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Hand- Trajectory Tracking Control with Bracing Utilization of Mobile Redundant Manipulator

*Yuto Washino[1], Mamoru Minami[1], Hidemi Kataoka[1], Takayuki Matsuno[1], Akira Yanou[1], Michiyuki Itoshima[1], Yosuke Kobayashi[1]

Graduate School of Natural Science and Technology, Okayama University
(Tel,Fax: +81-86-251-8924;Email: yanou@qumi.sys.okayama-u.ac.jp)

Abstract: This paper shows effectiveness of bracing for precise and low electrical energy consumption of the end-effector in the case with and without the constraint of the joint of mobile manipulator. Considering that human can do accurate task with less power by bracing elbow on the table, we believe that manipulators can save energy and do a task more precisely like human by bracing itself. Therefore this paper first discuss the motion equation of robot with constraint condition, and robots dynamics including motor's dynamics also. Then the effects of bracing are analyzed and displayed.

Keywords: Constraint condition, Electrical consumption, Accuracy

1. INTRODUCTION

Recently, multi-joint manipulator is mainly used on production sites, such as factories. Its redundancy increases according to the freedom degree of manipulator. It becomes possible to do complicated work and improve the obstacle avoidance ability. However, as the weight of manipulator increases along with the number of links rising, the control energy is increased in order to prevent a hand's accuracy from decreasing.

Here, human-being's behavior that utilizes bracing motion for writing characters on a paper, can be put into manipulator's control strategy. We consider that consumption energy can be cut down by the bracing motion. And we also expect that the hand's accuracy can be improved by contacting with surrounding environment and the total of consumption energy will be able to decrease. In this report, the validity of bracing an elbow is shown by simulations, by using mobile manipulator whose elbow is attached on the ground. In addition, we introduce the controller to simultaneously control the position and force, its effectiveness shown in the simulation.

2. MODELING WITH CONSTRAINT CONDITION

2.1 Eqation of Motion with Constraint Condition

The manipulator's model with constraint is shown in Fig.1.

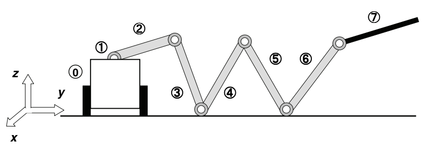

Fig. 1 Seven-link manipulator

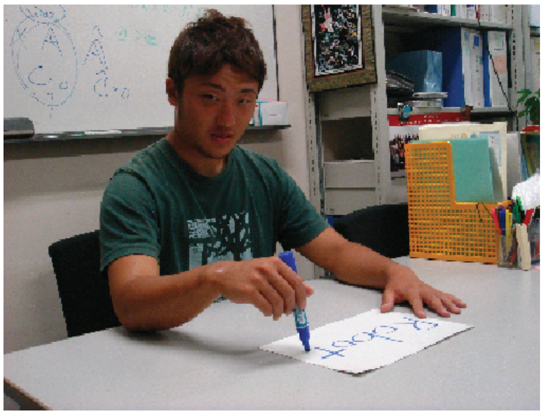

Fig. 2 Writing motion

To make the explanation of constraint motion with multi-elbow be easily understood, we discuss firstly about the model of the manipulator whose end-effector is contacing rigid environment without elasticity. Equation of motion of manipulator composing rigid structure of l links, and also contact relation between manipulator's end-effector and definition of constraint surface should be introduced firstly.

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{D}\dot{\boldsymbol{q}} = \boldsymbol{\tau} + \{(\frac{\partial C}{\partial \boldsymbol{q}^T})^T / \| \frac{\partial C}{\partial \boldsymbol{r}^T} \| \} f_n - (\frac{\partial \boldsymbol{r}}{\partial \boldsymbol{q}^T})^T \frac{\dot{\boldsymbol{r}}}{\|\dot{\boldsymbol{r}}\|} f_t \quad (1)$$

$\boldsymbol{M}$ is inertia matrix, $\boldsymbol{h}$ and $\boldsymbol{g}$ are $l \times 1$ vectors which indicate the effects from Coriolis force, centrifugal force and gravity. $\boldsymbol{D}$ is $l \times l$ diagonal matrix of coefficients of joint's viscous friction. $\boldsymbol{q}$ is joint angle and $\boldsymbol{\tau}$ is input torque. f_n is constraint force and f_t is friction force. Here, we set two assumptions: (i) f_n and f_t are orthogonal. (ii) $f_t = K \cdot f_n$ (K is proportional constant).

And, C included in Eq.(1) is an expression of constraint surface, and the relation expressed in Eq.(2) is constraint condition.

$$C(\boldsymbol{r}(\boldsymbol{q}(t))) = 0 \quad (2)$$

Eq.(2) is the equation realized constraint, and $\boldsymbol{r}(\boldsymbol{q}(t))$ means the coordinates of bracing point.

