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Force-sensorless shape-grinding for arbitrary curved surface object

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Abstract: This research aims to achieve a new grinding robot system that can grind an object into desired shape with force-sensorless control. In order to grind the target object into desired shape with sufficient accuracy, the hand of the robot arm has to generate desired constrained force immediately after the grindstone being contacted with the metal object to be ground. Based on the algebraic equation, we have proposed Constraint-Combined Force Controller(CCFC), which has the ability to achieve the force control without time delay if the motors should ideally generate required torques without time delay. In this paper, we propose a method for grinding arbitrary carved surface object without force-sensor, which is composed of a two-dimensional grinding robot and an articulated robot that handles an object to be ground in front of the grinding robot. By using proposed system, we conducted grinding an object with arbitrary-shape. Since the grinding robot is 2-link SCARA robot, other supporting robot that set an object with arbitrary pose is indispensable for the purpose of grind any surface-shaped object. Three-dimensional grinding is performed by posing the object by an articulated robot and repeating two-dimensional grinding by our 2-link SCARA robot.

Keywords: force-sensorless grinding, robot, shape-grinding.

Fig. 1. Grinding robot

1 INTRODUCTION

Industrial robots are used for many purposes, especially as machining facilities. For example, there are welding, assembling and grinding operations. This research aims to achieve a new grinding robot system that can grind an object into desired shape with force-sensorless control in real experiment. Based on the analysis of the interaction between a manipulator's hand and a work-piece, a model representing the constrained dynamics of the robot is first discussed. Many researches have discussed force control methods of robots for constrained tasks. These control strategies use force sensors generally to obtain force information[1]-[3], where the reliability and accuracy are limited since the work-sites of the robot tend to be filled with noise and thermal disturbances, reducing the sensor's reliability. On top of this, force sensors could lead to the falling of the structure stiffness of manipulators, which is one of the most essential defects for manipulators executing grinding tasks. To solve these problems, some approaches that don't use force sensors have been presented[4]-[8]. In previous our research, we discussed about grinding task of robot that have disk grinder as an end-effector. Our grinding robot is 2-link SCARA manipulator. The contact process of the grinder can be just thought as non-dynamical process but a kinematical one, so the prerequisite that there is no motion occurred in vertical direction to the surface to be ground could be justifiable. Therefore, equation of motion to describe constrained vertical process of the grinder contacting to the work-piece is represented by an algebraic equation. Based on this algebraic equation, we have proposed Constraint-Combined Force Controller[11]-[13], which has the ability to achieve the force control without time delay if the motors ideally should generate required torques without time delay, where force error will not be affected by the dynamical motion along to the surface on which the grinder can move[11], [12]. Our Constraint-Combined force/position control method without using tactile sensor can be thought to be essentially different from methods proposed so far. Constraint-Combined Force Controller we have proposed can compute the input torques to achieve desired force/position by using posture and angular velocity of the robot and frictional force. In this paper, we propose a method for grinding arbitrary carved surface object without force-sensor, which is composed of a two-dimensional grinding robot and a robot that handles an object to be ground in front of the grinding robot. By using proposed system, we conducted grinding an object with arbitrary-shape. Since the grinding robot is 2-link SCARA robot, other supporting robot that set an object with arbitrary pose is indispensable for the purpose of grind any surface-shaped object. Three-dimensional grinding is performed by posing the object by an articulated robot and repeating two-dimensional grinding by our SCARA robot.

2 MODELLING OF CONTACT DYNAMICS

A photo of the experiment device is shown in Fig.1. A concept of grinding robot of constrained motion is shown in Fig.2.

