The Eighteenth International Symposium on Artificial Life and Robotics 2013 (AROB 18th '13),
Daejeon Convention Center, Daejeon, Korea, January 30-February 1, 2013

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

Akira Yanou[1], Mamoru Minami[1] and Hiro Tanimoto[1]

[1]Graduate School of Natural Science and Technology, Okayama University, Japan
(Tel: +81-86-251-8924; E-mail: yanou@suri.sys.okayama-u.ac.jp)

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 an 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, we added estimating function of the constraint condition in real time for the adaptive force / position control, which is indispensable for our method instead of not 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 in order to verify the feature of the decoupling control of force and position of the tip.

Keywords: Continuous shape-grinding, Force / position hybrid control, Spline approximation

1. INTRODUCTION

Many researches have discussed on the force control of robots for contacting tasks. Most force control strategies are to use force sensors [1],[2] 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 using no force sensor have been presented [3]. 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[4],[5]. Their force control strategies have been explained intelligibly in books[6] and recently interaction control for six-degree-of-freedom tasks has been compiled in a book [7]. 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 be independent of target work-piece model, grinding task requires on-line estimation of changing constraint condition since the 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 have addressed the issue of control of a moving robot according to constraint condition and 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 involved the item of generalized 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 grinding manipulator shown in Fig. 1, whose endpoint is in contact with the constrained surface, is modeled according (1) with Lagrangian equations of motion in term of the constraint forces, referring to what Hemami and Arimoto have done:

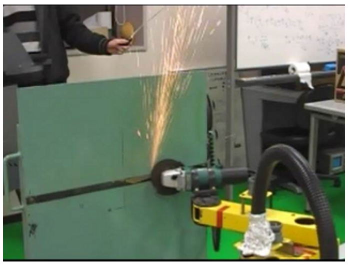

Fig. 1 Grinding robot system

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\boldsymbol{q}}}\right) - \left(\frac{\partial L}{\partial \boldsymbol{q}}\right) = \boldsymbol{\tau} + \boldsymbol{J_c}^T(\boldsymbol{q})F_n - \boldsymbol{J_r}^T(\boldsymbol{q})F_t, \quad (1)$$

where, F_n is the constrained force associated with constraint C, F_t is the tangential grinding force, $\boldsymbol{J_c}$ and $\boldsymbol{J_r}$ satisfy;

$$\boldsymbol{J_c} = \frac{\partial C}{\partial \boldsymbol{q}} / \parallel \frac{\partial C}{\partial \boldsymbol{r}} \parallel = \frac{\partial C}{\partial \boldsymbol{r}} \tilde{\boldsymbol{J}}_r / \parallel \frac{\partial C}{\partial \boldsymbol{r}} \parallel,$$

$$\tilde{\boldsymbol{J}}_r = \frac{\partial \boldsymbol{r}}{\partial \boldsymbol{q}}, \qquad \boldsymbol{J}_r^T = \tilde{\boldsymbol{J}}_r^{\,T} \dot{\boldsymbol{r}} / \parallel \dot{\boldsymbol{r}} \parallel,$$

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

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

L is the Lagrangian function, $\boldsymbol{q}$ is $l(\geq 2)$ generalized coordinates, $\boldsymbol{\tau}$ is l inputs. The discussing robot system does

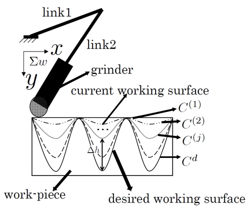

Fig. 2 Model of shape-grinding

not have kinematical redundancy. C is a scalar function of the constraint, and is expressed as an equation of constraints

$$C(\boldsymbol{r}(\boldsymbol{q})) = 0, \tag{3}$$

(1) can be derived to be

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}}+\boldsymbol{H}(\boldsymbol{q},\dot{\boldsymbol{q}})+\boldsymbol{G}(\boldsymbol{q}) = \boldsymbol{\tau}+\boldsymbol{J}_c^T(\boldsymbol{q})F_n-\boldsymbol{J}_r^T(\boldsymbol{q})F_t, \tag{4}$$