Moreover, Eq.(2) is differentiated by time t two times, and then we can derive the constraint condition of $\ddot{\boldsymbol{q}}$. In real control, it needs constraint on acceleration of level.

$$\dot{\boldsymbol{q}}^T\left[\frac{\partial}{\partial \boldsymbol{q}^T}(\frac{\partial C}{\partial \boldsymbol{q}^T})\right]\dot{\boldsymbol{q}} + (\frac{\partial C}{\partial \boldsymbol{q}^T})\ddot{\boldsymbol{q}} = 0 \qquad (3)$$

If the coefficients of f_n and f_t are defined as j_c^T and j_t^T ,

$$(\frac{\partial C_i}{\partial \boldsymbol{q}^T})^T / \|\frac{\partial C_i}{\partial \boldsymbol{r_i}^T}\| = \boldsymbol{j_c}_i^T \qquad (4)$$

$$(\frac{\partial \boldsymbol{r}_i}{\partial \boldsymbol{q}^T})^T \frac{\dot{\boldsymbol{r}}_i}{\|\dot{\boldsymbol{r}}_i\|} = \boldsymbol{j_t}_i^T \qquad (5)$$

Accumulating all the above vectors ($i = 1, 2, \cdots, p$) where p is the number of contact point, so the next relations are redefined.

$$\begin{aligned} \boldsymbol{C}(\boldsymbol{r}(\boldsymbol{q})) &= [C_1(\boldsymbol{r}_1), C_2(\boldsymbol{r}_2), \cdots, C_p(\boldsymbol{r}_p)]^T && (6)\\ \boldsymbol{J}_c^T &= [\boldsymbol{j_c}_1^T, \boldsymbol{j_c}_2^T, \cdots, \boldsymbol{j_c}_p^T] && (7)\\ \boldsymbol{J}_t^T &= [\boldsymbol{j_t}_1^T, \boldsymbol{j_t}_2^T, \cdots, \boldsymbol{j_t}_p^T] && (8)\\ \boldsymbol{f}_n &= [f_{n1}, f_{n2}, \cdots, f_{np}]^T && (9)\\ \boldsymbol{f}_t &= [f_{t1}, f_{t2}, \cdots, f_{tp}]^T && (10) \end{aligned}$$

$\boldsymbol{J}_c^T, \boldsymbol{J}_t^T$ are $n \times p$ matrices, $\boldsymbol{f}_n, \boldsymbol{f}_t$ are $p \times 1$ vectors. Considering about constraint of the intermediate links, the manipulator's equation of motion can be expressed as

$$\begin{aligned} &\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{D}\dot{\boldsymbol{q}} \\ &= \boldsymbol{\tau} + \sum_{i=1}^{p}(\boldsymbol{j_c}_i^T f_{ni}) - \sum_{i=1}^{p}(\boldsymbol{j_t}_i^T f_{ti}) \\ &= \boldsymbol{\tau} + \boldsymbol{J_c}^T \boldsymbol{f_n} - \boldsymbol{J_t}^T \boldsymbol{f_t} \qquad (11) \end{aligned}$$

where fn is a reaction force exerting from constraint surface to the robot's elbow, and ft is a friction force acting on the same point. To make sure that manipulator's elbow is contacting with the constraint surface all the time, value of q(t) in Eq (11) has always to satisfy Eq (2) whenever the time t has any value. For assuring that the solution q(t) of Eq (11) showed satisfy the constraint Eq (2) despite any time t, the value of $\ddot{q}$ in Eq (3) should have the same value with $\ddot{q}$ in Eq (11), then value of q(t) in Eq (11) and Eq (2) necessarily always keep the same regardless of time.

2.2 Robot Dynamics including Motor

For $i = 1, \cdots, 8$ is a number of joint consisting mobile manipulator, the moor's dynamics can be written as follows:

$$\begin{aligned} v_i(t) &= L_i\dot{i}_i + R_i i_i(t) + v_{gi}(t) && (12)\\ v_{gi}(t) &= K_{Ei}\dot{\theta}_i(t) && (13)\\ I_{mi}\ddot{\theta} &= \tau_{gi}(t) - \tau_{Li}(t) - d_{mi}\dot{\theta}_i && (14)\\ \tau_{gi}(t) &= K_{Ti} i_i(t) && (15)\\ & (i = 1, \cdots, 8) \end{aligned}$$

v_i is terminal voltage of motor, R_i is electrical resistance, L_i is inductance, i_i is electric current flowing through a circuit, θ_i is angular displacement of motor, τ_{gi} is generation of torque, τ_{Li} is load torque used for manipulator's motion, v_i is counter electromotive force, I_{mi} is moment of inertia of motor, K_{Ei} is constant of counter electromotive force, K_{Ti} is torque constant, d_{mi} is coefficient of viscous friction of decelerator. From the relation of magnetic field and the coefficients above, $K_{Ti} = K_{Ei}(= K_i)$ holds for motors used. Combine Eq (13) and Eq (12), and also Eq (15) and Eq (14), we derive

$$\begin{aligned} v_i &= L_i\dot{i}_i + R_i i_i + K_i\dot{\theta}_i && (16)\\ I_{mi}\ddot{\theta}_i &= K_i i_i - \tau_{Li} - d_{mi}\dot{\theta}_i && (17) \end{aligned}$$

Moreover, we consider to install gear train of motor of reduction ratio's k_i to manipulator.

