

Continuous shape-grinding experiment based on model-independent force/position hybrid control method with on-line spline approximation

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Abstract Based on the analysis of interaction between manipulator's hand and working object, a model representing the constrained dynamics of robot is first discussed. The constraint forces are expressed by algebraic function of states, input generalized forces, and constraint condition, and then a decoupling control method of force and position of manipulator's hand tip is proposed. In order to give the grinding system the ability to adapt to any object shape being changed by the grinding, estimating function of the constraint condition in real time for the adaptive force/position control was added, which is indispensable for the proposed method without using force sensor. This paper explores whether the performance of the proposed controller is independent of alloy work-piece models or not. The experimental result is shown to verify the feature of the decoupling control of force and position of the tip.

Keywords Continuous shape-grinding · Force/position hybrid control · Model-independent control · Spline approximation

1 Introduction

Many researches have discussed the force control of robots for contacting 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 without using any force sensors have been presented [4, 5]. To ensure the stabilities of the constrained motion, those force and position control methods have utilized Lyapunov's stability analysis under the inverse dynamic compensation [6–8]. Their force control strategies have been explained intelligibly in books [9, 10] and recently interaction control for six-degree-of-freedom tasks has been compiled in a book [11].

A work-piece model being ground by our grinding robot in this paper is alloy, whose spring constant is so huge to the extent that we can ignore the deformation of the work-piece model caused by the contacting force with robot's end effector. So the contact process of the grinder can be just thought as non-dynamical process but a kinematical one, and no motion occurred in the vertical direction. Therefore, in our research, we do not use the time-differential motion equation to analyze the contacting vertical process to the work-piece model; on the contrary, we consider an algebraic equation as the constraint condition to analyze this contact vertical force. Constraint-combined force controller based on this algebraic equation has the ability to achieve the force control without time delay; moreover, force error will not be affected by the dynamical motion along the surface in the horizontal direction. In

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model-based hybrid control field, some former researches have noticed this “just an immediate contact result but no motion occurred” problem and tried solving it using force or torque sensor. But since force or torque sensor is so costly, we consider a model-independent force/position control method without using sensors. Therefore, with these differences from those former force control methods, constraint-combined and model-independent force/position control method without using sensors introduced in this paper is essentially different from methods proposed so far. For example, recently although robot machining system for grinding, polishing and milling was developed [12], the system uses just position control of robot tip through scanned surface profile, not considering force control. Hamelin et al. [13] have considered underwater direct-drive grinding robot to repair dike and dam periodically for operability. This research focused on trajectory-tracking performance and it did not mention about force control although a constant grinding force was applied on work-piece. Song et al. [14] proposed a robot belt grinding system using force/position hybrid control method. Their method uses force sensor to control contact force, different from our system.

The problem to be solved in our approach is that the mathematical expression of algebraic constraint condition should be defined in the controller instead of the merit of not using force sensor. In order to make the performance of proposed controller independent of target work-piece model, grinding task requires on-line estimation of changing constraint condition since grinding is the action to change the constraint condition in nature. In this paper, we estimate the object's surface using the grinder as touch sensor. In order to give the system the ability to grind any working object into any shape, we focus on how to update the constraint condition in real time, obtaining the result that spline function is best for on-line shape estimation.

Based on the above preparation, we explored a continuous shape-grinding experiment to evaluate the proposed shape-grinding system, which aims for grinding to desired shape without force sensor.

2 Modeling

2.1 Constrained dynamic systems

Hemami and Wyman [15] have addressed the issue of control of a moving robot according to constraint condition. They examined the problem of the control of the biped locomotion constrained in the frontal plane. Their purpose was to control the position coordinates of the biped locomotion rather than generalized forces of constrained dynamic equation, which involves the item of generalized

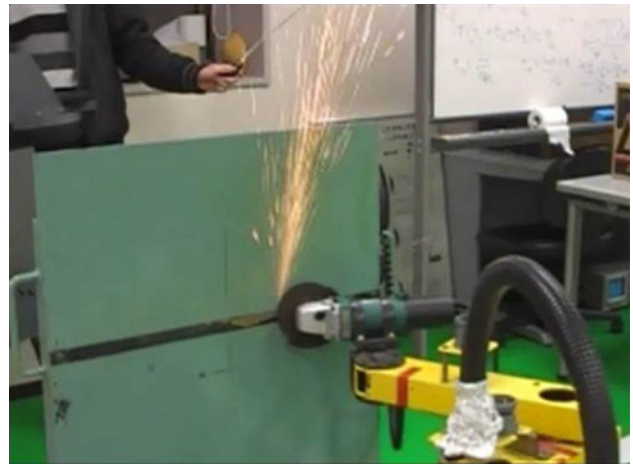


Fig. 1 Grinding robot system

forces of constraints. And the constrained force is used as a determining condition to change the dynamic model from constrained motion to free motion of the legs. In this paper, the end-point of the grinding manipulator shown in Fig. 1 is in contact with the constrained surface. The manipulator is modeled according to (1) with Lagrangian equations of motion in terms of the constraint forces, referring to what Hemami and Arimoto have done:

