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Friction Compensation for Micro Tele-Operation Systems

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Original scientific paper

In this project, we construct micro tele-operation systems which enable human operators to performe micro tasks, such as assembly or manufacturing, without feeling a stress. We introduce haptic interfaces that give operators the impression as if he/she were touching the expanded micro objects with his/her fingers. We construct simulator systems modeled on remote environment. In this paper we give an outline and concept of this project.

This research project can not only extend bilateral tele-operation to many other industries, it can also extend this human-friendly technique and thus help realize savings in resources, energy, costs and human support.

Key words: tele-operation, haptic interfaces, parallel link, serial link, master-slave, bilateral, micro works, network, simulator, scaling

1. INTRODUCTION

Most of the small quantity production for trial manufacture in laboratory when developing new products and works such as inspection or repairing of products have to be done by human manufacturing because it is difficult to hope dramatic development in AI fields today.

These works force human to suffer a lot of stress by using microscope and micro tools.

Today products are evolving precise and complex more and more, however, on the other hand, workers are becoming older and older. Thus it is easy to forecast that precise works become more difficult in the near future.

These stressful works are caused by the difference of the scale between human and targets. Connecting human and targets by teleoperation enables free scaling between human and targets, so it is possible to solve these problem. Furthermore, since it also enables to separate workspaces from human environment in the distance, we can reduce the scale of factories and save energy. As it is also possible to work wherever by using network, it leads to saving energy of human transportation.

In this research we will construct the micro teleoperation systems which enable human operators to operate micro tasks, such as assembly or manufacturing of small components, without feeling stress. We introduce haptic interfaces, which give operators the presence as if he/she touches the expanded micro objects with his/her fingers.

2. SYSTEM COMPOSITION

In this research we developed micro teleoperation systems shown in Figure 1. We introduce not only visual interfaces but also original haptic interfaces which feedback force and offer the presence to operators. For slave device, we developed a parallel link manipulator [1, 2]. In general, parallel link structure has good features of precision and stiffness, although it has small workspace and many singular points [3]. We adopted this structure because we thought its characteristic is proper for precise works.

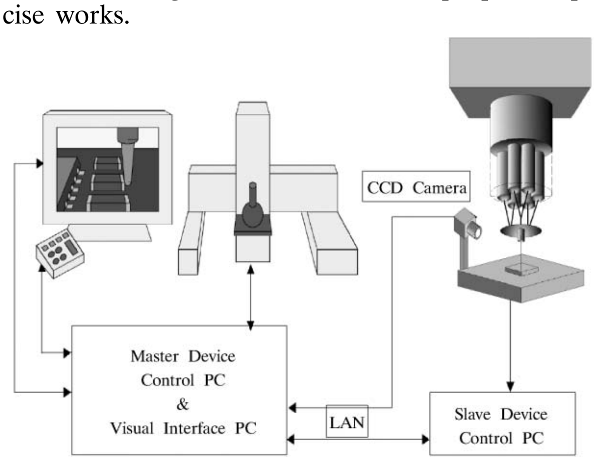

Fig. 1 Overview of the Micro Tele-Operation System

3. SLAVE DEVICE

As a slave device, we developed parallel link manipulator what has 6 degrees of freedom. It has 3 degrees of freedom for XYZ linear motion and 3 degrees of freedom for rotation of each axis. Its workspace is almost 30 mm × 30 mm × 30 mm for linear motion and 15 degrees for rotation. Different from general Stewart Platform, it has novel structure: Six links which sprouted verticality from base table can expand and contract. Each two links of six links are combined into one by sublink. Ultimately, the end effector table is holded by total 3 points. The structure is shown on Figure 2.

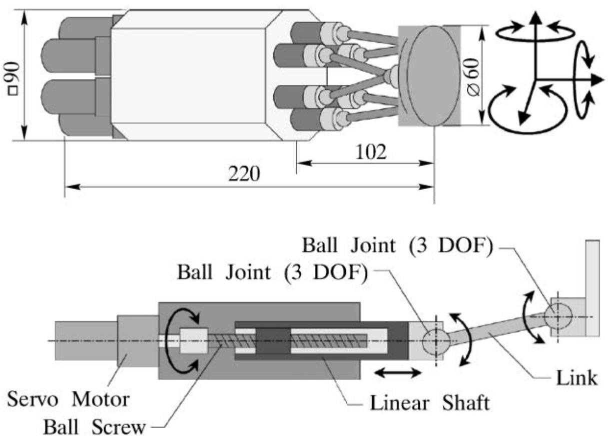

Fig. 2 Structure of slave device

Fig. 3 The appearance of the slave device

By adopting this structure, we can save space although analysis of kinematics and dynamics becomes difficult. Workspace and singular points, peculiar to this structure, need to be analyzed. The appearance of the slave device is shown in Figure 3.