$$\begin{aligned} \theta_i &= k_i q_i && (18)\\ \tau_{Li} &= \frac{\tau_i}{k_i} && (19) \end{aligned}$$

Combining Eq (16) and Eq (17) into equation with $\dot{i}_i$ and τ_i, following equations are obtained

$$\begin{aligned} L_i\dot{i}_i &= v_i - R_i i_i - K_i k_i \dot{q}_i && (20)\\ \tau_i &= -I_{mi}k_i^2\ddot{q}_i + K_i k_i i_i - d_{mi}k_i^2\dot{q}_i && (21) \end{aligned}$$

Then the vector forms of current and torque are given.

$$\begin{aligned} \boldsymbol{L}\dot{\boldsymbol{i}} &= \boldsymbol{v} - \boldsymbol{R}\boldsymbol{i} - \boldsymbol{K_m}\dot{\boldsymbol{q}} && (22)\\ \boldsymbol{\tau} &= -\boldsymbol{J_m}\ddot{\boldsymbol{q}} + \boldsymbol{K_m}\boldsymbol{i} - \boldsymbol{D_m}\dot{\boldsymbol{q}} && (23) \end{aligned}$$

$$\begin{aligned} \boldsymbol{v} &= [v_1, v_2, \cdots, v_s]^T\\ \boldsymbol{i} &= [i_1, i_2, \cdots, i_s]^T \end{aligned}$$

and the definitions are shown as follow, which always have positive value.

$$\begin{aligned} \boldsymbol{L} &= diag[L_1, L_2, \cdots, L_s]\\ \boldsymbol{R} &= diag[R_1, R_2, \cdots, R_s]\\ \boldsymbol{K_m} &= diag[K_{m1}, K_{m2}, \cdots, K_{ms}]\\ \boldsymbol{J_m} &= diag[J_{m1}, J_{m2}, \cdots, J_{ms}]\\ \boldsymbol{D_m} &= diag[D_{m1}, D_{m2}, \cdots, D_{ms}] \end{aligned} \qquad (24)$$

where $K_{mi} = K_i k_i$, $J_{mi} = I_{mi}k_i^2$, $D_{mi} = d_{mi}k_i^2$. Now substitute Eq (23) into Eq (11), we get

$$\begin{aligned} &(\boldsymbol{M}(\boldsymbol{q}) + \boldsymbol{J_m})\ddot{\boldsymbol{q}} + \boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) + (\boldsymbol{D} + \boldsymbol{D_m})\dot{\boldsymbol{q}} \\ &= \boldsymbol{K_m}\boldsymbol{i} + \boldsymbol{J_c}^T\boldsymbol{f_n} - \boldsymbol{J_t}^T\boldsymbol{f_t} \qquad (25) \end{aligned}$$

Similar to the same relation between Eq (11) and Eq (3), the value of $\ddot{\boldsymbol{q}}$ in Eq (25) have to be identical to the value of $\ddot{\boldsymbol{q}}$ in Eq (3) representing constrain condition.

2.3 Robot/Motor Equation with Contact Constraint

To make sure that $\ddot{\boldsymbol{q}}$ in Eq (25) and (3) be identical, constraint force f_n is subordinately decided by simultaneous equation. With an assumption $f_t = Kf_n$ considering, Eq (26),(27) should be transformed as follow

$$\begin{aligned} &(\boldsymbol{M} + \boldsymbol{J_m})\ddot{\boldsymbol{q}} - \left(\boldsymbol{J}_c^T - \boldsymbol{J}_t^T\boldsymbol{K}_e\right)\boldsymbol{f}_n \\ &= \boldsymbol{K}_m\boldsymbol{i} - \boldsymbol{h} - \boldsymbol{g} - (\boldsymbol{D} + \boldsymbol{D}_m)\dot{\boldsymbol{q}} \qquad (26) \end{aligned}$$

$$(\frac{\partial C_i}{\partial \boldsymbol{q}^T})\ddot{\boldsymbol{q}} = -\left[\frac{\partial}{\partial \boldsymbol{q}^T}(\frac{\partial C_i}{\partial \boldsymbol{q}^T})\dot{\boldsymbol{q}}\right]\dot{\boldsymbol{q}}$$
$$= -\dot{\boldsymbol{q}}^T\left[\frac{\partial}{\partial \boldsymbol{q}}(\frac{\partial C_i}{\partial \boldsymbol{q}^T})\right]\dot{\boldsymbol{q}} \quad (27)$$

Then Eq (26),(27),(22) can be expressed as follow,

$$\begin{bmatrix} \boldsymbol{M}+\boldsymbol{J_m} & -(\boldsymbol{j_c}^T - \boldsymbol{j_t}^T K) & \boldsymbol{0} \\ \frac{\partial C}{\partial \boldsymbol{q}^T} & 0 & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{L} \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{q}} \\ f_n \\ \dot{\boldsymbol{i}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{K_m i} - \boldsymbol{h} - \boldsymbol{g} - (\boldsymbol{D}+\boldsymbol{D_m})\dot{\boldsymbol{q}} \\ -\dot{\boldsymbol{q}}^T\left[\frac{\partial}{\partial \boldsymbol{q}}(\frac{\partial C}{\partial \boldsymbol{q}^T})\right]\dot{\boldsymbol{q}} \\ \boldsymbol{v} - \boldsymbol{R i} - \boldsymbol{K_m}\dot{\boldsymbol{q}} \end{bmatrix} \quad (28)$$