Constraint condition C is a scalar function of the constraint, and is expressed as an algebraic equation of constraints as

$$C(\boldsymbol{r}(\boldsymbol{q})) = 0, \tag{1}$$

where $\boldsymbol{r}(m \times 1)$ is the position vector from origin of coordinates to tip of grinding wheel and $\boldsymbol{q}(n \times 1)$ is joint angles. The grinder set at the robot's hand is in contact with the material that is to be ground. The equation of motion of grinding robot is modelled as following Eq.(2)[11]-[13],

$$\begin{aligned}\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{D}\dot{\boldsymbol{q}} = \\ \boldsymbol{\tau} + {\boldsymbol{J}_C}^T f_n - {\boldsymbol{J}_R}^T f_t,\end{aligned} \tag{2}$$

$${\boldsymbol{J}_C}^T = \frac{\left(\dfrac{\partial C}{\partial \boldsymbol{q}}\right)^T}{\left\|\dfrac{\partial C}{\partial \boldsymbol{r}}\right\|}, {\boldsymbol{J}_R}^T = \left(\frac{\partial \boldsymbol{r}}{\partial \boldsymbol{q}}\right)^T \frac{\dot{\boldsymbol{r}}}{\|\dot{\boldsymbol{r}}\|}, \tag{3}$$

where $\boldsymbol{M}$ is a $n \times n$ matrix, $\boldsymbol{h}$ is centrifugal and coriolis force vector, $\boldsymbol{D}$ is viscous friction coefficient matrix, $\boldsymbol{g}$ is gravity vector. f_n is the constrained force associated with C and f_t is the tangential disturbance force caused by grinding.

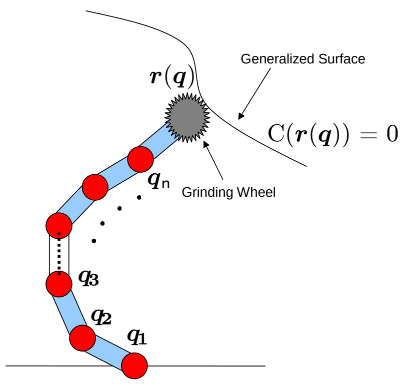

Fig. 2. Grinding robot model

Moreover, ${\boldsymbol{J}_C}^T$ is time-varying coefficient vector translating f_n into each joint disturbance torque and ${\boldsymbol{J}_R}^T$ is time-varying coefficient vector transmitting the tangential disturbance force f_t to joint disturbance torque. The equation represented by Eq.(2) must follow the constraint condition given by Eq.(1) during the contacting motion of grinding. Differentiating Eq.(1) by time twice, we have the following relation among $\boldsymbol{q}$, $\dot{\boldsymbol{q}}$ and $\ddot{\boldsymbol{q}}$ that should be maintained during contacting motion with the work-piece to be ground,

$$\left[\frac{\partial}{\partial \boldsymbol{q}}\left(\frac{\partial C}{\partial \boldsymbol{q}}\right)\dot{\boldsymbol{q}}\right]\dot{\boldsymbol{q}} + \left(\frac{\partial C}{\partial \boldsymbol{q}}\right)\ddot{\boldsymbol{q}} = 0. \tag{4}$$

Above constraint condition represents an algebraic condition of $\ddot{\boldsymbol{q}}$ that have to be determined dependently on $\boldsymbol{q}$ and $\dot{\boldsymbol{q}}$.

Putting $\ddot{\boldsymbol{q}}$ in Eq.(4) into $\ddot{\boldsymbol{q}}$ in Eq.(2) to be determined identically so as the solution of $\boldsymbol{q}$ and $\dot{\boldsymbol{q}}$ of Eq.(2) to comply simultaneously with the constraint condition Eq.(4), the solution $\ddot{\boldsymbol{q}}$ and f_n could be uniquely determined. The following Eq.(5) is the resulted solution of f_n [11]-[13],

$$f_n = a(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{B}(\boldsymbol{q}){\boldsymbol{J}_R}^T f_t - \boldsymbol{B}(\boldsymbol{q})\boldsymbol{\tau}. \tag{5}$$

