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Remote haptic sensing using sliding-mode assist disturbance observer as force detector

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Abstract: Bilateral controlled master–slave robot system is an important intermediary to realise remote haptic sensing. This study proposes a sliding-mode assist disturbance observer (SMADO) to detect force information in wider bandwidth without force sensors by making use of the fast switching of sliding-mode control values. Moreover, a bilateral control law is proposed based on the SMADO. The proposal tolerates the presence of disturbances and uncertainties in the robots. The influence of these factors is degraded by using the net forces to design the bilateral control rather than employing a robust compensation. This design shows such a feasibility that high performance haptic sensing can be achieved using the SMADO as a wide bandwidth force detector without any robust compensators. The validity of the proposal is confirmed by experiments in practice. The proposal realises the position tracking and action–reaction law between the two robots, which makes the operator vividly feel the remote object.

1 Introduction

Transmitting the haptic sense is a challenging technology to extend and enhance human hands with many potential applications, such as space exploration, nuclear engineering and telesurgery [1]. This technology can be traced back to the teleoperation with bilateral control law in past decades. In a bilateral control system, there is a master robot and a slave robot, which transmit the motion and the forces between the human operator and the environment object. Therefore bilateral control system plays a role of an intermediary between the human operator and the environment object [2–5].

Human beings sense an environment object through the mechanical distortion of the object and the reaction forces [6]. Therefore, in bilateral control system, a correspondence of positions and action–reaction forces between the master and the slave is always desired [7]. To achieve satisfactory performance, many efforts were reported in the literature. The most effective and famous one is Lawrence's four-channel control framework [8]. This method uses local and remote information of positions and forces in the control of each robot. However, there are two main problems in the algorithm. One is the requirement of force sensors. The other is the influence of disturbances and uncertainties.

The force sensors increase system cost, hardware mounting difficulty and spatial requirements [9]. Besides, the bandwidth of force sensor always limits the practical performance of a bilateral control algorithm. On the other hand, the forces from the operator and the environment are not only inputs to the bilateral control but also disturbances to the master and slave robots [10]. Moreover, uncertainties of the robots also influence the performance of traditional bilateral control. Therefore the bilateral control system with disturbance rejection and without force sensors are investigated by more and more researchers.

Sumiyoshi and Ohnishi [11] introduced the disturbance observer (DOB) [12] into the four-channel control, and successfully improved the performance of such a system. However, the DOB only deals with the disturbances and uncertainties in low frequencies. To improve the disturbance rejection and further improve the performance of haptic sensing, sliding-mode control was designed for bilateral control system [13–15]. These approaches still require force sensors in practice. To solve the problem of force measurement, sliding-mode observers were proposed [16, 17]. However, in these methods, low-pass filters (LPFs) are used to smooth the signals, which leads to the lack of force estimation in wider bandwidth. Besides, the model mismatching results in the force estimation error. Hace and Franc proposed the sliding-mode methods without force sensors [18–20]. In this method, the sliding-mode technique is still used to design a robust controller to suppress the disturbances. The force measurement is realised by the reaction force observer (RFOB) [21], which achieves force measurement in low frequency domain without force sensors. In our previous work, a sliding-mode assist disturbance observer (SMADO) was also presented to compensate the disturbances in wider bandwidth with better chattering alleviation in the robots [22]. The force measurement is also independently realised using the RFOB. It is proved that the sliding-mode methods effectively enhance the ability of disturbance rejection for a robot. However, there are significant problems in the previous methods. The disturbance compensation is a strong robust control loop in a robot. Limited by the system stability, complete disturbance compensation is difficult, because the gain in the disturbance compensation cannot be greater. Moreover, the force estimation error caused by the model mismatching is not considered in past works.

In fact, there are two factors influencing the performance of the haptic sensing. One is the robustness against the disturbances; the other is the accuracy of the force measurement. Therefore this paper proposed the second feasibility to achieve high performance bilateral control, which designs the SMADO as a 'force sensor' rather than a robust compensator. In the proposal, the disturbances, dynamic uncertainties are tolerated to remain in the system with little influence on the performance of haptic sensing. The key to realise such a system is a net forces measurement in wide bandwidth. In this paper, we present a SMADO to detect the residual forces in wider frequency domain. On the basis of this, a bilateral control algorithm is proposed. The SMADO does not work as a strong robust control loop. Then, it is not restricted by the stability of each single robot. Therefore the proposed algorithm is simpler to implement. More arbitrariness can be tolerated in designing the gain in the SMADO. In such a system, force sensors are not required anymore. The cost and complexity of the system

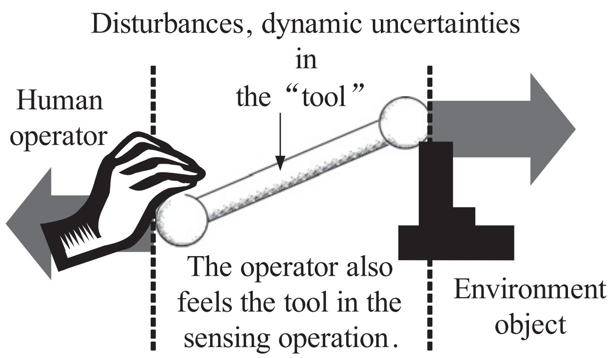

Fig. 1 *Haptic sensing system with tolerated disturbances and uncertainties*

are reduced. Experiments are implemented in practical system to confirm this method.

The paper is organised as follows. The problem of this research is formulated in Section 2. The SMADO-based bilateral control is designed in Section 3. The experimental results are illustrated in Section 4. Finally, Section 5 is the conclusion.

2 Problem formulation

The purpose of the proposed bilateral control is to realise such a system in Fig. 1. In the proposed system, the dynamic uncertainties and disturbances are treated as the natural characteristics and do not need to be compensated. In fact, the disturbances and dynamic uncertainties always exist in natural system. For example, when an operator uses a hammer to knock an object, the mechanical resonance always exists in the hammer, however, does not influence the sensing of the knocking operation. Therefore, in this paper, the operator senses an object through a 'tool' that is the bilateral control system. Meanwhile, the disturbances and dynamic uncertainties of the 'tool' does not influence the operator's haptic feeling.

