Symmetric Damping Bilateral Control for Parallel Manipulators

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Abstract
A symmetric damping bilateral master-slave control scheme is proposed in order to enable the stable contact between the slave manipulator end-effector and the rigid environment. In the conventional force reflecting position control method, control loops in master and slave sides are connected to each other in series and that causes unstable motion when the slave manipulator contacts with rigid objects. The new method has more stable dynamic characteristic, since lag time of the control loop is smaller due to the symmetric structure of the system. The master-slave system consists of two isomorphic parallel manipulators. Good features with parallel manipulator also improve the system stability. The stability of the proposed control method including the simple operator and object dynamics is analyzed by using the Hurwitz stability criterion and then compared with the conventional controller. Metal-to-metal contact and peg-in-hole experiments show practical and wide applicability of the control method.

Keywords : Damping Bilateral Control, Parallel Manipulators, Stability, Maneuverability, Peg-in-Hole.

1 Introduction
Generally the skilled tasks can be achieved by using skills of expert operators. The information of working conditions such as reacting forces of the environment are essential to achieve these tasks. For example, in geometrically constrained tasks such as polishing, the information of pressing force and friction force are important for the control of polishing quantity. In telemanipulation (task performed in a remote environment), transmission of such working information from an operator to a telemanipulation system and vice versa is most important to perform tasks with success [4,9,13]. Thus, the bilateral master slave control such as force reflecting position control was proposed and developed for efficient telemanipulator [1,12]. But in the conventional force reflecting position control, the control loops in master and slave sides are connected to each other in series and that causes unstable motion when the slave manipulator contacts with rigid objects [10]. The unstable motion may be suppressed by decrease of sensitivity to reacting force and it is a trade-off with fine force control and maneuverability.

In this paper, a bilateral master slave control scheme so called Symmetric Damping Bilateral Control (SDBC) is proposed in order to enable the stable contact between the slave manipulator end-effector and the rigid environment. The stability of the proposed control is improved by decrease of lag time in the control loop due to the symmetric structure of the master and slave servos. Also, it is further improved, since the system is composed of parallel mechanism based on the Modified Stewart Platform [11] for the master and the slave, which has good features such as simple inverse kinematics, light movable body, and stiffness. Many researchers have attempted to develop the master arms using parallel link mechanisms [5,6], but few works have been done for teleoperation using slave parallel link manipulators [2,3].

The relative stability between the proposed control method and the conventional force reflecting position control including the simple operator and object dynamics is also evaluated using Hurwitz stability criterion. The force reflecting position control is only chosen for comparison because it has been used until now in most nuclear industries and the new control presented in this paper is a variation of the above conventional bilateral control. The applicability of the proposed control is shown in metal-to-metal contact and peg-in-hole experiments. Some ideas to improve the maneuverability are also proposed.

2 Stability analysis
In this section, a maximum control gain for stable condition assuming a fixed human operator model is analyzed by using Hurwitz stability criterion in both conventional and proposed controls.

2.1 Analysis for the conventional force reflecting position control
The outline of conventional force reflecting position control is shown in Fig. 1.

![Fig. 1: The conventional force reflecting position servo](image-url)
In this control mode, the master manipulator is controlled by force error between operating force and reacting force, while the slave manipulator is controlled by position error between the master and slave positions. The block diagram of the force reflecting position control is shown in Fig. 2.

\[ G_m(s) \] and \[ G_f(s) \] are Laplace transfer functions of master and slave manipulators respectively, \( \tau_{op} \) is force generated by the operator's muscles, \( Z_h \) and \( Z_e \) are impedances of a human operator and environmental object respectively, and \( A_e \) is feedback gain of the slave reacting force. The impedance models of the simple operator and object dynamics can be represented as follows.

\[ Z_h = m_h s^2 + b_h s + k_h \quad \text{and} \quad Z_e = m_e s^2 + b_e s + k_e \quad (1) \]

where \( m_h, b_h \) and \( k_h \) denote mass, viscous coefficient and stiffness respectively of the human operator, and \( m_e, b_e \) and \( k_e \) denote mass, viscous coefficient and stiffness respectively of the object interacting with the slave manipulator. Using a similar assumption as in [12] for the system passivity, we suppose that the system stability is guaranteed for any passive environment and operator, therefore no active force has been generated by the operator's muscles, i.e. \( \tau_{op} = 0 \).