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

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

or the compact form is given as $\dot{\boldsymbol{x}} = \boldsymbol{F}(\boldsymbol{x},\boldsymbol{\tau},F_n,F_t)$. Using the inverted form of combination from (3) and $\dot{\boldsymbol{x}} = \boldsymbol{F}(\boldsymbol{x},\boldsymbol{\tau},F_n,F_t)$, F_n can be expressed as (this part had been detailedly introduced in [10] by us)

$$F_n = F_n(\boldsymbol{x},\boldsymbol{\tau},F_t), \tag{6}$$

$$\triangleq a(\boldsymbol{x}_1,\boldsymbol{x}_2)+\boldsymbol{A}(\boldsymbol{x}_1)\boldsymbol{J}_r^T F_t-\boldsymbol{A}(\boldsymbol{x}_1)\boldsymbol{\tau}, \tag{7}$$

where, $a(\boldsymbol{x}_1,\boldsymbol{x}_2)$ is a scalar representing the first term in the expression of F_n, and $\boldsymbol{A}(\boldsymbol{x}_1)$ is an l vector to represent the coefficient vector of $\boldsymbol{\tau}$ in the same expression. $\dot{\boldsymbol{x}} = \boldsymbol{F}(\boldsymbol{x},\boldsymbol{\tau},F_n,F_t)$ and (6) compose a constrained system that can be controlled, if $F_n = 0$, describing the unconstrained motion of the system. Substituting (7) into (5), the state equation of the system including the constrained force (as $F_n > 0$) can be rewritten as

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

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[10] to try to extend the grinding ability of our grinding robot[9]. Now in this paper, the continuous shape grinding experiment which has been done by the proposed force sensorless force/position control method will be introduced.

To make the grinding task to be different from the former flat grinding experiment[9], we want to grind the work-piece into the one with different kinds of shapes, for example, grinding the flat surface into a curved one, just like Fig. 2. In Fig. 2, we can find that the desired working surface is prescribed (it can be decided by us.), which means the desired constrained condition C^d is known, so

$$C^d = y - f^d(x) = 0 \tag{9}$$

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

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

where, y is the y position of manipulator's end-effector in the coordinates Σw depicted in Fig. 2 and we assume $C^{(1)}$ is known, that is to say, $f^{(1)}(x)$ is initially defined. $f^{(j)}(x)$ is 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, $f^{(j)}(x_2)$), $\cdots$, (x_p, $f^{(j)}(x_p)$), these observed points representing the (j)-th constraint condition obtained from the grinding tip position since we proposed previously the grinding tip used for 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, which means the current working surface $f^{(j)}(x)$ can be detected correctly, 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.

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

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

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

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 F_n. This condition is 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 $a(\boldsymbol{x}_1,\boldsymbol{x}_2)$ and $\boldsymbol{A}(\boldsymbol{x}_1)$ 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

$$\begin{aligned}\boldsymbol{\tau} &= -\boldsymbol{A}^+(\boldsymbol{x}_1)\left\{F_{nd}-a(\boldsymbol{x}_1,\boldsymbol{x}_2)-\boldsymbol{A}(\boldsymbol{x}_1)\boldsymbol{J}_r^T K_t F_{nd}\right\}\\ &\quad +(\mathbf{I}-\boldsymbol{A}^+(\boldsymbol{x}_1)\boldsymbol{A}(\boldsymbol{x}_1))\boldsymbol{k},\end{aligned} \tag{13}$$

where it is assumed that $F_t = K_t F_n \approx K_t F_{nd}$. K_t is an empirical coefficient, $\mathbf{I}$ is a $l \times l$ identity matrix, F_{nd} is the desired constrained forces, $\boldsymbol{A}(\boldsymbol{x}_1)$ is defined in (7) and $\boldsymbol{A}^+(\boldsymbol{x}_1)$ is the pseudoinverse matrix of it, $a(\boldsymbol{x}_1,\boldsymbol{x}_2)$ is also defined in (7) and $\boldsymbol{k}$ is an arbitrary vector which is defined as

$$\boldsymbol{k} = \widetilde{\boldsymbol{J}}_r^T(\boldsymbol{q})\Big\{\boldsymbol{K}_p(\boldsymbol{r}_d - \boldsymbol{r}) + \boldsymbol{K}_d(\dot{\boldsymbol{r}}_d - \dot{\boldsymbol{r}})\Big\}, \qquad (14)$$