Furthermore by redefining as

$$\boldsymbol{M}^* = \begin{bmatrix} \boldsymbol{M}+\boldsymbol{J_m} & -(\boldsymbol{j_c}^T - \boldsymbol{j_t}^T K) & \boldsymbol{0} \\ \frac{\partial C}{\partial \boldsymbol{q}^T} & 0 & 0 \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{L} \end{bmatrix} \quad (29)$$

$$\boldsymbol{b} = \begin{bmatrix} \boldsymbol{K_m i} - \boldsymbol{h} - \boldsymbol{g} - (\boldsymbol{D}+\boldsymbol{D_m})\dot{\boldsymbol{q}} \\ -\dot{\boldsymbol{q}}^T\left[\frac{\partial}{\partial \boldsymbol{q}}(\frac{\partial C}{\partial \boldsymbol{q}^T})\right]\dot{\boldsymbol{q}} \\ \boldsymbol{v} - \boldsymbol{R i} - \boldsymbol{K_m}\dot{\boldsymbol{q}} \end{bmatrix} \quad (30)$$

Then Eq (28) can be expressed as

$$\boldsymbol{M}^* \begin{bmatrix} \ddot{\boldsymbol{q}} \\ f_n \\ \dot{\boldsymbol{i}} \end{bmatrix} = \boldsymbol{b} \quad (31)$$

$\boldsymbol{M}^*$ has been confirmed to be nonsingular matrix so for through many numerical simulations, it has to be power by mathematical procedures. Through calculating $\boldsymbol{M}^*$, the unknown value of $\ddot{\boldsymbol{q}}$, $\boldsymbol{f_n}$,$\dot{\boldsymbol{i}}$ can be determined based on the above simultaneous equation.

2.4 Algebraic Relation in Bracing Dynamics

The manipulator's eqution of motion has been derived, shown as (1). We combine (3) to (11) and eliminate the $\ddot{\boldsymbol{q}}$, we can get the following eqution.

$$(\frac{\partial \boldsymbol{C}}{\partial \boldsymbol{q}^T})[\boldsymbol{M}^{-1}(\boldsymbol{\tau} + \boldsymbol{J}_c^T\boldsymbol{f}_n - \boldsymbol{J}_t^T\boldsymbol{f}_t - \boldsymbol{h} - \boldsymbol{g} - \boldsymbol{D}\dot{q}] + \dot{\boldsymbol{q}}^{\boldsymbol{T}}\left[\frac{\partial}{\partial \boldsymbol{q}}(\frac{\partial \boldsymbol{C}}{\partial \boldsymbol{q}^T})\right]\dot{\boldsymbol{q}} = \boldsymbol{0} \quad (32)$$

Here we can believe that $f_t i$ are proportional to$f_n i$, then the relation between $\boldsymbol{f}_t$ and $\boldsymbol{f}_n$ can be expressed as :

$$\boldsymbol{f}_t = \boldsymbol{K}\boldsymbol{f}_n \quad (33)$$
$$\boldsymbol{K} = diag[k_1, k_2, \cdots, k_p,] \quad (34)$$

then we can obtained,

$$(\frac{\partial \boldsymbol{C}}{\partial \boldsymbol{q}})\boldsymbol{M}^{-1}(\boldsymbol{J}_c^T - \boldsymbol{J}_t^T\boldsymbol{K})\boldsymbol{f}_n = (\frac{\partial \boldsymbol{C}}{\partial \boldsymbol{q}})\boldsymbol{M}^{-1}(\boldsymbol{h}+\boldsymbol{g}-\boldsymbol{D}\dot{\boldsymbol{q}}) - \dot{\boldsymbol{q}}^{\boldsymbol{T}}\left[\frac{\partial}{\partial \boldsymbol{q}}(\frac{\partial \boldsymbol{C}}{\partial \boldsymbol{q}^T})\right]\dot{\boldsymbol{q}} - (\frac{\partial \boldsymbol{C}}{\partial \boldsymbol{q}})\boldsymbol{M}^{-1}\boldsymbol{\tau} \quad (35)$$