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{\mathbf{q}}} \right) - \left(\frac{\partial L}{\partial \mathbf{q}} \right) = \boldsymbol{\tau} + \mathbf{J}_c^T(\mathbf{q})\mathbf{F}_n - \mathbf{J}_r^T(\mathbf{q})\mathbf{F}_t, \quad (1)$$

where \mathbf{F}_n is the constrained force associated with constraint C , \mathbf{F}_t is the tangential grinding force, $\mathbf{J}_c = \mathbf{J}_c(\mathbf{q})$ and $\mathbf{J}_r = \mathbf{J}_r(\mathbf{q})$ are their coefficient vectors and defined as:

$$\mathbf{J}_c = \frac{\partial C}{\partial \mathbf{q}} / \left\| \frac{\partial C}{\partial \mathbf{r}} \right\| = \frac{\partial C}{\partial \mathbf{r}} \tilde{\mathbf{J}}_r / \left\| \frac{\partial C}{\partial \mathbf{r}} \right\|, \\ \tilde{\mathbf{J}}_r = \frac{\partial \mathbf{r}}{\partial \mathbf{q}}, \quad \mathbf{J}_r^T = \tilde{\mathbf{J}}_r^T \mathbf{r} / \left\| \dot{\mathbf{r}} \right\|,$$

\mathbf{r} is the l position vector of the hand and can be expressed as a kinematic equation

$$\mathbf{r} = \mathbf{r}(\mathbf{q}). \quad (2)$$

L is the Lagrangian function, \mathbf{q} is $l(\geq 2)$ generalized coordinates, $\boldsymbol{\tau}$ is l inputs. The discussing robot system does not have kinematical redundancy. C is a scalar function of the constraint and is expressed as an equation of constraints

$$C(\mathbf{r}(\mathbf{q})) = 0, \quad (3)$$

(1) can be derived as

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{H}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}) = \boldsymbol{\tau} + \mathbf{J}_c^T(\mathbf{q})\mathbf{F}_n - \mathbf{J}_r^T(\mathbf{q})\mathbf{F}_t, \quad (4)$$

where \mathbf{M} is an $l \times l$ matrix, \mathbf{H} and \mathbf{G} are l vectors. The state variable \mathbf{x} is constructed by adjoining \mathbf{q} and $\dot{\mathbf{q}}$: $\mathbf{x} = (\mathbf{x}_1^T, \mathbf{x}_2^T)^T = (\mathbf{q}^T, \dot{\mathbf{q}}^T)^T$. The state-space equation of the system is

$$\begin{aligned}\dot{\mathbf{x}}_1 &= \mathbf{x}_2, \\ \dot{\mathbf{x}}_2 &= -\mathbf{M}^{-1}(\mathbf{H}(\mathbf{x}_1, \mathbf{x}_2) + \mathbf{G}(\mathbf{x}_1)) \\ &\quad + \mathbf{M}^{-1}(\boldsymbol{\tau} + \mathbf{J}_c^T(\mathbf{x}_1)\mathbf{F}_n - \mathbf{J}_r^T(\mathbf{x}_1)\mathbf{F}_t),\end{aligned}\quad (5)$$

or the compact form is given as $\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x}, \boldsymbol{\tau}, \mathbf{F}_n, \mathbf{F}_t)$. Using the inverted form of combination from (3) and $\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x}, \boldsymbol{\tau}, \mathbf{F}_n, \mathbf{F}_t)$, \mathbf{F}_n can be expressed as (this part had been detailedly introduced in [16] by us)

$$\mathbf{F}_n = \mathbf{F}_n(\mathbf{x}, \boldsymbol{\tau}, \mathbf{F}_t), \quad (6)$$

$$\triangleq \mathbf{a}(\mathbf{x}_1, \mathbf{x}_2) + \mathbf{A}(\mathbf{x}_1)\mathbf{J}_r^T\mathbf{F}_t - \mathbf{A}(\mathbf{x}_1)\boldsymbol{\tau}, \quad (7)$$

where $\mathbf{a}(\mathbf{x}_1, \mathbf{x}_2)$ is a scalar representing the first term in the expression of \mathbf{F}_n , and $\mathbf{A}(\mathbf{x}_1)$ is an l vector to represent the coefficient vector of $\boldsymbol{\tau}$ in the same expression. $\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x}, \boldsymbol{\tau}, \mathbf{F}_n, \mathbf{F}_t)$, and (6) composes a constrained system that can be controlled, if $\mathbf{F}_n = 0$, describing the unconstrained motion of the system.

Substituting (7) into (5), the state equation of the system including the constrained force (as $\mathbf{F}_n > 0$) can be rewritten as

$$\begin{aligned}\dot{\mathbf{x}}_1 &= \mathbf{x}_2, \\ \dot{\mathbf{x}}_2 &= -\mathbf{M}^{-1}[\mathbf{H}(\mathbf{x}_1, \mathbf{x}_2) + \mathbf{G}(\mathbf{x}_1) - \mathbf{J}_c^T(\mathbf{x}_1)\mathbf{a}(\mathbf{x}_1, \mathbf{x}_2)] \\ &\quad + \mathbf{M}^{-1}[(\mathbf{I} - \mathbf{J}_c^T\mathbf{A})\boldsymbol{\tau} + (\mathbf{J}_c^T\mathbf{A} - \mathbf{I})\mathbf{J}_r^T\mathbf{F}_t],\end{aligned}\quad (8)$$

Solutions of these dynamic equations always satisfy the constrained condition (3).

2.2 Shape-grinding

In the past, we did the continuous shape-grinding simulations [16] to extend the grinding ability of our grinding robot [17, 18]. Now in this paper, the continuous shape-grinding experiment through the proposed method will be introduced.

