})\hat{W} + [(\hat{A}_{21} - \hat{G}\hat{A}_{11})\hat{y} + (\hat{B}_2 - \hat{G}\hat{B}_1)u]
$$

(6)

So the estimations of the state variables are,

$$
\hat{x} = \begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \hat{W} + \hat{G}y \end{bmatrix}
$$

(7)

As for $\hat{x} = T\hat{x}$, the equation (7) is transformed o the state $\hat{x}$. Suppose $\lambda_1 = \lambda_2 = -10$ are the desired poles of the state observer, the feedback matrix,

$$
G = \begin{bmatrix} -1036 \\ 649676 \end{bmatrix}
$$

(8)

Substitute (8) to (6) and (7), then $\hat{x}_1, \hat{x}_2, \dot{\hat{x}}_2$ denote the estimations of $x_1, x_2, x_3$, the observer equation can be shown as,

$$
\begin{bmatrix}
\dot{\hat{W}}_1 \\
\dot{\hat{W}}_2
\end{bmatrix} =
\begin{bmatrix}
1036 & 1 \\
-1094116 & -1056
\end{bmatrix}
\begin{bmatrix}
\hat{W}_1 \\
\hat{W}_2
\end{bmatrix} +
\begin{bmatrix}
423620 \\
447446320
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2
\end{bmatrix} +
\begin{bmatrix}
0 \\
555560
\end{bmatrix} u
$$

(9)

The estimations of the system,

$$
\begin{bmatrix}
\hat{x}_1 \\
\hat{x}_2 \\
\dot{\hat{x}}_2
\end{bmatrix} =
\begin{bmatrix}
x_1 \\
\hat{W}_1 - 1036x_1 \\
\hat{W}_2 + 649676x_1
\end{bmatrix}
$$

(10)

Equation (10) is the full-state observer with feedback, which realizes full-state feedback control by simply using displacement sensors on the slave side. But high position control accuracy, good real-time performance and adaptability against random disturbance are needed in the system of electro-hydraulic servo tele-robot. While in the design of position controller with observer, the real-time estimated errors of the state variables have a great impact on position control accuracy so that the design of position controller should be optimized to meet operation requirements.

3. Design of Controller

In the aforementioned system shown in equation (1), $U(t) = -Kx(t) = -Kx(t)$ is regarded as a feedback control variable. Suppose $K = k$, then the state equation of the closed-loop system is shown as,
\[ x(t) = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -555560 & -444440 & -1056 \end{bmatrix} x(t) \]  
 Performance index is,

\[
J = \frac{1}{2} \int_0^\infty [x^T(t)Qx(t) + x^T(t)C^TK^TRKCx(t)]dt
\]

\[
= \frac{1}{2} \int_0^\infty x^T(t)Qx(t)dt
\]

The matrix \( Q \) and \( R \) are,

\[
Q = \begin{bmatrix} 29 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}
\]

Then,

\[
\tilde{Q} = \begin{bmatrix} k^2 + 29 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}
\]

This paper adopts the method of the Liapunov Equation,

\[
\dot{P} + PAX = -Q
\]

Where,

\[
P = \begin{bmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ p_{31} & p_{32} & p_{33} \end{bmatrix}
\]

\[
then p_{11} = -1.6(k^2 + 29)/k.
\]

Suppose the initial value \( x_1(0) = 1, x_2(0) = x_3(0) = 0 \), then,

\[
J = \frac{1}{2} x^T(0)PX(0) = \frac{1}{2} p_{11}
\]

With regard to Ladder Downhill Method, suppose \( \partial J(k)/\partial k = 0 \), then \( k = 5.3852 \), which is the optimal output feedback coefficient and the first number of optimal state regulator feedback coefficient matrix.

