実時間拘束条件推定に基づいた位置/力制御
Grinding-shaping by Direct Position / Force Control and On-line Constraint Estimation

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Abstract— Based on the analysis of the interaction between a manipulator's hand and a working object, a model representing the constrained dynamics of the robot is first discussed. The constrained forces are expressed by an algebraic function of states, input generalized forces, and constraint condition, and then direct position / force controller without force sensor is proposed based on the algebraic relation. To give the grinding system the ability to adapt to any object shape being changed by the grinding, we added estimating function of the shape in real time for the adaptive position / force control. Evaluations through simulations by fitting the changing constraint surface with such functions as linear, quadratic, and spline functions, indicate that reliable position / force control can be achieved by the proposed controller with spline curve fitting. And then we also did the shape grinding.

Key Words: grinding-shaping, spline, manipulator

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]-[4] 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. 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 any force sensor have been presented [5]-[7]. To ensure the stabilities of the constrained motion, force and position control have utilized Lyapunov's stability analysis under the inverse dynamic compensation [8]-[13]. Their force control strategies have been explained intelligibly in books [14], [15] and recently interaction control for six-degree-of-freedom tasks has been compiled in a book [16].

However, insofar as we survey the controllers introduced in the books or published papers don't base on the algebraic function of states and input generalized forces derived from the relation between the constraint condition and the equation of dynamics. So we discuss first a strategy for simultaneous control of the position and force without any force sensors, where the equation of dynamics in reference to the constrained force has been reformulated [18]. The constrained force is derived from the equation of dynamics and the constrained equation as an explicit algebraic function of states and input generalized forces [21], which means force information can be obtained by calculation rather than by force sensing. Equation (1), which has been pointed out by Hemami [17] in the analysis of biped walking robot, denotes also the kinematical algebraic relation of the controller, when robot's end-effecter being in touch with a surface in 3-D space:

$$F_n = a(\boldsymbol{x}_1, \boldsymbol{x}_2) - \boldsymbol{A}(\boldsymbol{x}_1)\boldsymbol{\tau}, \qquad (1)$$

where, F_n is exerting force on the constrained surface. $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$ are state variables. $a(\boldsymbol{x}_1, \boldsymbol{x}_2)$ and $\boldsymbol{A}(\boldsymbol{x}_1)$ are scalar function and vector one defined in following section. $\boldsymbol{\tau}$ is input torque. This algebraic equation has been known, but it was the first time in robotics to be applied to the sensing function of exerting force by Peng [10]. As a new control law, the controller doesn't include any force feedback sensors but realizes simultaneous control of position and force in the constrained motions and is different from the traditional ones [1], [4], [6], [9].

A strategy to control force and position proposed in this paper is also based on (1). Contrarily to Peng's Method to use (1) as a force sensor, we used the equation for calculating $\boldsymbol{\tau}$ to achieve a desired exerting force F_{nd}. Actually, the strategy is based on two facts of (1) that have been ignored for a long time. The first fact is that the force transmission process is an immediately process being stated clearly by (1) providing that the manipulator's structure is rigid. Contrarily, the occurrence of velocity and position is a time-consuming process. By using this algebraic relation, it's possible to control the exerting force to the desired one without time lag. Another important fact is the input generalized forces have some redundancy against the constrained generalized forces in the constrained motion. Shall we consider an articulated planar two-link manipulator with two input torques, whose end-effecter be in contact with the constrained surface without friction in the tangential direction of the constrained surface. And provide that only a force exerted on the normal direction of the constrained surface is required to be controlled, the two input torques have a redundancy to realize the force and the remaining freedom of the torque could be used for position control along to the tangential direction. Based on the above analysis, we had confirmed our force / position control method can realize the grinding task through real grinding robot [18].

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. Grinding task requires on-line estimation of changing constraint condition since the grinding changes the constraint condition. In this presentation, we estimate the object's surface using the grinder as a 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 surface shape in real time. We try three estimation methods (Fitting by linear, quadratic and spline function). The grinding simulations with three kinds of on-line estimations of constraint conditions show that the spline curve fitting is best and the position / force control accuracy can be acceptable when we use spline fitting.