To make the grinding task to be different from the former flat grinding experiment [17, 18], we ground the work-piece into the one with different kinds of shapes, for example, grinding the flat surface into a curved one, just as in Fig. 2. In Fig. 2, the desired working surface is prescribed (it can be decided by us), which means the desired constrained condition C^d is known, so

$$C^d = y - f^d(x) = 0. \quad (9)$$

But the constrained condition $C^{(j)}$ ($j = 1, 2, \dots, d-1$) changed by the previous grinding is hard to define as an initial condition. So we define

$$C^{(j)} = y - f^{(j)}(x) = 0, \quad (10)$$

where y is the position of manipulator's end-effector in the coordinates Σ_w depicted in Fig. 2. It is assumed that $C^{(1)}$ is known, that is to say, $f^{(1)}(x)$ is initially defined. $f^{(j)}(x)$ is

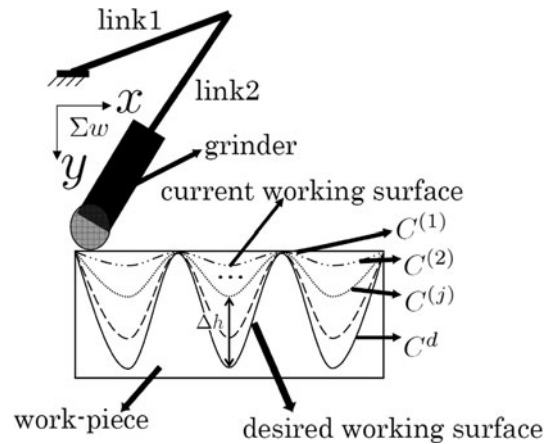


Fig. 2 Model of shape-grinding

the working surface remained by i th grinding. And $f^{(j)}(x)$ is a function passing through all points $(x_1, f^{(j)}(x_1)), (x_2, f^{(j)}(x_2)), \dots, (x_p, f^{(j)}(x_p))$. These observed points representing the (j) th constraint condition can be obtained from the grinding tip position since the proposed method uses the grinding tip as the touching sensor of ground new surface. Here we assume $f^{(j)}(x)$ could be represented by a polynomial of $(p-1)$ -th order of x . Given the above p points, we can easily decide the parameters of polynomial function $y = f^{(j)}(x)$. If the current constrained condition can be got successfully, then the current working surface $f^{(j)}(x)$ can be detected correctly. Therefore, the distance from the current working surface to the desired working surface, which is expressed as $\Delta h^{(j)}$ shown in Fig. 2, can be obtained easily.

$$\Delta h^{(j)}(x_i) = f^d(x)|_{x=x_i} - f^{(j)}(x)|_{x=x_i} \quad (11)$$

In this case, we can obviously find that the desired constrained force should not be a constant. It should be changed as $\Delta h^{(j)}$ changes. So we redefine the desired constrained force $F_{nd}^{(j)}$ as a function of $\Delta h^{(j)}$ with constant k' , as follows:

$$F_{nd}^{(j)}(x_i) = k' \Delta h^{(j)}(x_i). \quad (12)$$

3 Force/position controller

3.1 Controller using estimated constraint condition

Reviewing the dynamic equation (1) and constraint condition (3), it can be found that as $l > 1$, the number of input generalized forces is more than that of the constrained forces. From this point and (7), we can claim that there is some redundancy of constrained force between the input torque $\boldsymbol{\tau}$, and the constrained force \mathbf{F}_n . This condition is

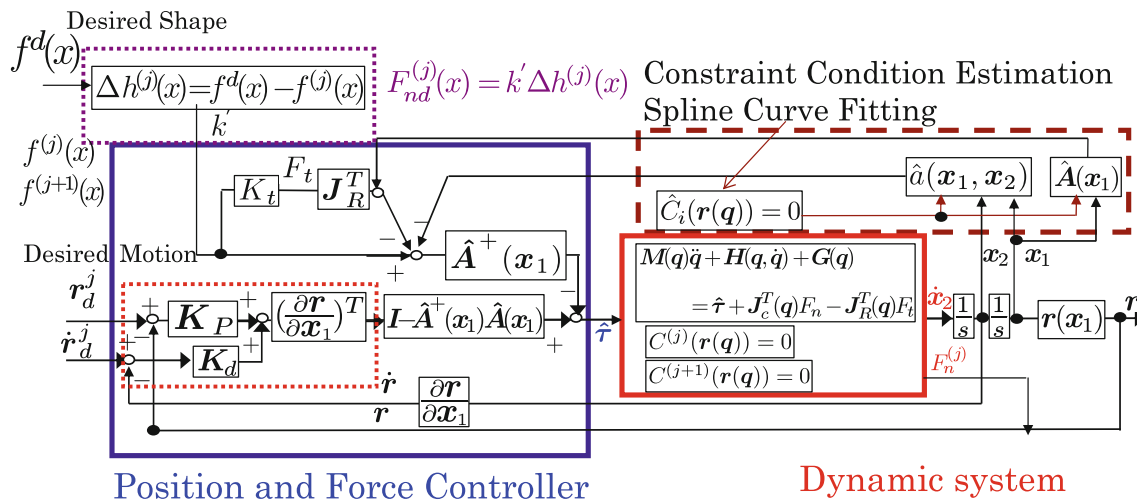


Fig. 3 Shape-grinding position/force control system

much similar to the kinematical redundancy of redundant manipulator. Based on the above argument and assuming that the parameters of the (7) are known and its state variables could be measured, and $a(x_1, x_2)$ and $A(x_1)$ could be calculated correctly, which means that the constraint condition $C = 0$ is prescribed. As a result, a control law is derived and can be expressed as

$$\tau = -A^+(x_1)\{F_{nd} - a(x_1, x_2) - A(x_1)J_r^T K_t F_{nd}\} + (I - A^+(x_1)A(x_1))k, \quad (13)$$

