Force-Reflecting Teleoperation for Grinding Work

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Abstract: This paper explains problems of force-reflecting teleoperation grinding work and proposes some methods to solve those. For stable contact between robot tool(grindstone) and contact surface the mechanical impedance force control is used. The sliding phenomenon of grindstone has been appeared at the contact surface during the grinding work. The sliding problems caused by friction and rotation of grindstone are eliminated by using tangential direction sliding compensation control. The rotation force of grindstone makes the tool move to tangential direction along the surface suddenly even though an operator pushes the tool only in normal direction to the surface. Normal direction force control is applied for grinder not to roll and fracture on the grinding surface. Vibration problem of grindstone is decreased by second order low-pass filter. Therefore we can precise grinding work at the grinding surface and feel the reality

Keywords: Teleoperation, Force-Reflecting, Grinding,, stability

1. INTRODUCTION

Commonly, teleoperation system is mainly used and researched in the universe, underwater and nuclear power plant and so on where men can't directly reach at the working environment. There are many cases needed to work with robot substituting for man. Industrial field such as heavy industry is a representative example. Especially, grinding work raise muscuoloskeletal disorders problem to workers which is a rising problem. In welding work lately robot substitutes for human but the work done by robot is only limited in straight-line and robot doesn't response actively to various work including the curved surfaces. There are advantages in which operation using teleoperation system by man operator is active and meet immediately the emergency situation to various work. Therefore the usage of teleoperation system is needed to meet actively to diverse workpiece and to work safely.

In the view of contact robot control is divided two parts; non-contact control and contact control. Non-contact control is used as position controller when robot works without contacting with workpiece. However, contact control use both position controller and force controller when robot contacts with workpiece. Grinding work also should be done by contact control because of the contacting work between robot and workpiece. Safety in contact is satisfied through the mechanical impedance control. In addition, grinding work is done not by point-to-point contact but by surface-to- surface contact in contacting between robot and workpiece and considerable impact force occur by the spin of grindstone and working instability increases. Precise grinding work is difficult because of sliding situation occurred by the spin of grindstone and friction at the surface.

Especially, it is difficult to transfer the situation of working environment to operator during grinding work in bilateral force reflection teleoperation system. First, grinder vibration according to the spin of grindstone gives operator considerable discomfort and over load to bones and sinews. Next, it is difficult for operator to control by the reasons, high contact force with working environment and slip phenomenon of grindstone.

The research about grinding using robot has done like followings. In domestic research about robot grinding control technology has not been spreaded widely. In 1993 Kang[1] made grinding path extracted from data modeled using 2 dimension visual sensor system sensing the roof and side plate of a car in working environment and implemented real time work. In 1997 Lee and Choi[2][3] implemented real time position and velocity control using high stiffness hybrid mechanism combined serial and parallel robot for grinding propeller blades.

In 1985 foreign Asada and Goldfine[4] added actuator to decrease vibration occurring for grinding and designed optimal compliance tool support determined through dynamic analysis, simulation and experiment without active control. In 1988 Asada and Asari[5] controlled the robot by analysis of force and position data received through searching the impedance of man operator by direct teaching. In 1990 Kashiwagi[6] implemented force control for grinding work using two algorism, that is, Gradient Prediction Method and Progressive Stiffness Method. In 1991 Lu[7] suggested sliding mode controller based on impedance, in 1996 Jenkins[8] designed normal direction and tangential direction control loop separately for compensating stiff force control of grinding system. In 2000 Wang[9] implemented active torque control to apply desired force to normal direction of contact surface observing contact force of grind, but up to the present it seems that the research about grinding work using force reflection teleoperation has not been done variously.

In this research, hence, we suggest occurring problems when grinding work is done and find solutions to those.

2. IMPEDANCE CONTROL

Impedance control is passive and active impedance method divided by the method of controlling position and force setting mechanical impedance to operator's hand against the external force. Passive impedance is method of setting the mechanical impedance of operator's hand by passive mechanical element such as spring, damper and so on. Active impedance drives actuators by doing feedback position, velocity and force of hand and is method of implementing suitable mechanical impedance.

Fig. 1 is a simplified model to mechanical impedance contact. The current position of robot has error with desired end position of robot and for compensating the error virtual spring and damper system is made to make force.