If we let

$$(\frac{\partial \boldsymbol{C}}{\partial \boldsymbol{q}})\boldsymbol{M}^{-1}(\boldsymbol{J}_c^T - \boldsymbol{J}_t^T\boldsymbol{K}) = \boldsymbol{A}(\boldsymbol{q}),$$
$$(\frac{\partial \boldsymbol{C}}{\partial \boldsymbol{q}})\boldsymbol{M}^{-1}(\boldsymbol{h}+\boldsymbol{g}-\boldsymbol{D}\dot{\boldsymbol{q}}) - \dot{\boldsymbol{q}}^{\boldsymbol{T}}\left[\frac{\partial}{\partial \boldsymbol{q}}(\frac{\partial C}{\partial \boldsymbol{q}^T})\right]\dot{\boldsymbol{q}} = \boldsymbol{a}(\boldsymbol{q}, \dot{\boldsymbol{q}}),$$
$$(\frac{\partial \boldsymbol{C}}{\partial \boldsymbol{q}})\boldsymbol{M}^{-1} = \boldsymbol{B}(\boldsymbol{q}), \quad (36)$$

we get the algebraic relation between $\boldsymbol{f}_n$ and $\boldsymbol{\tau}$ representing force instantaneous transmission as

$$\boldsymbol{A}(\boldsymbol{q})\boldsymbol{f}_n = \boldsymbol{a}(\boldsymbol{q}, \dot{\boldsymbol{q}}) - \boldsymbol{B}(\boldsymbol{q})\boldsymbol{\tau}. \quad (37)$$

2.5 Decoupled Force and Position Controller

Decoupled Controller of Constraint Forces and Positions given a desired force vector exerting between plural bracing links and environment as $\boldsymbol{f}_{nd}$, whose dimension is equal to the one of $\boldsymbol{C}(\boldsymbol{r}(\boldsymbol{q}))$, a control law can be derived directly from (37) as

$$\boldsymbol{\tau} = \boldsymbol{B}^+(\boldsymbol{a} - \boldsymbol{A}\boldsymbol{f}_{nd}) + (\boldsymbol{I} - \boldsymbol{B}^+\boldsymbol{B})\boldsymbol{l}. \quad (38)$$

Since $\partial\boldsymbol{C}/\partial\boldsymbol{q}$ is row full rank matrix and $\boldsymbol{M}$ is always non-singular, then $p \times n$ matrix $\boldsymbol{B}$ is rank($\boldsymbol{B}$)=p, i.e., $\boldsymbol{B}$ is row full matrix. Then $\boldsymbol{\tau}(n \times 1)$ has $n - p$ redundancy after controlling $\boldsymbol{f}_{nd}$, that is rank($\boldsymbol{I} - \boldsymbol{B}^+\boldsymbol{B}$)=$n - p$. Therefore the remaining control input in $\boldsymbol{\tau}$ can be used through arbitrary vector $\boldsymbol{l}$ to track hand desired trajectory $\boldsymbol{r}_d$ and some other tasks up to remaining dimension of $n - p$.

(37) has been derived on the assumption that bracing constraint conditions number is p. $\boldsymbol{l}$ can be used for position control of bracing point p and position control as

$$\boldsymbol{l} = \sum_{i=1}^{p}\boldsymbol{J}_i^T[K_{pi}(\boldsymbol{r}_{di} - \boldsymbol{r}_i) + K_{ui}(\dot{\boldsymbol{r}}_{di} - \dot{\boldsymbol{r}}_i)] + \boldsymbol{J}_n^T[K_{pn}(\boldsymbol{r}_{dn} - \boldsymbol{r}_n) + K_{rn}(\dot{\boldsymbol{r}}_{dn} - \dot{\boldsymbol{r}}_n)], \quad (39)$$

The last term is for controlling the hand's position, and the first p term are used for position control of bracing points. Notice that null rank ($\boldsymbol{I}$–$\boldsymbol{B}^+\boldsymbol{B}$)=$n - p$, the dimension of task includled in (39) cannot go beyond $n-p$, otherwise a conflict between the tasks in (39).

Considering the closed loop of the $\boldsymbol{\tau}$ in (38) being input to Eq (37) and assuming $p \times n$ matrix $\boldsymbol{B}(\boldsymbol{q})$ is row full rank, we get

$$\boldsymbol{A}(\boldsymbol{q})\boldsymbol{f}_n = \boldsymbol{a}(\boldsymbol{q}, \dot{\boldsymbol{q}}) - \boldsymbol{B}(\boldsymbol{q})\{\boldsymbol{B}^+(\boldsymbol{a} - \boldsymbol{A}\boldsymbol{f}_{nd}) + (\boldsymbol{I} - \boldsymbol{B}^+\boldsymbol{B})\boldsymbol{l}\}$$
$$= \boldsymbol{A}\boldsymbol{f}_{nd}. \quad (40)$$

When it can be assumed that $p \times p$ matrix $\boldsymbol{A}$ is invertible, we get $\boldsymbol{f}_n = \boldsymbol{f}_{nd}$.

The (33) can be used for the robot that have direct-drive motor able to generate torques directly, but normal motors' inputs are voltages. In this case the above controller (33) can be replaced by the following controller as

$$\boldsymbol{v} = \boldsymbol{K}_V\boldsymbol{B}^+(\boldsymbol{a} - \boldsymbol{A}\boldsymbol{f}_{nd}) + (\boldsymbol{I} - \boldsymbol{B}^+\boldsymbol{B})\boldsymbol{l}, \quad (41)$$

where $\boldsymbol{v}$ is input voltage to motors and $\boldsymbol{K}_V$ is coefficient matrix with positive definite.