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

$$m_c \triangleq \left(\frac{\partial C}{\partial \boldsymbol{q}}\right)\boldsymbol{M}^{-1}\left(\frac{\partial C}{\partial \boldsymbol{q}}\right)^T, \tag{6}$$

$$\begin{aligned}a(\boldsymbol{q}, \dot{\boldsymbol{q}}) \triangleq {m_c}^{-1}\left\|\frac{\partial C}{\partial \boldsymbol{r}}\right\|\left\{-\left[\frac{\partial}{\partial \boldsymbol{q}}\left(\frac{\partial C}{\partial \boldsymbol{q}}\right)\dot{\boldsymbol{q}}\right]\dot{\boldsymbol{q}}\right. \\ \left. + \left(\frac{\partial C}{\partial \boldsymbol{q}}\right)\boldsymbol{M}^{-1}(\boldsymbol{h} + \boldsymbol{g})\right\},\end{aligned} \tag{7}$$

$$\boldsymbol{B}(\boldsymbol{q}) \triangleq {m_c}^{-1}\left\|\frac{\partial C}{\partial \boldsymbol{r}}\right\|\left\{\left(\frac{\partial C}{\partial \boldsymbol{q}}\right)\boldsymbol{M}^{-1}\right\}. \tag{8}$$

Substituting Eq.(5) into Eq.(2), the equation of motion of the constrained robot dynamics (as $f_n > 0$) can be rewritten as

$$\begin{aligned}&\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) = {\boldsymbol{J}_C}^T a(\boldsymbol{q}, \dot{\boldsymbol{q}}) \\ &+(\boldsymbol{I} - {\boldsymbol{J}_C}^T\boldsymbol{B})\boldsymbol{\tau} + ({\boldsymbol{J}_C}^T\boldsymbol{B} - \boldsymbol{I}){\boldsymbol{J}_R}^T f_t.\end{aligned} \tag{9}$$

Solutions of above dynamic equation always satisfy the constrained condition, Eq.(4), then accordingly $\boldsymbol{q}$ satisfies Eq.(1).

3 CONSTRAINT-COMBINED FORCE/POSITION CONTROL METHOD

In the following discussions of grinding task, we assume that $m = 2$, $n = 2$, C is scalar function, since we use two link manipulator as a experimental device. Putting the above assumptions and Eq.(5) into consideration we can claim that there is a redundancy of the number of the constrained force, one, against the number of the input torque $\boldsymbol{\tau} = [\tau_1, \tau_2]$. This condition is much similar to the kinematical redundancy. Based on the above argument and assume that, the parameters of the Eq.(5) are known and its state variables could be measured, and $a(\boldsymbol{q}, \dot{\boldsymbol{q}})$ and $\boldsymbol{B}(\boldsymbol{q})$ could be calculated correctly, which means that the constraint condition $C = 0$ be prescribed or measured correctly. As a result, a control law is derived from Eq.(5) and can be expressed as

$$\begin{aligned}\boldsymbol{\tau} = -\boldsymbol{B}^{+}(\boldsymbol{q})\{f_{nd} - a(\boldsymbol{q}, \dot{\boldsymbol{q}}) - \boldsymbol{B}(\boldsymbol{q})\boldsymbol{J}_R{}^T f_t\} \\ +\{\boldsymbol{I} - \boldsymbol{B}^{+}(\boldsymbol{q})\boldsymbol{B}(\boldsymbol{q})\}\boldsymbol{k}, \qquad (10)\end{aligned}$$

where $\boldsymbol{I}$ is a 2×2 identity matrix, f_{nd} is the desired constrained forces, $\boldsymbol{B}(\boldsymbol{q})$ is defined as Eq.(8) and $\boldsymbol{B}^{+}(\boldsymbol{q})$ is the pseudoinverse matrix of it, $a(\boldsymbol{q}, \dot{\boldsymbol{q}})$ is defined as Eq. (7) and $\boldsymbol{k}$ is an arbitrary vector used for hand position control, which is given as

$$\boldsymbol{k} = \left(\frac{\partial \boldsymbol{r}}{\partial \boldsymbol{q}}\right)^T \{\boldsymbol{K}_P(\boldsymbol{r}_d - \boldsymbol{r}) + \boldsymbol{K}_V(\dot{\boldsymbol{r}}_d - \dot{\boldsymbol{r}})\}, \qquad (11)$$