When the force applied by the human operator acts as an input and the reaction force acting on the slave as an output, the global transfer function of the closed loop system \( G_{ref} \) is given as follows.

\[ G_{ref} = \frac{Z_h Z_e K_{jm} \alpha G_m^2(s)}{1 + Z_e A_e K_{jm} \alpha G_m(s) + Z_h Z_e A_e K_{jm} \alpha G_m^2(s)} \quad (2) \]

where

\[ \alpha = \frac{K_p G(s)}{1 + K_p G(s)} \quad (3) \]

The transfer function of the master and slave manipulators are assumed in relation (4), since in this system the same type of manipulator is employed for master and slave manipulators.

\[ G_m(s) = G_f(s) = G(s) \quad (4) \]

The transfer function of the force reflecting position control \( G_{ref} \) is derived in equation (5) by using equation (2) and relation (4).

\[ G_{ref} = \frac{Z_h Z_e K_{jm} K_{rv} G^3(s)}{1 + K_p G(s) + Z_e A_e K_{jm} K_{rv} G^2(s) + Z_h Z_e A_e K_{jm} K_{rv} G^3(s)} \quad (5) \]

The servo \( G(s) \) system in each manipulator is composed of a conventional PD position servo portion \( G_{servo} \) and an integral element \( 1/s \) as illustrated in Fig. 3.

\[ G_{servo} = \frac{1}{s} \]

\[ G_{servo} \] is given in equations (6) and then \( G(s) \) is obtained in equation (7).

\[ G_{servo} = \frac{b}{s^2 + a s + b} \quad (6) \]

\[ G(s) = \frac{b}{s^3 + a s^2 + b s} \quad (7) \]

By merging equations (1), (5) and (7), the global transfer function of the force reflecting position control is derived as

\[ G_{ref} = \frac{N(s)}{D(s)} \]

Its characteristic equation is obtained by

\[ D(s) = 0 \]

Thus we have

\[ \sum_{k=0}^{q} c_k s^k = 0 \quad (8) \]

where

\[ c_0 = b^3 A_e K_{jm} K_{rv} k_{k} k_{e} \]

\[ c_1 = b^3 A_e K_{jm} K_{rv} \{ k_e + K_{jm} (b_{k} k_{e} + k_{e} b_{k}) \} \]

\[ c_2 = b^3 K_{rv} + b^3 A_e K_{jm} K_{rv} (b_{k} e + a_{k}) + b^3 A_e K_{jm} K_{rv} (m_{k} k_{e} + b_{k} e + k_{e} m_{k}) \]

\[ c_3 = b^3 + 2 ab K_{rv} + b^3 A_e K_{jm} K_{rv} (b_{k} e + a_{k}) + b^3 A_e K_{jm} K_{rv} (m_{k} k_{e} + b_{k} e + k_{e} m_{k}) \]

\[ c_4 = 3a b^2 + 3 a b + 2 b K_{rv} + b^3 A_e K_{jm} K_{rv} (m_{k} e + a_{k}) + b^3 A_e K_{jm} K_{rv} (m_{k} k_{e} + b_{k} e + k_{e} m_{k}) \]

\[ c_5 = 3a b^2 + 3 b^2 + 2 a b K_{rv} + b^3 A_e K_{jm} K_{rv} (m_{k} e + a_{k}) + b^3 A_e K_{jm} K_{rv} (m_{k} k_{e} + b_{k} e + k_{e} m_{k}) \]

\[ c_6 = a^3 + 6 a b + b K_{rv} \]

\[ c_7 = 3 a b^2 + 3 b \]

\[ c_8 = 3 a \]