2. Analysis of Grinding Task

There are four kinds of grinding processes in common use, called respectively vertical surface grinding, horizontal surface grinding, internal grinding and cylindrical grinding. A grinding machine usually can only perform one or two of these processes because of kinematical limitation. However, all of the four kinds of tasks can be finished by a single robot manipulator for its dexterity in movement. To do so, the grinding wheel has to contact with the workpiece. A set of contacting surfaces, especially the surfaces being machined, will form constraints to the motions of the grinding wheel.

In general, the desired grinding position trajectory is given by processing drawings for each grinding procedure, which the grinding allowance is considered. As for grinding forces F_n, F_t and F_s, the desired values should be determined carefully for different grinding conditions. 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 formulae available for the determination of grinding power, and the desired force trajectory can then be planned according to the power. The normal grinding force F_n is exerted in the perpendicular direction of the surface. It 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

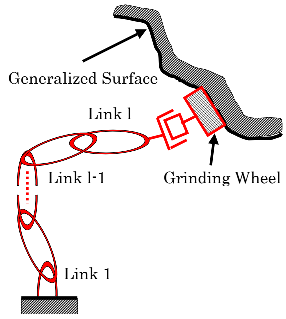


Fig.1 A Grinding Robot

$$F_t = \mathrm{K_t} F_n, \qquad (2)$$

where, $\mathrm{K_t}$ is an empirical coefficient, F_t is the tangential grinding force[19].

The axial grinding force F_s is proportional with the feed rate, and is much smaller than the former force.

Equation (2) is based on the situation that position of the grinding cutter is controlled like currently used machining center. But when a robot is used for the grinding task, the exerting force to the object and the position of the grinding cutter should be controlled simultaneously. And the F_n is generally determined by the constrained situation, and it is not suitable to apply (2) to grinding motion by the robots.

For grinding task, the normal force and tangential velocity are the most important two factors. To improve grinding quality, it is usually desired that the normal force is constant while the velocity is also constant in the middle term of a grinding stroke.

Grinding is a kind of precision machining method and the working condition is hard for a robot to do it precisely to a certain extent because of the rather large contacting forces. Hence, force control is necessary except position control. Usually, force sensor is an essential element to control the force. However, the sensors pose many problems as the above-mentioned. If possible, sensing without sensors is much better for the merit of that there is no difficulty on the design and no cost. The following will present how to obtain force information by calculating rather than by using force sensors.

3. Modeling

3·1 Constrained Dynamic Systems

Hemami and Wyman[17] 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[17],[20]. In this paper, the grinding manipulator shown in Fig. 1, whose end-point is in contact with the constrained surface, is modelled as following (3) with Lagrangian equations of motion in term of the constraint forces, refering to what Hemami and Arimoto[6] have done:

$$\frac{d}{dt}(\frac{\partial L}{\partial \dot{\boldsymbol{q}}}) - (\frac{\partial L}{\partial \boldsymbol{q}}) = \boldsymbol{\tau} + \boldsymbol{J_c}^T(\boldsymbol{q})F_n - \boldsymbol{J_r}^T(\boldsymbol{q})F_t, \quad (3)$$

where, $\boldsymbol{J_c}$ and $\boldsymbol{J_r}$ satisfy,

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

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

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

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

L is the Lagrangian function, $\boldsymbol{q}$ 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 constraint, and expressed as an equation of constraints

$$C(\boldsymbol{r}(\boldsymbol{q})) = 0, \quad (4)$$

F_n is the constrained force associated with C and F_t is the tangential disturbance force.

Equation (3) can be derived to be

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{H}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{G}(\boldsymbol{q})$$

$$= \boldsymbol{\tau} + \boldsymbol{J}_c^T(\boldsymbol{q})F_n - \boldsymbol{J}_r^T(\boldsymbol{q})F_t, \quad (5)$$