The bilateral control system employs two robots, the master and slave robots. To simplify the deduction, the two robots are both considered as single-degree-of-freedom actuators without losing generality. The position response of the master robot, the position response of the slave robot, the external force exerted on the master robot and the external force exerted on the slave robot are denoted as $x_{\mathrm{m}}(t)$, $x_{\mathrm{s}}(t)$, $f_{\mathrm{m}}(t)$ and $f_{\mathrm{s}}(t)$, respectively.

The objective of this research is to realise a bilateral haptic transmission by designing bilateral control law. Human beings feel the property of the environment object, mainly the hardness and softness, by touching the object and feeling the deformation and reaction force. Therefore, to realise the haptic transmission, the bilateral control system should be designed to achieve following objectives:

(1) To transmit the human action and make the operator sense the deformation of remote object, the system should make the error of position tracking between the master and the slave converge to zero that is, $x_{\mathrm{m}}(t) - x_{\mathrm{s}}(t) \to 0(t \to +\infty)$.
(2) If a robot contacts an environment object, the operator's force should be transmitted to the other robot; meanwhile, the force from the environment should be transmitted to the operator vividly when the system is in steady state, that is, $f_{\mathrm{m}}(t) + f_{\mathrm{s}}(t) = 0$ ($\ddot{x}_{\mathrm{m}}(t) = \ddot{x}_{\mathrm{s}}(t) = \dot{x}_{\mathrm{m}}(t) = \dot{x}_{\mathrm{s}}(t) = 0$).

Time variable t is omitted for simplification except particular explanation in this paper.

3 Proposed remote haptic sensing system

In this section, we present the SMADO-based bilateral control system to realise the remote haptic sensing with only position sensors.

3.1 Sliding-mode assist disturbance observer

The SMADO is designed to achieve a net force detection for each single robot in the bilateral control system. The SMADO in the master is the same as the one in the slave. In the system, the dynamics of a robot is described as the following equation

$$M_i\ddot{x}_i + B_i\dot{x}_i = u_iK_{\mathrm{f}i} + f_{\mathrm{d}i} + \delta_i(x,t), \quad i = \mathrm{m,s} \tag{1}$$

where M, B, x, u and K_{f} denote the inertia mass, damping, position response, control input and the force coefficient of the motor, respectively. The subscript i ($i = \mathrm{m,s}$) denotes the variable in the master robot or in the slave robot. For simplification, this subscript is omitted except special explanation.

The force coefficient K_{f} nearly does not change when the motor and motor driver are fixed. f_{d} denotes the external disturbance force that is applied on the robot after overcoming other disturbance forces, which means

$$f_{\mathrm{d}} = f - f_{\mathrm{F}} \tag{2}$$

where f_{F} is the disturbance that is mainly the friction in the robot. Therefore, if there is no force exerted on the robot, the robot mainly suffers from the friction. Normally, f_{F} is a non-linear function that has the Stribeck characteristic as (3). Here, f_{c}, f_{s}, c_{v} and D denote the Coulomb friction, maximum static friction, model coefficient and the viscous factor, respectively

$$f_{\mathrm{F}} = [f_{\mathrm{c}} + (f_{\mathrm{s}} - f_{\mathrm{c}})\exp(-c_{\mathrm{v}}|\dot{x}|)]\,\mathrm{sgn}(\dot{x}) + D\dot{x} \tag{3}$$

In (1), $\delta(x,t)$ is unknown time-varying non-linear dynamics of the robot, which is difficult for modelling. By assembling the parameters mismatching and the unknown dynamics into an equivalent uncertainty Δ, (1) can be rewritten as the following equation

$$M_{\mathrm{n}}\ddot{x} + B_{\mathrm{n}}\dot{x} = uK_{\mathrm{f}} + f_{\mathrm{d}} + \Delta \tag{4}$$

where M_{n} and B_{n} are the nominal mass and the nominal damping, respectively. Δ is the equivalent uncertainty as

$$\Delta = (M_{\mathrm{n}} - M)\ddot{x} + (B_{\mathrm{n}} - B)\dot{x} + \delta(x,t) \tag{5}$$

It is reasonable that $\sup_{\forall t\in[0,\infty)}|f_{\mathrm{d}} + \Delta| < \infty$ for a practical system. Then the force that is applied on the robot after overcoming the disturbance and the uncertainties can be detected to realise a high performance haptic sensing via the SMADO.

The SMADO contains a linear DOB and a non-linear compensation term based on the sliding-mode technique. The DOB estimates the component of $f_{\mathrm{d}} + \Delta$ in low frequency domain [12]. The block diagram is shown in Fig. 2, where, g_{dis} denotes the cutoff frequency of the LPF in the DOB. s is a Laplace operator. g_{v} is the cutoff frequency of the pseudo derivation. If g_{v} is great enough, $\hat{\dot{x}} \to \dot{x}$.

Then, the external force after overcoming the uncertainty is estimated through the LPF as the following equation

$$\widehat{f_{\mathrm{d}} + \Delta} = \frac{g_{\mathrm{dis}}}{s + g_{\mathrm{dis}}}(f_{\mathrm{d}} + \Delta) \tag{6}$$

The DOB only estimates $f_{\mathrm{d}} + \Delta$ in low frequency domain. The remain part in high frequency is estimated by the sliding-mode assist value.