4. SLIDING MODE BASED DISTURBANCE OBSERVER

Consider the following model with external disturbances and uncertain parameters satisfying the so-called Drazenovic condition [4], written in the regular state equation form,

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} \begin{bmatrix} \overline{A}_{11} & \overline{A}_{12} \\ \overline{A}_{21} + \Delta A_{21} & \overline{A}_{22} + \Delta A_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \\ + \begin{bmatrix} 0 \\ \overline{B}_2 + \Delta B_2 \end{bmatrix} u^0 + \begin{bmatrix} 0 \\ E_2 \end{bmatrix} f(t) \qquad (3)$$

where $x_1 \in R^{n-m}, x_2 \in R^m, u \in R^m, \overline{A}_{ij}(i,j=1,2)$ and $\overline{B}_2$ denote the nominal or desired (ideal) system matrices. The bar $\overline{\bullet}$ refers to the reference value in this paper. $\Delta A_{2,j}(j=1,\ 2)$ and $\Delta \overline{B}_2$ are the respective uncertain perturbations and $f(t)$ is an unknown, but bounded disturbance with bounded first time derivative with respect to time.

Now η is defined as the uncertainties and the disturbance of the system.

$$\eta = \Delta\overline{A}_{21} x_1 + \Delta\overline{A}_{22} x_2 + \Delta\overline{B}_2 u^0 + E_2 f(t) \qquad (4)$$

The second line of (3) can be rewritten by η.

$$\dot{x}_2 = \overline{A}_{21} x_1 + \overline{A}_{22} x_2 + \overline{B}_2 u^0 + \eta \qquad (5)$$

According to [5], $\hat{x}_2$ is estimated by a discontinuous observer:

$$\dot{\hat{x}}_2 = \overline{A}_{21} x_1 + \overline{A}_{22} \hat{x}_2 + \overline{B}_2 (u^0 + \nu) \qquad (6)$$

where ν is the discontinuous feedback. The goal of the design to find a feedback signal, denoted ν, such that the motion of the system (3) is restricted to belong the manifold S.

$$S = \left\{ x_2 \middle| \sigma = x_2 - \hat{x}_2 = 0 \right\} \quad \text{where} \quad \sigma \in R^m. \qquad (7)$$

The simplest control law, which can lead to sliding mode, is the relay:

$$\nu_i = M_i \operatorname{sign}(\sigma_i). \qquad (8)$$

If η is in the range of B_2 ($\eta \subset \text{range}\ (B_2)$), the ideal sliding mode occurs [6].

If the system trajectory is on the sliding surface then there is a continuous control signal, so called equivalent control signal, v_{eq}, which can hold the system on the sliding manifold, (but it does not guarantee the convergence to the sliding manifold in general). If the system is in sliding mode ($\sigma = 0$ and $\dot{\sigma} = 0$),

$$\dot{\sigma} = \underbrace{\Delta A_{21} x_1 + \Delta A_{22} x_2 + \Delta B_2 u^0 + E_2 f}_{\eta} - \overline{B}_2 v_{eq} \quad (9)$$

$$\overline{B}_2 v_{eq} = \Delta A_{21} x_1 + \Delta A_{22} x_2 + \Delta B_2 u^0 + E_2 f = \eta \, . \quad (10)$$

Clearly, v_{eq} contains information on the system's parametric uncertainties and the external disturbance, which can be used for feedback compensation.

Supposing for the time being that v_{eq} is known and a modified control input signal is used.

$$u^0 = u - v_{eq} \, . \quad (11)$$

According to (5) and (10), the system response for (11) coincides with the nominal or ideal, undisturbed system response for the control u,

$$\dot{x}_2 = \overline{A}_{21} x_1 + \overline{A}_{22} x_2 + \overline{B}_2 u \underbrace{- \overline{B}_2 v_{eq} + \eta}_{0} \, . \quad (12)$$

In the practice, there is no way to calculate the equivalent control v_{eq} precisely, but it can be estimated by a low pass filter for v as showed in Figure 4. In [7] an additional control parameter introduced, instead of low pass filter. There are two loops on Figure 4. The observer – sliding mode controller loop should be as fast as possible to achieve an ideal sliding mode. This is granted because this loop is realized in a computation engine in the recent application. The real system – compensator (consisting of Sliding Mode Controller and LPF) loop should be faster than the change of the disturbance. On the other hand, the smallest unmodeled resonant frequency of real system should be out of the bandwith of that loop to avoid chattering.

