Improvement of Accuracy to Grind by Changing Position Control Gain for Shape-grinding

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Abstract. This research aims to achieve a new grinding robot system that can grind an object into desired shape with force-sensorless feed-forward control. However, there is a problem that vibration occurs during the grinding work has emerged, which makes the accuracy of the grinding become worse. Therefore, this paper proposes a method that changes the gain of position control for suppressing the vibration. Results observed by real grinding experiment have confirmed how our proposed method effectively improved accuracy of the grinding.

Introduction

Many researches have discussed force control methods of robots for constrained tasks. Most force control strategies use force sensors [1]-[3] to obtain force information, where the reliability and accuracy are limited since the work-sites of the robot are filled with noise and thermal disturbances, reducing the sensor's reliability. On top of this, force sensors could lead to the falling of the structure stiffness of manipulators, which is one of the most essential defects for manipulators executing grinding tasks. To solve these problems, some approaches that don't use force sensor have been presented [4]-[8]. Pratical use of polishing robots have been reported for finish process of mechanical parts in which infomation were utilized for detecting surface roughness [9], [10].

In this paper, we discuss about grinding task of robot that have grinder as an end-effector. The work-piece used for the grinding by the robot in this paper is iron, of which the spring constant of deformation against unit force is so huge to the extent that we can ignore the deformation of the work-piece caused by the constrained force with robot's end-effector since the grinding force exerted by the grinder to the work-piece in no more than 10 to 20 [N]. So the contact process of the grinder can be just thought as non-dynamical process but a kinematical one, so the prerequisite that there is no motion occurred in vertical direction to the surface to be ground could be undeniable. Therefore, in our research we don't use the time-differential equation of motion to describe constrained vertical process of the grinder to evaluate the proposed shape-grinding system, which aims for grinding to desired shape without force sensor. Moreover we confirmed the effectiveness of improving the transient responses of contact force by reshaping the time profile of the desired constrained force with several varieties.

Modeling

A photo of the experiment device is shown in Fig. 1. A concept of grinding robot of constrained motion is shown in Fig. 2. Constraint condition C is a scalar function of the constraint, and is expressed as an algebraic equation of constraints as

(1)

$$C(r(q))=0,$$



$$r(q) = \begin{bmatrix} r_x(q) \\ r_y(q) \end{bmatrix},\tag{2}$$

where r is the position vector from origin of coordinates to tip of grinding wheel and q is angles of motors. The grinder set at the robot's hand is in contact with the constrained surface, which is modeled as following Eq. (3),

$$M(q)\ddot{q} + h(q,\dot{q}) + g(q) + D\dot{q} = \tau + J_c^T f_n - J_R^T f_t, \qquad (3)$$

$$\left(\partial C\right)^T$$

$$J_{C}^{T} = \frac{\left(\frac{\partial C}{\partial q}\right)}{\left\|\frac{\partial C}{\partial r}\right\|},\tag{4}$$

$$J_R^{\ T} = \left(\frac{\partial r}{\partial q}\right)^T \frac{\dot{r}}{\|\dot{r}\|},\tag{5}$$

where M is a 2×2 matrix, h is centrifugal and Coriolis force vector, D is viscous friction coefficient matrix, g is gravity vector. f_n is the constrained force associated with C and f_t is the tangential friction force. Moreover, J_c^T is time-varying coefficient vector of f_n and J_R^T is time-varying coefficient vector of f_t . The equation of motion represented by Eq. (3) must follow the constraint condition denoted by Eq. (1) during the contacting motion of grinding. Differentiating Eq. (1) by time twice, we have the following condition of the robot's grinder keeping in contact with the work-piece to be ground,

$$\left[\frac{\partial}{\partial q}\left(\frac{\partial C}{\partial q}\right)\dot{q}\right]\dot{q} + \left(\frac{\partial C}{\partial q}\right)\ddot{q} = 0.$$
(6)

The above constraint condition represents an algebraic condition of \ddot{q} that have to be determined dependently following to q and \dot{q} . Putting \ddot{q} in Eq. (6) and \ddot{q} in Eq. (3) to be determined identically so as to the solution of q and \dot{q} of Eq. (3) satisfy simultaneously with the constraint condition Eq. (6), the solution \ddot{q} and f_n could be uniquely determined. The following Eq. (7) is the resulted solution of f_n [11]-[13],

$$f_n = a(q, \dot{q}) + B(q) J_R^T f_t - B(q) \tau.$$
⁽⁷⁾

Where m_c , $a(q,\dot{q})$ and B(q) are

$$\boldsymbol{m}_{c} = \left(\frac{\partial C}{\partial q}\right) \boldsymbol{M}^{-1} \left(\frac{\partial C}{\partial q}\right)^{T}, \qquad (8)$$

$$a(q,\dot{q}) = m_c^{-1} \left\| \frac{\partial C}{\partial r} \right\| \left\{ -\left[\frac{\partial}{\partial q} \left(\frac{\partial C}{\partial q} \right) \dot{q} \right] \dot{q} + \left(\frac{\partial C}{\partial q} \right) M^{-1} \left(h + g \right) \right\},$$
(9)

$$B(q) = m_c^{-1} \left\| \frac{\partial C}{\partial r} \right\| \left\{ \left(\frac{\partial C}{\partial q} \right) M^{-1} \right\}.$$
 (10)

Solutions of the above equation of motion always satisfy the constrained condition, Eq. (6), then q satisfies Eq. (1) accordingly.

