Proceedings of the ASME 2012 International Mechanical Engineering Congress & Exposition
IMECE2012
November 9-15, 2012, Houston, Texas, USA

IMECE2012-87354

DEVELOPMENT OF CUTTING SUPPORT SYSTEM BY BILATERAL CONTROL WITH VARIABLE CONNECTING FORCE BETWEEN MASTER AND SLAVE ROBOT

Tsuginobu Osada, Norihiko Kato and Ken'ichi Yano
Department of Mechanical Engineering
Mie University
1577 Kurimamachiya-cho
Tsu-city, Mie, 514-8507
Japan
osada@robot.mach.mie-u.ac.jp

Mustapha. S. Fofana
Department of Mechanical Engineering
Worcester Polytechnic Institute
100 Institute Road,
Worcester, MA 01609-2280
USA
msfofana@wpi.edu

ABSTRACT

Finishing processes such as deburring are performed on a wide variety of products in various quantities by workers on a piece-by-piece basis. Accordingly, the accuracy of the product depends on the worker's skill. To solve this problem, the bilateral control system is applied to a machining support system. The aim of this research is to develop a machining support system via the bilateral control system which can accept various machining theories and to reflect the operation force into the machining geometry. This system has a construction which makes it possible to change the connecting force between a master and a slave robot based on a symmetrical bilateral controller. This construction is useful to change the feature of a system dynamically according to machining condition. The effect of this system is shown by the experiment results.

INTRODUCTION

At present, a great number of working processes are carried out automatically by using industrial robots. Such a production method has been widely adopted for mass production. However, if production is limited to a number of diversified products, deburring these products is difficult because of time and accuracy constraints. For example, a long time is required to prepare CAD data on positioning and configuration of the products. It is difficult to cope with differences in the set position or warping of the products. As a result, these processes have to be carried out manually by workers and require the careful control of force. The absence of skill will cause the machining miss and the increase in cost.

To solve these problems, finish machining systems combined with the bilateral control shown in Fig. 1 have been studied. The bilateral control is one type of a master-slave control method and its control target is both the position and force [1]. The important component for the bilateral control which performs the contact process with objects is how a slave has a stable contact with them. In several researches, this point has been studied and solved by introducing the control method in the controller for a slave robot which realizes the stable contact by correcting its motion [2] [3]. As an application example of this method for machining support, Hisatomi et al. investigated the machining process using the bilateral control system constructed by combining a PHANoM1.5/6DOF (SenAble Technologies) and a force display driven by hydraulics [4].

We proposed the teleoperating machining support system via the bilateral control which has a special construction [5]. Here, the slave robot works automatically during machining because the control signal from the master robot to the slave robot is disconnected for the thrusting direction. As a result, the motion of the slave robot depends only on the controller that the slave robot has independently. In addition, we proposed the control method that makes it possible to perform a debbur process accurately even if the feed speed changes irregularly due to the worker's operation as well. This study achieved a certain result.

 Copyright © 2012 by ASME

However, this method is not suitable to apply another field of the machining support because this system has the space to accept the operator's intention only at a start position and a stop position. This problem is caused by the used system that cannot accept the operation toward a thrusting direction during machining. In order to broaden the region of application, this system should be improved to accept the operator's intention by changing the system component during the operation so that the operator can work the machining robot with an arbitrary way.

In this paper, the bilateral control system structured for the machining support system is proposed. This control method makes it possible to change the rate of connecting force given to the master robot or the slave robot. As a result, the slave robot can change the priority to trace the master robot or to achieve the target value such as the target machining force. We will present the design of control proposed newly and the experimental result with the machining experiment.

FIGURE 1. Devices used as bilateral control system

MACHINING SUPPORT SYSTEM DESIGN OF CONTROLLER

In this section, we will discuss the concept of a proposed bilateral controller and its application example.

Desired Controller for Machining Support

The desired components in the machining support can be separated into following three conditions.

1. The slave robot traces the master robot without making contact.
2. The slave robot makes contact with an object and performs machining according to machining theory.
3. The operator corrects the tool's trajectory in thrust direction during machining.

In the first condition, the slave robot is required to trace the position of master robot by being given only the connecting force. In the second condition, the slave robot is required to trace the target trajectory precisely calculated with the machining condition equation or others. This time, the force signal measured by the slave robot has to be transferred to master robot so that the operator gets the machining condition such as machining force. In the third condition, the operator corrects the tool's trajectory by adding the operation force when the operator determines that the correction is required. In this research, a symmetrical type bilateral control is adopted in order to present these three conditions as motion equation.