where $\boldsymbol{K}_p$ and $\boldsymbol{K}_d$ are gain matrices for position and the velocity control by the redundant degree of freedom of $\boldsymbol{A}(\boldsymbol{x}_1)$, $\boldsymbol{r}_d(\boldsymbol{q})$ is the desired position vector of the end-effector along the constrained surface and $\boldsymbol{r}(\boldsymbol{q})$ is the real position vector of it. (14) describes the 2-link rigid manipulator's arm compliance, we have to set $\boldsymbol{K}_p$ and $\boldsymbol{K}_d$ 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 by 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, "ˆ" means the situation of unknown constraint condition). Hence, $a(\boldsymbol{x}_1, \boldsymbol{x}_2)$ and $\boldsymbol{A}(\boldsymbol{x}_1)$ including $\partial\hat{C}/\partial\boldsymbol{q}$ and $\partial/\partial\boldsymbol{q}(\partial\hat{C}/\partial\boldsymbol{q})$ are changed to $\hat{a}(\boldsymbol{x}_1, \boldsymbol{x}_2)$ and $\hat{\boldsymbol{A}}(\boldsymbol{x}_1)$ 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

$$\begin{aligned}\hat{\boldsymbol{\tau}} &= -\hat{\boldsymbol{A}}^+(\boldsymbol{x}_1)\Big\{F_{nd} - \hat{a}(\boldsymbol{x}_1, \boldsymbol{x}_2) - \hat{\boldsymbol{A}}(\boldsymbol{x}_1)\boldsymbol{J}_R^T F_t\Big\} \\ &\quad + (\mathbf{I} - \hat{\boldsymbol{A}}^+(\boldsymbol{x}_1)\hat{\boldsymbol{A}}(\boldsymbol{x}_1))\boldsymbol{k}, \qquad (15)\end{aligned}$$

$$m_c{}^{-1}\|\frac{\partial\hat{C}}{\partial\boldsymbol{r}}\|\{-[\frac{\partial}{\partial\boldsymbol{q}}(\frac{\partial\hat{C}}{\partial\boldsymbol{q}})\dot{\boldsymbol{q}}]\dot{\boldsymbol{q}} + (\frac{\partial\hat{C}}{\partial\boldsymbol{q}})\boldsymbol{M}^{-1}(\boldsymbol{h} + \boldsymbol{g})\} \triangleq \hat{a}(\boldsymbol{x}_1, \boldsymbol{x}_2) \qquad (16)$$

$$m_c{}^{-1}\|\frac{\partial\hat{C}}{\partial\boldsymbol{r}}\|\{(\frac{\partial\hat{C}}{\partial\boldsymbol{q}})\boldsymbol{M}^{-1}\} \triangleq \hat{\boldsymbol{A}}(\boldsymbol{x}_1) \qquad (17)$$

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 given to be 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 following,

Assumptions:

1. The end point position of the manipulator during performing the grinding task can be surely measured and updated.
2. The grinding task is defined in $x - y$ plane.

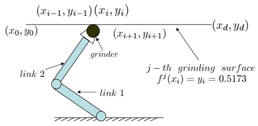

Fig. 3 Situation of known constraint surface model

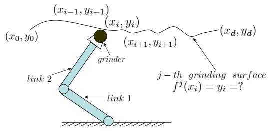

Fig. 4 On-line estimation model

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 written here, in this section, you'd better remember these relations because it will help you understand the concept of "on-line estimation method".

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

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

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

Before on-line estimation method is introduced, let's take a look at the situation of known flat constraint surface. For example, just like the grinding surface shown in Fig. 3, the expression of this surface is straight linear equation

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

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 $t <= t_0 + i\Delta t$. In the next moment, when time $t_{i+1} = t_0 + (i+1)\Delta t$, constraint condition

$$C^j_{i+1} = y - f^j(x_i) = 0 \qquad (22)$$

can be used for calculation of deriving torque $\boldsymbol{\tau}$. And also, grinder will move to next point (x_{i+1}, y_{i+1}) with no hesitation driven by the input torque $\boldsymbol{\tau}$. By "no hesitation", it means on this known surface, grinder has nowhere to go but point (x_{i+1}, y_{i+1}), since this whole grinding surface $f^j(x_i) = y_i = 0.5173(i = 0, 1, 2, 3...n)$ 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^j_{i+1} if the grinding surface is unknown? Like the situation shown in Fig. 4, 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 $\boldsymbol{\tau}$ cannot be derived without constraint condition C^j_{i+1}. To solve this problem, we consider that some kind of on-line estimation function should be utilized to imitate the unknown grinding surface, in order to

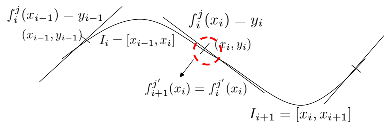

Fig. 5 Fitting by quadratic spline curve

obtain an unknown constraint condition $\hat{C}_{i+1}^j$, which can be used to calculate the input torque $\hat{\boldsymbol{\tau}}$.

