

# Grinding Experiment by Force-sensorless Grinding Robot with Feed-forward control

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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. In order to grind the target object into desired shape with sufficient accuracy, the hand of the robot arm has to generate desired constrained force immediately after the grindstone being contacted with the metal object to be ground. Based on the algebraic equation, we have proposed Constraint-Combined Force Controller, which has the ability to achieve the force control without time delay if the motors ideally should generate required torques without time delay, where, force error will not be affected by the dynamical motion along to the surface in nonconstraining direction. The Constraint-Combined force/position control method without using sensors is essentially different from methods proposed so far that relied on force sensors.

**Keywords:** force-sensorless grinding, constrained force, robot.

## 1 INTRODUCTION

Industrial robots are used for many purposes, especially as machining facilities. For example, there are welding, assembling and grinding operations. This research aims to achieve a new grinding robot system that can grind an object into desired shape with force-sensorless feed-forward control.

Many researches have discussed force control methods of robots for constrained tasks. These 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 sensors have been presented[4]-[8].

In this paper, we discuss about grinding task of robot that have disk grinder as an end-effector. Our grinding robot is 2-link SCARA manipulator. The work-piece used for the grinding by the robot in this paper is iron, where 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 is no more than 10[N] in case of that human makes exercise of grinding task by hand. 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-

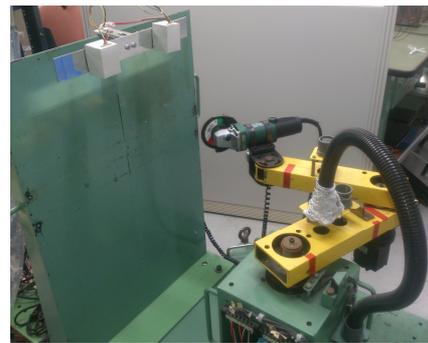


Fig. 1. Grinding robot

differential equation of motion to describe constrained vertical process of the grinder contacting to the work-piece. Oppositely, we consider an algebraic equation as the constraint condition to analyze this contacting motion.

Based on this algebraic equation, we have proposed Constraint-Combined Force Controller (CCFC), which has the ability to achieve the force control without time delay if the motors ideally should generate required torques without time delay [11]-[13], where, force error will not be affected by the dynamical motion along to the surface in nonconstraining direction [11], [12]. The Constraint-Combined force/position control method without using sensors can be thought to be essentially different from methods proposed so far [6]-[9]. CCFC we have proposed can compute the input torques to achieve desired force/position by using posture and angular velocity of the robot and frictional force between the grinder and work-piece.

Posture, angular velocity can be detected easily but the frictional force and frictional coefficient that influences the

contacting force control results in our CCFC are difficult to measure correctly. In this paper, the grinding resistance coefficient is obtained by experiment and it is confirmed that appropriate grinding control is being performed.

## 2 MODELING

An 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

$$C(r(q)) = 0, \quad (1)$$

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. (2),

$$M(q)\ddot{q} + h(q, \dot{q}) + g(q) + D\dot{q} = \tau + J_C^T f_n - J_R^T f_t, \quad (2)$$

$$J_C^T = \frac{\left(\frac{\partial C}{\partial q}\right)^T}{\left\|\frac{\partial C}{\partial r}\right\|}, \quad (3)$$

$$J_R^T = \left(\frac{\partial r}{\partial q}\right)^T \frac{\dot{r}}{\|\dot{r}\|}, \quad (4)$$

where  $M$  is a  $n \times n$  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 disturbance force. Moreover,  $J_C^T$  is time-varying coefficient vector translating  $f_n$  into each joint disturbance torque and  $J_R^T$  is time-varying coefficient vector