In the symmetrical type bilateral control, the master and the slave robot are considered to be connected by the spring and the damper. This control is able to perform the synchronized motion between the master and the slave robot by connecting them with admittance control via measured value of front edge location or joint angle. Therefore, we can consider that the connecting force generated by the spring damper system is distributed to the master and the slave robot as shown in motion equations (1) and (2).

$$M_m\ddot{q}_m + C_m\dot{q}_m = f_{op} + u_m \tag{1}$$
$$M_s\ddot{q}_s + C_s\dot{q}_s = f_{env} + u_s \tag{2}$$

where M_m and M_s show the mass coefficient, C_m and C_s show the viscosity coefficient of the master and the slave. f_{op} and f_{env} show the force given by the operator or environment, u_m and u_s show the connecting force between the master and the slave robot.

These equations are restructured to fulfill above three conditions. First condition is shown as (3) and (4).

$$M_m\ddot{q}_m + C_m\dot{q}_m = f_{op} \tag{3}$$
$$\begin{aligned} M_s\ddot{q}_s + C_s\dot{q}_s &= u_s + f_{env} - f_{Aenv} \\ &= u_s \end{aligned} \tag{4}$$

where f_{Aenv} works to compensate the force given by environment f_{env}. Generally, f_{Aenv} is set as $f_{Aenv} = f_{env}$. In these motion equations, only the operation force is given to the master robot and only the tracing force toward the master robot is given to the slave robot. Obviously, gravity, friction and other compensations for the master and the slave robot should be considered. However, these problems will be solved by each robot independently. Then, these correcting forces do not affect to the motion of another robot. We don't describe these force inputs in motion

Copyright © 2012 by ASME

equation. The block diagram of this controller is shown in Fig. 2.

Next, the second condition is shown as (5) and (6).

$$M_m\ddot{q}_m + C_m\dot{q}_m = f_{op} + u_m + f_{tenv} \tag{5}$$

$$\begin{aligned} M_s\ddot{q}_s + C_s\dot{q}_s &= f_{env} + f_s - f_{Aenv} \\ &= f_s \end{aligned} \tag{6}$$

where f_{tenv} shows the force measured by the slave robot and transferred to the master robot. f_s shows the force given in order to achieve the target position, the target velocity or the target press force. In these motion equations, not only the operation force but also the force generated by the deviation of position between the master and the slave robot and the force that the slave robot is measuring is given to the master robot. The most important point in this condition is that the slave robot works according as the target value, such as the target press force or the target feed speed. In addition, it is also important that the operator can recognize the force that the slave robot is measuring and the deviation of the position between the master and the slave robot. When $u_m = 0$, the master robot is given only f_{op} and f_{tenv}. Then, the operator can recognize the force that the slave is measuring precisely. The block diagram of this controller is shown in Fig. 3.

Finally, the third condition is shown as (7) and (8).

$$M_m\ddot{q}_m + C_m\dot{q}_m = f_{op} + u'_m + f'_{tenv} \tag{7}$$

$$\begin{aligned} M_s\ddot{q}_s + C_s\dot{q}_s &= f_{env} + u'_s + f'_s - f_{Aenv} \\ &= u'_s + f'_s \end{aligned} \tag{8}$$

In these equations, the symbols with dash have the $0 \sim 1$ value times to their originals used in (3)$\sim$(6). In these motion equations, the operation force, the connecting force and the measured force are given to the master robot. The tracing force toward the target and the connecting force are given to the slave robot. This condition is constructed as the combination of the first and the second condition. The process of transition to the third condition from the first or the second condition should be performed continuously not to lose the stability of the system. The block diagram of this controller is shown in Fig. 4.

From these problem establishments, we find that the three conditions desired to perform the machining support can be shown as the motion equation based on the symmetrical bilateral control.