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

$$\dot{\boldsymbol{x}}_1 = \boldsymbol{x}_2,$$
$$\dot{\boldsymbol{x}}_2 = -\boldsymbol{M}^{-1}(\boldsymbol{H}(\boldsymbol{x}_1, \boldsymbol{x}_2) + \boldsymbol{G}(\boldsymbol{x}_1))$$
$$+\boldsymbol{M}^{-1}(\boldsymbol{\tau} + \boldsymbol{J}_c^T(\boldsymbol{x}_1)F_n - \boldsymbol{J}_r^T\boldsymbol{x}_1)F_t), \quad (6)$$

or in the compact form

$$\dot{\boldsymbol{x}} = \boldsymbol{F}(\boldsymbol{x}, \boldsymbol{\tau}, F_n, F_t), \quad (7)$$

where the dimension of $\boldsymbol{x}$ is $n = 2l$. In order to control the system (7) with constraints (4) , it can be done firstly by differentiating the constraint equation (4) twice with respect to time and rewriting the result in terms of $\boldsymbol{x}$:

$$\boldsymbol{D}(\boldsymbol{x})\dot{\boldsymbol{x}} = 0, \quad (8)$$

where, $\boldsymbol{D}(\boldsymbol{x})$ is an n vector that the constrained motion of the system is orthogonal. Premultiplying (7) by $\boldsymbol{D}(\boldsymbol{x})$ derived from (8),

$$\boldsymbol{D}(\boldsymbol{x})\boldsymbol{F}(\boldsymbol{x}, \boldsymbol{\tau}, F_n, F_t) = 0. \quad (9)$$

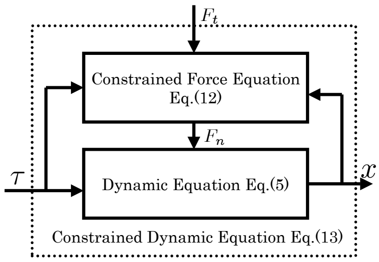


Fig.2 Model of Constrained Dynamic System

This is a linear equation about the unknown constrained force F_n , combining the constrained equation and the equation of motion.(9) can be uniquely solved for F_n as a function of the state $\boldsymbol{x}$ and input $\boldsymbol{\tau}$,

$$-[\frac{\partial}{\partial \boldsymbol{q}}(\frac{\partial C}{\partial \boldsymbol{q}})\dot{\boldsymbol{q}}]\dot{\boldsymbol{q}} + (\frac{\partial C}{\partial \boldsymbol{q}})\boldsymbol{M}^{-1}(\boldsymbol{H}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{G}(\boldsymbol{q}) + \boldsymbol{J_r}^T F_t)$$
$$-(\frac{\partial C}{\partial \boldsymbol{q}})\boldsymbol{M}^{-1}\boldsymbol{\tau} = [(\frac{\partial C}{\partial \boldsymbol{q}})\boldsymbol{M}^{-1}(\frac{\partial C}{\partial \boldsymbol{q}})^T]F_n / \parallel \frac{\partial C}{\partial \boldsymbol{r}} \parallel, \quad (10)$$

because the value of $(\frac{\partial C}{\partial \boldsymbol{q}})\boldsymbol{M}^{-1}(\frac{\partial C}{\partial \boldsymbol{q}})^T$ is always positive, hence it is also invertible. In this case, F_n can be worked out from (10) as

$$F_n = F_n(\boldsymbol{x}, \boldsymbol{\tau}, F_t), \quad (11)$$

or a more detailed form

$$F_n = [(\frac{\partial C}{\partial \boldsymbol{q}})\boldsymbol{M}^{-1}(\frac{\partial C}{\partial \boldsymbol{q}})^T]^{-1} \parallel \frac{\partial C}{\partial \boldsymbol{r}} \parallel$$

$$\{-[\frac{\partial}{\partial \boldsymbol{q}}(\frac{\partial C}{\partial \boldsymbol{q}})\dot{\boldsymbol{q}}]\dot{\boldsymbol{q}} + (\frac{\partial C}{\partial \boldsymbol{q}})\boldsymbol{M}^{-1}(\boldsymbol{H}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{G}(\boldsymbol{q}) + \boldsymbol{J_r}^T F_t)\}$$

$$-[(\frac{\partial C}{\partial \boldsymbol{q}})\boldsymbol{M}^{-1}(\frac{\partial C}{\partial \boldsymbol{q}})^T]^{-1} \parallel \frac{\partial C}{\partial \boldsymbol{r}} \parallel \{(\frac{\partial C}{\partial \boldsymbol{q}})\boldsymbol{M}^{-1}\}\boldsymbol{\tau}$$

$$\triangleq a(\boldsymbol{x}_1, \boldsymbol{x}_2) + \boldsymbol{A}(\boldsymbol{x}_1)\boldsymbol{J}_r^T F_t - \boldsymbol{A}(\boldsymbol{x}_1)\boldsymbol{\tau}, \quad (12)$$

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. Eqs.(7) and (11) compose a constrained system that can be controlled, if $F_n = 0$, describing the unconstrained motion of the system.

