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ON THE DEVELOPMENT OF A MACHINING SUPPORT SYSTEM TO IMPROVE SURFACE FINISH

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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. The aim of this research is to develop a finish machining support system. The machining is supported by using a haptic device and controlled by a bilateral control system. Here, we propose a original bilateral controller which have the gain components on the line used to transfer the force signal between master and slave robot. These gains change the binding force between master and slave robot to change the construct of the system. The effectiveness of this system is shown in simulations using haptic device and virtual model of slave robot.

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. In addition, the effect of the tool's rotation causes disturbances. If the ability of the worker is insufficient, these factors will in turn cause machining errors or a fall in the accuracy of production.

To solve these problems, the correspondence of haptics with machining support systems has been studied. Yasuda improved control performance by eliminating the effect of the tool's rotation by using adaptive modeling that estimates the friction between the tool and work piece [1]. This system does not require information about the quality and shape of the work piece. The use of these systems makes it possible to clearly transmit the best cutting resistance force, which is difficult to feel without the assistance from the robot, and to reduce machining errors by eliminating disturbances during machining. Finish machining systems combining haptics and bilateral control shown in Fig. 1 have been studied as well. The Bilateral control is the one type of master-slave control method. This control system can transmit forces which provide the worker a feeling of independence even if the robot is controlled remotely. 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 [2].

When the bilateral control is applied to the machining support system, the contact force or the feed speed does not stabilize compared with automated machining. As a result, the accuracy of the product depends on the skill of the worker. In previous studies, a hybrid control method with position control and force control systems has been used [3] [4]. However, these control methods cannot make the height of the machining surface flat and smooth due to the irregular change of feed speed or the irregular state of burrs.

We proposed the teleoperating machining support system via bilateral control which have special construction [5]. Here, slave robot works automatically during machining because the control signal from master robot to slave robot is disconnected about for the thrusting direction. As a result, the motion of slave robot depends on only the controller that slave robot has independently. In addition, we proposed the control method that makes it possible to perform debbur process accurately even if the feed speed changes irregularly due to the workers operation as well. This study achieved a certain result. However, this method is not suitable to apply another field of machining support because this system has the space to accept the operator's opinion only about start position and stop position. This problem is caused by the used system that can not accept the operation toward thrusting direction during machining. In order to broaden the region of application, this system should be improved to accept the operator's opinion by changing the system component during operation so that the operator can work the machining robot with arbitrary way.

In this paper, the bilateral control system structured for the machining support system is proposed. In this control method, the gain changed by the machining condition is set on the line of force signal between master and slave robot. The value of this gain is defined to achieve desired control characteristic. For example, slave robot will move automatically toward thrusting direction during machining by setting the gain on the line from master to slave robot as 0. We will present the design of control proposed newly and the simulation results using this controller is shown.

FIGURE 1. DEVICES USED AS BILATERAL CONTROL SYSTEM

DESIGN OF CONTROLLER

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

Concept of Proposed Bilateral Controller

In order to develop the machining support system via bilateral control, the machining control method researched in development of automatic controlled robots should be applied in order to construct the useful system. In this system, the gain changed according to the machining condition is set on the line of the force signal between master and slave robot. The system model of this controller is shown in Fig. 2. By this gain, the domination rate of master and slave robot to the system can be controlled. This means that this controller can select several patterns and features of control. For example, slave robot is controlled by master robot during normal performance and controlled to trace the reference path calculated by machining theory during machining. The motion equations of this system are shown in (1) and (2).