where $\boldsymbol{K}_P$ and $\boldsymbol{K}_V$ are gain matrices for position and the velocity control. The position and velocity control is conducted through the redundant degree of range space of $\boldsymbol{B}$, that is null space of $\boldsymbol{B}$, specifically $\{\boldsymbol{I} - \boldsymbol{B}^{+}\boldsymbol{B}\}$. $\boldsymbol{r}_d$ is the desired position vector of the end-effector along to the constrained surface and $\boldsymbol{r}$ is the real position vector on it. $\boldsymbol{K}_P$ and $\boldsymbol{K}_V$ is needed to be set with a reasonable value, otherwise high-frequency oscillation of position error may appear.

3.1 The method based on Linear approximation of constraint condition

Now let us take a look at Fig.3, 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 linear function

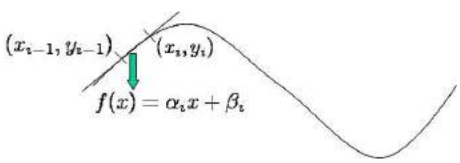

Fig. 3. Fitting by linear function

$$y_{i-1} = \alpha_i x_{i-1} + \beta_i, \qquad (12)$$

$$y_i = \alpha_i x_i + \beta_i, \qquad (13)$$

from Eq.12, Eq.13, coefficients of linear equation α_i, β_i can be derived as

$$\alpha_i = \frac{y_i - y_{i-1}}{x_i - x_{i-1}}, \qquad (14)$$

$$\beta_i = \frac{x_i y_{i-1} - x_{i-1} y_i}{x_i - x_{i-1}}. \qquad (15)$$

From the above results, the equation of the constrained surface estimated by linear approximation is

$$f_{i+1}(x) = \frac{y_i - y_{i-1}}{x_i - x_{i-1}} x + \frac{x_i y_{i-1} - x_{i-1} y_i}{x_i - x_{i-1}} = \alpha_i x + \beta_i. \quad (16)$$

The equation of the constrained surface estimated by linear approximation $y = \alpha_i x + \beta_i$ is used for deriving constraint condition $\hat{C}_{l,i+1}(\boldsymbol{r}(\boldsymbol{q}(t)))$.

$$\hat{C}_{l,i+1}(\boldsymbol{r}(\boldsymbol{q}(t))) = y - (\alpha_i x + \beta_i) = 0 \qquad (17)$$

then $\boldsymbol{r}(\boldsymbol{q}(t))$ is expressed as

$$\boldsymbol{r}(\boldsymbol{q}(t)) = \begin{bmatrix} x(\boldsymbol{q}(t)) \\ y(\boldsymbol{q}(t)) \end{bmatrix} = \begin{bmatrix} l_1 \cos q_1 + l_2 \cos(q_1 + q_2) \\ l_1 \sin q_1 + l_2 \sin(q_1 + q_2) \end{bmatrix}. \quad (18)$$

From the following, we set $\cos q_1 = c_1$, $\cos q_2 = c_2$, $\sin q_1 = s_1$, $\sin q_2 = s_2$ for simplification of notation.
Differentiate constraint condition $\hat{C}_l$ with position vector $\boldsymbol{r}$ as follow.

$$\frac{\partial \hat{C}_l}{\partial \boldsymbol{r}} = [-\alpha_i \quad 1] \qquad (19)$$

And $\partial \hat{C}_l / \partial \boldsymbol{q}$ can be expressed by $(\partial \hat{C}_l / \partial \boldsymbol{r})$ and $(\partial \boldsymbol{r} / \partial \boldsymbol{q})$,

$$\frac{\partial \hat{C}_l}{\partial \boldsymbol{q}} = \frac{\partial \hat{C}_l}{\partial \boldsymbol{r}} \frac{\partial \boldsymbol{r}}{\partial \boldsymbol{q}} \qquad (20)$$