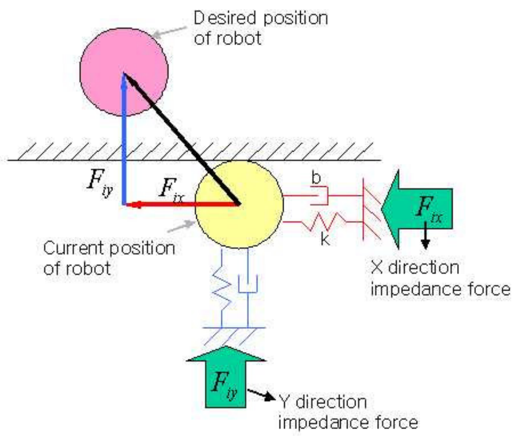

Fig. 1 Mechanical impedance contact model

Here, F_{ix}, K_x, B_x, x_d are respectively impedance force, spring constant, damping coefficient, desired position imposed to x direction, desired mechanical impedances are following to each direction.

$$F_{ix} = K_x(x - x_d) + B_x(\dot{x} - \dot{x}_d) \quad (1)$$

$$F_{iy} = K_y(y - y_d) + B_y(\dot{y} - \dot{y}_d) \quad (2)$$

value shows the degree of stiffness. If stiffness of link or workpiece is low, K value is small, if stiffness is high, K value is large. B value depend on velocity and viscosity of link and workpiece each other. If B value is high when moving fast has high resistance. That is similar effect having more resistance when moving fast into water.

Equation (3) produces torque at driving link required to make impedance force of equation (1) and (2) on the end point of robot.

$$\begin{pmatrix} \tau_2 \\ \tau_4 \end{pmatrix} = J^T \begin{pmatrix} F_{ix} \\ F_{iy} \end{pmatrix} \quad (3)$$

3. Grinding Control

In method of robot contact, grinding contact shows other type with existing general contact in analysis. For detail explanation of two contact method normal direction force besides tangential direction force is only considered.

For the general contact case of Fig. 2 eventually the end point of robot doesn't move and sustain at the same position and tangential force doesn't exist.

However, for the case of grinding contact in Fig. 3 friction force, F_f, which appears by contacting between the rotation of grinder and workpiece make tangential direction force. Therefore, it is known for tangential direction force to be produced in the case of no tangential direction force by operator.

In Fig. 4 it is shown two parts separately. One is the range occurring slip between grindstone and friction surface, the other is the range of without occurring slip. First, for the left range of the figure, when friction force is zero at friction surface grinder only rotates at friction surface and doesn't slip to tangential direction and grinding work is also impossible. With arise friction little by little grinder spinning force as large as friction force magnitude makes action and reaction then grinder is slid in tangential direction.

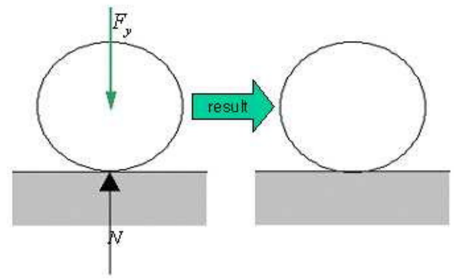

Fig. 2 General contact model without tangential force

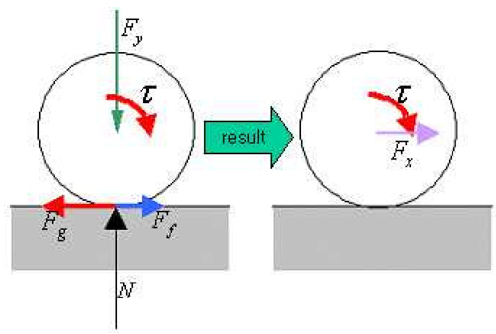

Fig. 3 Grinding contact model without tangential force

Grinding work is possible with this friction. If friction is the same as tangential force $F_g = \tau / r$ occurring by spin, the friction point is being instant center and slip between grindstone and friction surface is disappear, the velocity is zero. Grinder's rotation force centering friction point is sliding force (F_x) to tangential direction. This moving is a phenomenon as if with F_x pushing to tangential direction.

When friction increase more at the contact surface a situation is happened that rolling to tangential direction without slip or even grinder stops or fractures. In this situation, grinding work is impossible.

3.1 Normal Direction Force Control

On the above we discussed about grinding work possible range and impossible range. An important factor to determine the range is friction force which depend on friction coefficient and normal reaction (normal direction force). Friction coefficient is already determined according to material's dynamic or static and by controlling normal reaction friction force can be adjusted. Grinding work is possible when friction is smaller than grinder rotation force by controlling normal direction force.

$$F_f = \mu_k |F_y| = \tau / r \quad (\text{critical point}) \quad (4)$$

$$F_{cy} = \begin{cases} F_y & (F_y < \dfrac{\tau}{r\mu_k}) \\ \dfrac{\tau}{r\mu_k} & (F_y \geq \dfrac{\tau}{r\mu_k}) \end{cases} \tag{5}$$

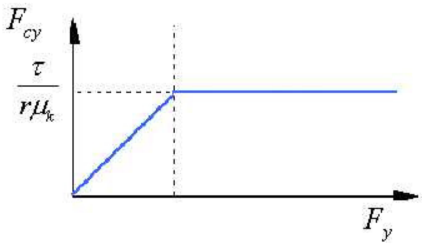

Fig. 4 Normal direction force control

In equation (5) if we have normal force larger than maximum critical normal force ($\tau/(r\mu_k)$) being possible grinding work it can be controlled not to have bigger normal force.