Force and Position Controller

Reviewing the equation of motion Eq. (3) and constraint condition Eq. (1), it can be found that as the number of link is 2, the number of input torque is 2 and it is more than that of the constrained force, i.e., 1. From this point and Eq. (7) we can claim that there is a redundancy of the number of the constrained force against the number of the input torque τ . This condition is much similar to the kinematical redundancy. Based on the above argument, we assume that the parameters of the Eq. (7) are known and its state variables could be measured, and $a(q, \dot{q})$ and B(q) could be calculated correctly, which means that the constraint condition C = 0 be prescribed or measured correctly. As a result, a control law is derived from Eq. (7) and can be expressed as

$$\tau = -B^{+}(q) \Big\{ f_{nd} - a(q, \dot{q}) - B(q) J_{R}^{T} f_{t} \Big\} + \Big\{ I - B^{+}(q) B(q) \Big\} k , \qquad (11)$$

where I is a 2×2 identity matrix, f_{nd} is the desired constrained force, B(q) is defined in Eq. (12) and $B^+(q)$ is the pseudoinverse matrix of it, $a(q,\dot{q})$ is also defined in Eq. (11) and k is an arbitrary vector used for hand position control, which is defined as

$$k = \left(\frac{\partial r}{\partial q}\right)^T \left\{ K_P(r_d - r) + K_D(\dot{r}_d - \dot{r}) \right\},\tag{12}$$

where K_P and K_D are gain matrices for position and velocity control. The position and velocity control is executed through the redundant degree of range space of B, that is null space of B, $I - B^+B$. r_d is the desired position vector of the end-effector along to the constrained surface and ris the real position vector on it. Eq. (12) describes the required torque to achieve f_{nd} firstly with the minimum norm torque. We have to set K_P and K_D with a reasonable value, otherwise high frequency response of position error will appear. The controller presented by Eq. (11) and Eq. (12) assumes that the constraint condition C = 0 be known precisely as we can see $a(q, \dot{q})$ and B(q)include constraint condition C in Eq. (11) and Eq. (12) respectively, even though the grinding operation is a task to change the constraint condition.

Results

The end-effector's position is restricted by constraint condition C. A distance to grinding surface is 0.51[m] in y axis direction as shown in Fig. 3. In the experiments reported in this paper, we assumed

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that C is estimated by using grinder as touching sensor, then C = 0 is thought to be not changed and constant, then we have,

$$C(r(q)) = 0.51 - r_y(q) = 0, \qquad (13)$$

$$r_d(q) = \begin{bmatrix} r_{xd}(q) \\ r_{yd}(q) \end{bmatrix} = \begin{bmatrix} 0.02t \\ 0.51 \end{bmatrix}.$$
(14)

Desired constrained force f_{nd} is given as 10.0 [N] and grinding time is 10.0 [s] for 0.2 [m] to x-direction. The grinder has not been rotated to avoid that the grinding process add noises on the measured force data. Desired constrained force f_{nd} to use by experiments is given as

$$f_{nd} = 10\{1 + 16te^{-10t}\cos(8t)\}.$$
(15)

The above equation shows that desired constrained force converges to 10 [N] when time passes. Moreover, this equation is obtained from the precedent research. A rising time has been shorten, and an overshoot has been suppressed. We experimented on derivative gain of position control as 5 in the precedent research. In this paper, We experimented on these gain as 5, 10, 50. Fig. 4 represents time profile of constrained force mesured by a force sensor located between grinder and robot end-effector in case of $K_D = 5$. The depicted force is result calculated by averaging ten experiments of same contacting motion. In addition, The force data did moving average by ten data to remove a noise. Similarly, the force data is shown in Fig. 5, Fig. 6 in case of $K_D = 10$, 50. Moreover, we measured grinding surface of the work-piece using a surface roughness measuring instrument. This instrument is the Form Talysurf PGI1240 made Taylor Hobson. We show the measurement results of the surface roughness curve for each case in the Fig. 7, Fig. 8, Fig. 9. For an evaluation index, we find arithmetic average roughness R_a in the following equation.

$$R_{a} = \frac{1}{l_{p}} \int_{0}^{l_{p}} |y_{p}(x_{p})| dx_{p} .$$
(16)

Table. 1. Arithmetic average of surface roughness parameter

K_D [Ns]	5	10	50
$R_a [\mu m]$	2.8055	2.4688	2.0911



Fig. 9. Roughness curve y_p ($K_D = 50$)

Fig. 10. Work-piece after the experiment

Where, l_p is sampling length and $y_p(x_p)$ is roughness curve of x-axis. Tab. 1 shows results in each case that we calculated from Eq. (16). Further, a photo of the work-piece which we experimented for each case is shown in Fig. 10. From these results, we have confirmed that the grinding robot system could grind the work-piece accurately in case of $K_p = 50$.

Conclusion

In this paper, we have done some force-sensorless grinding experiments using the grinding robot system. Then it was confirmed that the system could grind the work-piece accurately when we experimented on the derivative gain of position control $K_D = 50$. In the future, we are going to do force-sensorless continuous shape-grinding experiment using $K_D = 50$ as the derivative gain of position control.

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