Notice the dynamics of the robot and define a virtual subsystem as

$$M_{\mathrm{n}}\ddot{x}_{\mathrm{n}} + B_{\mathrm{n}}\dot{x}_{\mathrm{n}} = uK_{\mathrm{f}} + \widehat{f_{\mathrm{d}} + \Delta} + u_{\mathrm{c}} \tag{7}$$

where u_{c} is a sliding-mode assist value to be designed. $\widehat{f_{\mathrm{d}} + \Delta}$ is the output of the DOB. Then, define an error as the following equation

$$e = x - x_n \tag{8}$$

If $e = 0$, then $u_{\mathrm{c}} = f_{\mathrm{d}} + \Delta - (\widehat{f_{\mathrm{d}} + \Delta})$. Therefore, when $e = 0$, the output of the SMADO, $\widehat{f_{\mathrm{d}} + \Delta} + u_{\mathrm{c}}$, is equal to the real force

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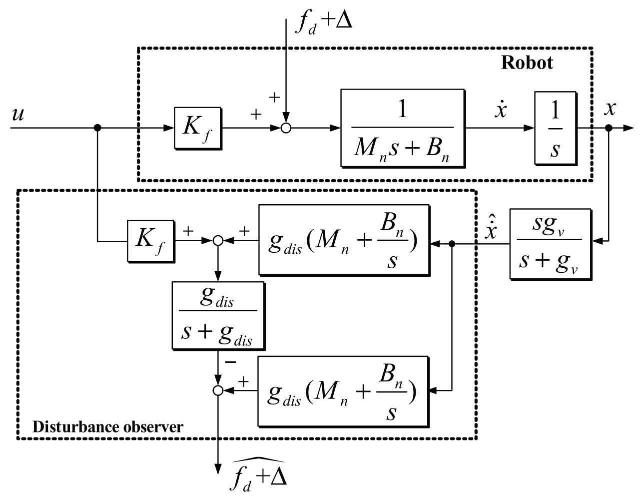

Fig. 2 *Block diagram of DOB*

after overcoming the uncertainties $f_\text{d} + \Delta$. The design of u_c should guarantee $e \to 0$.

Define a sliding mode z as the following equation

$$z = \dot{e} + \gamma e, \quad \gamma = \frac{B_\text{n}}{M_\text{n}} \tag{9}$$

Then, u_c is designed as the following equation

$$u_\text{c} = \kappa z + \psi \,\text{sgn}(z) \tag{10}$$

where κ is a positive constant gain and ψ is a positive switching gain. sgn(z) is a sign function that is defined as the following equation

$$\text{sgn}(z) = \begin{cases} 1, & z > 0 \\ 0, & z = 0 \\ -1, & z < 0 \end{cases} \tag{11}$$

There is the following theorem.

Theorem 1: For system (4), if the condition $\psi \geq |f_\text{d} + \Delta - \widehat{(f_\text{d} + \Delta)}|$ is satisfied, z exponentially decays to zero, and e asymptotically decays to zero using the u_c in (10).

The proof of this theorem is shown in Appendix.

In this method, the sliding mode helps the DOB to estimate the net force. Here, the switching gain ψ is only required to be greater than $|f_\text{d} + \Delta - \widehat{(f_\text{d} + \Delta)}|$. In fact, the insufficient estimation of the original DOB is the high-frequency component. In practical system, the magnitude of this component is small. Therefore the required switching gain is also small. The chattering can be alleviated.

In the above design, the sliding-mode control value is an assistant for the estimation of the DOB: the insufficiency of the original DOB, the high-frequency component, is also estimated. In previous work on sliding-mode control, the switching gain always has to be designed conservatively as a constant. Moreover, the previous designs of the switching gain show arbitrariness because there is no benchmark to evaluate the magnitude of unknown disturbances. Here, we present a method on deciding the switching gain.

According to (6), the expression of the insufficient estimation $e_\text{d} = f_\text{d} + \Delta - \widehat{(f_\text{d} + \Delta)}$ is rewritten as (12) in Laplace domain

$$e_\text{d} = f_\text{d} + \Delta - \widehat{(f_\text{d} + \Delta)} = \frac{s}{s + g_\text{dis}}(f_\text{d} + \Delta) \tag{12}$$

It is clear that the insufficient estimation is caused by the limited bandwidth of DOB. Different cutoff frequencies mean the outputs of the DOBs contain information in different bandwidths. By comparing the outputs between the original DOB and another one with different bandwidths, the magnitude of the insufficient estimation of the original DOB can be also estimated. Therefore we should find the breakthrough to design the switching gain from the bandwidth. We design another parallel DOB with the cutoff frequency of g'_dis ($g'_\text{dis} > g_\text{dis}$). Calculating the error between the disturbance estimations of the parallel DOB and the original one, there is

$$\begin{aligned} \widehat{(f_\text{d} + \Delta)}' - \widehat{(f_\text{d} + \Delta)} &= \frac{g'_\text{dis}}{s + g'_\text{dis}}(f_\text{d} + \Delta) - \frac{g_\text{dis}}{s + g_\text{dis}}(f_\text{d} + \Delta) \\ &= \frac{(g'_\text{dis} - g_\text{dis})s}{(s + g'_\text{dis})(s + g_\text{dis})}(f_\text{d} + \Delta) \end{aligned} \tag{13}$$

where $\widehat{(f_\text{d} + \Delta)}'$ means the estimation of the parallel DOB. Equation (13) yields to

$$\begin{aligned} |e_\text{d}| &= \left| \frac{s}{s + g_\text{dis}}(f_\text{d} + \Delta) \right| \\ &= \left| \frac{s + g'_\text{dis}}{g'_\text{dis} - g_\text{dis}} [\widehat{(f_\text{d} + \Delta)}' - \widehat{(f_\text{d} + \Delta)}] \right| \end{aligned} \tag{14}$$

Therefore the switching gain in SMADO can be decided using (14) as a benchmark.

Equation (14) means that the switching gain ψ can be decided as $|e_\text{d}|$ directly without conservative design. A derivation is required here, which has calculation error in practice. However, if $g'_\text{dis} - g_\text{dis}$ is larger, the derivation term is smaller. Although there must be the calculation error, the benchmark can be still used to evaluate the unknown disturbance in some degree, which is better than a constant design. Besides, the gain $1/(g'_\text{dis} - g_\text{dis})$ of the derivation term also reduces the influence of the calculation error. In practice, one can also use the benchmark to design the switching gain by adding a small constant η as $\psi = |e_\text{d}| + \eta$ with a little conservation. In this paper, we directly use (14) as the switching gain to verify the effectiveness of the benchmark.