Therefore, now let's take a look at Fig. 4, in current time $t_i = t_0 + i\Delta t$, 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) have become known because they were 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 point (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

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

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. 5.

(A) Go through two ends of the interval

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

$$y_i = f_i^j(x_i) \tag{25}$$

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

$$f_{i+1}^{j'}(x_i) = f_i^{j'}(x_i) \tag{26}$$

From the relation among (23), (24), (25) and (26), we can obtain:

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

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

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

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. 6, we can see the first half of grinding surface before the current position - point (x_i, y_i) is shown by black line, which means this part has been already ground, and second half after point (x_i, y_i) is shown by break point line, which means this part has not been ground yet. Now let's 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

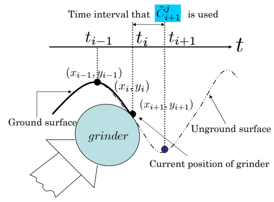

Fig. 6 Expansion of interval between point (x_{i-1}, y_{i-1}) and point (x_{i+1}, y_{i+1}) on the on-line estimation model

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

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 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 doesn't 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[11],[12] 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. 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 by using three types of alloy models with different hardness. Fig. 2 shows the experiment's grinding task. In Fig. 2, we can find that the desired surface is known (it can be determined by us, here we use (31) as this desired surface)

$$\begin{aligned} f^d(x_i) &= 0.5173 + \left| 0.015 \cos(3 \times 5\pi x_i - \frac{\pi}{2}) \right| \text{[m]} \\ & \quad (0.0\text{[m]} \le x_i \le 0.2\text{[m]}) \end{aligned} \tag{31}$$

and also the initial flat surface is known as $f^1(x_i) = 0.5173\text{[m]}$. 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 $f^j(x_i)$ who

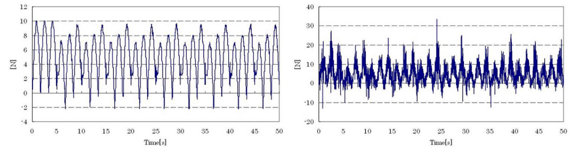

Fig. 7 Desired constraint force F_{nd} (left) and real constraint force F_n measured by force sensor (right) (Alloy type: S45C)

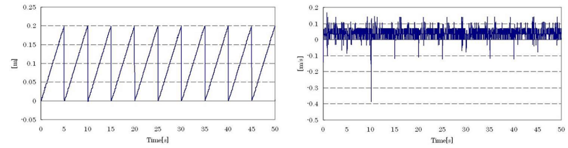

Fig. 8 Grinding position x_i (left) and its velocity $\dot{x}_i$ (right) (Alloy

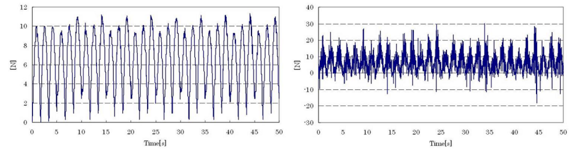

Fig. 9 Desired constraint force F_{nd} (left) and real constraint force F_n measured by force sensor (right) (Alloy type: A2017P)

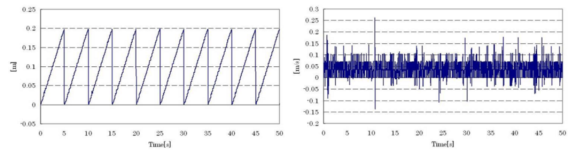

Fig. 10 Grinding position x_i (left) and its velocity $\dot{x}_i$ (right) (Alloy type: A2017P)