\[ c_9 = 1 \]
The stable conditions in the Hurwitz method are given in Appendix B. The first condition of stability is satisfied by the physical conditions, since \( K_{fm} > 0, K_{vs} > 0, A_5 > 0, m_h > 0, b_h > 0, k_h > 0, m_e > 0, b_e > 0 \) and \( k_e > 0 \), it implies all \( c_k > 0 \) \((k=0,\ldots,9)\). For the second condition, the nine Hurwitz determinants are derived from Mathematica 2.2 as function of parameters \( K_{fm}, K_{vs}, A_5, m_h, b_h, k_h, m_e, b_e \) and \( k_e \). The maximum control gain \( K_{fm} \) of the master manipulator is then analyzed in function of parameters \( k_e \) and \( A_5 \), whereas the other parameters are assumed to be fixed as follows.

\[
\begin{align*}
  m_h &= 2.0 \; [\text{kg}], \quad b_h = 2.0 \; [\text{Ns/m}], \quad k_h = 50 \; [\text{N/m}], \\
  m_e &= 10.0 \; [\text{kg}], \quad b_e = 1.0 \times 10^2 \; [\text{Ns/m}], \quad K_{vs} = 0.1 \; [\text{Hz}] 
\end{align*}
\]

The parameters of \( Z_h \) correspond to an operator with the master handle firmly in hand, with little arm tension and with small hand motion. Those of \( Z_e \) correspond to a relatively hard object to a nearly rigid one depending mainly on \( k_e \). The above assumptions seem to be compatible with experimental peg-in-hole task in which quasi-static forces and motions are mainly considered. The results of the stability analysis are shown in Fig. 5.

![Fig. 5: Results of stability analysis for force reflecting position control](image)

In Fig. 5, the maximum control gain \( K_{fm} \) is \( 1.0 \times 10^3 \) \([\text{m/s/N}]\) while the contact object stiffness \( k_e \) is smaller than \( 1.0 \times 10^4 \) \([\text{N/m}]\). When \( k_e \) increases, the maximum control gain \( K_{fm} \) decreases in accordance with the increase of the feedback gain \( A_5 \).

### 2.2 Analysis for the proposed SDBC method

The block diagram of the proposed Symmetric Damping Bilateral Master Slave Control (SDBC) is shown in Fig. 6.

![Fig. 6: Block diagram of SDBC method](image)

The stability of the proposed control can be improved, since it has a symmetrical structure of master and slave manipulators and its lag time is smaller than that in the conventional force reflecting position control. Here, \( K_f \) is damping control gain for master and slave manipulators, \( G_m(s) \) and \( G_s(s) \) are transfer functions of master and slave manipulators respectively, \( Z_h \) and \( Z_e \) are impedances of an operator and a contact object respectively, and \( A_5 \) is feedback gain of the slave reacting force.

When the operating force acts as an input and the contact force is produced as an output, the transfer function of the whole closed loop system of the proposed control can be obtained as follows.

\[
G_{SDBC} = \frac{Z_h \cdot Z_e \cdot K_f \cdot K_s \cdot G_m(s) \cdot G_s(s)}{1 + Z_h \cdot A_s \cdot K_f \cdot G_m(s) + Z_e \cdot Z_h \cdot A_s \cdot K_s \cdot G_m(s) \cdot G_s(s)}
\]

The transfer functions of the manipulators are assumed as in relation (4), since the same manipulators are employed for master and slave manipulators. Thus, the transfer function of the proposed control is derived in equation (10) by using equation (9) and relation (4).

\[
G_{SDBC} = \frac{Z_h \cdot Z_e \cdot K_f \cdot K_s \cdot G_m(s) \cdot G_s(s)}{1 + Z_h \cdot A_s \cdot K_f \cdot G_m(s) + Z_e \cdot Z_h \cdot A_s \cdot K_s \cdot G_m(s) \cdot G_s(s)}
\]

The characteristic equation is obtained in equation (11) from equations (1), (7) and (10) as follows.