3.2 SMADO-based bilateral control

The remote haptic sensing is realised by the bilateral control. In such a system, the dynamics of the master–slave system is described as the following equation

$$M_\text{n}\ddot{x}_i + B_\text{n}\dot{x}_i = u_i K_{\text{f}i} + f_{\text{d}i} + \Delta_i, \quad i = \text{m, s} \tag{15}$$

The bilateral control based on the SMADO is presented as the following equation

$$\begin{aligned} &u_i = [K_\text{p}(x_j - x_i) + K_\text{v}(\dot{x}_j - \dot{x}_i) + \widehat{f_{\text{d}j} + \Delta_j} + u_{\text{c}j}]K_{\text{f}i}^{-1}, \\ &i, j = \text{m, s and } i \neq j \end{aligned} \tag{16}$$

Suppose that $e_\text{ms} = x_\text{m} - x_\text{s}$. With the bilateral control law (16), there is the following equation

$$\begin{aligned} &M_\text{n}\ddot{e}_\text{ms} + (B_\text{n} + 2K_\text{v})\dot{e}_\text{ms} + 2K_\text{p}e_\text{ms} \\ &\quad = f_\text{dm} + \Delta_\text{m} - (\widehat{f_\text{dm} + \Delta_\text{m}} + u_\text{cm}) \\ &\qquad - [f_\text{ds} + \Delta_\text{s} - (\widehat{f_\text{ds} + \Delta_\text{s}} + u_\text{cs})] \end{aligned} \tag{17}$$

According to the principle of the SMADO, (18) can be guaranteed

$$f_{\text{d}i} + \Delta_i - (\widehat{f_{\text{d}i} + \Delta_i} + u_{\text{c}i}) \to 0, \quad i = \text{m, s} \tag{18}$$

Therefore there is

$$M_\text{n}\ddot{e}_\text{ms} + (B_\text{n} + 2K_\text{v})\dot{e}_\text{ms} + 2K_\text{p}e_\text{ms} \to 0 \tag{19}$$

This means that the position response error between the master robot and the slave one converges to zero. The aim of $x_\text{m} - x_\text{s} \to 0$ is realised.

By calculating the sum of the dynamic equations of the two robots, it is obtained that

$$\begin{aligned} &M_n\ddot{x}_m + B_n\dot{x}_m + M_n\ddot{x}_s + B_n\dot{x}_s \\ &\quad = f_{dm} + \Delta_m + (\widehat{f_{dm} + \Delta_m} + u_{cm}) + f_{ds} + \Delta_s \\ &\qquad + (\widehat{f_{ds} + \Delta_s} + u_{cs}) \to 2(f_{dm} + \Delta_m + f_{ds} + \Delta_s) \end{aligned} \tag{20}$$

Since $x_m - x_s \to 0$, (20) also means (21) by supposing $x_{ms} = x_m = x_s$ when the system enters in the stationary state

$$M_n\ddot{x}_{ms} + B_n\dot{x}_{ms} = (f_{dm} + f_{ds}) + (\Delta_m + \Delta_s) \tag{21}$$

Equation (21) means that the external forces on the robots 'push' the two robots together. The direction of the two robots' motion follows the direction of the one under bigger force. Especially, when the robots does not move, there must be $f_{dm} + f_{ds} = 0$. It means that the external forces on the two remote robots are action–reaction forces. By the transmission of the consistent motion of the two robots and the action–reaction relationship, the remote haptic sensing is realised.

In the proposed scheme, the system needs less cost because there are no force sensors. Besides, the proposal has better stability because no robust compensators are required in the system. The estimated forces by the SMADOs contain more information than conventional DOB in high-frequency domain, which leads to better performance of the haptic sensing. In the above algorithm, only position and velocity are required. The system can be built with only high accuracy position sensors. The velocity information can be obtained by the pseudo differential to further decrease the system cost. The algorithm of the SMADO-based bilateral control is illustrated as the block diagram in Fig. 3.

To simplify the deduction, the master and slave robots are considered as single-degree-of-freedom actuators in this paper. For multi-degree-of-freedom robots, the application of the proposal can follow two lines. If each robot is mechanically decoupled, the proposal can be directly applied on each joint of the robot. If each robot is built with parallel mechanism and difficult to be decoupled, it is not hard to extend the proposal to multi-degree-of-freedom robots by describing the system in state-space equations and designing a multi-degree-of-freedom SMADO.

3.3 Analysis

To evaluate the performance of the proposal, transparency of the overall system is analysed as follows.

By substituting (16) into (15), the bilateral controlled system is rewritten as the following equation

$$\begin{aligned} M_n\ddot{x}_i + B_n\dot{x}_i &= K_p(x_j - x_i) + K_v(\dot{x}_j - \dot{x}_i) \\ &\quad + f_i + f_j + \Delta_i + \Delta_j - f_{Fi} - f_{Fj} + \tilde{\Delta}_j, \\ &\qquad i,j = \mathrm{m,s} \text{ and } i \neq j \end{aligned} \tag{22}$$

where

$$\tilde{\Delta}_j = f_{dj} + \Delta_j - (\widehat{f_{dj} + \Delta_j} + u_{cj}) \tag{23}$$

In past works, the hybrid matrix $\mathbf{H}$ is quantitatively evaluated as an effective indicator of the performance for bilateral control system as the following equation

$$\begin{bmatrix} f_m \\ -x_s \end{bmatrix} = \underbrace{\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}}_{\mathbf{H}} \begin{bmatrix} x_m \\ -f_s \end{bmatrix} \tag{24}$$