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 $f^j(x_i) = f_{spline}(x_i)$. 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 $F^j_{nd}(x_i) = k'\Delta h^j(x_i)$. 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. Fig. 7 and Fig. 8 give the experimental result for alloy type S45C with Vickers hardness 170-195 [HV]. The result of Fig. 9 and Fig. 10 is for alloy type A2017P with Vickers hardness 125-130 [HV]. And the result of Fig. 11 and Fig. 12 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]. Fig. 7, Fig. 9 and Fig. 11 show desired constraint force F_{nd} and real constraint force F_n measured by force sensor. Fig. 8, Fig. 10 and Fig. 12 show grinding position x_i and the velocity $\dot{x}_i$. From these figures, it can finds 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

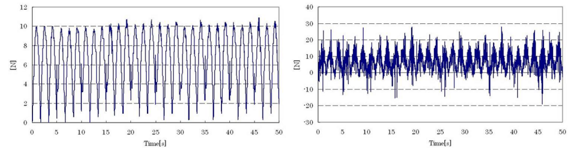

Fig. 11 Desired constraint force F_{nd} (left) and real constraint force F_n measured by force sensor (right) (Alloy type: A5083P)

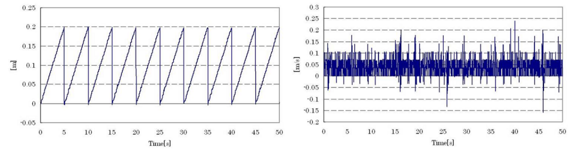

Fig. 12 Grinding position x_i (left) and its velocity $\dot{x}_i$ (right) (Alloy type: A5083P)

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. As future work, the relation between hardness of alloy model and shape to be ground will be explored in order to utilize in many robotic control fields.

REFERENCES

[1] M.H.Raibert and J.J.Craig: Hybrid Position/Force Control of Manipulators, Trans. of the ASME, J. of Dynamic Systems, Measurement and Control, Vol.102, pp.126-133, June, 1981.

[2] T. Yoshikawa: Dynamic Hybrid Position/Force control of Robot Manipulators — Description of Hand Constraints and Calculation of Joint Driving Force, IEEE J. on Robotics and Automation, Vol.RA-3, No.5, pp.386-392, 1987.

[3] L. Whitcomb, S. Arimoto, T. Naniwa and F. Osaki, Experiments in Adaptive Model-Based Force Control, IEEE Control Systems Society, Vol.16, No.1, pp.49-57, 1996.

[4] D.Wang and N.H. McClamroch: Position and Force Control for Constrained Manipulator Motion: Lyapunov's Direct Approach, IEEE Trans. Robotics and Automation, Vol.9, pp.308-313, 1993.

[5] Jaydeep. Roy and Louis L. Whitcomb: Adaptive Force Control of Position/Velocity Controlled Robots: Theory and Experiment, IEEE Transactions on Robotics and Automation, Vol.18, No.2, April, 2002.

[6] B. Siciliano, L. Villani, Robot Force Control, Kluwer Academic Publishers, U.K., 1999.

[7] C. Natale, Interaction Control of Robot Manipulators, Springer Tracts in Advanced Robotics, Germany, 2003.

[8] Hooshang Hemami and Bostwick F. Wyman: Modeling and Control of Constrained Dynamic Systems with Application to Biped Locomotion in the Frontal Plane, IEEE Trans. on Automatic Control, Vol.AC-24, No.4, pp.526-535, 1979.

[9] Takeshi Ikeda, Mamoru Minami, Position/Force Control of a Manipulator by Using an Algebraic Relation and Evaluations by Experiments, The 2003 IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics (AIM2003), Proceeding CD-ROM paper No.159, 503-508, 2003

[10] Mamoru Minami, Weiwei Xu, Shape-grinding by Direct Position / Force Control with On-line Constraint Estimation, 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, Acropolis Convention Center, Nice, France, Sept, 22-26, 2008. pp. 943-948

[11] Hiro Tanimoto, Mamoru Minami, Akira Yanou and Masaki Takebayashi, Continuous Shape-Grinding Experiment based on Constraint-combined Force / Position Hybrid Control Method, Proceedings of 2012 IEEE/SICE International Symposium on System Integration (SII2012), 2012.

[12] Hiro Tanimoto, Mamoru Minami, Akira Yanou and Masaki Takebayashi, Constraint-combined Force / Position Decoupling Control Experiment for Shape-Grinding, The 2013 IEEE International Conference on Robotics and Automation (ICRA 2013) (to be submitted)