Suggestion of bilateral controller for machining support system

In order to realize the conditions shown in the previous section, the new bilateral controller is proposed in this section. This

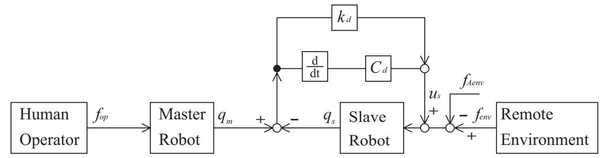

FIGURE 2. Block diagram in motion condition 1

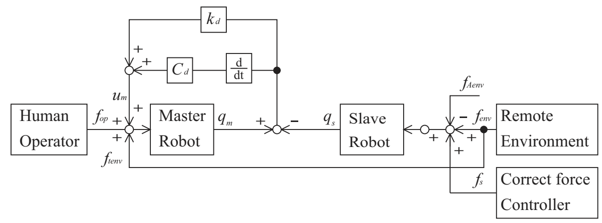

FIGURE 3. Block diagram in motion condition 2

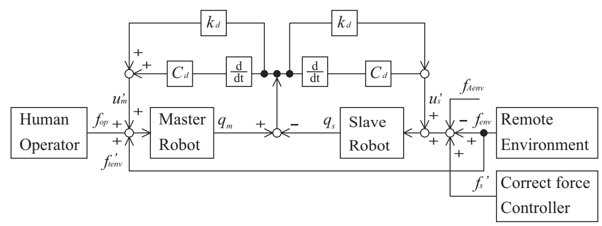

FIGURE 4. Block diagram in motion condition 3

controller has the feature in having the arbitrary variables μ_i on the force transfer lines. The motion equations of it are shown as (9) and (10).

$$\begin{aligned} M_m\ddot{q}_m(t) &+ C_m\dot{q}_m(t) + C_{mp}\dot{q}_m(t-\tau_{m1}) \\ &= f_{op}(t) + \mu_{m1}u_m + \mu_{m2}f_m \\ &+ \mu_{m3}f_{tenv}(t-\tau_{s2}-\tau_{tr}(t)) \end{aligned} \tag{9}$$

$$\begin{aligned} M_s\ddot{q}_s(t-\tau_{s1}) &+ (C_s + C_{sp})\,\dot{q}_s(t-\tau_{s1}) \\ &= f_{env}(t-\tau_{s2}) - f_{Aenv}(t-\tau_{s2}) \\ &+ \mu_{s1}u_s + \mu_{s2}f_s \\ &+ \mu_{s3}f_{top}(t-\tau_{m2}-\tau_{tr}(t)) \end{aligned} \tag{10}$$

where q_m and q_s show the position of the master and the slave robot. M_i, C_i and C_{ip} $(i = m, s)$ show the mass, viscosity and virtual viscosity coefficient of each robot. f_i show the tracing force toward the target value. f_{top} and f_{tenv} show the force signal transferred from another robot. The angle errors of each joint of the slave robot are compensated by PID controller and we assume that the slave robot will move according to reference signal ac-

Copyright © 2012 by ASME

curately. Then, we set the virtual impedance model for the slave robot and give the arbitrary impedance attribution. It is set so that the tool can make stable contact with object. Although the system used in this research doesn't cause the transfer time delay, we estimate the condition that the time delay exists by the reproduction of it by using the software's function so as to show the effectiveness of the proposed system. Then, the motion equation is described by containing the time delay components. τ_{m1} and τ_{s1} show the time delay caused by the filter for position encoders of each robot, τ_{m2} and τ_{s2} show the time delay caused by the filter for a force sensor and τ_{tr} shows the transfer time delay between the master and the slave robot. As a filter, we use the lowpass filter and set $\tau_{m1} = \tau_{s1} = 0.05$s, $\tau_{m2} = \tau_{s2} = 0.1$s. u_i and f_i are shown as (11)~(14).

$$\begin{aligned} u_m(t) &= k_d\left(q_s(t-\tau_{s1}-\tau_{tr}(t)) - q_m(t-\tau_{m1})\right) \\ &+ C_d\left(\dot{q}_s(t-\tau_{s1}-\tau_{tr}(t)) - \dot{q}_m(t-\tau_{m1})\right) \\ &+ O_3\left(q_s(t-\tau_{s1}-\tau_{tr}(t)) - q_m(t-\tau_{m1})\right)^3 \end{aligned} \tag{11}$$

$$\begin{aligned} u_s(t) &= k_d\left(q_m(t-\tau_{m1}-\tau_{tr}(t)) - q_s(t-\tau_{s1})\right) \\ &+ C_d\left(\dot{q}_m(t-\tau_{m1}-\tau_{tr}(t)) - \dot{q}_s(t-\tau_{s1})\right) \\ &+ O_3\left(q_m(t-\tau_{m1}-\tau_{tr}(t)) - q_s(t-\tau_{s1})\right)^3 \end{aligned} \tag{12}$$