According to the objectives mentioned in Section 2, ideal transparency means $h_{11} = h_{22} = 0$ and $h_{12} = -h_{21} = 1$. However, ideal transparency is impossible to realise in practical system. According to (22), the transparency of the proposed system can be illustrated as the following equation

$$\begin{bmatrix} f_m - f_{Fm} + \Delta_m \\ -x_s \end{bmatrix} = \mathbf{H} \begin{bmatrix} x_m \\ -(f_s - f_{Fs} + \Delta_s) \end{bmatrix} + \tilde{\mathbf{H}} \begin{bmatrix} \tilde{\Delta}_m \\ \tilde{\Delta}_s \end{bmatrix} \tag{25}$$

where

$$\mathbf{H} = \begin{bmatrix} \dfrac{1}{G} & 1 \\ -1 & 0 \end{bmatrix} \tag{26}$$

$$\tilde{\mathbf{H}} = \begin{bmatrix} \dfrac{G^{-1} + C_p}{G^{-1} + 2C_p} & \dfrac{C_p}{G^{-1} + 2C_p} \\ \dfrac{1}{G^{-1} + 2C_p} & -\dfrac{1}{G^{-1} + 2C_p} \end{bmatrix} \tag{27}$$

In the equations, G means the transfer function of a robot as (28). C_p denotes the position controller as the following equation

$$G = \frac{1}{M_n s^2 + B_n s} \tag{28}$$

$$C_p = K_p + K_v s \tag{29}$$

When conventional DOB is used to realise the proposed bilateral control algorithm (16), the term $[\tilde{\Delta}_m \ \tilde{\Delta}_s]^T$ equals the estimation error of the DOB in high-frequency domain. This means the transparency of the bilateral control system is degraded. However, the SMADOs in the robots guarantee that (18) is satisfied, which means $[\tilde{\Delta}_m \ \tilde{\Delta}_s]^T \to \mathbf{0}$ in (25). Therefore the sliding-mode value effectively helps to improve the transparency.

With the SMADO, (25) is simplified to (30). The dynamic uncertainties Δ_m, Δ_s and the viscous friction are small values in low frequency domain. Besides, $|1/G|$ is also a quite small value in low frequency domain. Therefore, high transparency can be achieved with the proposal

$$\begin{bmatrix} f_m - f_{Fm} + \Delta_m \\ -x_s \end{bmatrix} = \underbrace{\begin{bmatrix} \dfrac{1}{G} & 1 \\ -1 & 0 \end{bmatrix}}_{\mathbf{H}} \begin{bmatrix} x_m \\ -(f_s - f_{Fs} + \Delta_s) \end{bmatrix} \tag{30}$$

Compared with conventional schemes of bilateral control, deliberate force control is not designed in the proposed approach. However, equivalent performance of force control is still achieved with unity gain.

4 Experiments

The experiments are implemented to verify the proposal. The experimental setup and the results are illustrated in Sections 4.1 and 4.2, respectively.

4.1 Experimental setup

The experiments are separated into two parts. Firstly, simulation experiments are conducted to evaluate the advantages of using the proposed control scheme. Secondly, practical experiments are implemented to assess the performance of the proposal in real systems.

4.1.1 Simulation setup: In this paper, the SMADO plays the role of 'force sensor' rather than the robust compensator. Virtually, some real robots have complex uncertainties such as the resonances in high frequency. Such a system may be unstable when a robust compensator is used. In this paper, two cases are simulated. In case one, two SMADOs are employed as robust compensators, which is same as the situation of [22]. In case two, the