Differentiate $\boldsymbol{r}$ with $\boldsymbol{q}$ as follows.

$$\frac{\partial \boldsymbol{r}}{\partial q_1} = \begin{bmatrix} \frac{\partial x}{\partial q_1} \\ \frac{\partial y}{\partial q_1} \end{bmatrix} \qquad (21)$$

$$\frac{\partial \boldsymbol{r}}{\partial q_2} = \begin{bmatrix} \frac{\partial x}{\partial q_2} \\ \frac{\partial y}{\partial q_2} \end{bmatrix} \qquad (22)$$

From the above, the component of the equation obtained by differentiating the constraint condition $\hat{C}_l$ with the joint angle $\boldsymbol{q} = [q_1, q_2]$

$$\begin{aligned}\frac{\partial \hat{C}_l}{\partial q_1} &= \frac{\partial \hat{C}_l}{\partial \boldsymbol{r}} \frac{\partial \boldsymbol{r}}{\partial q_1} = \begin{bmatrix} -\alpha_i & 1 \end{bmatrix} \begin{bmatrix} \frac{\partial x}{\partial q_1} \\ \frac{\partial y}{\partial q_1} \end{bmatrix} \\ &= \alpha_i (l_1 s_1 + l_2 s_{12}) + l_1 c_1 + l_2 c_{12}, \qquad (23)\end{aligned}$$

$$\begin{aligned}\frac{\partial \hat{C}_l}{\partial q_2} &= \frac{\partial \hat{C}_l}{\partial \boldsymbol{r}}\frac{\partial \boldsymbol{r}}{\partial q_2} = \begin{bmatrix} -\alpha_i & 1 \end{bmatrix}\begin{bmatrix} \frac{\partial x}{\partial q_2} \\ \frac{\partial y}{\partial q_2} \end{bmatrix} \\ &= \alpha_i l_2 s_{12} + l_2 c_{12}. \end{aligned} \tag{24}$$

Firstly, when the constraint condition $\hat{C}_l$ is differentiated at time t,

$$\begin{aligned}&\frac{d^2\hat{C}_l}{dt^2}\frac{d}{dt}\frac{d\hat{C}_l}{dt} = \frac{d}{dt}\hat{P}_l + \frac{\partial \hat{C}_l}{\partial \boldsymbol{q}}\ddot{\boldsymbol{q}} = \frac{\partial \hat{P}_l}{\partial \boldsymbol{q}}\dot{\boldsymbol{q}} + \frac{\partial \hat{C}_l}{\partial \boldsymbol{q}}\ddot{\boldsymbol{q}} \\ &= \begin{bmatrix} \frac{\partial \hat{P}_l}{\partial q_1} & \frac{\partial \hat{P}_l}{\partial q_2} \end{bmatrix}\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} \frac{\partial \hat{C}_l}{\partial q_1} & \frac{\partial \hat{C}_l}{\partial q_2} \end{bmatrix}\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix}. \end{aligned} \tag{25}$$

And $\partial \hat{P}_l/\partial q_1$, $\partial \hat{P}_l/\partial q_2$

$$\begin{aligned}\frac{\partial \hat{P}_l}{\partial q_1} &= [\alpha_i(l_1 c_1 + l_2 c_{12}) - l_1 s_1 - l_2 s_{12}]\dot{q}_1 \\ &\quad + [\alpha_i l_2 c_{12} - l_2 s_{12}]\dot{q}_2, \end{aligned} \tag{26}$$

$$\frac{\partial \hat{P}_l}{\partial q_2} = [\alpha_i l_2 c_{12} - l_2 s_{12}]\dot{q}_1 + [\alpha_i l_2 c_{12} - l_2 s_{12}]\dot{q}_2. \tag{27}$$