$$\begin{aligned}M_m\ddot{x}(t) &= -c_m\dot{x}(t) - c_{mp}\dot{x}(t-\tau_{m1})\\&+ \mu_{m1}[k_d\{y(t-\tau_{s1}-\tau_{st}(t)) - x(t-\tau_{m1})\}\\&+ c_d\{\dot{y}(t-\tau_{s1}-\tau_{st}(t)) - \dot{x}(t-\tau_{m1})\}]\\&+ f_{op}(t) + f_m(t) + \mu_{m2}f_{env}(t-\tau_{s2}-\tau_{st}(t)) \qquad (1)\\M_s\ddot{y}(t) &= -c_s\dot{y}(t) - c_{sp}\dot{y}(t-\tau_{s1})\\&+ \mu_{s1}[k_d\{x(t-\tau_{m1}-\tau_{mt}(t)) - y(t-\tau_{s1})\}\\&+ c_d\{\dot{x}(t-\tau_{m1}-\tau_{mt}(t)) - \dot{y}(t-\tau_{s1})\}]\\&+ f_{env}(t) + f_s(t) + \mu_{s2}f_{op}(t-\tau_{m2}-\tau_{mt}(t)) \qquad (2)\end{aligned}$$

Where, x and y show the position of master and slave robot. M_m and M_s show the mass coefficient, c_m and c_s show the viscosity coefficient of them. k_d and c_d show the spring coefficient and viscosity coefficient between master and slave robot. f_{op} shows the force given by operator and f_{env} shows the force given by environment. Here, c_{mp} and c_{sp} are set in order to stabilize master and slave robot by themselves by decaying the energy remaining in the system. τ_{m1} and τ_{s1} show the time delay components caused by the filter used for shaping measured encoder value and τ_{m2} and τ_{s2} are for force sensor signals. τ_{mt} and τ_{st} show the time delay components which will happen when the signals are transfereed between master and slave robot. When we consider about nonlinear connection force between master robot and slave robot, (1) and (2) are written as,

$$\begin{aligned}M_m\ddot{x}(t) &= -c_m\dot{x}(t) - c_{mp}\dot{x}(t-\tau_{m1})\\&+ \mu_{m1}[k_d\{y(t-\tau_{s1}-\tau_{st}(t)) - x(t-\tau_{m1})\}\\&+ c_d\{\dot{y}(t-\tau_{s1}-\tau_{st}(t)) - \dot{x}(t-\tau_{m1})\}\\&+ O_3\{y(t-\tau_{s1}-\tau_{st}(t)) - x(t-\tau_{m1})\}^3\\&+ O_2 sign\{\dot{y}(t-\tau_{s1}-\tau_{st}(t)) - \dot{x}(t-\tau_{m1})\}\end{aligned}$$

$$
\begin{aligned}
&\{\dot{y}(t-\tau_{s1}-\tau_{st}(t))-\dot{x}(t-\tau_{m1})\}^2] \\
&+ f_{op}(t)+f_m(t)+\mu_{m2}f_{env}(t-\tau_{s2}-\tau_{st}(t)) \qquad (3)
\end{aligned}
$$

$$
\begin{aligned}
M_s\ddot{y}(t) &= -c_s\dot{y}(t)-c_{sp}\dot{y}(t-\tau_{s1}) \\
&+ \mu_{s1}[k_d\{x(t-\tau_{m1}-\tau_{mt}(t))-y(t-\tau_{s1})\} \\
&+ c_d\{\dot{x}(t-\tau_{m1}-\tau_{mt}(t))-\dot{y}(t-\tau_{s1})\} \\
&+ O_3\{x(t-\tau_{m1}-\tau_{mt}(t))-x(t-\tau_{s1})\}^3 \\
&+ O_2 sign\{\dot{x}(t-\tau_{m1}-\tau_{mt}(t))-\dot{y}(t-\tau_{s1})\} \\
&\quad \{\dot{x}(t-\tau_{m1}-\tau_{mt}(t))-\dot{y}(t-\tau_{s1})\}^2] \\
&+ f_{env}(t)+f_s(t)+\mu_{s2}f_{op}(t-\tau_{m2}-\tau_{mt}(t)) \qquad (4)
\end{aligned}
$$

In these equations, f_m and f_s work in order to achieve the target force, target position or target velocity. They are shown as (5) and (6).