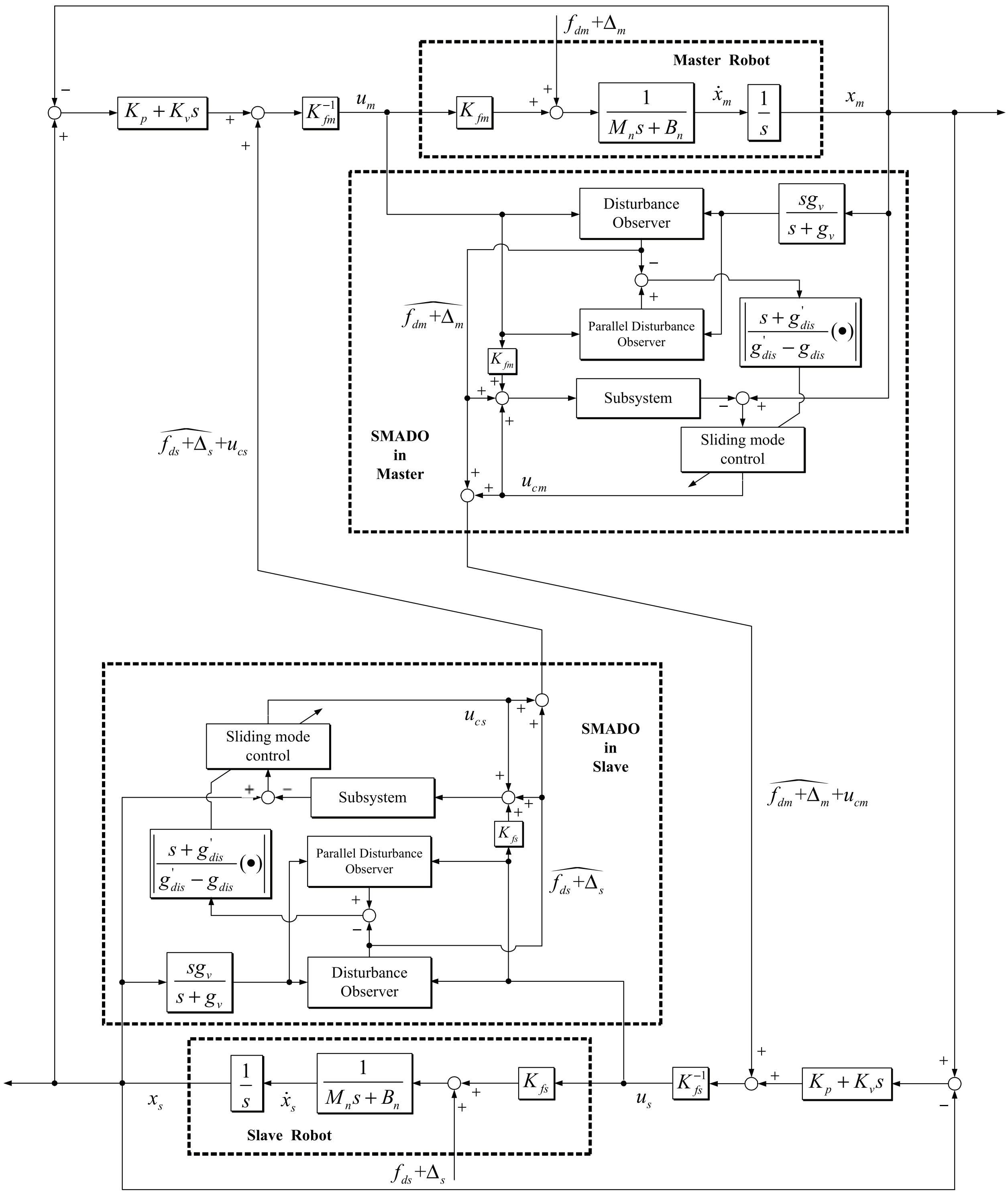

Fig. 3 *DOB-based four-channel bilateral control structure*

SMADOs are used as the force detectors as Fig. 3. In the simulation, resonances are added into the master and the slave robots. The transfer function of the robots are both $[1/(0.5s^2 + 0.1s)] + [5/(s^2 + 2 \times 0.04 \times 3000 + 3000^2)]$.

In the simulation, random noise with the magnitude of 0.5 µm is added in the response of each robot to simulate the measurement noise. In both the cases, the human operator and the environment are described using the spring-damping model as (31) and (32). K_h, D_h, K_e and D_e are the stiffness of the operator, damping of the operator, stiffness of the environment and the damping of the environment, respectively. x_h and x_e denote the desired position of the operator's motion and the placed position of the environment, respectively. The parameters of the operator and the environment are listed in Tables 1 and 2. Other parameters of the bilateral control are shown in Table 3.

$$f_\text{m} = K_\text{h}(x_\text{h} - x_\text{m}) - D_\text{h}\dot{x}_\text{m} \quad (31)$$

$$f_\text{s} = \begin{cases} -D_\text{e}\dot{x}_\text{s}, & x_\text{s} < x_\text{e} \\ K_\text{e}(x_\text{e} - x_\text{s}) - D_\text{e}\dot{x}_\text{s}, & x_\text{s} \geq x_\text{e} \end{cases} \quad (32)$$

Table 1 Parameters of the operator and environment in simulation

Parameters	Value
stiffness of the operator, N/m	$K_h = 280.0$
damping of the operator, kg/s	$D_h = 20.0$
stiffness of the environment, N/m	$K_e = 10000.0$
damping of the environment, kg/s	$D_e = 20.0$
placement position of the environment, m	$x_e = 0.05$

Table 2 Desired position of the operator in simulation

Time t, s	Desired position of operator, m
0–1	$x_h(t) = x_m(t)$
1–5	$x_h(t) = 0.015(1 - \cos 2\pi(t-1))$
5–9	$0.045(7t - (t^2/2) - 22.5)$
after 9	$x_h(t) = x_m(t)$

Table 3 Algorithm parameters in simulation

Parameters	Value
nominal mass, kg	$M_{nm} = M_{ns} = 0.35$
nominal damping, kg/s	$B_{nm} = B_{ns} = 0.5$
position gain, kg/s^2	$K_p = 10.0$
velocity gain, kg/s	$K_v = 40.0$
force coefficient, kg	$K_f = 30.0$
DOB cutoff frequency, rad/s	$g_{dis} = 200.0$
parallel DOB cutoff frequency, rad/s	$g'_{dis} = 300.0$
range of the saturation function [–]	$\chi = 2.0 \times 10^{-4}$
gain in SMADO [–]	$\kappa = 10.0$

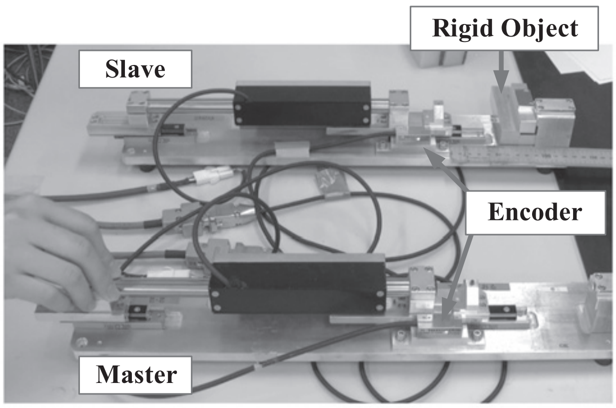

Fig. 4 *Experimental devices*

4.1.2 *Practical experiments:*

The devices in the experiments are shown in Fig. 4. Two single-degree-of-freedom robots are employed. The position information is measured by the optical-electricity encoders. The velocity of each robot is measured by the pseudo derivation as $500s/(s+500)$. The algorithms are programmed in a Linux RTAI real time system with the sampling time T_s of 0.1 ms. The SMADO is designed with the saturation function (36) as in the Appendix. Other parameters are the same as the parameters in Table 3. In the experiments, the operator senses a rigid aluminium block. After once sensing operation, the place of the operator is swapped with the object to test the bilateral haptic sensing.

4.2 Experimental results

4.2.1 *Results of simulation:*

Firstly, the results of the two cases in simulation are illustrated in Figs. 5 and 6. According to Fig. 5, the system is unstable. In this case, the SMADO works as a strong robust against the disturbance including the model uncertainties, which means the system has low sensitivity in wide bandwidth. According to the small gain theorem, the stability of such a system is weakened. In such robots, the uncertainties may be stimulated by the compensated values of the SMADOs.