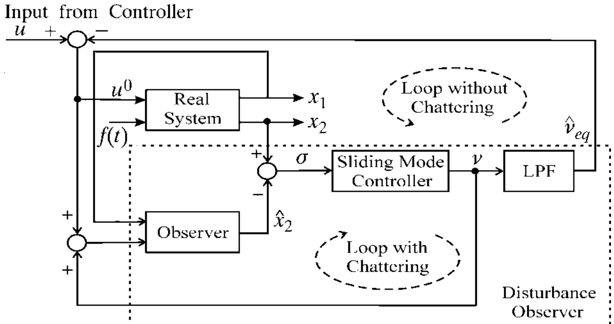

Fig. 4 Sliding mode based feedback compensation

5. CHATTERING FREE IMPLEMENTATION OF SLIDING MODE

The robustness of continuous time sliding mode control is realized by the high-frequency switching of the discontinuous observer feedback signal ν. To adapt the sliding mode philosophy for a discrete time observer [7], the sampling frequency should be increased compared to Lumberger observer. If the switching frequency of the relay (8) is not enough high, σ might chatter around the manifold $\sigma = 0$ as shown on Figure 5, where T^k denotes the time of k-th sampling. In case of discrete-time observer, the observer feedback signal ν may switch from $+M_i$ and $-M_i$ and vice versa resulting $\nu_{eq}^k = 0$ even if $\nu_{eq} \neq 0$. The bigger the M_i is, the bigger the chattering is. In the other hand, if M_i is smaller than the disturbances, it cannot eliminate it.

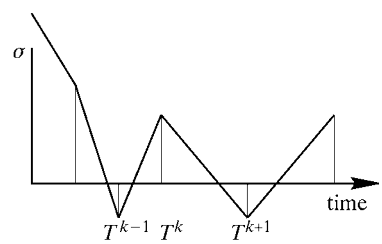

Fig. 5 Discrete-time chattering phenomenon

Applying the Lyapunov stability theory, let the positive definite Lyaponov function candidate is chosen in the following form:

$$V = \sigma^T \frac{\sigma}{2} \, . \quad (13)$$

The observer feedback is chosen in such a way, that the derivation of the Lyaponov function meet the following condition:

$$\dot{V} = \sigma^T \dot{\sigma} < 0 \, , \quad (14)$$

As it was proposed in [7, 8], the condition (14) is satisfied if

$$\dot{V} = -\sigma^T D \sigma \quad \text{in other words:} \quad \dot{\sigma} = -D\sigma \quad (15)$$

where D is a positive definite matrix. According to (5), (6) and (7)

$$\dot{\sigma} = \overline{A}_{22} \underbrace{(x_2 - \hat{x}_2)}_{\sigma} - \overline{B}_2 (\nu + \eta) \quad (16)$$

Applying (10), the equivalent observer feedback can be expressed from (16)

$$\nu_{eq} = \nu + \overline{B}_2^{-1} (\dot{\sigma} - \overline{A}_{22} \sigma) \quad (17)$$

To meet the condition (15), the observer feedback is chosen in the following way

$$\nu = \bar{B}_2^{-1}\sigma(D + \bar{A}_{22}) + \nu_{eq} \,. \qquad (18)$$

The first term is responsible for the chattering free reaching of the sliding manifold, but it is 0, if the system in sliding mode. Since ν_{eq} is not known, it must be estimated. Supposing, that the equivalent observer feedback is changing smoothly, (17) is estimated at the k-th sampling period by

$$\hat{\nu}_{eq}^{k} = \nu^{k-1} + \bar{B}_2^{-1}\left((\sigma^k - \sigma^{k-1})/T - \bar{A}_{22}\sigma^k\right) \quad (19)$$

where T is the sampling period. Substituting (19) in the discrete form of (18)

$$\nu^k = \nu^{k-1} + (\bar{B}_2')^{-1}(D'\sigma^k - \sigma^{k-1}) \qquad (18)$$

where $\bar{B}_2' = \bar{B}_2 T$, and $D' = TD + I$.