where it is assumed that $F_t = K_t F_n \approx K_t F_{nd}$. K_t is an empirical coefficient, I is a $l \times l$ identity matrix, F_{nd} is the desired constrained forces, $A(x_1)$ is defined in (7) and $A^+(x_1)$ is the pseudoinverse matrix of it, $a(x_1, x_2)$ is also defined in (7) and k is an arbitrary vector which is defined as

$$k = \tilde{J}_r^T T(q)\{K_p(r_d - r) + K_d(\dot{r}_d - \dot{r})\}, \quad (14)$$

where K_p and K_d are gain matrices for position and the velocity control by the redundant degree of freedom of $A(x_1)$, $r_d(q)$ is the desired position vector of the end-effector along the constrained surface and $r(q)$ is the real position vector of it. Equation (14) describes the 2-link rigid manipulator's arm compliance; 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 (13) and (14) assumes that the constraint condition $C = 0$ be known precisely even though the grinding operation is a task to change the constraint condition. This looks like to be a contradiction, so we need to observe time-varying constraint conditions in real time using grinding tip as a touch sensor. The time-varying

condition is estimated as an approximate constrained function by position of the manipulator hand, which is based on the estimated constrained surface location. The estimated condition is denoted by $\hat{C} = 0$ (in this paper, “ \sim ” means the situation of unknown constraint condition). Hence, $a(x_1, x_2)$ and $A(x_1)$ including $\partial\hat{C}/\partial q$ and $\partial/\partial q(\partial\hat{C}/\partial q)$ are changed to $\hat{a}(x_1, x_2)$ and $\hat{A}(x_1)$ as shown in (16) and (17). They were used in the later experiments of the unknown constrained condition. As a result, a controller based on the estimated constrained condition is given as

$$\hat{\tau} = -\hat{A}^+(x_1)\{F_{nd} - \hat{a}(x_1, x_2) - \hat{A}(x_1)J_r^T F_t\} + (I - \hat{A}^+(x_1)\hat{A}(x_1))k, \quad (15)$$

$$m_c^{-1} \left\| \frac{\partial \hat{C}}{\partial r} \right\| \left\{ - \left[\frac{\partial}{\partial q} \left(\frac{\partial \hat{C}}{\partial q} \right) \dot{q} \right] \dot{q} + \left(\frac{\partial \hat{C}}{\partial q} \right) M^{-1}(h + g) \right\} \triangleq \hat{a}(x_1, x_2) \quad (16)$$

$$m_c^{-1} \left\| \frac{\partial \hat{C}}{\partial r} \right\| \left\{ \left(\frac{\partial \hat{C}}{\partial q} \right) M^{-1} \right\} \triangleq \hat{A}(x_1) \quad (17)$$

Figure 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 (7) and (15) 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. In the next section, we will introduce an estimation method which is used to get \hat{C} in current time.

3.2 On-line estimation method of constraint

Now shape-grinding method is solved in our research. But how to estimate the unknown constraint surface is the nodus and key point. Here, an unknown constrained condition is assumed as in the following.

Assumptions:

1. The end-point position of the manipulator during the grinding task can be surely measured and updated.
2. The grinding task is defined in the x - y plane.
3. When beginning to work, the initial condition of the end-effector is known and it has touched the work object.
4. The chipped and changed constraint condition can be approximated by connections of minute sections.

Some relations between position value and time value are provided here; in this section, one would better remember these relations because it will help understand the concept of “on-line estimation method”.

$$x_{i-1} = x(t_{i-1}) = x(t_0 + (i-1)\Delta t), \quad (18)$$

$$x_i = x(t_i) = x(t_0 + i\Delta t), \quad (19)$$

$$x_{i+1} = x(t_{i+1}) = x(t_0 + (i+1)\Delta t). \quad (20)$$

Before on-line estimation method is introduced, let us take a look at the situation of known flat constraint surface. For example, just like the grinding surface shown in Fig. 4, the expression of this surface is a straight linear equation

$$f^j(x_i) = y_i = 0.5173 (i = 0, 1, 2, 3 \dots n), \quad (21)$$

and point (x_i, y_i) is the current position of grinding robot's end-effector. As a result, points before (x_i, y_i) have been already ground by grinder when $t \leq t_0 + i\Delta t$. In the next moment, when time $t_{i+1} = t_0 + (i+1)\Delta t$, constraint condition

$$C_{i+1}^j = y - f^j(x_i) = 0 \quad (22)$$

can be used for calculation of deriving torque τ . And also, grinder will move to the next point (x_{i+1}, y_{i+1}) with no hesitation driven by the input torque τ . By “no hesitation”,

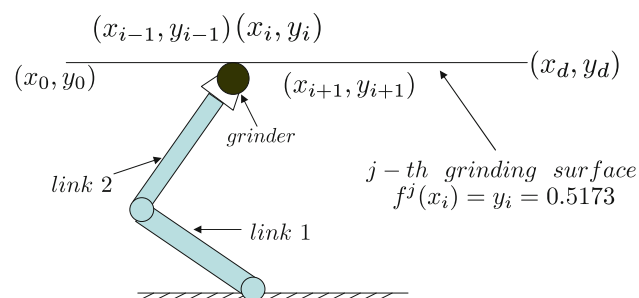


Fig. 4 Situation of known constraint surface model

it means on this known surface, grinder has nowhere to go but point (x_{i+1}, y_{i+1}) , since this whole grinding surface $f^j(x_i) = y_i = 0.5173$ ($i = 0, 1, 2, 3 \dots n$) is determined obviously. However, we all know that the grinding surface on work-piece after ground will turn into some kind of irregular shape that no mathematic equation can express. What should we do to obtain the future constraint condition C_{i+1}^j if the grinding surface is unknown? Like the situation shown in Fig. 5, the grinding surface is not a simple straight line or some curve line which can be defined and expressed by some certain curve equation, after current time $t_i = t_0 + i\Delta t$, where should the grinder go? Grinding robot has no idea since input torque τ cannot be derived without constraint condition C_{i+1}^j . To solve this problem, we consider that some kind of on-line estimation function is utilized to imitate the unknown grinding surface, to obtain an unknown constraint condition \hat{C}_{i+1}^j , which can be used to calculate the input torque $\hat{\tau}$.