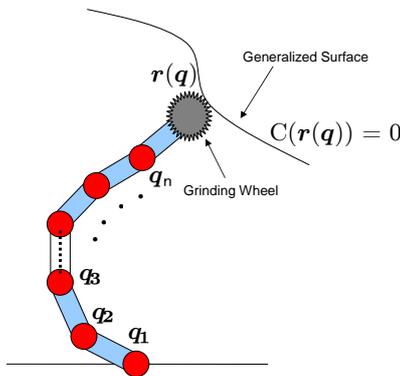


Fig. 2. Grinding robot model

transmitting the tangential disturbance force  $f_t$  to joint disturbance torque. The dynamic equation represented by Eq. (2) 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,

$$\left[\frac{\partial}{\partial q} \left(\frac{\partial C}{\partial q}\right) \dot{q}\right] \dot{q} + \left(\frac{\partial C}{\partial q}\right) \ddot{q} = 0. \quad (5)$$

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. (5) and  $\ddot{q}$  in Eq. (2) to be determined identically so as to the solution of  $q$  and  $\dot{q}$  of Eq. (2) comply simultaneously with the constraint condition Eq. (5), the solution  $\ddot{q}$  and  $f_n$  could be uniquely determined. The following Eq. (6) is the resulted solution of  $f_n$  [11]-[13],

$$f_n = a(q, \dot{q}) + B(q)J_R^T f_t - B(q)\tau. \quad (6)$$

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

$$m_c \triangleq \left(\frac{\partial C}{\partial q}\right) M^{-1} \left(\frac{\partial C}{\partial q}\right)^T, \quad (7)$$

$$a(q, \dot{q}) \triangleq m_c^{-1} \left\| \frac{\partial C}{\partial r} \right\| \left\{ - \left[ \frac{\partial}{\partial q} \left(\frac{\partial C}{\partial q}\right) \dot{q} \right] \dot{q} + \left(\frac{\partial C}{\partial q}\right) M^{-1} (h + g) \right\}, \quad (8)$$

$$B(q) \triangleq m_c^{-1} \left\| \frac{\partial C}{\partial r} \right\| \left\{ \left(\frac{\partial C}{\partial q}\right) M^{-1} \right\}. \quad (9)$$

Substituting Eq. (6) into Eq. (2), the equation of motion of the constrained robot dynamics (as  $f_n > 0$ ) can be rewritten as

$$M(q)\ddot{q} + h(q, \dot{q}) + g(q) = J_C^T a(q, \dot{q}) + (I - J_C^T B)\tau + (J_C^T B - I)J_R^T f_t. \quad (10)$$

Solutions of above dynamic equation always satisfy the constrained condition, Eq. (5), then accordingly  $q$  satisfies Eq. (1).

## 3 FORCE AND POSITION CONTROLLER

Reviewing the dynamic equation Eq. (2) and constraint condition Eq. (1), it can be found that as the number of links are 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. (6) we can claim that there is a redundancy of the number of the constrained force against the number of the input torque  $\tau$ . This condition is much similar to the kinematical redundancy. Based on the above argument and assuming

that, the parameters of the Eq. (6) 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. (6) and can be expressed as

$$\tau = -B^+(q)\{f_{nd} - a(q, \dot{q}) - B(q)J_R^T f_t\} + \{I - B^+(q)B(q)\}k, \quad (11)$$

where  $I$  is a  $n \times n$  identity matrix,  $f_{nd}$  is the desired constrained forces,  $B(q)$  is defined in Eq. (9) and  $B^+(q)$  is the pseudoinverse matrix of it,  $a(q, \dot{q})$  is also defined in Eq. (8) and  $k$  is an arbitrary vector used for hand position control, which is defined as

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

where  $K_P$  and  $K_V$  are gain matrices for position and the 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  $r$  is 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  $K_V$  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. (8) and Eq. (9) respectively, even though the grinding operation is a task to change the constraint condition. This looks like a contradiction, so we need to observe time-varying constraint conditions in real time by using grinding tip as a touch sensor.