Substituting the (12) into (6), the state equation of the system including the constrained force (as $F_n > 0$) can be rewritten as

$$\dot{\boldsymbol{x}}_1 = \boldsymbol{x}_2,$$

$$\dot{\boldsymbol{x}}_2 = -\boldsymbol{M}^{-1}[\boldsymbol{H}(\boldsymbol{x}_1, \boldsymbol{x}_2) + \boldsymbol{G}(\boldsymbol{x}_1) - \boldsymbol{J}_c^T(\boldsymbol{x}_1)a(\boldsymbol{x}_1, \boldsymbol{x}_2)]$$

$$+\boldsymbol{M}^{-1}[(\boldsymbol{I} - \boldsymbol{J}_c^T\boldsymbol{A})\boldsymbol{\tau} + (\boldsymbol{J}_c^T\boldsymbol{A} - \boldsymbol{I})\boldsymbol{J}_r^T F_t]. \quad (13)$$

As the model of the constrained dynamic system denoted in Fig. 2, the solution of these dynamic equations will always satisfy the constrained equation (4), as a result of the normal position error will always be zero,too.

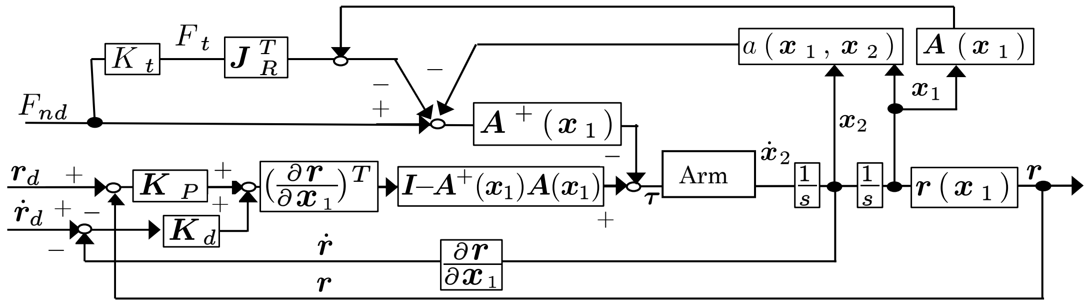


Fig.3 Control system

4. Force and position controller

4·1 Controller using predicted constraint condition

Reviewing the dynamic equation (3) and constraint condition (4), 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 (12) 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 (12) 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 $C = 0$ be known. As a result, a control law is derived and can be expressed as

$$\boldsymbol{\tau} = -\boldsymbol{A}^{+}(\boldsymbol{x}_1)\Big\{F_{nd} - a(\boldsymbol{x}_1, \boldsymbol{x}_2) - \boldsymbol{A}(\boldsymbol{x}_1)\boldsymbol{J}_R^T F_t\Big\} + (\mathbf{I} - \boldsymbol{A}^{+}(\boldsymbol{x}_1)\boldsymbol{A}(\boldsymbol{x}_1))\boldsymbol{k}, \quad (14)$$

where $\mathbf{I}$ is an identity matrix of $l \times l$, F_{nd} is the desired constrained forces, $\boldsymbol{A}(\boldsymbol{x}_1)$ is defined in (12) and $\boldsymbol{A}^{+}(\boldsymbol{x}_1)$ is the pseudoinverse matrix of it, $a(\boldsymbol{x}_1, \boldsymbol{x}_2)$ is also defined in (12) and $\boldsymbol{k}$ is an arbitrary vector which is defined as

$$\boldsymbol{k} = \tilde{\boldsymbol{J}}_r^T(\boldsymbol{q})\Big\{\boldsymbol{K}_p(\boldsymbol{r}_d - \boldsymbol{r}) + \boldsymbol{K}_d(\dot{\boldsymbol{r}}_d - \dot{\boldsymbol{r}})\Big\}, \quad (15)$$