$$
\begin{aligned}
f_m &= a_{mf}\{f_{tm}(t)-f_{op}(t-\tau_{m2})\} \\
&+ a_{mp}\{x_t(t)-x(t-\tau_{m1})\} \\
&+ a_{mv}\{\dot{x}_t(t)-\dot{x}(t-\tau_{m1})\} \qquad (5) \\
f_s &= a_{sf}\{f_{ts}(t)-f_{env}(t-\tau_{s2})\} \\
&+ a_{sp}\{y_t(t)-y(t-\tau_{s1})\} \\
&+ a_{sv}\{\dot{y}_t(t)-\dot{y}(t-\tau_{s1})\} \qquad (6)
\end{aligned}
$$

Where, a_{mf}, a_{mp}, a_{mv}, a_{sf}, a_{sp} and a_{sv} show coefficients used for each robots to achieve the target value. f_{tm}, x_t, $\dot{x}_t$, f_{ts}, y_{ts} and $\dot{y}_{ts}$ show target force, target position and target velocity for each robots. When these values are constant,

$$
\begin{aligned}
f_m &= a_{mf}\{f_{tm}-f_{op}(t-\tau_{m1}-\tau_{m2})\} \\
&+ a_{mp}\{x_t-x(t-\tau_{m1})\} \\
&+ a_{mv}\{\dot{x}_t-\dot{x}(t-\tau_{m1})\} \qquad (7) \\
f_s &= a_{sf}\{f_{ts}-f_{env}(t-\tau_{s1}-\tau_{s2})\} \\
&+ a_{sp}\{y_t-y(t-\tau_{s1})\} \\
&+ a_{sv}\{\dot{y}_t-\dot{y}(t-\tau_{s1})\} \qquad (8)
\end{aligned}
$$

When this controller is used for support system, the target value will become time varying value and we can select which target value is used. For example, the controller used for machining generally indicates how strongly the machining tool is pressed toward thrusting direction.

Design Examples of Bilateral Control System for Machining

In this section, we present the design examples of this controller in order to apply this to machining support system. We prepare the 2 patterns set value of μ. During normal control, this mean without machining working, μ_{m1} and μ_{s1} are set as $\mu_{m1} = 1, mu_s 1 = 1$. Master robot doesn't equip the force sensor. So, μ_{m2} is set as $\mu_{m2} = 0$. In this condition, the system has a same construction of force reflective type bilateral control. In addition, slave robot controller has a compliance controller in order to not yield the over load when it contacts with some object.

During machining, μ_{m1} and μ_{s1} are set as $\mu_{m1} = 1$, $\mu_{s1} = 0$ toward the normal direction. By using this condition, the motion of master robot doesn't influence the motion of slave robot. That is, slave robot has a completely dominating rate to the system. In addition, slave robot will move independently with a motion calculated by the machining theory if slave robot has a controller which control it independently based on the machining theory.

SIMULATION VIA PROPOSED BILATERAL CONTROLLER

First, we performed the simulation via virtual 1 DOF master robot and 1 DOF slave robot. This simulation was performed in 5 conditions.

1. No transfer time delay.
2. Include constant transfer time delay (0.2s).
3. Include time varying transfer time delay (shown in Fig. 3).
4. Slave robot has a target position ($y = 0$).
5. Slave robot has a target velocity ($\dot{y} = 0.5$[m/s]).