6. EXPERIMENTAL RESULTS: DESIGN OF FRICTION COMPENSATION FOR A SINGLE JOINT

The method described in Section 4 was applied for a single joint. From the point of view of the operator the whole dynamics of the mechanism (not only the friction) is disturbance. The whole dynamics of the system cannot be eliminated (since it would needed infinite input power) but the effect of the friction can be depressed. The aim of the compensation is to make the system follow an ideal model, which has small friction and with small dynamics. In other words, because of the compensation, the operator feels that it is very easy to move the master device. The optimal force feedback for the most comfortable telemanipulation can be a subject of another research. In this paper, the nominal parameters of the corresponding motor are used to calculate the ideal model of the dynamic of a joint. In other words, the effect of the mechanism are ignored. The control parameters were tuned and the effect of friction compensation was verified by a position control experiment.

In this experimental two type of control pattern was introduced:

– PD type controller without friction compensation
– PD type controller with friction compensation.

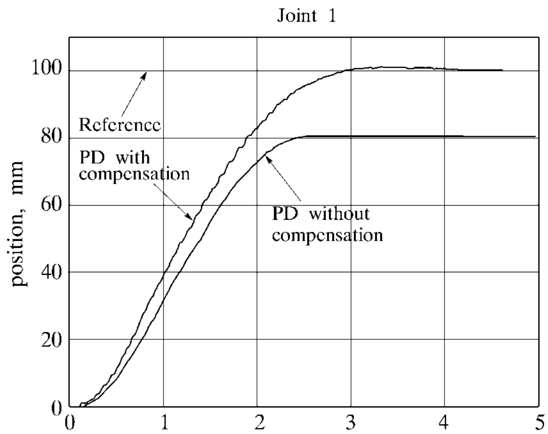

Fig. 7 PD type controller with and without disturbance observer

Figure 7 shows the time functions of the reference and the measured positions. It is well known, that the PD controller can not eliminate the steady state error (see Figure 7) the motor is sticked before reaching the reference value. The additional external disturbance increases the error dramatically. The same PD controller with disturbance observer and compensator can eliminate these errors (see Figure 7). The position signal can reach the reference signal and the external disturbance is also eliminated. These results demonstrate the effectiveness of the sliding mode based disturbance observer, when external disturbance occurs. The advantage of this method that it does not need model inversion, which was the main problem in case of the inverted model, based disturbance observer.

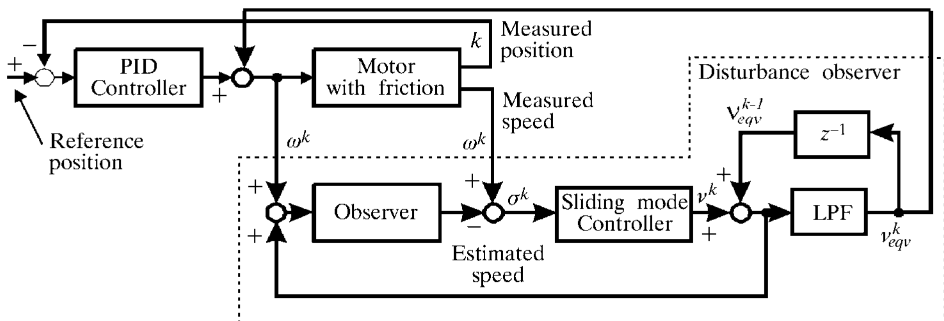

Fig. 6 Overall control sheme for position control

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Kompenzacija trenja u mikrosustavima upravljanja na daljinu. Opisana je izvedba mikrosustava za rad na daljinu koji omogućava bez stresa obavljanje mikroradnji, kao što su montaža i proizvodnja. Prikazano je haptičko sučelje kojim se oponaša dodir uvećanog mikroobjekta prstima rukovatelja. Također je opisan koncept sustava i simulator sustava. Istraživanje izloženo u ovome radu, osim što može uvesti daljinsko upravljanje na mikro razini u mnogim granama industrije, otvara i mogućnosti primjene za štednju resursa, energije i troškova.

Ključne riječi: upravljanje na daljinu, haptičko sučelje, paralelna veza, serijska veza, bilateralnost, mikrorad, mreža, simulator

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