where $\boldsymbol{K}_p$ and $\boldsymbol{K}_d$ are coefficient matrices applied to the 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. The controller presented by (14) and (15) 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 predict time-varying constraint conditions 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 based on the estimated constrained surface. The estimated condition is denoted by $\hat{C} = 0$. 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 (17), (18). They were used in the later simulations of the unknown constrained condition. As a result, a controller based on the estimated constrained condition is given as

$$\hat{\boldsymbol{\tau}} = -\hat{\boldsymbol{A}}^{+}(\boldsymbol{x}_1)\Big\{F_{nd} - \hat{a}(\boldsymbol{x}_1, \boldsymbol{x}_2) - \hat{\boldsymbol{A}}(\boldsymbol{x}_1)\boldsymbol{J}_R^T F_t\Big\} + (\mathbf{I} - \hat{\boldsymbol{A}}^{+}(\boldsymbol{x}_1)\hat{\boldsymbol{A}}(\boldsymbol{x}_1))\boldsymbol{k}, \quad (16)$$

$$m_c{}^{-1}\|\frac{\partial\hat{C}}{\partial\boldsymbol{r}}\|\{-[\frac{\partial}{\partial\boldsymbol{q}}(\frac{\partial\hat{C}}{\partial\boldsymbol{q}})\dot{\boldsymbol{q}}]\dot{\boldsymbol{q}} + (\frac{\partial\hat{C}}{\partial\boldsymbol{q}})\boldsymbol{M}^{-1}(\boldsymbol{h}+\boldsymbol{g})\} \triangleq \hat{a}(\boldsymbol{x}_1, \boldsymbol{x}_2) \quad (17)$$

$$m_c{}^{-1}\|\frac{\partial\hat{C}}{\partial\boldsymbol{r}}\|\{(\frac{\partial\hat{C}}{\partial\boldsymbol{q}})\boldsymbol{M}^{-1}\} \triangleq \hat{\boldsymbol{A}}(\boldsymbol{x}_1) \quad (18)$$

Fig. 3 illustrates a control system constructed according to the above control law that consists of a position control loop and a force control loop. It can be found from (12) and (16) 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.

The experiment when the constraint is known have been done successfully in Fig. 4. The maxima of position error is about 8[mm], and the maxima of force error is about 3[N] which is presented [21]. Besed on the experiment when the constraint is known, we propose the methods when the constraint is unknown.

4·2 Shape grinding

In the past, we did the experiment when working surface was always flat, so we can just do flat grinding. Now 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. 5. In

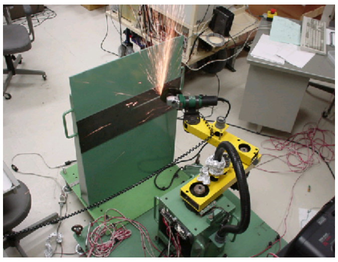


Fig.4 The experiment when the constraint is known

Fig. 5, we can find that the desired working surface is known (it can be decided by us.), which means the desired constrained condition C_d is known, so

$$C_{(d)} = y - f_{(d)}(x) = 0 \qquad (19)$$

But the constrained condition $C^{(j)}$ $(j = 1, 2, \cdots, d-1)$ is hard to known. So we assume

$$C^{(j)} = y - f^{(j)}(x) = 0 \qquad (20)$$

Here, y is the coordinate y of manipulator's end-effector. $f^{(j)}(x)$ is the working surface.

If the current constrained condition can be got successfully, which means the current working surface $f^{(j)}(x)$ can be known, so the distance from the current working surface to the desired working surface which is expressed as $\Delta h^{(j)}$ shown in Fig. 5 can be obtained easily.

$$\Delta h^{(j)}(x_i) = f^{(j)}(x)\big|_{x=x_i} - f_d(x)\big|_{x=x_i} \qquad (21)$$

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 $\Delta h^{(j)}$, shown as follows:

$$F_{nd}^{(j)}(x_i)_{nd} = k\Delta h^{(j)}(x_i) \qquad (22)$$

Here, k is a constant.