In condition 1, 2 and 3, μ_{m1} and μ_{s1} are set as $\mu_{m1} = 1$ and $\mu_{s1} = 1$. In condition 4 and 5, μ_{m1} and μ_{s1} are set as $\mu_{m1} = 1$ and $\mu_{s1} = 0$. Simulation results are shown in Fig. 4-8. The yellow markers are plotted every 0.1s and the green marker is plotted at 10s. In this simulation, we set $M_m = 1.0$[kg], $C_m = 50$[Ns/m], $C_{mp} = 20$[Ns/m], $M_s = 1.0$[kg], $C_s = 50$[Ns/m], $C_{sp} = 20$[Ns/m], $K_d = 100$[N/m], $C_d = 50$[Ns/m], $a_{sp} = 500$[N/m], $a_{sv} = 10$[Ns/m]. Each position signal and force signal of master and slave robot is run through the low pass filter with frequency 20Hz. The initial position of slave robot is set as $y_0 = 1$[m]. By comparing the simulation results in condition 1, 2, and 3, we can detect that the deviation between master and slave robot position become smaller as the simulation continue and becomes static. These movements can be observed even if there is transfer time delay. In this study, master robot and slave robot is connected by the spring component. The deviation can be reduced by setting more large spring coefficient. However, it is known that the overlarge spring coefficient make the system unstable. It is also known that the small impedance parameter leads the good response to input signal. The impedance parameter of master robot has limitation about its value because the operator and master robot are considered as one dynamics and it is difficult to reduce the impedance parameter of operator's hand. In this study, master robot can perform as dominator for slave robot by setting $\mu_{m1} = 0$ and $\mu_{s1} = 1$ and as followership by setting $\mu_{m1} = 1$ and

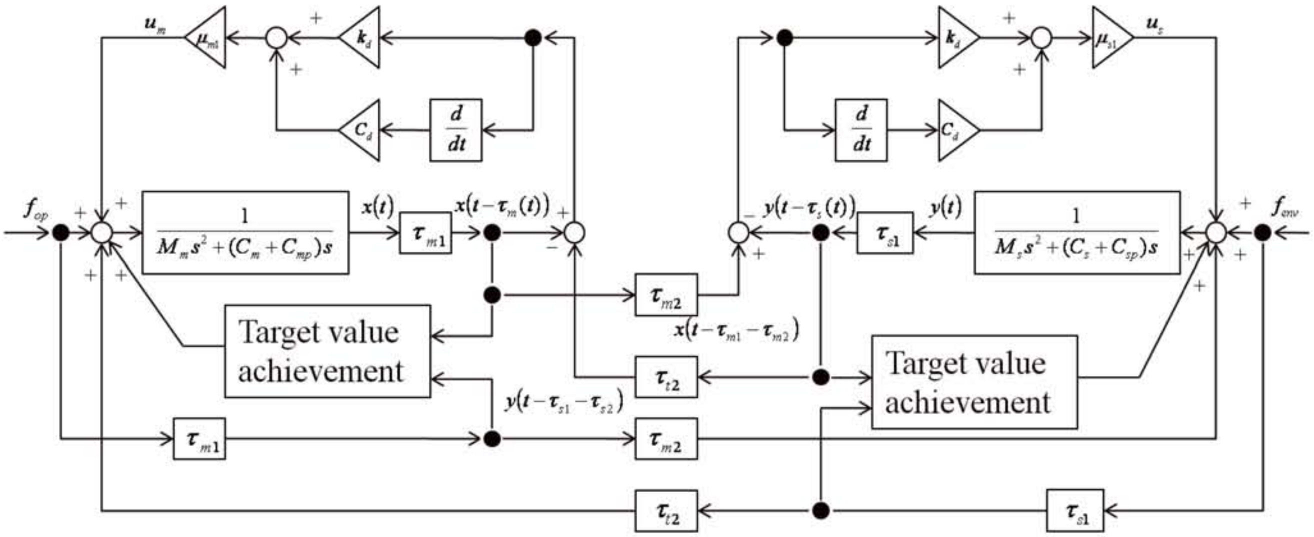

FIGURE 2. PROPOSED BILATERAL CONTROL SYSTEM FOR MACHINING SUPPORT

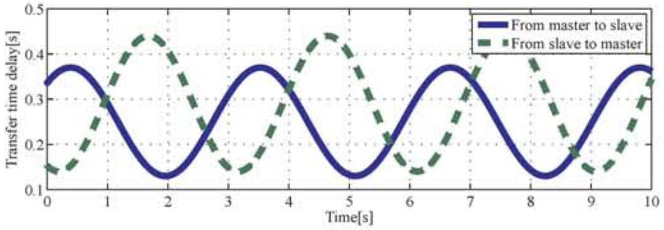

FIGURE 3. TRANSFER TIME DELAY

$\mu_{s1} = 0$. This mean that the optimum condition for one parameter setting may not be optimum one for another parameter setting. Therefore, we should define the spring coefficient carefully.