Therefore, now let us take a look at Fig. 5, in current time $t_i = t_0 + i\Delta t$, the end-effector of grinding robot is at position (x_i, y_i) , so far, point (x_{i-1}, y_{i-1}) and point (x_i, y_i) are known because they are just ground by the grinder in the moment $t_{i-1} = t_0 + (i-1)\Delta t$ and $t_i = t_0 + (i)\Delta t$ and the information of points (x_{i-1}, y_{i-1}) and (x_i, y_i) can be derived through the position of robot's end-effector. Now building an estimation function going through these two points, for example, a quadratic spline function

$$\begin{aligned} f_i^j(x_i) &= f_{\text{spline}}(x_i) = y_i \\ &= \alpha_i(x - x_{i-1})^2 + \beta_i(x - x_{i-1}) + \gamma_i \\ x &\in [x_{i-1}, x_i] (i = 0, 1, 2, 3 \dots n), \end{aligned} \quad (23)$$

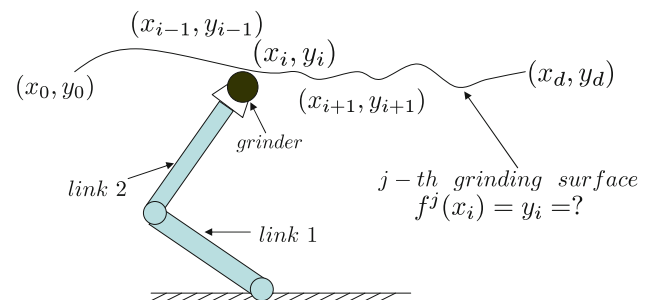


Fig. 5 On-line estimation model

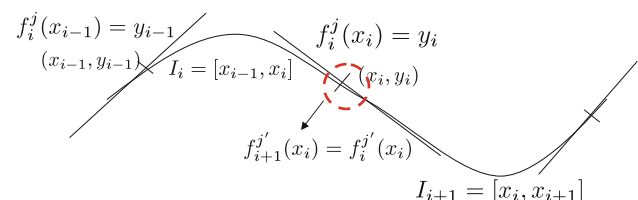


Fig. 6 Fitting by quadratic spline curve

we can figure out the coefficients α_i , β_i and γ_i uniquely according to the information of points (x_{i-1}, y_{i-1}) , (x_i, y_i) and derivation at point (x_i, y_i) as follows.

Firstly, let $f_i^j(x_i)$ satisfy the following conditions shown in Fig. 6.

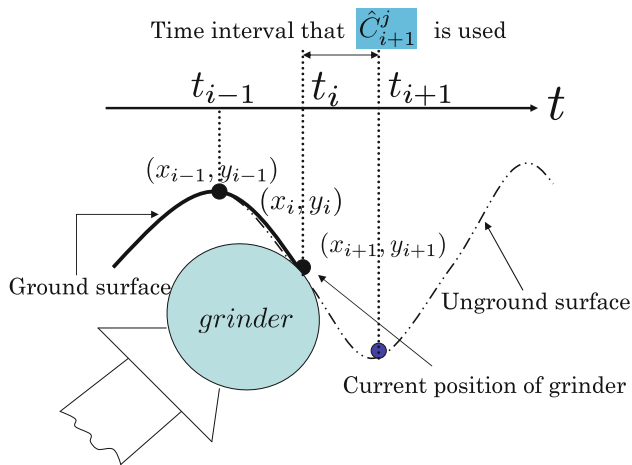


Fig. 7 Expansion of interval between point (x_{i-1}, y_{i-1}) and point (x_{i+1}, y_{i+1}) on the on-line estimation model

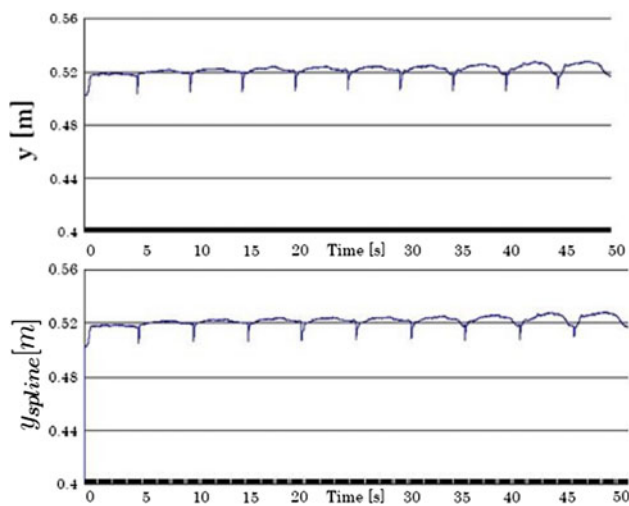
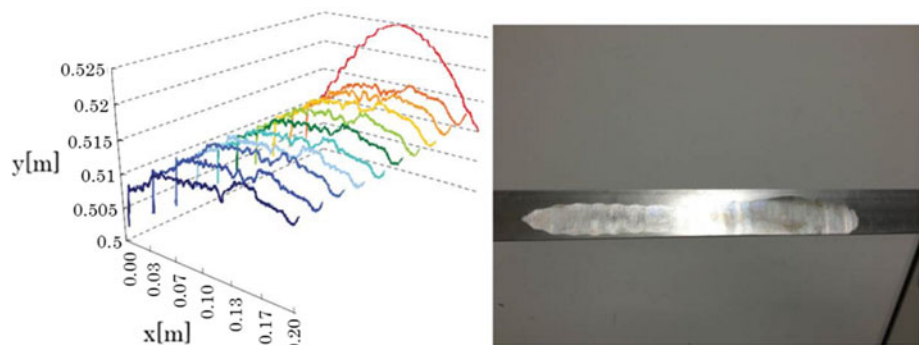