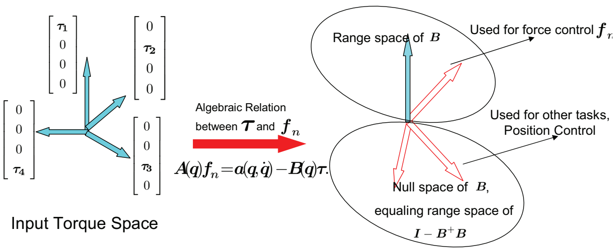

Fig. 3 Algebraic Relation

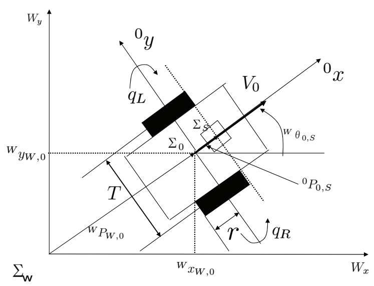

Fig. 4 mobile robot

3. THE BASEMENT MODEL OF REDUNDANT MOBILE MANIPULATOR

The movement of i-th link of manipulator should be given force and torque, so they can be obtained by

$$^W\boldsymbol{f}_i = ^W\boldsymbol{f}_{i+1} + m_i\,^W\ddot{\boldsymbol{P}}_{Gi} \tag{42}$$

$$^W\boldsymbol{n}_i = ^W\boldsymbol{n}_{i+1} + ^W\boldsymbol{I}_i\,^W\dot{\boldsymbol{w}}_i + ^W\dot{\boldsymbol{w}}_i \times (^W\boldsymbol{I}_i\,^W\dot{\boldsymbol{w}}_i) + ^W\boldsymbol{S}_i \times m_i\,^W\ddot{\boldsymbol{P}}_{Gi} + ^W\boldsymbol{P}_{i,i+1} \times ^W\boldsymbol{f}_{i+1} \tag{43}$$

$$\boldsymbol{\tau}_i = (^W\boldsymbol{n}_i{}^T)^W z_i + \boldsymbol{I}_{ai}\ddot{\boldsymbol{q}}_i + \boldsymbol{C}_i\dot{\boldsymbol{q}}_i \tag{44}$$

So the equation of motion of mobile robot can be derived by calculating exerting force and torque on the origin of Σ_0 from the mobile robot as,

$$^W\boldsymbol{f}_0 = ^W\boldsymbol{f}_1 + m_0\,^W\ddot{\boldsymbol{P}}_{G0} \tag{45}$$

$$^W\boldsymbol{n}_0 = ^W\boldsymbol{n}_1 + ^W\boldsymbol{I}_0\,^W\dot{\boldsymbol{\omega}}_0 + ^W\boldsymbol{\omega}_0 \times (^W\boldsymbol{I}_0\,^W\boldsymbol{\omega}_0) + ^W\boldsymbol{S}_0 \times m_0\,^W\ddot{\boldsymbol{P}}_{G0} + ^W\boldsymbol{P}_{0,1} \times ^W\boldsymbol{f}_1 \tag{46}$$

$\ddot{\boldsymbol{P}}$ is translational acceleration, $^{\boldsymbol{w}}\boldsymbol{S_i}$ is position vector, $^{\boldsymbol{w}}\boldsymbol{I_i}$ is inertia tensor, $\boldsymbol{\omega}$ is angular velocity, $\boldsymbol{C}$ is viscous resistance.

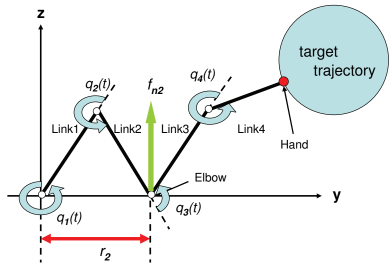

Fig. 5 Four-link manipulator

Table 1 Parameters of simulation

	1-st link	2-nd link	3-rd link	4-th link
$m_i[kg]$	1.0	1.0	0.5	1.0
$l_i[m]$	0.5	0.5	0.5	0.5
$r_i[m]$	0.03	0.03	0.01	0.03
D_i	2.0	2.0	2.0	2.0
$K_i[V \cdot s/rad]$	0.2	0.2	0.2	0.2
$R_i[\Omega]$	0.6	0.6	0.6	0.6
$L_i[H]$	0.17	0.17	0.17	0.17
I_{mi}	0.000164	0.000164	0.000164	0.000164
k_i	3.0	3.0	3.0	3.0
d_{mi}	0.1	0.1	0.1	0.1

4. SIMULATION

In this section we will conduct simulations to evaluate whether the model and the controller proposed in this paper is plausible or not. We give the target positions y_{4d} and y_{2d} for the hand's position of y_4 and elbow's position of y_2, and also elbow's contracting desired force is given as f_{2d}, shown in Fig5.

Simulation time is $10[s]$ and sampling time is $1[ms]$. Target trajectory is shown as follows.

$$x_d(t) = 0.0 \tag{47}$$

$$y_d(t) = 1.1 + 0.2\cos(-\frac{2\pi}{10}t) \tag{48}$$

$$z_d(t) = 0.6 + 0.2\sin(-\frac{2\pi}{10}t) \tag{49}$$

The initial angle of each joint is $(q_1, q_2, q_3, q_4) = (-0.2\pi, -0.6\pi, 0.8\pi, -0.4\pi)$[rad].