In condition 4 and 5, slave robot has the target position or the target velocity. This simulation results assume to perform some works by separating the control of slave robot from the movement of master robot. From these results, we can detect that this system make it possible to realize such features by changing μ. Slave robot can perform such a movement even if there are transfer time delay components because the movement of slave robot doesn't depend on movement of master robot. If we set $\mu_{m1} = 1$ and $\mu_{s1} = 1$, slave robot will receive both effect from master robot(u_s) and effect from its controller(f_s). This feature is also useful. For example, the velocity of slave robot should be reduced when it enter the region which has possibilities of collision with some object.

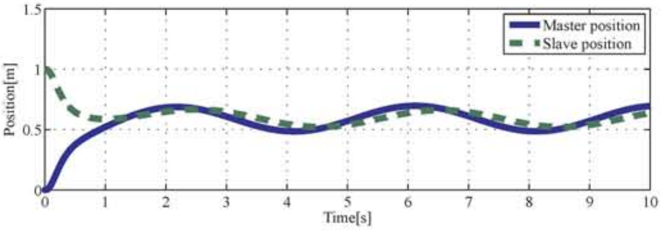

FIGURE 4. SIMULATION RESULT ABOUT POSITION OF MASTER AND SLAVE ROBOT IN CONDITION 1

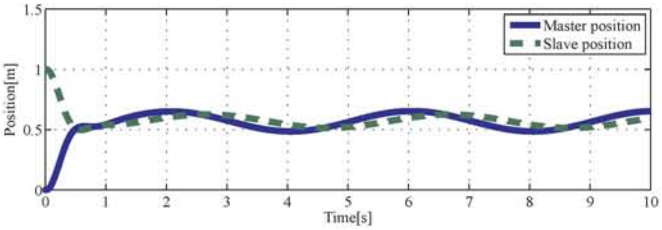

FIGURE 5. SIMULATION RESULT ABOUT POSITION OF MASTER AND SLAVE ROBOT IN CONDITION 2

EXPERIMENT RESULT

We perform the experiment with objective robot and virtual robot. Three-dimensional haptic device (Falcon, Novint) is used as master robot. This robot has the parallel mechanism and can output the 3 dimensional position signals. The force sensor is not equipped and 3dimensional force signal can be inputted. At this time, we consider only about one dimension. As a slave robot, we use the 1 DOF robot which have mass coefficient M_s and damper coefficient C_s. We assume that this robot can output the position signal and accept force signal. In addition, this robot has

