A Shared Compliant Control Scheme based on Internal Model Control

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Abstract: A shared compliant control scheme based on IMC is proposed for the position-force force reflecting control system. The controller of the slave manipulator is designed by IMC method for the open loop unstable plant. The compliant control is implemented by first order low pass filter. In the proposed scheme, the slave manipulator well tracks the position of the master manipulator in free space and the compliance of the slave manipulator is autonomously controlled in contact condition. The simulation results show that the excellence of the proposed controller.

Keywords: Compliant control, force reflecting, teleoperation, internal model control

1. INTRODUCTION

Force reflecting control systems present a technical alternative for intelligent robotic systems performing dexterous tasks in unstructured environments such as nuclear facility, outer space and underwater. Since force reflecting control systems include continuous human intervention into the control loop, it is important to provide realistic sensory feedback of the environmental interactive forces to the operator. When the slave manipulator contacts on the highly rigid environment, the contact force is rapidly increased. Compliance control method is introduced to increase the compliance of the slave manipulator in contact case. The compliance of the slave manipulator can be controlled by passive or active compliance method. In the passive compliance method, the specially designed mechanical structures such as a spring-loaded wrist or a RCC (remote compliance center) are used. The passive mechanical devices are typically capable of quick responses and are relatively inexpensive. However, since the compliance parameters of a passive mechanical device are fixed, different tasks may require different mechanical structures. In active compliance method, a programmable active device allows adjusting compliance parameters and coordinate transformation in software. Different parameters and transforms can be used according to different phases of an assembly task. However, quick response is usually difficult to achieve with active compliance due to the stability problem of the force/torque feedback. Shared compliant control has been implemented recently as a new feature added on the force reflecting control system. Shared compliant control means that the control task is shared by both the human operator's direct manual control and the autonomous compliant control of the slave manipulator. Kim proposed a shared compliance control scheme, which is implemented by first order low pass filter [1], and Venkataraman proposed a compliance control scheme based on neural network [2]. Ahn et al proposed a compliance control scheme for the force reflecting control system in which the slave manipulator has the saturation nonlinearity [3].

The IMC (internal model control) structure has been implemented as an alternative to the classic feedback structure. The main advantage of the IMC is that closed loop stability is assured simply by choosing a stable IMC controller for the open loop stable plants [4]. Goodwin et al proposed an IMC structure for the open loop unstable plants [5].

In this paper, a shared compliant control scheme based on IMC is proposed for the position-force force reflecting control system. The controller of the slave manipulator is designed by IMC method for the open loop unstable plant. The autonomous compliant control is implemented by first order low pass filter. The compliant control problems are formulated for 1-DOF position-force force reflecting system in section 2, and a proposed shared compliant control scheme and a controller design method are proposed in section 3. In section 4, the performances of the proposed scheme are shown through a simulation study.

2. PROBLEM FORMULATION

2.1 Modeling of 1-DOF force reflecting system

Most force reflecting control systems consist of arms with multiple DOF. However, a 1-DOF system is considered in order to make the problem simple. Fig. 1 shows the schematic diagram of the 1-DOF force reflecting control system. The dynamics of master manipulator and slave manipulator is given by the following equations:

$$\tau_m + f_m = m_m \ddot{x}_m + b_m \dot{x}_m , \qquad (1)$$

$$\tau_s - f_s = m_s \ddot{x}_s + b_s \dot{x}_s , \qquad (2)$$

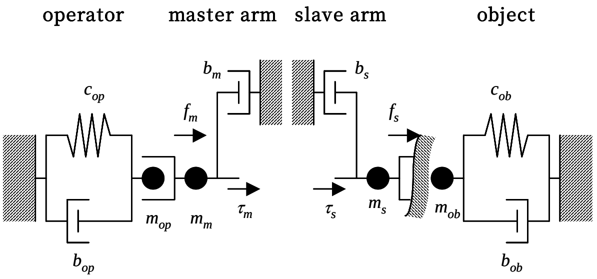


Fig. 1. Master and slave arms, operator and object.

where x_m and x_s denote the displacements of the master and slave manipulators. And m_m and b_m represent mass and viscous coefficient of the master manipulator respectively, whereas m_s and b_s are those of the slave manipulator. In addition, f_m denotes the force that the operator applies to the master manipulator, and f_s denotes the force applies to the object. Actuator driving forces of the master and slave manipulators are represented by τ_m and τ_s , respectively.