$$\begin{aligned} f_m(t) &= a_{mf}\left(f_{op}(t-\tau_{m2}) - f_{mt}(t)\right) \\ &+ a_{mp}\left(q_{mt}(t) - q_m(t-\tau_{m1})\right) \\ &+ a_{mv}\left(v_{mt}(t) - \dot{q}_m(t-\tau_{m1})\right) \end{aligned} \tag{13}$$

$$\begin{aligned} f_s(t) &= a_{sf}\left(f_{env}(t-\tau_{s2}) - f_{st}(t)\right) \\ &+ a_{sp}\left(q_{st}(t) - q_s(t-\tau_{s1})\right) \\ &+ a_{sv}\left(v_{st}(t) - \dot{q}_s(t-\tau_{s1})\right) \end{aligned} \tag{14}$$

where f_{it}, q_{it} and v_{it} show the target force, the target position and the target velocity. a_{if}, a_{ip} and a_{iv} show coefficients which are determined to define the trace performance toward each target values. k_d and C_d show the spring and the damper coefficient between the master and the slave robot. By changing the μ_i, we can change the connecting condition between the master and the slave robot and control the feature of the system. For example, the slave robot will be affected by both the connecting force u_s and the tracing force f_s in the condition of $\mu_{s1} = 0.5$ and $\mu_{s2} = 0.5$. The slave robot will be affected only by the tracing force f_s and perform to achieve the target value in the condition $\mu_{s1} = 0$ and $\mu_{s2} = 1$. By calculating f_{ts}, q_st, v_st with machining condition equation [6], we can control the slave robot according to the machining condition or the cutting theory.

Robot control model

The slave robot has the arbitrary character by being added the virtual impedance model as shown in the previous section. From the experimental result of contact performance between the slave robot and the object, the stiffness value of the slave robot and its machining tool is found as 8.2×10^3N/m. The impedance parameter of the slave robot should be definded in mind this stiffness value and the time delay due to the lowpass filter for the force sensor. In this research, the parameters of impedance model robot for the slave robot are set as $M_s = 5.0$kg, $C_s + C_{sp} = 2.0 \times 10^3$Ns/m. These parameters are set so that the slave robot contacts the object with stability. Then, these values are higher than those of the master robot. The parameters for connecting force between the master and the slave robot are set as $K_d = 8.2 \times 10^3$N/m, $C_d = 5.0 \times 10$Ns/m. O_3 is set in order to reduce the rapid deviation of position if it becomes larger. Then, O_3 is set as 1.0×10N/m^3 not to affect the connecting force when the deviation is small. In addition, the master robot has $C_{mp} = 8.0$Ns/m so as to stabilize its motion. This value is determined so that the master robot which has $K_d = 8.2 \times 10^2$N/m and the initial deviation 10cm stops without an overshoot in the condition that the motion of the master robot becomes most unstable, that is, the operator lets go his grip of the master robot.

The coefficients μ_{mi} and μ_{si} can be rewritten as the product with a new coefficient μ. In this research, these coefficients are set as $\mu_{m1} = \mu \times 0.10$, $\mu_{m2} = 0.0$, $\mu_{m3} = \mu \times 1.0$, $\mu_{s1} = 1.0 - \mu$, $\mu_{s2} = \mu$, $\mu_{s3} = 0.0$. By controlling this coefficient μ dynamically, the character of the system can be changed as the change of one coefficient. The difference of the impedance parameter between the master and the slave robot is very large. The motion of these robots will become unstable if the connecting force is given to each robot in the same condition. Then, μ_{m1} is set as $\mu_{m1} = \mu \times 0.10$.

Control algorithm for μ

The arbitrary variable μ is controlled based on the machining force or the press force measured by the slave robot, and the connecting force between the master robot and slave robot generated by the deviation of the position between them. We consider the bell shaped trajectory which has the target force as center axis as shown in Fig. 5. This trajectory means how the input force to the slave robot will change. When the slave robot start to contact with machining object, quantity of μ will become large as the measured force become large (shown as range A in Fig. 5). Once the slave robot attains range B, it will control the force so as to achieve the target force until the total force is within range B. If the slave robot can keep its force as the target force, there is only the force generated by the deviation of position between the master robot and the slave robot which removes the total force from range B. By increasing the deviation of position, the quantity of the total force moves to range A or C. To remove the total force into range C means that the operator aims to increase the cutting value. The contact between the machining tool and the object bring huge stiffness. Then, this control has