From the above, we can know that how to get $C^{(j)}$ is a key-point. So we assume $C^{(1)}$ is known, that is

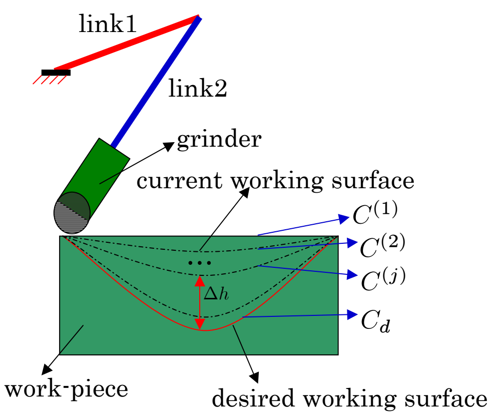


Fig.5 The model of shape grinding

to say, $f^{(1)}(x)$ is known. And we also know if $F_{nd}^{(j)}$ increases, the grinding part will increase. So we get

$$f^{(j+1)}(x_i) - f^{(j)}(x_i) = k' F_{nd}^{(j)}(x_i) \qquad (23)$$

Here, k' is a constant. a condition that the new object shape $f^{(j+1)}(x)$ have to satisfy, i.e.,

$$y = f^{(j+1)}(x) \qquad (24)$$

is a function passing through all points, (x_1, $f^{(j+1)}(x_1)$), (x_2, $f^{(j+1)}(x_2)$), $\cdots$, (x_p, $f^{(j+1)}(x_p)$). Here we chose the p as 10, and assumed $f^{(j+1)}(x)$ could be represented by a polynomial of 9-th order of x. Given the above ten points, we can easily decide the parameters of polynomial function $y = f^{(j+1)}(x)$. From above, we can get $f^{(j+1)}(x)$, and then $C^{(j+1)}$ can also be known:

$$C^{(j+1)} = y - f^{(j+1)}(x) = 0 \qquad (25)$$

So, if $C^{(1)}$ is assumed, all of $C^{(j)}$ can be decided. In the next part, we will introduce several prediction methods which are used to get $\hat{C}_i$ in current time.

4·3 Prediction methods

When the constraint surface of the manipulator is unknown, we fit respectively the constraint surface with linear function, quadratic function, and spline curve. Three simulations have been done to base on different constraint conditions. Here, an unknown constrained condition is estimated 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.
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.

Three methods which are fitting by linear function, quadratic function and spline function had been used to get the online estimation of the unknown constrained condition. Here we just introduce the spline curve fitting.

4·3.1 Fitting by quadratic spline curve

The unknown constrained surface is estimated and expressed as,

$$\hat{C}_{i+1} = y - [A_i(x - x_{i-1})^2 + B_i(x - x_{i-1}) + C_i] \qquad (26)$$

The end-effector position at time $(i-1)\Delta t$, $i\Delta t$ are denoted respectively as (x_{i-1}, y_{i-1}), (x_i, y_i).

The coefficients of quadratic spline curve denoted as

$$S_i(x) = A_i(x - x_{i-1})^2 + B_i(x - x_{i-1}) + C_i, \quad x \in [x_{i-1}, x_i](i = 1, 2, 3 \cdots n) \qquad (27)$$

can be calculated as follows. The constrained condition $\hat{C}_{i+1} = y - (A_i(x - x_{i-1})^2 + B_i(x - x_{i-1}) + C_i)$ can be determined.And we can get the coefficients of the spline curve uniquely as follows.

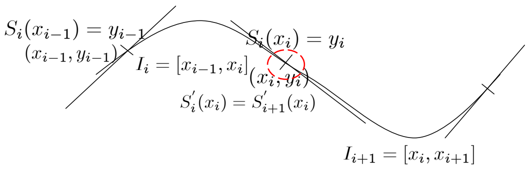


Fig.6 Fitting by quadratic spline curve

Firstly, let $S_i(x)$ satisfy the following conditions shown in Fig. 6.