Fig. 8 Comparison of actual shape (upper) and estimated shape (lower)

Fig. 9 Real ground result, desired surface and its photo



(A) Go through the two ends of the interval

$$y_{i-1} = f_i^j(x_{i-1}) \quad (24)$$

$$y_i = f_i^j(x_i) \quad (25)$$

(B) First-order differential of the spline polynomials is equal at the end-point of the adjoined function.

$$f_{i+1}'(x_i) = f_i'(x_i) \quad (26)$$

From the relation among (23)–(26), we can obtain:

$$\gamma_i = y_{i-1}, (i = 1, 2, \dots, n) \quad (27)$$

$$\beta_{i+1} = 2u_i - \beta_i, (i = 1, 2, \dots, n-1) \quad (28)$$

$$\alpha_i = \frac{\beta_{i+1} - \beta_i}{2h_i}, (i = 1, 2, \dots, n-1), \quad (29)$$

where $h_i = x_i - x_{i-1}$, $u_i = \frac{y_i - y_{i-1}}{h_i}$. The above-mentioned result can update the constrained conditional expression \hat{C}_{i+1}^j step by step.

Making an expansion of the interval between point (x_{i-1}, y_{i-1}) and point (x_{i+1}, y_{i+1}) on the grinding surface which is shown in Fig. 7, we can see the first half of grinding surface before the current position, point (x_i, y_i) is shown by a black line, which means this part has been already ground, and second half after point (x_i, y_i) is shown by a break point line, which means this part has not been ground yet. Now let us pay our attention on the interval between point (x_i, y_i) and point (x_{i+1}, y_{i+1}) , which means this part has been estimated by quadratic spline function. With the estimation function, the next point (x_{i+1}, y_{i+1}) can easily be found to be known, and then this point can be the position where grinder should go in the next moment when $t_{i+1} = t_0 + (i+1)\Delta t$. At the same time, this imitative function can be used as the on-line estimation function to obtain the unknown constraint condition

$$\begin{aligned} \hat{C}_{i+1}^j &= y - f_i^j(x) \\ &= y - [\alpha_i(x - x_{i-1})^2 + \beta_i(x - x_{i-1}) + \gamma_i] = 0, \quad (30) \\ (x_i \leq x \leq x_{i+1}) \end{aligned}$$

during the period when grinder goes from point (x_i, y_i) to point (x_{i+1}, y_{i+1}) , which means in this unknown interval on

the grinding surface, the future unground part (x_i, y_i) to (x_{i+1}, y_{i+1}) can be ground by this on-line estimation method based on the information obtained from the already ground part (x_{i-1}, y_{i-1}) to (x_i, y_i) . So, in the situation of unknown constraint surface, using this on-line estimation method point to point, the problem for grinding robot that it does not know where it should go in future time can be solved theoretically.

4 Experiment

In this section, we verify the feature of the proposed controller (13). In the previous papers [19], we have already confirmed the ability in on-line shape measurement based on spline approximation (on-line estimation of the constraint condition \hat{C}_{i+1}^j) and continuous shape-grinding as shown in Figs. 8 and 9. Whereas alloy model of work-piece to be ground has been just one type, and the performance of

proposed force/position controller has not been confirmed for various types of alloy models with different hardness. In other words, it is necessary to confirm whether its performance is independent of alloy model or not. Therefore, this section shows the experimental results of model-independent force/position hybrid control using three types of alloy models with different hardness. Figure 2 shows the experiment's grinding task. In Fig. 2, we can find the desired surface (it can be determined by us, here we use (31) as this desired surface) as

$$f^d(x_i) = 0.5173 + \left| 0.015 \cos(3 \times 5\pi x_i - \frac{\pi}{2}) \right| (m) \quad (0.0(m) \leq x_i \leq 0.2(m)) \quad (31)$$

and also the initial flat surface is known as $f^1(x_i) = 0.5173$ (m). Here we notice that although the initial constraint surface $f^1(x_i)$ and desired constraint surface $f^d(x_i)$ are known already, those functions $f^j(x_i)$ which can express the constraint working surfaces between $f^1(x_i)$ and $f^d(x_i)$ are unknown. Therefore, we utilize the quadratic spline function to estimate them by means of $f^j(x_i) = f_{\text{spline}}(x_i)$. The initial constraint surface to be ground is defined as $(x, y) = (0.0, 0.5173) \sim (0.2, 0.5173)$ (m) in time 5.0 s, and the desired velocity along the surface is 0.04 m/s. The desired force F_{nd} is set as $F_{nd}^j(x_i) = k' \Delta h^j(x_i)$. k' is set to be 666 and $\Delta h^j(x_i) = f^d(x_i) - f^j(x_i)$ indicates the distance between the current surface and desired surface as shown in Fig. 2. Grinding