Substituting Eq.26 and Eq.27 into Eq.25,

$$\begin{aligned}\frac{d^2\hat{C}_l}{dt^2} &= \begin{bmatrix} \frac{\partial \hat{P}_l}{\partial q_1} & \frac{\partial \hat{P}_l}{\partial q_2} \end{bmatrix}\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} \frac{\partial \hat{C}_l}{\partial q_1} & \frac{\partial \hat{C}_l}{\partial q_2} \end{bmatrix}\begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} \\ &= [\alpha_i(l_1 c_1 + l_2 c_{12}) - l_1 s_1 - l_2 s_{12}]\dot{q}_1^2 \\ &\quad + 2[\alpha_i l_2 c_{12} - l_2 s_{12}]\dot{q}_1\dot{q}_2 + [\alpha_i l_2 c_{12} - l_2 s_{12}]\dot{q}_2^2 \\ &\quad + [\alpha_i(l_1 s_1 + l_2 s_{12}) + l_1 c_1 + l_2 c_{12}]\ddot{q}_1 + [\alpha_i l_2 s_{12} + l_2 c_{12}]\ddot{q}_2 \end{aligned} \tag{28}$$

$$\frac{\partial}{\partial \boldsymbol{q_1}}\left(\frac{\partial \hat{C}_l}{\partial \boldsymbol{q_1}}\right) = \alpha_i(l_1 c_1 + l_2 c_{12}) - l_1 s_1 - l_2 s_{12} \tag{29}$$

$$\frac{\partial}{\partial \boldsymbol{q_1}}\left(\frac{\partial \hat{C}_l}{\partial \boldsymbol{q_2}}\right) = \alpha_i l_2 c_{12} - l_2 s_{12} \tag{30}$$

$$\frac{\partial}{\partial \boldsymbol{q_2}}\left(\frac{\partial \hat{C}_l}{\partial \boldsymbol{q_1}}\right) = \alpha_i l_2 c_{12} - l_2 s_{12} \tag{31}$$

$$\frac{\partial}{\partial \boldsymbol{q_2}}\left(\frac{\partial \hat{C}_l}{\partial \boldsymbol{q_2}}\right) = \alpha_i l_2 c_{12} - l_2 s_{12} \tag{32}$$

$\hat{a}(\boldsymbol{q}, \dot{\boldsymbol{q}})$, $\hat{\boldsymbol{A}}(\boldsymbol{q})$ is defined as follows.

$$\left(\frac{\partial \hat{C}_l}{\partial \boldsymbol{q}}\right)\boldsymbol{M}^{-1}\left(\frac{\partial \hat{C}_l}{\partial \boldsymbol{q}}\right)^T \triangleq m_c \tag{33}$$

$$m_c{}^{-1}\left\| \frac{\partial \hat{C}_l}{\partial \boldsymbol{r}} \right\| \left\{\left(\frac{\partial \hat{C}_l}{\partial \boldsymbol{q}}\right)\boldsymbol{M}^{-1}\right\} \triangleq \hat{\boldsymbol{A}}(\boldsymbol{q}) \tag{34}$$

$$\begin{aligned}m_c{}^{-1}\left\| \frac{\partial \hat{C}_l}{\partial \boldsymbol{r}} \right\| \left\{-\left[\frac{\partial}{\partial \boldsymbol{q}}\left(\frac{\partial \hat{C}_l}{\partial \boldsymbol{q}}\right)\dot{\boldsymbol{q}}\right]\dot{\boldsymbol{q}} + \left(\frac{\partial \hat{C}_l}{\partial \boldsymbol{q}}\right)\boldsymbol{M}^{-1}(\boldsymbol{h}+\boldsymbol{g})\right\} \\ \triangleq \hat{a}(\boldsymbol{q}, \dot{\boldsymbol{q}}) \end{aligned} \tag{35}$$

When the constraint condition is estimated by linear approximation, $\hat{\boldsymbol{\tau}}$ can be obtained as follow.

$$\begin{aligned}\hat{\boldsymbol{\tau}} = -\hat{\boldsymbol{A}}^{+}(\boldsymbol{q})\{f_{nd} - \hat{a}(\boldsymbol{q}, \dot{\boldsymbol{q}}) - \hat{\boldsymbol{A}}(\boldsymbol{q})\boldsymbol{J}_R^T f_t\} \\ + \{\boldsymbol{I} - \hat{\boldsymbol{A}}^{+}(\boldsymbol{q})\hat{\boldsymbol{A}}(\boldsymbol{q})\}\boldsymbol{k} \end{aligned} \tag{36}$$