The dynamics of the object interacting with the slave manipulator is modeled by the following linear system:

$$f_s = m_{ob} \ddot{x}_s + b_{ob} \dot{x}_s + c_{ob} x_s \qquad (3)$$

where m_{ob}, b_{ob} , and c_{ob} denote mass, viscous coefficient, and stiffness of the object, respectively. As the displacement of the object is represented by x_s in Eq. (3), we assume that the slave manipulator is rigidly contacting with the object or firmly grasping the object, in such a way that it may not depart from the object.

It is also assumed that the dynamics of the operator can be approximately represented as a simple spring-damper-mass system:

$$\tau_{op} - f_m = m_{op}\ddot{x}_m + b_{op}\dot{x}_m + c_{op}x_m , \tag{4}$$

where m_{op}, b_{op}, and c_{op} denote mass, viscous coefficient, and stiffness of the operator respectively, whereas τ_{op} means force generated by operator's muscles. Similarly to Eq. (3), the displacement of the master manipulator is represented by x_m in Eq. (4). We assume that the operator is firmly grasping the master manipulator and he/she never releases the master manipulator during the operation. The reflecting force to the operator in position-position force reflection system is denoted by

$$\tau_m = K_{fr} f_s , \tag{5}$$

where K_{fr} means the force reflection ratio.

2.2 Shared compliant control system

Fig. 2 shows the block diagram of the conventional shared compliant control scheme for position-force force reflecting system. In Fig. 2, $C(s)$ is the controller for the slave manipulator. The control inputs of master and slave manipulator are given by

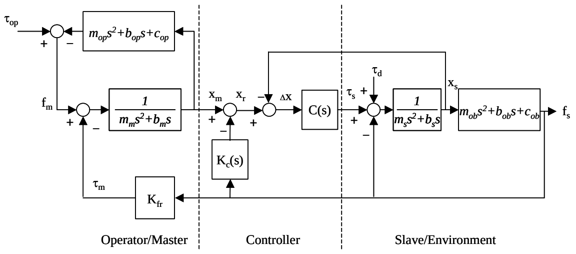


Fig. 2. Conventional shared compliant control scheme.

In Fig. 2, $K_c(s)$ is the autonomous compliant control filter. When the slave manipulator contacts on the environment, the contact force of the slave manipulator is shared to the operator and autonomous compliant control filter. And the reference position, x_r, which is tracked by slave manipulator is reduced. Consequently, compliant contact is achieved since the displacement of the slave manipulator is reduced. In Fig.2, $C(s)$ is designed considering the position tracking performance of the slave manipulator for the master manipulator in free space. And $K_c(s)$ is designed considering the compliance performance.

3. PROPOSED SCHEME

Fig. 3 shows the proposed shared compliance control scheme. The open loop transfer function from the control input to the displacement of the slave manipulator in free space is unstable function, which has a pole in origin. The controller of the slave manipulator is designed by IMC method for the open loop unstable systems.

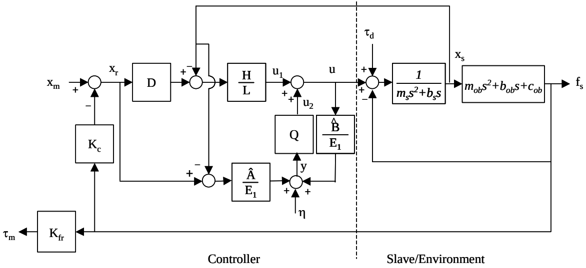


Fig. 3. The proposed shared compliance control scheme.

In Fig. 1, the transfer function in free space from the control input, $u(s)$, to the output, $x_s(s)$, is given by

$$P(s) = \frac{1}{s(m_s s + b_s)} = \frac{B(s)}{A(s)} = \frac{B(s)}{sA_s(s)} , \tag{6}$$

where $A_s(s)$ and $B(s)$ are Hurwitz.

The modeling of the transfer function $P(s)$ is denoted by (5)

$$P_m(s) = \frac{\hat{B}(s)}{\hat{A}(s)} , \tag{7}$$

where

$$\hat{A}(s) = s\hat{A}_s(s) , \tag{8}$$

and $\hat{A}_s(s)$ and $\hat{B}(s)$ are Hurwitz.