\[
\sum_{k = 0}^{\infty} d_k s^k = 0
\]

where

\[
\begin{align*}
  d_0 &= b^2 A_s K_f k_e \\
  d_1 &= b^2 A_s K_f k_e + b^2 A_s K_f^2 (b b_e + k_e + k_e) \\
  d_2 &= b^2 + b a A_s K_f (b b_e + a_k e) + b^2 A_s K_f^2 (b b_e + a_k e + k_e) \\
  d_3 &= 2 a b + b a A_s K_f (a m_e + a_k e) + b^2 A_s K_f^2 (a m_e + b b_e) \\
  d_4 &= a^2 + 2 b + b a A_s K_f (a m_e + b b_e) + b^2 A_s K_f^2 (a m_e + b b_e) \\
  d_5 &= 2 a + b a A_s K_f m_e \\
  d_6 &= 1
\end{align*}
\]

The stable conditions of the Hurwitz method are also applied for the analysis. The first condition of stability is satisfied by physical conditions. For the second one, the six Hurwitz determinants are derived symbolically as function of parameters \( K_f, A_5, m_h, b_h, k_h, m_e, b_e \) and \( k_e \). The maximum damping control gain \( K_f \) of the master manipulator is analyzed in function of parameters \( k_e \) and \( A_5 \), whereas the other parameters are assumed to be fixed as in the case of force reflecting position control. The results of the stability analysis are shown in Fig. 7, in the same way as the previous analysis.

![Fig. 7: Results of stability analysis for SDBC method](image)
In Fig. 7, the maximum damping control gain $K_f$ is now $1.0 \times 10^5 \text{[(m/s)/N]}$ while the contact object stiffness is smaller than $1.0 \times 10^4 \text{[N/m]}$. When $K_f$ increases, the maximum damping control gain $K_f$ decreases in accordance with the increase of the feedback gain $A_0$.

2.3 Summary from the stability analysis of the two controls

In this section, the relation between the maximum damping control gain for the master manipulator, the stiffness of contact object, and the slave feedback gain of reacting force is analyzed. The following results are summarized.

The magnitude of the damping control gain for the SDBC can be a hundred times larger than that for the force reflecting position control when the stiffness of contact object is smaller than $1.0 \times 10^4 \text{[N/m]}$. For the larger stiffness, it can be twice larger.

3 Experimental setup and results

In this section, the applicability of the proposed control is shown in metal-to-metal contact and peg-in-hole experiments.

3.1 Experimental setup

The experimental setup is shown in Fig. 8.

![Fig. 8: View of experimental system](image)

It consists of two geometrically similar parallel manipulators based on the Modified Stewart Platform [11] and designed to have uniform force and moment actuating capability at the end-effector (load capacity = 100 N). Each manipulator is controlled by i80486 based personal computer. Both computers are able to communicate with each other through a bus adaptor. Master and slave force data are transferred to each other by dual port memories (MEMOLINK/Interface). A material of contact object and a tool are steel, the peg and the hole are 20 [mm] in diameter, and the clearance is 10 [µm]. The controller of each parallel manipulator is based on the hybrid position/force controller developed by Arai et al. [2] for the prototype parallel-link manipulator assisted by human teleoperation via joystick. The block diagram of the Symmetric Damping Bilateral Control is shown in Fig. 9.

![Fig. 9: Block diagram of experimental system](image)

The master and slave manipulators are controlled by force which are measured by the 6 axis F/T sensors on the end plate of manipulators. Stability of the proposed control is improved by smaller lag time in the control loop, since the system has the symmetric structure. The force error is converted to tool velocity through the damping gain matrix $K_f$. Then, both master and slave computers check link interference, solve the inverse kinematics and provide position servos. Since the forward kinematics is extremely difficult to solve analytically, utilisation of the available sensor redundancy on each manipulator provides a minimum least squared error solution [7] and allows to determine efficiently the position and orientation of the end-effector. The master and slave computers have the same sampling period of 6ms including force-velocity command conversion, constraint velocity using link interference checking [8], solution of forward kinematics, Jacobian calculations, solution of inverse kinematics and position servo. The values of digital $PD$ control gains are selected experimentally to get the best time response with minimum steady state position error and without overshoot or actuator saturation.