(A)Go throough two ends of the interval

$$y_{i-1} = S_i(x_{i-1}) \tag{28}$$

$$y_i = S_i(x_i) \tag{29}$$

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

$$\left.\frac{dS_{i+1}(x)}{dx}\right|_{x=x_i} = \left.\frac{dS_i(x)}{dx}\right|_{x=x_i} S_{i+1}'(x_i) = S_i'(x_i) \tag{30}$$

Inputting (27) into (28), (29) and (30), we can obtain:

$$C_i = y_{i-1}, (i = 1, 2, \cdots, n) \tag{31}$$

$$B_{i+1} = 2u_i - B_i, (i = 1, 2, \cdots, n-1) \tag{32}$$

$$A_i = \frac{B_{i+1} - B_i}{2h_i}, (i = 1, 2, \cdots, n-1) \tag{33}$$

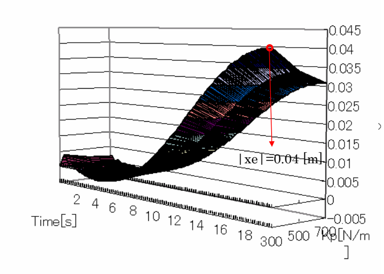
Here, $h_i = x_i - x_{i-1}$, $u_i = \frac{y_i - y_{i-1}}{h_i}$. From the above-mentioned result, the constrained conditional expression $\hat{\boldsymbol{C}}_{i+1}$ can be updated step by step.

In this one, we can see that the spline curve is defined by two points and a derivative at some point. Compare to the quadratic function fitting and liner function fitting, Fitting by quadratic spline curve is more precise because a derivative is used instead of a point. So we can say fitting by quadratic spline curve is the best method among the three methods.

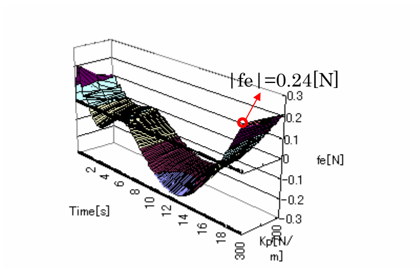
5. simulation

A planar two-link manipulator is applied for simulation so as to examine the behaviour of the proposed controller. The goals were to examine the feasibility of the proposed method with regard to the accuracy and stability. Three simulations have been done based on different constraint conditions.

The model of grinding robot manipulator used in the simulation is shown in Fig.5, whose parameters are: length of link 1 is 0.3[m], length of link 2 is 0.5[m], and the mass of link 1 is 12.28[kg], the mass of link 2 is 7.64[kg]. The end-effector velocity, 0.01[m/s], the desired constrained force, $F_{nd} = 5$[N], grinding resistance, $F_t = 0$[N].

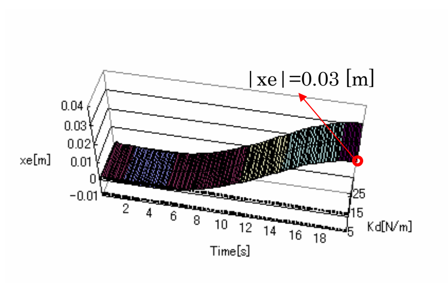


(a) Position error x_e

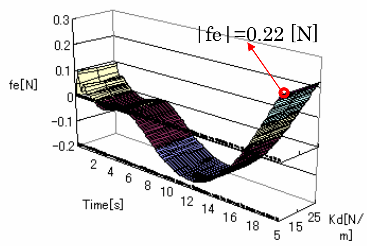


(b) Force error f_e

Fig.7 Quadratic spline curve fitting for the unknown constraint surface, here k_d=5



(a) Position error x_e



(b) Force error f_e

Fig.8 Quadratic spline curve fitting for the unknown constraint surface, here k_p=700

The desired constrained surface is denoted as

$$f(x) = p - k\cos(\omega x) \tag{34}$$

Here, p=0.51, k=0.1, ω=10.

5·1 Grinding with quadratic spline curve fitting

The simulation results are shown in Fig. 7 and Fig. 8. From these figures, we can find when k_p $\in$[300,700], k_d=5, $|x_{e(max)}|$ is 0.04[m] in Fig. 7(a), and $|f_{e(max)}|$ is 0.24[N] in Fig. 7(b). When k_p=700,k_d $\in$ [5,25], $|x_{e(max)}|$ is 0.03[m] in Fig. 8(a), and $|f_{e(max)}|$ is 0.22[N] in Fig. 8(b).