Assume that $P_m(s)$ is the perfect model of $P(s)$. In other words, $A_s(s) = \hat{A}_s(s)$, $B(s) = \hat{B}(s)$. In Fig. 3, the force feedback loop is not connected in free space. In other words, f_s and τ_m are zero. The controller of the slave manipulator is designed considering the position tracking performance of the slave manipulator. And $K_c(s)$ is designed by first order low pass filter and given by

$$K_c(s) = \frac{K_{cc}}{\tau_c s + 1} . \tag{9}$$

The transfer functions from arbitrary external inputs to internal states in free space of Fig. 3 are denoted by

$$\begin{bmatrix} x_s(s) \\ u(s) \\ y(s) \end{bmatrix} = \frac{1}{\Delta(s)} \begin{bmatrix} y_{11}(s) & y_{12}(s) & y_{13}(s) \\ y_{21}(s) & y_{22}(s) & y_{23}(s) \\ y_{31}(s) & y_{32}(s) & y_{33}(s) \end{bmatrix} \begin{bmatrix} x_r(s) \\ \tau_d(s) \\ \eta(s) \end{bmatrix} . \tag{10}$$

Where,

$$\Delta(s) = A(s)L(s) + B(s)H(s) , \tag{11}$$

$$y_{11}(s) = B(s)\left\{ D(s)H(s) - \frac{Q(s)A(s)L(s)}{E_1(s)} \right\} \tag{12}$$

$$y_{12}(s) = B(s)L(s)\left\{1 - \frac{Q(s)B(s)}{E_1(s)}\right\}, \quad (13)$$

$$y_{13}(s) = Q(s)B(s)L(s), \quad (14)$$

$$y_{21}(s) = A(s)\left\{D(s)H(s) + \frac{Q(s)A(s)L(s)}{E_1(s)}\right\}, \quad (15)$$

$$y_{22}(s) = -B(s)\left\{H(s) + \frac{Q(s)L(s)}{E_1(s)}\right\}, \quad (16)$$

$$y_{23}(s) = Q(s)A(s)L(s), \quad (17)$$

$$y_{31}(s) = \frac{A(s)}{E_1(s)}\{L(s) + D(s)B(s)H(s)\}, \quad (18)$$

$$y_{32}(s) = -\frac{B(s)}{E_1(s)}\{A(s)L(s) + B(s)H(s)\}, \quad (19)$$

$$y_{33}(s) = A(s)L(s) + B(s)H(s). \quad (20)$$

The open loop transfer function is an unstable function in free space, which has an unstable pole at origin. The controller design conditions of the slave manipulator for satisfying system internal stability are as follows:

i) $Q(s)$ is proper and stable transfer function, and designed as

$$Q(s) = f(s)\frac{E_1(s)}{\hat{B}(s)}. \quad (21)$$

ii) $L(s)$ and $H(s)$ satisfy

$$\hat{A}(s)L(s) + \hat{B}(s)H(s) = E_1(s)E_2(s) \quad (22)$$

iii) $E_1(s)$ and $E_2(s)$ are Hurwitz

For satisfying the internal stability of the closed loop system, all individual transfer functions in Eq. (10) have to be stable [5]. If upper three conditions are satisfied, all individual transfer functions in Eq. (10) are stable, then the internal stability of Fig. 3 is satisfied. The displacement of the slave manipulator, $x_s(s)$, for $x_r(s)$ and $\tau_d(s)$ is given by

$$\frac{x_s(s)}{x_r(s)} = \frac{\{f(s)A(s)L(s) + B(s)H(s)D(s)\}}{A(s)L(s) + B(s)H(s)}, \quad (23)$$

$$\frac{x_s(s)}{\tau_d(s)} = \frac{B(s)L(s)\{1 - f(s)\}}{A(s)L(s) + B(s)H(s)}. \quad (24)$$

For Eq. (23) and Eq. (24), $D(s)$ and $f(s)$ is designed as

$$D(s) = f(s), \quad (25)$$

$$f(0) = 1. \quad (26)$$

Then, the transfer function Eq. (23) becomes

$$\frac{x_s(s)}{x_r(s)} = f(s) \quad (27)$$

that the transfer function is simply given by a filter system. Also, the steady state response of $x_s(s)$ for $\tau_d(s)$ becomes

$$\frac{x_s(0)}{\tau_d(0)} = 0 \quad (28)$$

that the disturbance is rejected in the steady state.