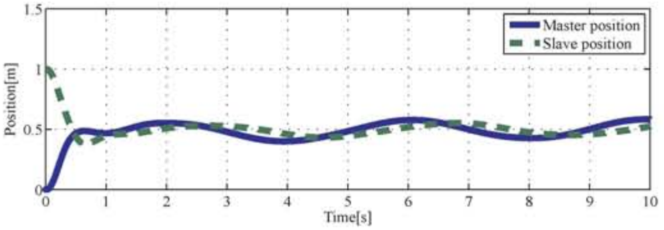

FIGURE 6. SIMULATION RESULT ABOUT POSITION OF MASTER AND SLAVE ROBOT IN CONDITION 3

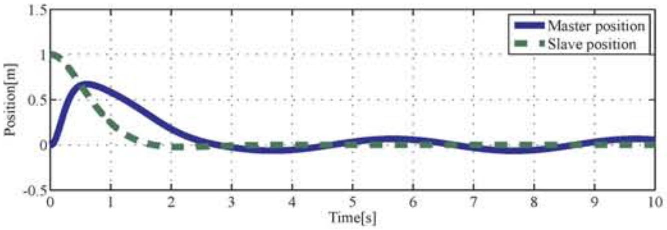

FIGURE 7. SIMULATION RESULT ABOUT POSITION OF MASTER AND SLAVE ROBOT IN CONDITION 4

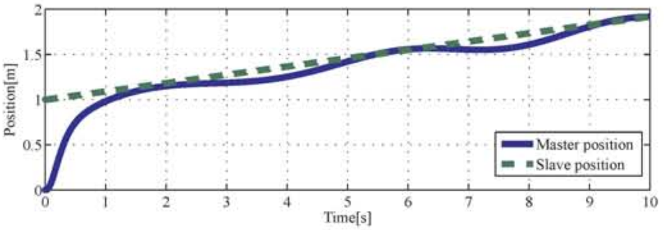

FIGURE 8. SIMULATION RESULT ABOUT POSITION OF MASTER AND SLAVE ROBOT IN CONDITION 5

the force sensor and measure the force signal which is given by the environment. From these conditions, (1) and (2) are rewritten as,

$$\begin{aligned} M_m\ddot{x}(t) &= -c_m\dot{x}(t) - c_{mp}\dot{x}(t-\tau_{m1}) \\ &\quad + \mu_{m1}[c_d\{y(t-\tau_{s1}) - x(t-\tau_{m1})\} \\ &\quad + k_d\{\dot{y}(t-\tau_{s1}) - \dot{x}(t-\tau_{m1})\}] \\ &\quad + f_{op}(t) + f_m(t) + \mu_{m2}f_{env}(t-\tau_{s2}) \qquad (9) \\ M_s\ddot{y}(t) &= -c_s\dot{y}(t) - c_{sp}\dot{y}(t-\tau_{s1}) \\ &\quad + \mu_{s1}[c_d\{x(t-\tau_{m1}) - y(t-\tau_{s1})\} \\ &\quad + k_d\{\dot{x}(t-\tau_{m1}-\tau_{m2}) - \dot{y}(t-\tau_{s1})\}] \\ &\quad + f_{env}(t) + f_s(t) \qquad (10) \end{aligned}$$

In this study, a master robot and slave robot are controlled by one computer. Then, we consider that there is no transfer time delay. We set as $C_{mp} = 50$[Ns/m], $M_s = 0.1$[kg], $C_s = 10$[Ns/m], $C_{sp} = 0$[Ns/m], $K_d = 1000$[N/m], $C_d = 100$[Ns/m].

This experiment was performed in 3 conditions.

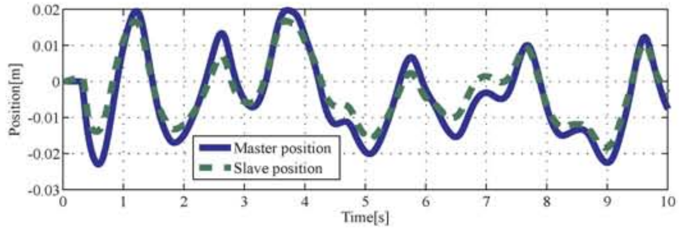

FIGURE 9. EXPERIMENT RESULT ABOUT POSITION IN CONDITION 1

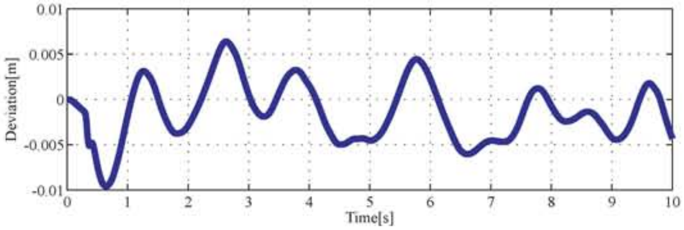

FIGURE 10. EXPERIMENT RESULT ABOUT DEVIATION IN CONDITION 1

1. $\mu_m 1 = 1$, $\mu_s 1 = 1$
2. $\mu_m 1 = 0.4$, $\mu_s 1 = 0$
3. $\mu_m 1 = 0$, $\mu_s 1 = 1$