However, when the SMADOs are employed as force detectors, the bilateral control system is stable even though there are resonances in the robots. The stability of each robot is not degraded, because the SMADOs work as only wide bandwidth force detectors rather than robust compensators.

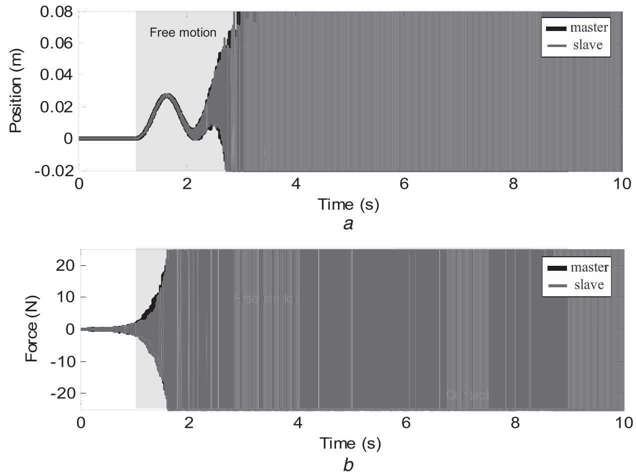

Fig. 5 *Results when the SMADOs work as robust compensators*

a Position responses
b Force responses

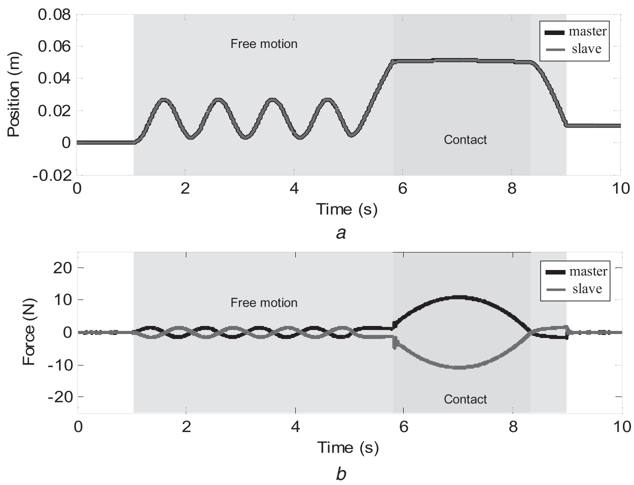

Fig. 6 *Results when the SMADOs work as force detectors*

a Position responses
b Force responses

4.2.2 *Results of practical experiments:*

Fig. 7 shows the results when the aluminium block is used as the rigid object to be sensed. According to Figs. 7*a* and *c*, good performance of the position tracking between the two robots is obtained even though the slave robot contacts the aluminium block and the operator changes the operational force. There is some position error in the state of contact, which is caused by the calculating error in the differential estimation of the pseudo derivation. However, this position error is still small and converges to zero after the contact action. According to Figs. 7*b* and *d*, the detected forces in the two robots satisfy the action–reaction law when contact occurs. According to Figs. 7*e* and *f*, the switching gains are small except in the moment of

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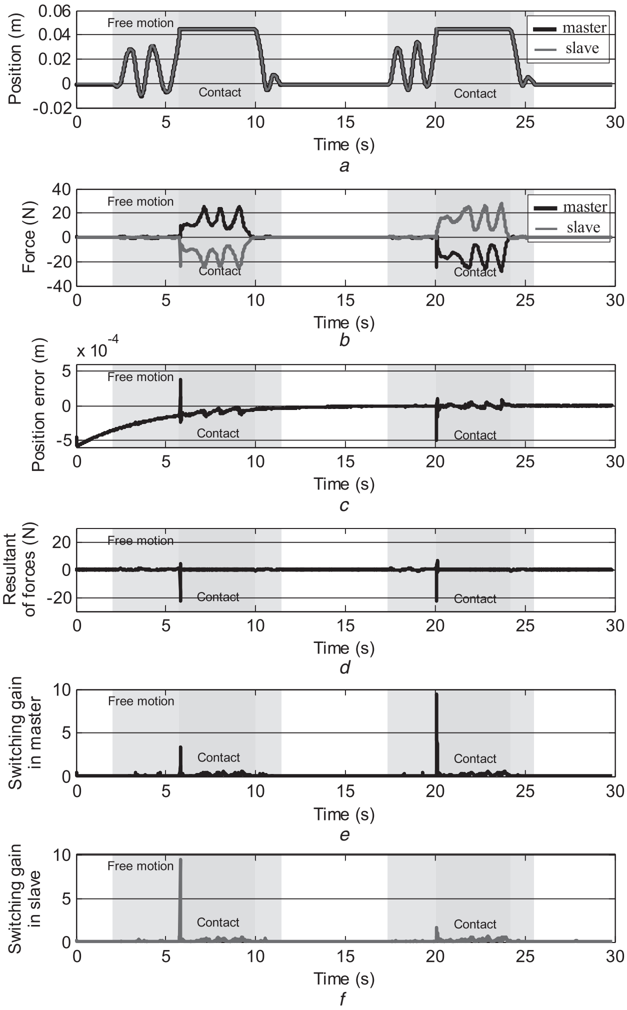

Fig. 7 *Results of sensing the rigid object by the proposal*

a Position responses *b* Force responses
c Position error between the master and the slave
d Resultant of the forces on the master and the slave
e Switching gain of the SMADO in the master
f Switching gain of the SMADO in the slave

contact. The reason is that the impact action on a hard object generates great reaction force in the moment. According to Figs. 7*d–f*, there is a transient error in the summation of the forces. This only occurs at the beginning of the contact, because the switching gain is great at the moment. However, this error is well reduced benefiting from the adjustment of the switching gain. The proposal has quite small chattering at most of the time. The SMADOs successfully detect the fast changing forces and provide this information for the bilateral control. Therefore high performance haptic sensing is guaranteed.