The time-varying condition is estimated as an approximate constrained function by position of the manipulator grinder used as touch sensor to presume the ground surface shape. The estimated condition is denoted by  $\hat{C} = 0$  (in this paper, “^” means the presumption of unknown constraint condition). Hence,  $a(q, \dot{q})$  and  $B(q)$  including  $\partial\hat{C}/\partial q$  and  $\partial/\partial q(\partial\hat{C}/\partial q)$  are changed to  $\hat{a}(q, \dot{q})$  and  $\hat{B}(q)$  as shown in Eq. (14) and Eq. (15). They were used in the estimation experiments of the unknown constrained condition. As a result, a controller based on the estimated constrained condition is given as

$$\hat{\tau} = -\hat{B}^+(q)\{f_{nd} - \hat{a}(q, \dot{q}) - \hat{B}(q)J_R^T f_t\} + \{I - \hat{B}^+(q)\hat{B}(q)\}k, \quad (13)$$

$$\hat{a}(q, \dot{q}) \triangleq m_c^{-1} \left\| \frac{\partial \hat{C}}{\partial r} \right\| \left\{ - \left[ \frac{\partial}{\partial q} \left( \frac{\partial \hat{C}}{\partial q} \right) \dot{q} \right] \dot{q} + \left( \frac{\partial \hat{C}}{\partial q} \right) M^{-1}(h + g) \right\}, \quad (14)$$

$$\hat{B}(q) \triangleq m_c^{-1} \left\| \frac{\partial \hat{C}}{\partial r} \right\| \left\{ \left( \frac{\partial \hat{C}}{\partial q} \right) M^{-1} \right\}. \quad (15)$$

Fig. 3 illustrates a control system constructed according to the above control law that consists of a position feedback control loop and a force feedforward control. It can be found from Eq. (6) and Eq. (13) that the constrained force always equals to the desired one explicitly if the estimated constraint condition equals to the real one, i.e.,  $C = \hat{C}$  and  $f_t = 0$ . This is based on the fact that force transmission is an instant process.

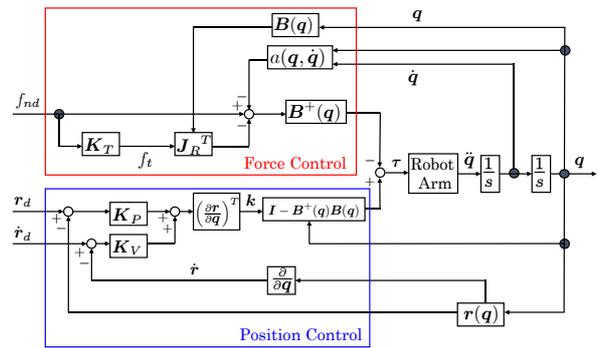


Fig. 3. Block diagram

#### 4 ANALYSIS OF GRINDING TASK

Generally speaking, the grinding power is related to the metal removal rate—weight of metal being removed within unit time—, which is determined by the depth of cut, the width of cut, the linear velocity of the grinding wheel, the feed rate and so on. There are many empirical formula available for the determination of grinding power, and the desired force trajectory can then be planned according to the power. The constrained force  $f_n$  is exerted on the workpiece in the perpendicular direction of the surface, and is a significant factor that affects ground accuracy and surface roughness of workpiece. The value of it is also related to the grinding power or directly to the tangential grinding force as

$$f_t = K_T f_n, \quad (16)$$

where,  $K_T$  is an empirical coefficient,  $f_t$  is the tangential grinding force.

#### 5 CONSIDERING GRINDING RESISTANCE

In the previous chapter, we mentioned that the input  $\tau$  can be determined as  $q, \dot{q}, f_t$  can be observed. When expressing the tangential grinding force using Eq.(16) in the control law,

Eq.(11), by substituting into the Eq.(6), the relationship between the constrained force  $f_n$  and the target constrained force  $f_{nd}$  is

$$f_n = f_{nd} + \mathbf{B}(\mathbf{q})\mathbf{j}_t^T(f_t - K_T f_{nd}). \quad (17)$$

Therefore, it can be seen from Eq. (17) that the second term on the right side corresponds to the friction force error made by the difference between actual friction force  $f_t$  and eliminated friction force  $K_T f_{nd}$ .  $\mathbf{B}(\mathbf{q})\mathbf{j}_t^T$  is determined by the attitude of the robot. The error between the actual constrained force  $f_n$  obtained from the experimental result and the desired force  $f_{nd}$  is considered to be proportional to  $(f_t - K_T f_{nd})$ .