4. SIMULATION RESULTS

Computer simulation was performed with MATLAB. The system parameters used for the simulation are as follows.

Master manipulator: $m_m = 6kg,\ b_m = 0.1Ns/m$,

Slave manipulator: $m_s = 6kg,\ b_s = 0.1Ns/m$,

Operator: $m_{op} = 2kg,\ b_{op} = 2Ns/m,\ c_{op} = 10N/m$,

Object: $m_{ob} = 10kg, b_{ob} = 100Ns/m,\ c_{ob} = 200N/m$,

Force reflection ratio: $K_{fr} = 0.05$,

$$A(s) = \hat{A}_s(s) = 6s + 0.1, \quad (29)$$

$$B(s) = \hat{B}(s) = 1, \quad (30)$$

$$L(s) = s + 2, \quad (31)$$

$$H(s) = 6s + 0.1, \quad (32)$$

$$E_1(s) = (s+1)^2, \quad (33)$$

$$f(s) = \frac{1}{(0.01s+1)^2}. \quad (34)$$

$$K_c(s) = \frac{0.1}{0.01s+1} \quad (35)$$

Fig. 4 shows the position tracking response of the slave manipulator for the master manipulator in free space. It is shown in Fig. 4 that the slave manipulator well tracks the reference position. Fig. 5 shows the force responses for the force reflecting scheme without compliance control and the proposed scheme. It is shown in Fig. 5 that the contact force of the slave manipulator is reduced in the proposed scheme compared with the force reflecting scheme without compliance control. Consequently, the compliance control performance is achieved in the proposed scheme.

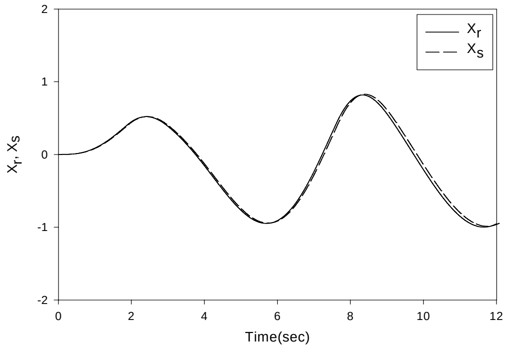
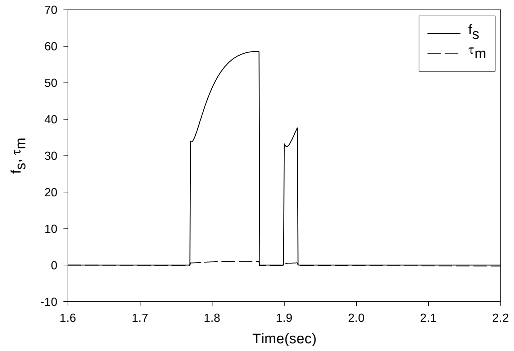
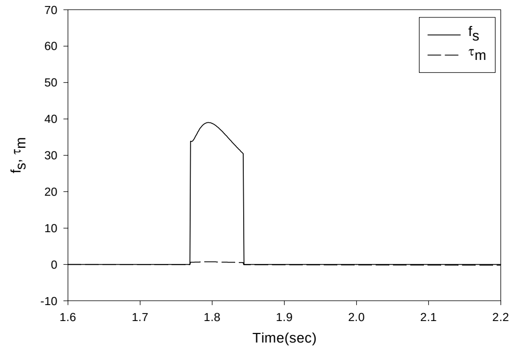


Fig. 4. Tracking response.



(a) without compliance control



(b) for the proposed scheme
Fig. 5. Force responses.

5. CONCLUSIONS

When the slave manipulator contacts on the highly rigid environment, the contact force is rapidly increased. Shared compliant control has been implemented recently as a new feature added on the force reflecting control system. Shared compliant control shares the contact force to the human operator's direct manual control loop and the autonomous compliant control loop. In this paper, a shared compliant control scheme based on IMC is proposed for position-force force reflecting control system. The controller of the slave manipulator is designed by IMC method for the open loop unstable systems. The autonomous compliant control is implemented by first order low pass filter. The simulation results show that the excellent compliance control performance of the proposed scheme.

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