Each parameter of this simulation is as the value shown in the following table1.

From Figs.6-16, we can see on condition that $(k_p = 300, k_d = 50, k_{pe} = 100, k_{de} = 20)$, reaction force f_{n2}, the bracing joint and end-effector y_2, y_4 can well follow their target f_{nd2}, y_{2d}, y_{4d}.

Figs.9-16 shows the track trajectory of the end-effector and the position and reaction force of elbow when the simulation was carried out respectively in the torque input condition and voltage input condition. When the coefficient of proportional gain and velocity gain is degreasing, in the torque input condition, the reaction force of elbow can be controlled completely, while the position of the elbow and end-effector will not be able to be controlled. In the voltage input condition, the position of the elbow and end-effector also will not be able to be controlled and the reaction force of elbow can be controlled except for little a error occur at the beginning. In other words, it can be said that this controller can be decoupling of the position and force control.

5. CONCLUSION

In this paper, we proposed a new control method called Position/Force control method. By the experiment, we confirm that Position/Force Control is non-interference with each other. In the future, we will use this control method in hyper-redundancy manipulator, and we think it can control the hyper-redundancy manipulator better. We are going to present the mobile redundant manipulator as Fig.1 at the time of presentation.

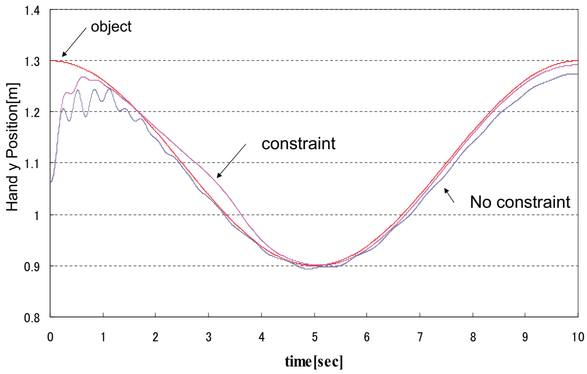

Fig. 6 Hand y Position (Voltage Input)

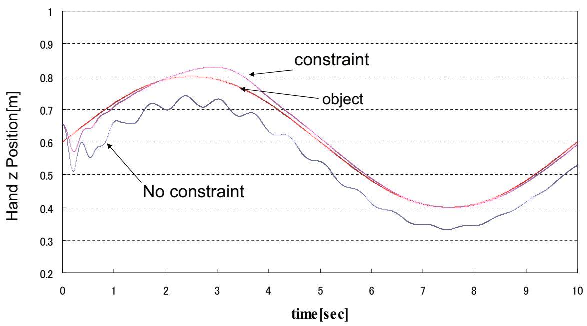

Fig. 7 Hand z Position (Voltage Input)

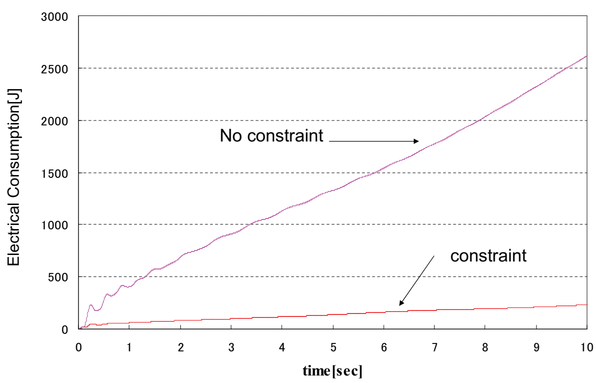

Fig. 8 Electric consumption(Voltage Input)

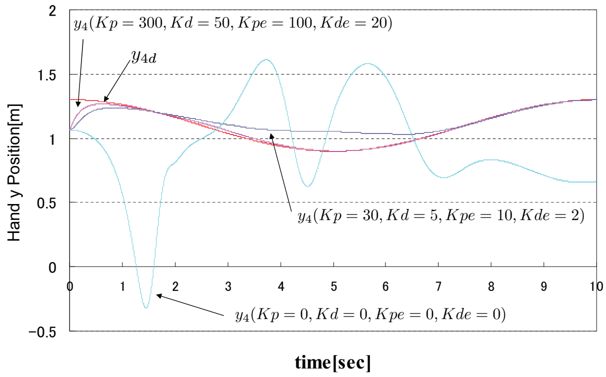

Fig. 9 Hand y Position (Torque Input)

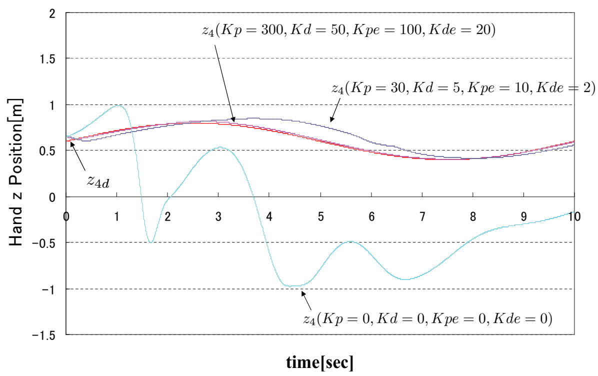

Fig. 10 Hand z Position (Torque Input)