$K_p = \text{diag}(K_{pi})$ and $K_d = \text{diag}(K_{di}) \ (i = 1,6)$

where $K_{pi} = 10.0 \text{[Volt/pulse]}$ and $K_{di} = 6.67 \text{[Volt/s/pulse]}$.

3.2 Experimental results

An example of experimental results for metal-to-metal contact is shown in Fig. 10. The operating time is shown in the horizontal axis. The master operating and slave reacting forces in the contact direction are shown in the vertical axis.

![Fig. 10: Experimental results for rigid contact (K_f = 2000)](image)
In Fig. 10, when the tool contacts with the object, the master operating force and the slave reacting force fit well, and no unstable motion happens in spite of rigid contact. This shows excellent control and stable operation. However, small operating load (around 8.0[N]) appears even at noncontact. Experimentally, the operating load may be decreased by increase of control gain $K_f$ to 5000, but stability is no more ensured when the tool has rigid contact.

In the peg-in-hole experiment, much time is spent to achieve the task, since the operator's feeling of the reacting moments is relatively small when the feedback gain $A_s$ is 1.0.

4 Improvement of maneuverability

Two problems for the maneuverability of the proposed control are small feeling of reacting moments in the peg-in-hole task, and operating load when the tool has noncontact. In this section, the improvements are proposed to solve these problems.

4.1 Adequate feedback gain for the task

Generally, the operator's feeling of reacting forces and moments depends on both the object and the shape of the tool. If the feeling of required force information to achieve the task is small, much time is spent for the task. For example, in the peg-in-hole task the detection of the hole position is important in order to achieve task quickly. During this detection the reacting moments are important information. In our peg-in-hole experiment the feeling of reacting moments is smaller than that of forces, since the diameter of used tool is small. That causes more time spent in the achievement of the task. The method allowing to regulate adequate feedback gain $A_s$ is proposed. The outline of the experiment is shown in Fig. 11.

![Diagram](image)

**Fig. 11**: Outline of experiment for maneuverability

In the experiment the reacting moments are measured when the tool slides on the contact plate passing by the hole. The experimental results are shown in Fig. 12. The tool position on the contact plate is shown in the horizontal axis, and the reacting moments are shown in the vertical axis. When the tool passes in the hole, the reacting moments become larger if the feedback gain $A_s$ increases. Thus, The detection of the hole position becomes easier and faster with high adequate feedback gain $A_s$.

![Graph](image)

**Fig. 12**: Experimental results for maneuverability

4.2 Method of switching damping control gain

In the Symmetric Damping Bilateral Control, the manipulators are controlled by the master operating force, and small operating load exists even if no forces are required in the slave. The operating load can be decreased by increase of damping control gain, but stability is not ensured when the tool has contacts. Thus, if the tool has noncontact, the high gain can be used for small operating load. On the other hand, the lower gain should be selected for the stability with any contact. The possible method is to switch the control gain $K_f$ depending on contact condition. The block diagram of this method is shown in Fig. 13.

![Diagram](image)

**Fig. 13**: Block diagram of gain switching method

The control gain is varied by using the information on the feedback force of the slave manipulator. The experimental results for without and with gain switching method are shown in Fig. 14a and Fig. 14b respectively.

![Graph](image)

**Fig. 14a**: Results for without gain switching method

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5 Conclusions

In order to improve the stability and the maneuverability for the bilateral master slave control, the Symmetric Damping Bilateral Control is proposed.

The efficiency of the proposed control for stability is evaluated by the Hurwitz method in comparison with the conventional force reflecting position control. When the tool contacts with a relatively hard object, the damping control gain can be a hundred times larger, and when the tool contacts rigidly, it can be twice larger than that of the force reflecting position control. To improve the operator's small feeling of reacting moments in the peg-in-hole task, the well balanced feedback gains in forces and moments are taken into consideration. Also, to reduce the operating load and to achieve a good maneuverability, the damping control gain switching method is proposed. The efficiency of the stability and the two improvement ideas are evaluated by the metal-to-metal contact and peg-in-hole experiments.

References