3.2 Tangential Direction Force Control

Even though force control of tangential direction is being, sliding situation give a rise in grinding able range. The sliding force can be known using F/T sensor but that is possible that only tangential force by operator is not exist. In the view of friction the sliding force is known and resistant force (F_{cx}) is needed not to be behind as the same as that force.

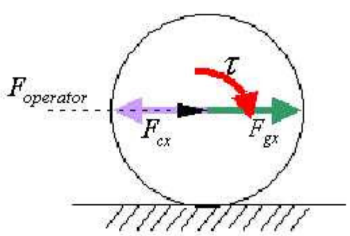

Fig. 5 Tangential direction force control

$$\begin{aligned} \sum F_x &= F_{operator} + F_{gx} + F_{cx} \\ &= F_{operator} + F_{gx} - F_{gx} \\ &= F_{operator} \end{aligned} \tag{6}$$

In analysis the force of tangential direction that consist of tangential force by operator, grinder's sliding force to tangential direction and the force against to the sliding force. If sliding grinder force and compensated force are cancelled each other tangential direction force by operator is on left. By making offset the force to tangential direction occurring by the rotation of grinder grinding work is possible at operator's desired position.

3.3 Master Robot Control

In above when slave robot control is done sliding force to tangential direction by rotation and friction of grinder occur and the same magnitude force against the sliding force prevent from sliding. However, from the control unnecessary force is sensed to F/T sensor and reflect the force.

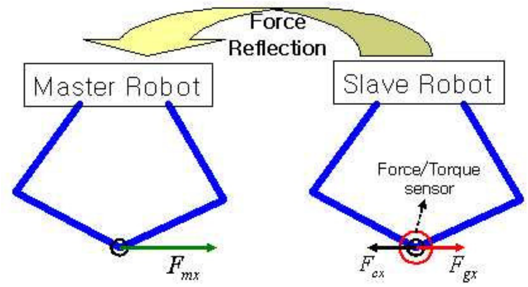

Fig. 6 Useless reflecting force caused by sla ve control

In Fig. 6 there are force (F_{gx}) slided by grinder rotation and motor control force (F_{cx}) applied to opposite direction to compensate that. Therefore, finally two times of the force occurring by grinding work in F/T sensor is measured.

$$F_{gx} - F_{cx} = F_{gx} - (-F_{gx}) = 2F_{gx} \tag{7}$$

Though the sliding of slave robot could be compensated By transferring measured from F/T sensor unless operator grasp firmly grinder would be slid. This is why if master robot is slid with force(F_{sx}) slave robot also follow as much as the position thrust. From this reason, exact position grinding work is difficult.

Therefore not to reflect the force to master robot we should transfer the value subtract, 2 F_{gx} from F_{sx} , to master robot. If desired tangential direction force transferred to master is F_{mx} ,

$$F_{mx} = F_{sx} - 2F_{gx} \tag{8}$$

4. EXPERIMENTAL DEVICE

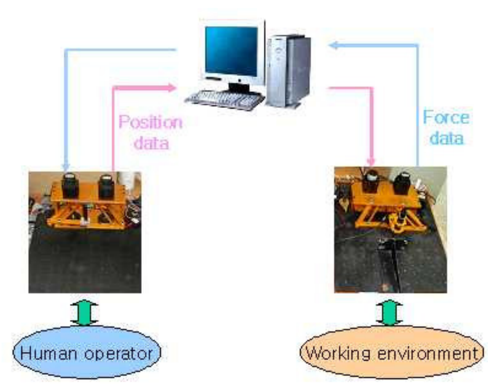

Fig. 7 Force-reflecting Teleoperation grinding system

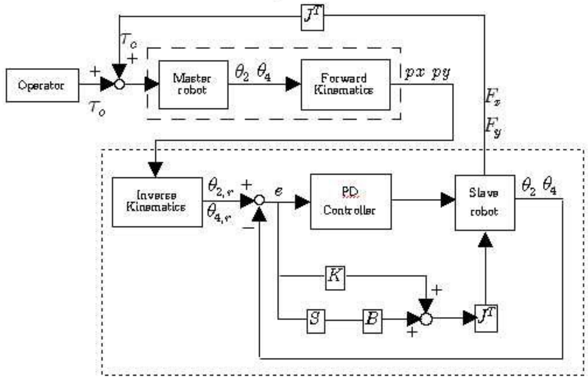

Fig. 8 Control loop block diagram

Fig. 8 shows a block diagram of force reflecting teleoperation grinding control loop. First, τ_c extracted from J^T times torque τ_o of operator and measured value of F/T sensor on slave robot drive master robot and desired position(p_x, p_y) is transmitted to slave robot through forward kinematics. Angle of driving link is obtained through slave robot inverse kinematics and slaver robot follows the position through PD controller. Here, slave robot is controlled by force control and impedance force determined using position error.