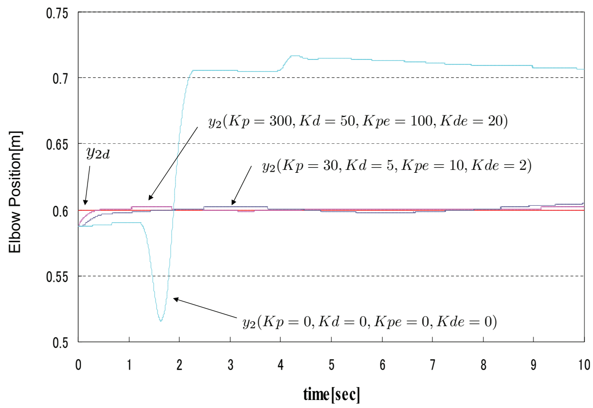

Fig. 11 Elbow Position (Torque Input)

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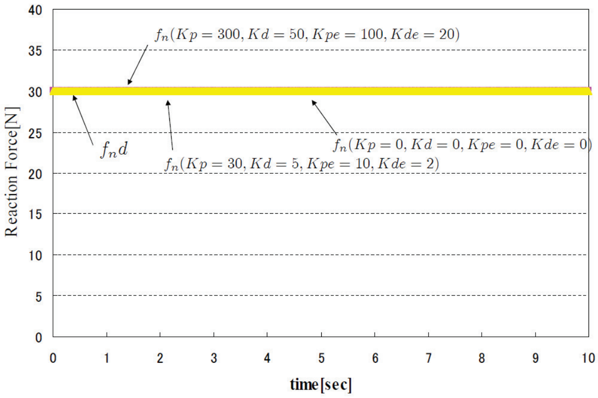

Fig. 12 Reaction Force (Torque Input)

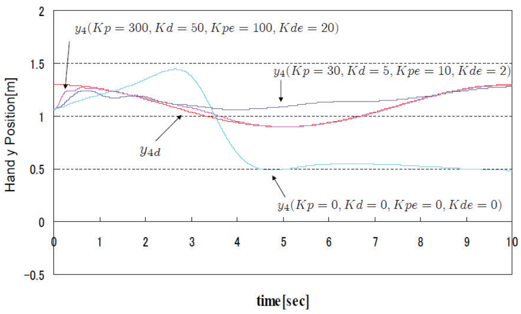

Fig. 13 Hand y Position (Voltage Input)

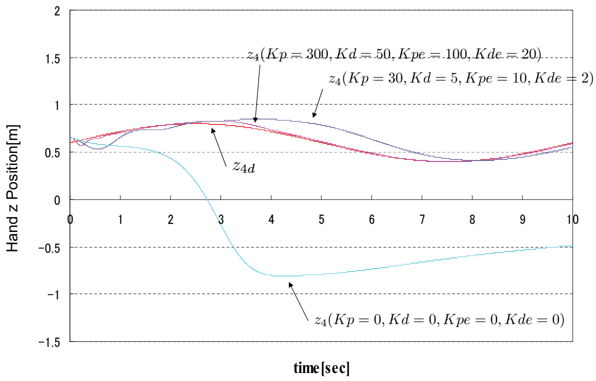

Fig. 14 Hand z Position (Voltage Input)

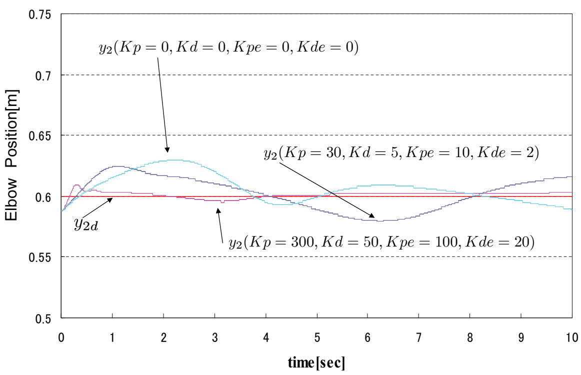

Fig. 15 Elbow Position (Voltage Input)

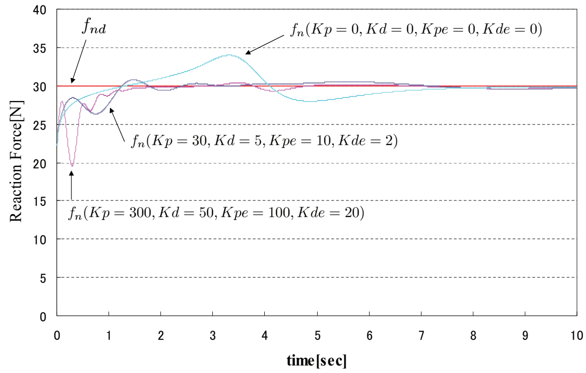

Fig. 16 Reaction Force (Voltage Input)

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