When we define  $\Delta f = f_{nd} - f_n$  that Eq.(17) can be changed into

$$\Delta f = \mathbf{B}(\mathbf{q})\mathbf{j}_t^T K_T f_{nd} - \mathbf{B}(\mathbf{q})\mathbf{j}_t^T f_t. \quad (18)$$

Considering the change of the manipulators shape during grinding dose not large extent,  $\mathbf{B}(\mathbf{q})\mathbf{j}_t^T$  seems to be generally constant.

In this report, the tangential grinding force which reduces the error of the constrained force is obtained from the experiment, and the control performance at that time is confirmed.

## 6 EXPERIMENT

### 6.1 Determination of grinding resistance coefficient

The target binding force is kept constant, and the grinding resistance coefficient is changed. At this time, the grinding resistance coefficient from which the error between the target binding force and the actual binding force is eliminated is obtained from the experiment. With the condition that the change in the posture of the robot is constant, the target binding force is set to  $f_{nd} = 10$  [N], and the grinding resistance coefficient  $K_T$  is changed by 0.1 from 0.1 to 0.6 at 0.1 times, and the grinding force The average of the measured values was examined. Fig.6 shows the average value of the binding force at each grinding resistance coefficient. The grinding resistance of  $K_T$  when achieving the target binding force from

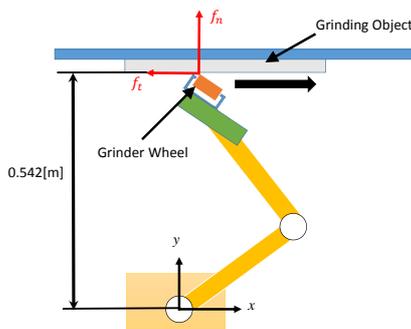


Fig. 4. Experimental device



Fig. 5. Work piece

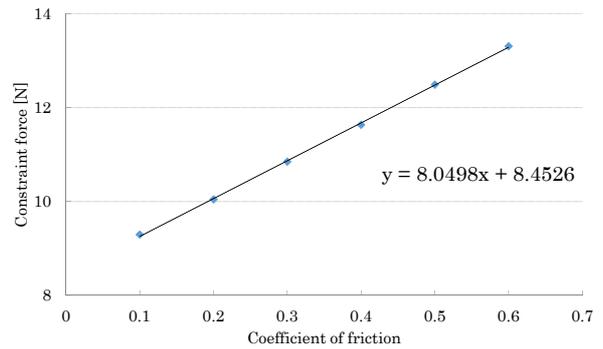


Fig. 6. Constraint force

Table 1. Error between target restraint force on each grinding resistance coefficient

$K_t$	$f_n$ [N]	$f_{nd} - f_n$ [N]
0.1	9.30	-0.70
0.2	10.05	0.05
0.3	10.85	0.85
0.4	11.63	1.63
0.5	12.49	2.49
0.6	13.31	3.31

the intersection of the approximate straight line derived from the graph of Fig. 6 and the x axis is set to 0.192.

### 6.2 Verification of derived grinding resistance coefficient

An arbitrary binding force should be achieved by control using the determined grinding resistance coefficient. In order to verify the validity of the grinding resistance coefficient  $K_t$ , grinding was performed by changing the value of the target binding force  $f_{nd}$  to 6 to 10 [N], and the actual measurement value of the binding force at that time and the change of the grinding resistance Examined.  $K_t$  was set to 0.192 and other experimental environments and conditions were the same as in the previous section, and only the target binding force  $f_{nd}$  was changed. Table 2 shows the error between the average value of the binding force actually measured and the target.