4 SHAPE RECOGNITION

We have researched to estimate constraint conditions during grinding operation and perform surface grinding on unknown shape object that can not be given constraint conditions[13]. By tracing the surface of the object with a grinding robot and acquiring the surface shape from the hand trajectory, the shape of the object can be recognized. By using the grasped shape, it is possible to perform cooperative operation of a grinding robot and an articulated robot for grinding an arbitrary area, and to process a target shape given by cutting out an object.

5 RECOGNITION EXPERIMENT

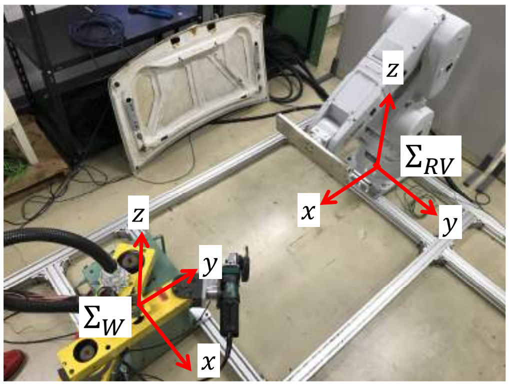

Fig. 4. Experimental device

Fig. 5. Objects used for experiments

The experimental equipment is shown in Fig.6. The reference coordinate system Σ_W and the coordinate system of the articulated robot Σ_{RV} are on the same plane. A car bonnet is used as a target for recognition experiments. The target appearance is shown in Fig.5. Appropriate grinding start

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position for the object is given as the initial condition, and thereafter the constraint condition is estimated by linear approximation from the trajectory of the hand position. The object is moved by an articulated robot and the entire surface is traced by grinding robot.

6 ESTIMATION OF SURFACE SHAPE

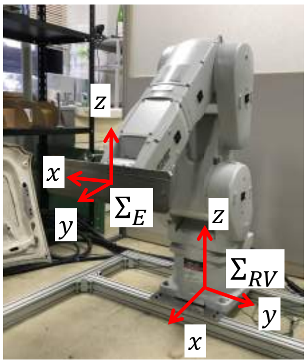

Fig. 6. Coordinate systems of RV-20F

To represent the surface shape from the obtained hand data, the coordinate system is converted to Σ_E, which is hand coordinate system of the articulated robot in Fig.6. Fig.7 shows the result of coordinate transformation of the hand trajectory data to Σ_E, the hand coordinate system of the articulated robot. When plotting the result of tracing the surface in three dimensions, the outline of the object appears.

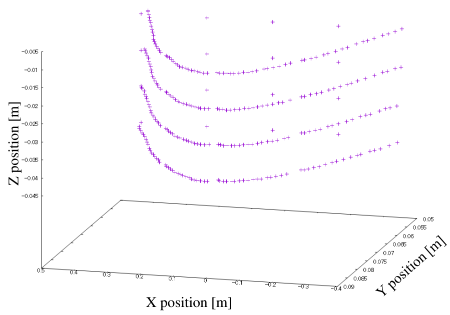

Fig. 7. Position of the hand from Σ_E tracing the surface of the target

6.1 Shape estimation by Cubic Bezier surface

Surface shape is estimated using cubic Bezier surface. A cubic Bezier surface is obtained from 16 points group $\boldsymbol{P}_{ij}(i, j = 0, 1, 2, 3)$ and is expressed as follows.

$$\boldsymbol{S}(u, v) = \sum_{i=0}^{3} \sum_{j=0}^{3} B_i^3(u) B_j^3(v) \boldsymbol{P}_{ij} \tag{37}$$

$B^3_{i,j}(t)$ is called Bernstein polynomial (Bernstein polynomials) and It can be represented by the following equation using binomial coefficient.