Copyright © 2012 by ASME

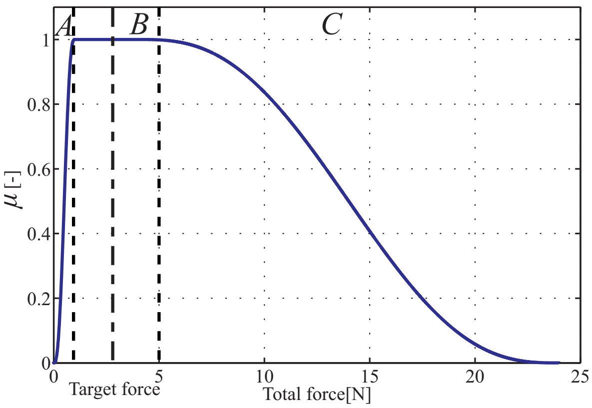

FIGURE 5. Bell shaped trajectory for μ controller

to be performed carefully. Therefore, we set the length of horizontal axis for range C longer than that for range A. In order to make this change smoother, minimum jerk trajectory is used to calculate the trajectory. The horizontal axis shows the total value of the forces, the external force measured by the slave robot and the connecting force toward the master robot. The slave robot will keep the machining force as to achieve the target machining force. Then, a little position deviation between the master robot and the slave robot will keep $\mu = 1$. The arbitrary variable μ will close to $\mu = 0$ as the deviation becomes large.

EXPERIMENT

In order to perform the practical machining works, the slave robot should realize the stable machining motion and the according target value motion. In this section, the control algorithm for an arbitrary variable μ is applied to the bilateral controller proposed in the previous section. The effectiveness of this control method is shown through the press motion operation and machining experiment.

Experiment with contact and press motion

First, we performed the experiment with contact and press motion via the proposed method. The experiment result is shown in Fig. 6. In case 1 (between 12s and 20s), the contact motion between the slave robot and the object was performed. In case 2 (between 28s and 51s), the operator moved the master robot toward the normal direction during the contact motion. In case 3 (between 57s and 70s), the contact and the separate motion were repeated. In case 4 (between 75s and 83s), the operator moved the robot toward tangential direction with the pressing motion. In case 5 (between 85s and 97s), the operator pushed the robot toward normal direction during performing as case 4. The slave robot worked in order to accomplish the target force precisely. Especially, this phenomenon was observed when the slave robot was moving toward tangential direction clearly. When the master robot is moved toward object during working, the slave robot continued the contact motion with the constant force due to the small operation force as seen in case 4 and was effected by the large operation force as seen in case 5. In addition, the repulsive force yield in onset of the contact between the slave robot and the object became large in case 1 and case 4. This force didn't affect the motion of the slave robot and the press motion with the target force was accomplished quickly. In this controller, the contact yield at the onset of contact force between the slave robot and the object is transferred to the master robot and the operator feels the repulsive force as the previous experiment. However, the motion condition for the slave robot is changed as the condition 2 shown in the previous section. Then, the operator is not required to control the robot carefully. Furthermore, larger impedance parameters of the slave robot set to have stable contact with the object are one of the reasons for these results.

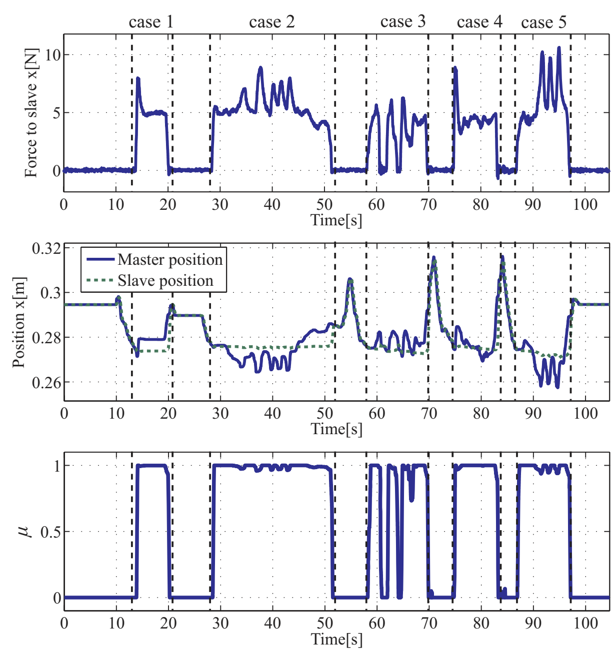

FIGURE 6. Experiment result via proposed control

Machining experiment with proposed bilateral control

We performed the machining experiment via proposed bilateral control and the control algolithm for μ. There is no transfer