Now linear quadratic control will be used. The noise of observed system and sensors will be eliminated when a Kalman filter is added to the control system with output feedback. Define the state equation of the object model,

\[
\dot{x}(t) = A(t)x(t) + B(t)u(t) + G\omega(t)
\]

\[
y(t) = C(t)x(t) + v(t)
\]

Where, \( \omega(t) \) denotes the white noise signal of system disturbance; \( v(t) \) denotes the white noise signal generated by sensors. Suppose the noise signals are the Gauss process with zero-mean, the covariance matrices are shown as,

\[
E[\omega(t)\omega^T(t)] = Q_1 \geq 0, E[v(t)v^T(t)] = R_1 \geq 0
\]

The objective function,

\[
J = \int_0^\infty [x^T(t)Qx(t) + u^T(t)Ru(t)]dt
\]

Where, \( Q \) denotes the given positive semi-definite real symmetric constant matrix; \( R \) denotes the given positive definite real symmetric constant matrix.

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**Fig.3 Simulink structure of optimal control with disturbance observer**

(a)

(b)

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**Fig.4 Simulink structure of optimal control with disturbance observer**

Establish the simulink simulation structure (Fig.3) of the optimal control based on the state observer. The approximation level of the state variable estimated by the observer can be shown in Fig.4. The curve of observable nearly coincides with the curve of practical measurement, which indicates that the state observer has a good reconstruction effect.

In this system, define the weighting matrices of the quadratic control are \( Q=29, R=1 \). The step response of quadratic control system without the Kalman filter can be shown in Fig.5 (a) and the step response of linear quadratic
control is shown in Fig.5 (b). Therefore, the quadratic Gauss control with the Kalman filter can eliminate the white noise disturbances of the system effectively.

![Fig.5 Step response of close loop system](image)

**4. CONTROL STRATEGY AND EXPERIMENT**

The system adopts the bilateral servo control strategy. The force deviation signal can be achieved by subtracting working resistance on the slave-side manipulator from the operation force multiplied by a certain coefficient on the master-side manipulator, which is used by the system to actuate the slave-side manipulator; the position deviation between the master and slave side determines the master-side manipulator’s displacement, which makes the displacement of the master side completely follow the slave side. The displacement sensors, DC differential transformer, are FX-11 with the basic error bound ±0.2% used as displacement measure devices. The data acquisition card of 12 bit resolution, PCL-812PG, is produced by Advantech Company in Taiwan in the forward channel, while in the backward channel, this system adopts a six-channel D/A card PCL-726 produced by Advantech Company. As to the force measure device, S type pull-pressure sensor, NS-WL1, is used.

The position controller on the master-slave side uses the quadratic optimal control algorithm based on the state observer. Experiments are done respectively when the slave side has no load and elastic load. The curves of displacement and force response as the slave side has no load are shown in Fig.6. As shown in Fig.6 (a), it shows that when the slave side has no load, the master-slave displacement following error is so small that the displacement of the manipulator on the master side completely follows the slave side, which indicates that the state variables’ estimation of the designed observer has good accuracy. From the force response curves shown in Fig.6 (b), it shows that the load of the slave side is nearly zero and the force of the master side, the driven force that operators operate the manipulator, is very small and mainly aims to overcome the inertia and friction force on the manipulator. In the experiment, operators can operate the manipulator freely without sensing the feedback force.

![Fig.6 Response curves of slave side in free space](image)

![Fig.7 Response curves of slave side in spring load](image)
Random disturbance signal is added into the detection system continuously when testing the elastic load on the slave side. From the master-slave side displacement response curves shown in Fig.7 (a), it shows that the master-slave displacement following error is still very small, which means the state variables' estimation of the designed observer has good accuracy. During the test, the displacement and force signal on the slave side vibrate all the time because of the random disturbances, but the displacement and feedback force signal on the master side change smoothly. That is to say, the controller based on quadratic optimal control can eliminate the impact on master-side displacement and feedback force caused by random noise and it has a strong robustness.

5. CONCLUSION

The result of simulation and experiment indicates that the proposed optimal position controller based on the observer simplify the structure of the detection system on the slave side and meet the operation requirements of position following accuracy on the master-slave side, realizes position following and force feedback bilateral servo control on the master-slave side, and has a strong robustness against random disturbance. Thus, it improves the operation performance of tele-operation system.

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