These results are shown in Fig. 9-14. In condition 1 and 2, the target position is given as a form of sin wave. This motion can be observed in Fig. 11. In condition 1, master robot and slave robot have an equal condition. Therefore, both of the force from master robot and the force yield by controller of slave robot are given to slave robot. This phenomenon is observed in Fig. 9. In condition 2, slave robot is completely controlled only by the controller of slave robot. At this time, the overlarge spring coefficient destabilizes the motion of master robot. In this experiment, the connecting force between master robot and slave robot is adjusted by reducing the value of μ_{m1}. In condition 3, f_s is set as 0. Then, slave robot is controlled to trace master robot entirely. In order to improve the following capability of slave robot to master robot, impedance parameter is set as smaller value. Then, slave robot can trace master robot successfully and its accuracy can be improved by set μ_{s1} as higher gain. These results can be observed in Fig. 13 and 14.

CONCLUSION

In this study, a bilateral control system for a finish machining process was designed. This system have the arbitrary value μ on the line for force translation between master robot and slave robot. By changing this value, we can achieve the desired bilateral control system for machining support system. The relation natures between μ and motion of master and slave robot are

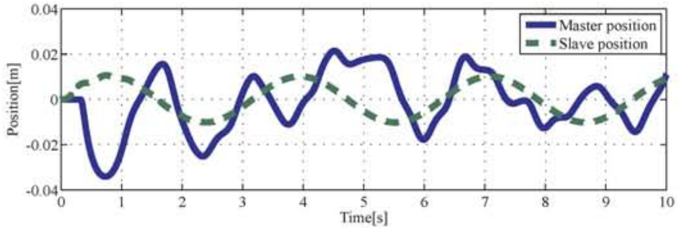

FIGURE 11. EXPERIMENT RESULT ABOUT POSITION IN CONDITION 2

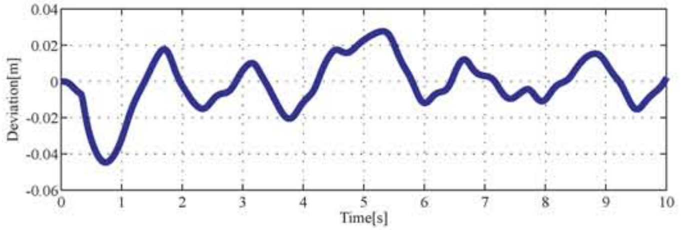

FIGURE 12. EXPERIMENT RESULT ABOUT DEVIATION IN CONDITION 2

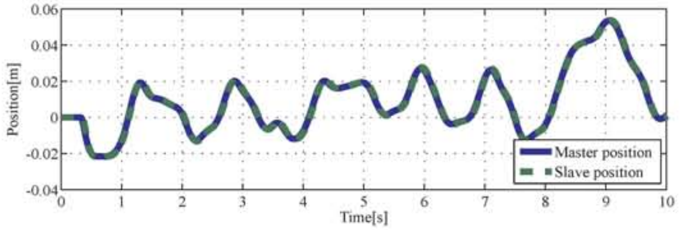

FIGURE 13. EXPERIMENT RESULT ABOUT POSITION IN CONDITION 3

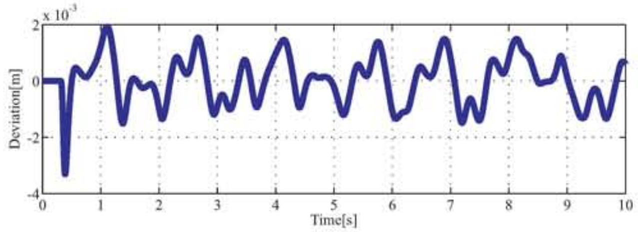

FIGURE 14. EXPERIMENT RESULT ABOUT DEVIATION IN CONDITION 3

shown through simulation and experiment results. These results show that this system can be applied to several operating conditions. The most important point is to define how should μ is changed. This should be discussed for each works such as debbur process, welding and others.

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