The bilateral control is symmetric. Therefore the performance of the position tracking and the forces transmission does not change with whether the master robot is operated or the slave one is operated. This is also verified by the experiments.

For comparison, another experiment is also implemented using conventional DOB as the force detector. In this experiment, the bilateral control scheme still follows Fig. 3. However, the role of SMADO is replaced by the conventional DOB. The parameters are also the same as Table 3. According to the results in Fig. 8, the position error between the master and the slave is obviously bigger than the situation when the SMADO is used. The fast changed operational force and the reaction force from the environment are not completely measured and transmitted to the other robot. Then, the real operational force is not balanced by the reaction force rapidly. The insufficiency of the force measurement degrades the

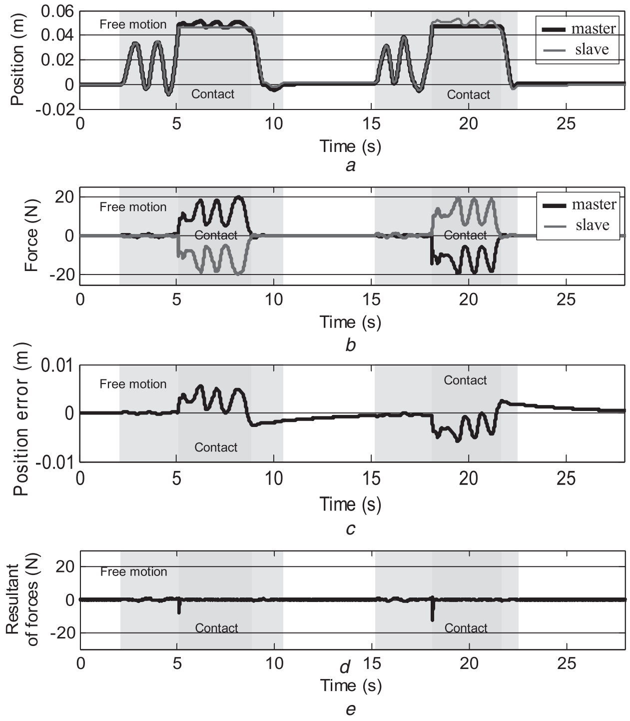

Fig. 8 *Results of sensing the rigid object by conventional DOB*

a Position responses
b Force responses
c Position error between the master and the slave
c Resultant of the forces on the master and the slave

performance of the bilateral control system. This result agrees with the analysis of transparency. The comparison illustrates that the SMADO effectively improves the performance.

5 Conclusions

The remote haptic sensing has many potential applications. In this paper, the method of SMADO was presented to detect the net forces exerted on the robots in wider bandwidth instead of force sensors. The switching control value was small in this proposal, which alleviated the oscillation in the output of the SMADO. The presented SMADO was not designed as a robust controller any more. The output of SMADO was not fed back, but provided to the other robot as a net force measurement.

With wide bandwidth estimation of the force information, a simplified bilateral control was proposed. In theory, the position error between the two robots converges to zero when the algorithm is implemented. Besides, the action and reaction law is realised between the forces exerted on the two robots in low frequency. This proposal shows another feasibility to realise high performance haptic transmission by improving the force detection rather than using the robust compensation. Besides, the system needs only position sensors, which means the reduction of system cost.

Simulation and experiments were implemented. The proposal improves the stability of the bilateral control when there are model uncertainties in the robots. According to the experimental results, the remote haptic sensing system was well realised even though the object to be sensed was rigid. The availability and the validity were confirmed.

In future works, the technique of terminal sliding-mode control will be investigated to shorten convergence time of the SMADO. Then, the output of the SMADO will faster converge to the real value of the equivalent disturbance force, which improves the performance of haptic transmission at the moment of the contact operation.

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8 Appendix

Proof of Theorem 1: Define a positive definite Lyapunov candidate by the following equation

$$V(z) = \frac{1}{2}M_{\text{n}}z^2 \tag{33}$$

Then, the time derivative of $V(z)$ is deduced as (34) according to (7)–(10)

$$\begin{aligned}\dot{V}(z) = z \cdot M_{\text{n}}\dot{z} &= -\kappa z^2 - z\psi\,\text{sgn}(z) + z[f_{\text{d}} + \Delta - (\widehat{f_{\text{d}} + \Delta})] \\ &\le -\kappa z^2 - z\psi\,\text{sgn}(z) + |z||f_{\text{d}} + \Delta - (\widehat{f_{\text{d}} + \Delta})| \\ &= -\kappa z^2 - |z|\left[\psi - |f_{\text{d}} + \Delta - (\widehat{f_{\text{d}} + \Delta})|\right]\end{aligned} \tag{34}$$

If $\psi \ge |f_{\text{d}} + \Delta - (\widehat{f_{\text{d}} + \Delta})|$, there is $|z|\left[\psi - |f_{\text{d}} + \Delta - (\widehat{f_{\text{d}} + \Delta})|\right] \ge 0$. Therefore $\dot{V}(z) \le -\kappa z^2 = -2(\kappa/M_{\text{n}})V(z) \le 0$ is met. According to (33), there is

$$z^2(t) \le z^2(0)\exp\left(-\frac{2\kappa}{M_{\text{n}}}t\right) \tag{35}$$

which implies that z exponentially decays to zero. Then, according to the definition of $z = \dot{e} + \gamma e$, e asymptotically decays to zero.

Remark 1: The convergence is local asymptotic stability. Any outer loop controllers also influence the stability of a closed-loop control system. Therefore the parameters of outer loop controllers should be adjusted by trial and error in engineering practice.

In engineering practice, the sgn(z) is usually replaced by the saturation function (36) to weaken the chattering further

$$\text{sat}\,(z) = \begin{cases} 1, & z > \chi \\ \frac{z}{\chi}, & |z| \le \chi \\ -1, & z < -\chi \end{cases} \tag{36}$$

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