Table 1 Parameters of grinding robot

| | Link 1 | Link 2 |
|----------------------------|----------------|----------------|
| Mass of link (kg) | $m_1 = 12.28$ | $m_2 = 7.64$ |
| Length of link (m) | $l_1 = 0.3$ | $l_2 = 0.5$ |
| Gravity center of link (m) | $a_1 = 0.24$ | $a_2 = 0.25$ |
| General coordinates (rad) | q_1 | q_2 |
| Input torque (N) | $\hat{\tau}_1$ | $\hat{\tau}_2$ |

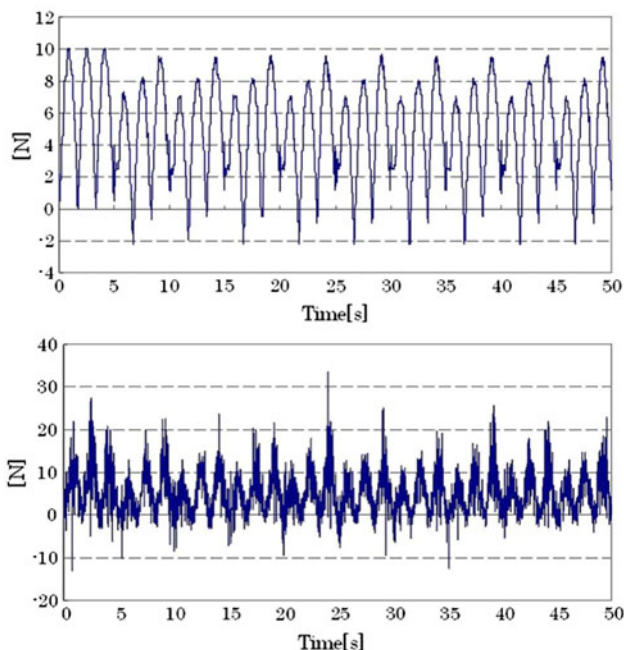


Fig. 10 Desired constraint force F_{nd} (upper) and real constraint force F_n measured by force sensor (lower) (alloy type: S45C)

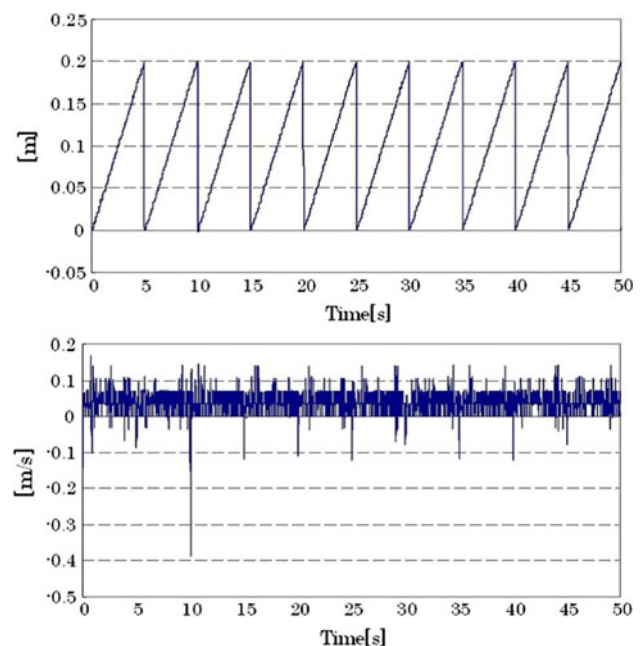


Fig. 11 Grinding position x_i (upper) and its velocity \dot{x}_i (lower) (alloy type: S45C)

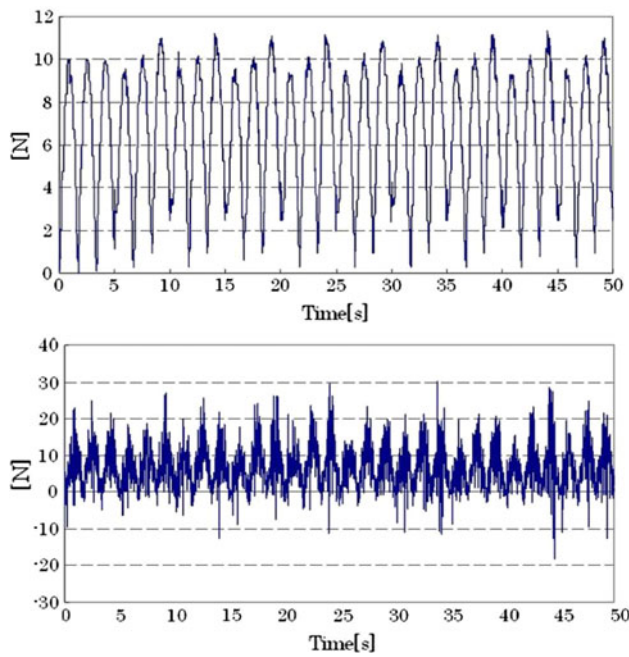


Fig. 12 Desired constraint force F_{nd} (upper) and real constraint force F_n measured by force sensor (lower) (alloy type: A2017P)