$$\begin{aligned} B_i^3(t) &= {}_3C_i t^i (1-t)^{3-i} \\ &= \frac{3!}{i!(3-i)!} t^i (1-t)^{3-i} \end{aligned} \tag{38}$$

$$\begin{aligned} B_j^3(t) &= {}_3C_j t^j (1-t)^{3-j} \\ &= \frac{3!}{j!(3-j)!} t^j (1-t)^{3-j} \end{aligned} \tag{39}$$

A Bezier surface is generated from the acquired bonnet data. In Fig.8,the following processing is performed to estimate the shape.

Process 1 Remove outliers from sampling data.

Process 2 Select points to be used for generating cubic Bezier surfaces. In this experiment, average value was taken.

Process 3 A Bezier surface is generated from the points. By appropriately combining from the 64 points, four Bezier surfaces are generated.

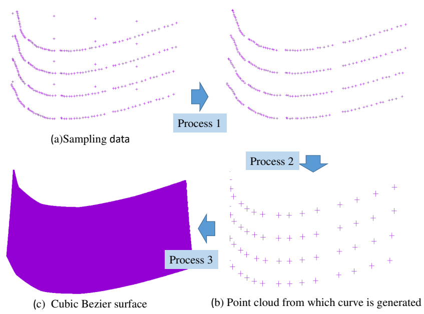

Fig. 8. Process of Generation Cubic Bezier surface

7 GRINDING EXPERIMENT

We conduct grinding experiments targeting bonnet of the car using the recognition results. An area to be ground by the grinding robot is select from the result of shape recognition. Then, the result of shape recognition is also used for force and position control and surface grinding is performed with a constant desired force. As shown in Figs.9,10, the desired area can be ground with highly accuracy. As for the result of the constant binding force control, when the desired force is set to $F_{nd} = 8$ [N], the average of the force for the whole experiment time is 8.13 [N], and the transition is as shown in Fig.11.

8 CONCLUSION

By tracing surface of a object with a grinding robot, the surface shape was acquired from the hand trajectory. For the unknown shape object, the constraint condition was not given

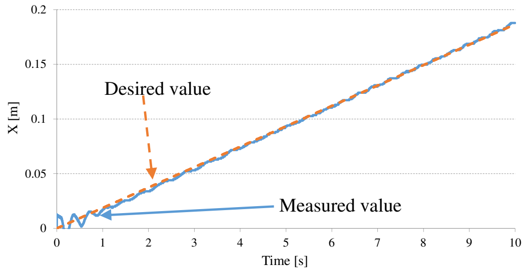

Fig. 9. Experiment result of bonnet grinding operation in x direction

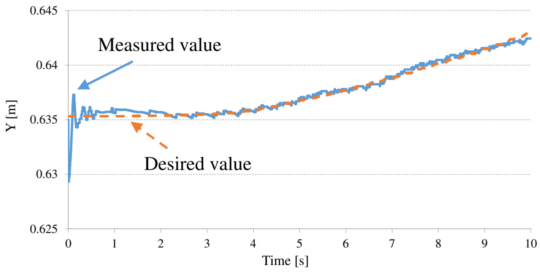

Fig. 10. Experiment result of bonnet grinding operation in y direction

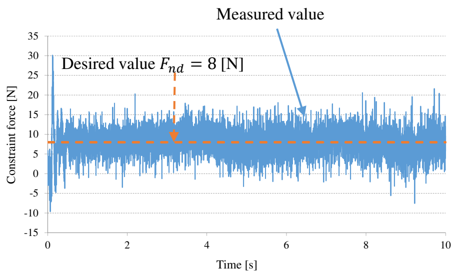

Fig. 11. Experiment result of constraint force F_n

as the initial condition, but our grinding robot can trace the surface with estimated constraint condition by straight line approximation. From the hand trajectory data obtained from the experiment, the shape of a object can be estimated by Bezier surface. We have confirmed that the desired grinding area, which is selected from the estimated shape, can be ground by experiments.

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