Copyright © 2012 by ASME

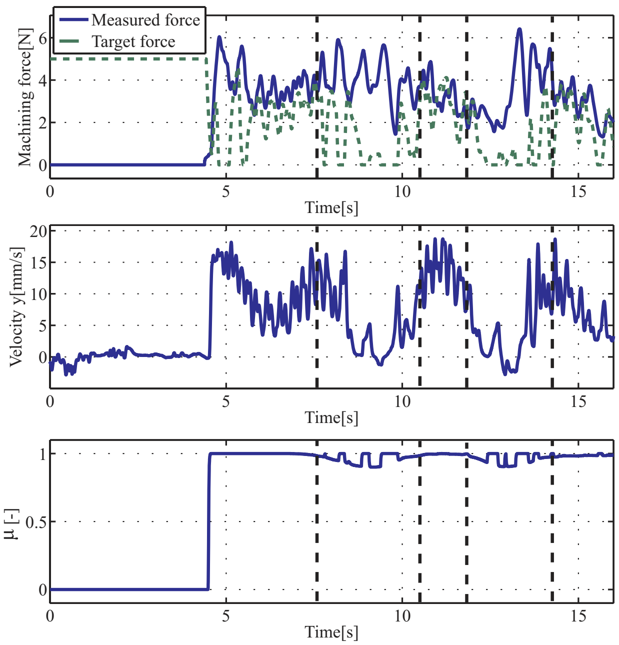

FIGURE 7. Experimental result of machining with proposed bilateral control and constant machining value method

time delay components between the master robot and the slave robot in this experiment. The experimental machining result is shown in Fig. 7. The machining tool is fed during machining with the caluclated machining force based on the controller for achieving the constant machining value proposed in the author's previous research [6]. This method has the feature that the machining value per unit length is kept constant even if the random change of the feed rate is happen. This method is useful for our study because the control method for the machining force or value that we propose will lead the demand that the user want to operate the robot slowly. The operator pushed the master robot toward the machining surface and μ reduced in the range surrounded by dash lines shown in Fig 7. In this range, the feed rate decreace and then, the target force close to 0 in order to keep the machining value constant. The machining force is kept by operator. Then, the machining value at its point becomes large. In this study, μ is set as $\mu = 0$ when the target force becomes 0N and over machining force is prevented. The machining surface achieved by this experiment is shown in Fig. 8. The operator had made the machining value large in circle A and the method for making machining value constant had been worked in circle B. From these experimental results, we see that the proposed method can make machining value constant and can increase it at arbitrary point.

FIGURE 8. Machining surface

CONCLUSION

In this study, the control methods and the motion equations which are required during machining were shown. From these conditions, the bilateral controller which can change the connecting force between the master and the slave robot dynamically was proposed. This system makes it possible to reflect the motion of the master robot in the motion of the slave robot which is controlled based on the machining theory. As a result, the machining trajectory is corrected by the operator. The effectiveness of this system was shown via the contact motion and machining experiment result. As a future works, we have to discuss the force feedback method for the operator in order to transfer the machining states such as the machining force or others precisely even if there are components of transfer time delay.

REFERENCES

[1] Alfi, A., and Farrokhi, M., 2008. "Force reflecting bilateral control of master-slave systems in teleoperation". *2009 ASME International Mechanical Engineering Congress and Exposition*, ***52***(2), pp. 209–232.

[2] E. Benjiamin, T. K., and Yokokohji, Y., 2008. "Robust variable-scale bilateral control for micro teleoperation". *IEEE International Conference on Robotics and Automation (ICRA 2008)*, pp. 655–662.

[3] J. Prak, R. C., and Khatib, O., 2003. "Robust and adaptive teleoperation for copmliant motion task". *International Conference on Advanced Robotics*, pp. 513–519.

[4] Yamada, H., Kudomi, S., and Muto, T., 2004. "Application to a bilateral master-slave system for grinding". *Proceedings of the 6th IASTED International Conference Intelligent Systems and Control*, pp. 13–17.

[5] T. Osada, K. Y., and Fofana, M. S., 2011. "On the development of a machining support system to improve surface finish". *Proceedings of the ASME 2011 International Mechanical Engineering Congress & Exposition*, pp. IMECE2011–64539.

[6] Osada, T., Yano, K., and Fofana, M. S., 2010. "Development of bilateral control system for process machining subject to changing cutting conditions". *Journal of Machine Engineering*, ***10***(3), pp. 90–101.

Copyright © 2012 by ASME