In the above simulations, regardless of any controllers above are used to the situation when the constrained condition is not known, x_e and f_e always appeared. The trajectories of the end-effector is always in contact with the constrained condition defined by (34). However the difference of the control results of postition and force depends on the constrained conditions C(known constraint) or $\hat{C}$(unknown constraint).

As shown in Table 1 and Table 2, the errors of position and force controlled by quadratic spline fitting is minimum, no matter how k_p and k_d change. And the quadratic spline fitting for unknown constrained surface is the most closed to the known constrained surface, regarding with both x_e and f_e. So we can see the performance of controller with quadratic spline fitting is best.

Compare to the experiment result of known constraint(x_e is about 8[mm], f_e is about 3[N]), we can say the experiment with these methods can be done. We can also say some work whose working surface is not known can be done using the quadratic spline curve fitting by robot.

Table 1 Comparision of the four results when k_p $\in$ [300,700], k_d=5

	$\lvert x_{e(max)}\rvert$ [m]	$\lvert f_{e(max)}\rvert$ [N]
Known constrained surface	0.051	0
Linear function fitting	0.108	29.3
Quadratic function fitting	0.090	1.43
Quadratic spline curve fitting	0.04	0.24

Table 2 Comparision of the four results when k_p=700, k_d $\in$ [5,25]

	$\lvert x_{e(max)}\rvert$ [m]	$\lvert f_{e(max)}\rvert$ [N]
Known constrained surface	0.039	0
Linear function fitting	0.1	26
Quadratic function fitting	0.067	0.60
Quadratic spline curve fitting	0.03	0.22

5·2 Shape Grinding

Since we know that the spline curve fitting is the best, we can use it to do the shape grinding just like Fig. 5. In this simulation, the constant k shown in (22) is 50, and k' shown in (23) is 0.002. The trajectory of simulation is showing Fig. 9. The trajectory named $O-A$ is first grinding, and then go back to the starting point through a line which is named $A-B$. The trajectory of second grinding is $B-A$. From the result, we can easily find that the part between $O-A$ and $B-A$ are cut. The error of x position and force are showing Fig. 10, and Fig. 11. From the errors, we can say it is so small. Hence, we can say that we can do the shape grinding with this method.

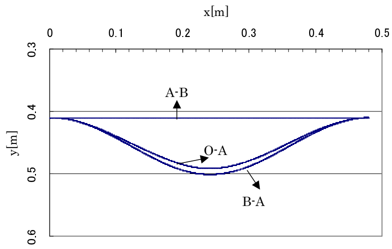


Fig.9 the trajectory of simulation

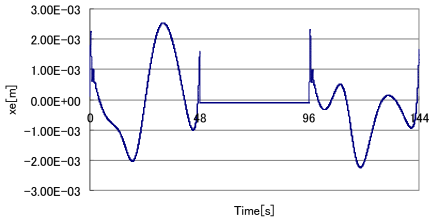


Fig.10 the error of x position

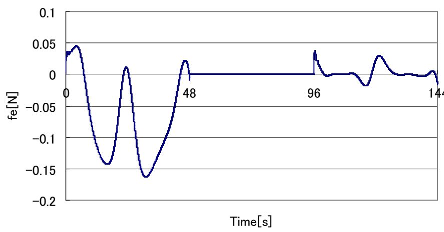


Fig.11 the error of force

6. Conclusions

The constrained dynamic equations of a manipulator are derived and the constrained forces are expressed as an explicit function of the state and inputs. The presented methodology allows computation of the forces, as an alternative to sensing. Hence, the system is controlled with no force sensor. The control law presented is constructed by using the dynamical redundancy of constrained systems. The controller designed with this control law can be used for simultaneous control of force and position. In the paper, we present three methods for estimating the constrained condition to attain time-varying unknown constrained information. The simulations indicate the perfermance of controller with quadratic spline fitting is the best. And the quadratic spline fitting for unknown constrained surface is the most closed to the known constrained surface.

The quadratic spline fitting for unknown constrained surface is used in the shape grinding, the errors are so small, so we can say it can be done in the shape grinding.

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