5. EXPERIMENTAL RESULTS

Fig. 9 and Fig. 10 show tangential direction error of master and slaver robot. The case of sliding compensation control of Fig. 10 has less tangential direction error than the case of Fig. 9 using only force controller. In Fig. 9 the range having sudden arising error is when grinder contact with working environment. The error is the value that minus slaver robot position from master robot position. At contact negative value means that master robot by force reflection slide before slaver robot do. Therefore it is shown that grinding control of master robot is also important.

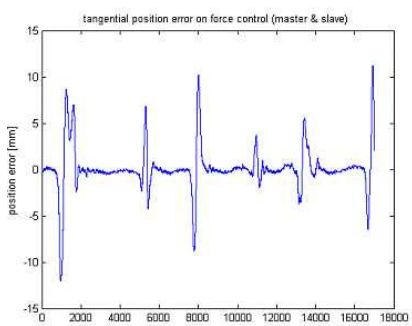

Fig. 9 Tangential position error with force control

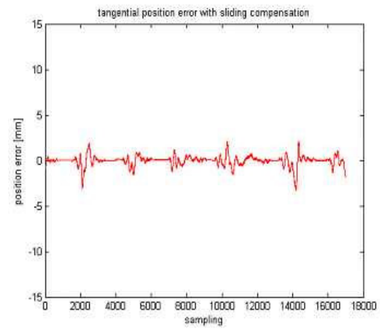

Fig. 10 Tangential position error with force control and sliding compensation

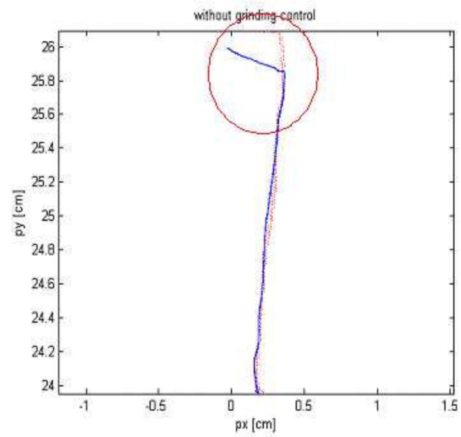

Fig. 11 Trajectory of master-slave robot without grinding control

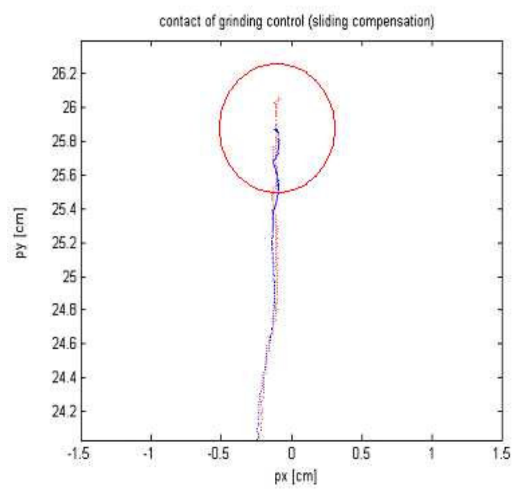

Fig. 12 Trajectory of master-slave robot with grinding control

In Fig. 11 and Fig. 12 two dimension contour is drawn when master and slave robot contact with environment. It is clear that tangential direction position error is decreased on using sliding compensation control. Fig. 11 shows that slave robot slides to tangential direction.

5. CONCLUSIONS

In this research we analyzed various problems occurring at teleoperation grinding work and suggested solutions.

2 D.O.F parallel robot is used for experiment. Bilateral force reflecting teleoperation control is implemented and calculating forward/inverse kinematics and robot jacobian is adopted.

It is analyzed to tangential direction sliding situation by rotation and friction force of grinder with surface-to-surface contact. Normal direction force control and tangential direction sliding compensation control are used. Some method is suggested for safety of master robot and low pass filter is used to decrease high frequency range vibration. Master robot is also controlled using tangential direction force control not to slide to tangential direction.

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