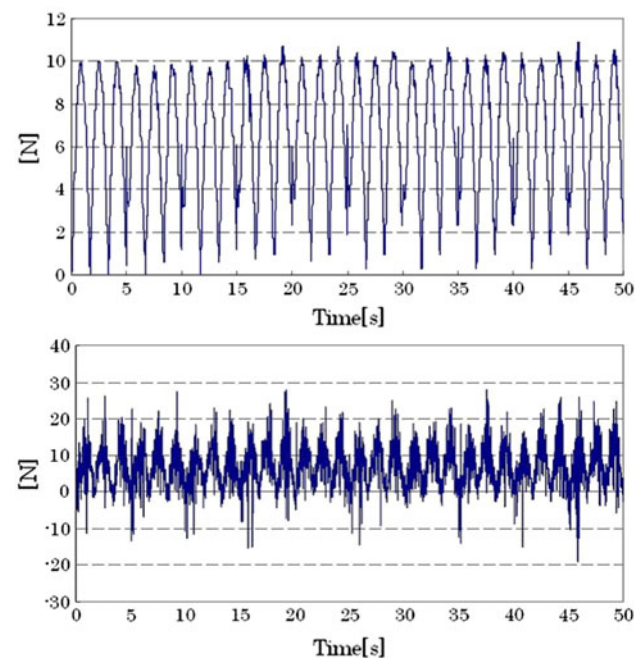


Fig. 14 Desired constraint force F_{nd} (upper) and real constraint force F_n measured by force sensor (lower) (alloy type: A5083P)

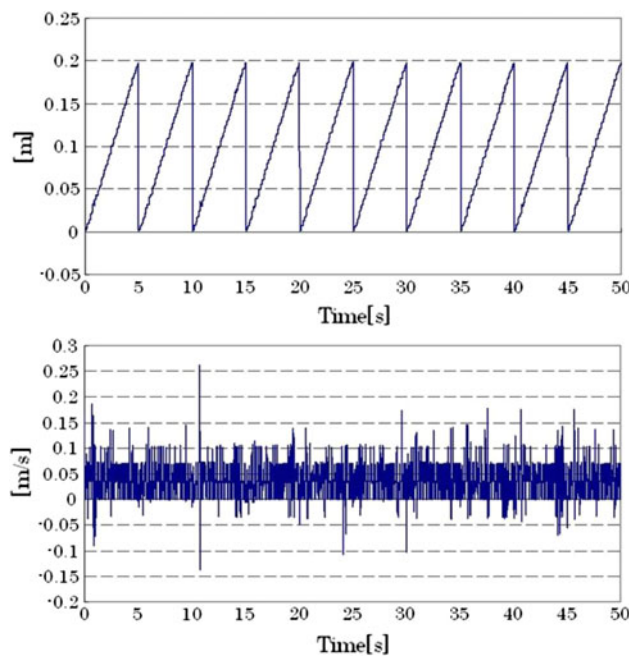


Fig. 13 Grinding position x_i (upper) and its velocity \dot{x}_i (lower) (alloy type: A2017P)

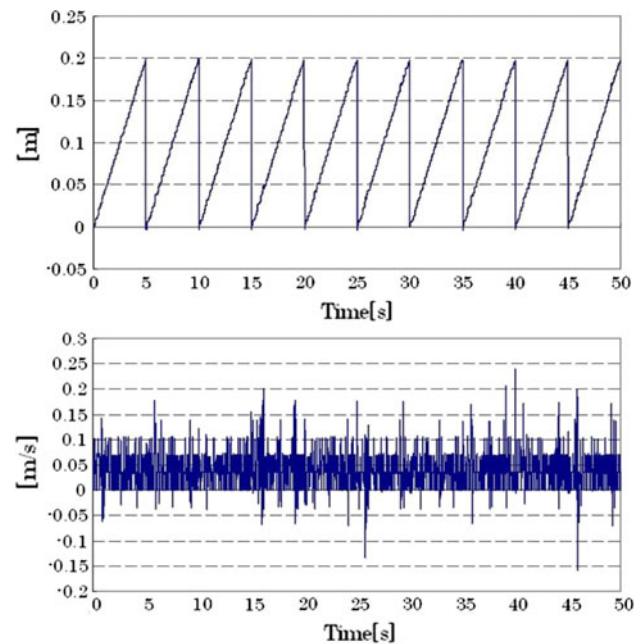


Fig. 15 Grinding position x_i (upper) and its velocity \dot{x}_i (lower) (alloy type: A5083P)

robot's parameters are listed in Table 1, and there are two motors (produced by YASKAWA Ltd.) mounted on those two links used in torque control mode whose output torque can be designated by the input voltage to the amplifier to each motor, where motor of AC (400 W, 200 V) drives

link 1, motor of AC (200 W, 200 V) drives link 2. Link 1's torque/voltage is 0.42 Nm/V, link 2's torque/voltage is 0.21 Nm/V.

Figures 10 and 11 give the experimental result for alloy type S45C with Vickers hardness 170–195 HV. The result

of Figs. 12 and 13 is for alloy type A2017P with Vickers hardness 125–130 HV. And the result of Figs. 14 and 15 is for alloy type A5083P with Vickers hardness 80–90 HV. One trial takes 5 s and the number of trials is 10 in these experimental results. So the experiment of each alloy type takes 50 s. Figures 10, 12 and 14 show desired constraint force F_{nd} and real constraint force F_n measured by force sensor. Figures 11, 13 and 15 show grinding position x_i and the velocity \dot{x}_i . From these figures, it is found that the proposed controller (13) can decouple position and force control independent of alloy models, although the results of real constraint force and grinding velocity are affected by grinding.

5 Conclusions

In order to verify the feature of the proposed force-sensorless force/position hybrid control, the experiments of the proposed force/position hybrid control method were executed for three types of alloy models with different hardness. From the experimental results, it is found that the proposed controller can decouple force and position control for continuous shape-grinding independent of alloy models. Although this paper does not discuss the correspondence of the desired force and the measured force, or the correspondence of positions and velocities in detail, in future works, these correspondences and the relation between hardness of alloy model and shape to be ground should be explored to utilize in many robotic control fields.

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