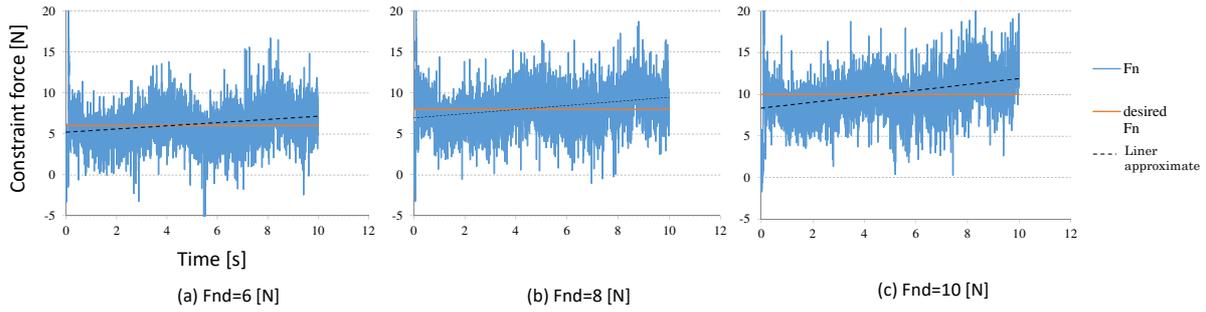


Fig. 7. Experiment result  $f_n$

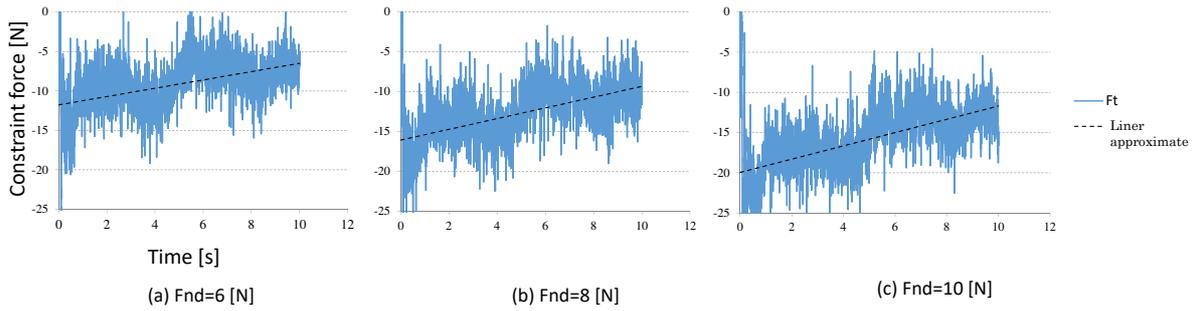


Fig. 8. Experiment result  $f_t$

Table 2. Error between measured constrained force and target

$f_{nd}[N]$	$f_n[N]$	$f_n - f_{nd}[N]$
6	6.19	0.19
7	7.15	0.15
8	8.22	0.22
9	8.94	-0.06
10	10.13	0.13

Also, the transition of the actual binding force during grinding is shown in FIGS. 8 and 9 as a representative of the case where the target binding force is 6 [N] and 10 [N].

### 7 CONSIDERATION

From the Eq.(17), it is expected that the error between the actual binding force obtained from the experimental result and the target becomes a value proportional to  $(f_t - K_t f_{nd})$ . From Fig.6, it can be confirmed that the error between the actual binding force and the target appears in the form of a first-order proportion. However, from Fig. 8, it can be seen that the constraint force increases with time from the linear approximation line of the constraint force represented by the broken line. This is because the experimental apparatus is a 2-link manipulator, the angle of the object to be ground and the disc grinder varies depending on the position, as can be seen from the graph of the actually measured value of the grinding resistance force in Fig.8, it is considered to change the grinding resistance force .

### 8 CONCLUSION

In this report, the effect of grinding resistance on grinding work was described by grinding experiment. . Calculate that the appropriate value of  $K_T$  is 0.192 from the approximate straight line of the graph of  $K_T$  and the error, and verify the validity of the value of  $K_t$  by performing grinding with varying the target binding force using it And confirmed that the average value of the binding force satisfies the target binding force.

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