Hybrid Position/Force Control of a Mobile Manipulator based on Cooperative Task Sharing

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Abstract— **This paper proposes a hybrid position/force control of a mobile manipulator to cooperate with its subsystems that consist of a wheeled mobile robot and a manipulator arm. These subsystems have different dynamic characteristics. Moreover, a wheeled mobile robot is subject to nonholonomic constraints. In general, these issues are taken into consideration in developing a planning and control algorithm. This paper describes a unified approach to control a mobile manipulator which can be regarded as a redundant manipulator. In the proposed approach, realizing an optimal configuration control according to the motion of end-effector, the redundancy of the proposed system is utilized under consideration of the dynamical behavior of the mobile manipulator. Several experimental results show the effectiveness of the proposed method.**

I. Introduction

A mobile manipulator in this study is a manipulator arm mounted on a wheeled mobile robot. This system has infinite work area by movement of its mobile robot and can be performed dexterously by operating its arm. In the recent industrial field, it is expected as a sophisticated and high performance robot, and several researches and developments have been done.

In general approach, there are mainly two types of control strategies for the mobile manipulator. One is a decentralized control of the mobile robot and the manipulator arm. In this case, it is possible to construct each controller easily, but there are some problem about its interaction and so on. The other is a unified control of both of them.

This paper discusses the latter approach. In this case, the mobile manipulator is regarded as a redundant manipulator and this feature makes it possible to keep the optimal configuration for the mobile manipulation system. However, the mobile manipulator has significant dynamic characteristics between the mobile robot and the arm, and the wheeled mobile robot is subject to nonholonomic constraints. In such a condition, it is impossible to increase the manipulability of the whole system by using the traditional approach for the fixed-base manipulator. The considered issue for a realization of the high manipulability is an efficient use of the redundancy.

In this paper, we present a hybrid control for work-space which is subject to a trajectory planned by a time function. The force in the work-space is decomposed into a tangential direction and a vertical one of the trajectory. The position is controlled for the tangential direction and the force is controlled for the vertical one. Then we propose a controller to raise characteristics of response in work-space by control of the configuration and distribution of the joint torque.

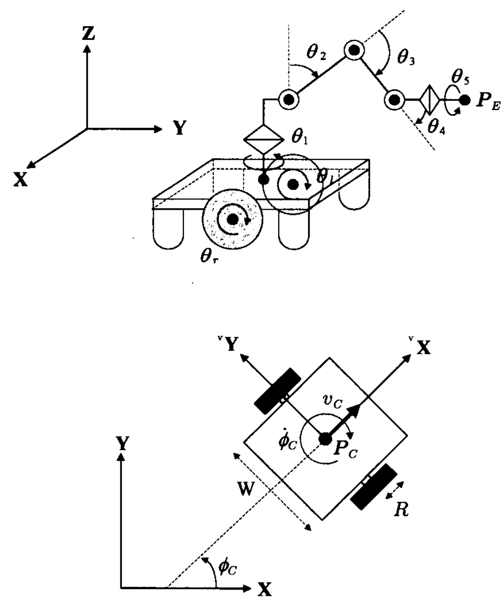

Fig. 1. Model of a mobile manipulator

II. A Modeling of Mobile Manipulator

In this paper, the mobile manipulator is composed of a mobile robot with a pair of independent driving wheels on a horizontal plane and a manipulator arm with 4 degree-of-freedom in a 3-dimensional space. Its model is shown in Fig.1.

The configuration of the mobile manipulator can define as the following vectors.

$$\boldsymbol{\theta}_w = [\theta_r \ \theta_l]^T, \ \boldsymbol{x} = [x_C \ y_C \ \phi_C]^T, \ \boldsymbol{\theta}_a = [\theta_1 \ \ldots \ \theta_5]^T$$

where

- θ_l, θ_r : rotational angles of the left wheel and the right one, respectively;
- $[x_C \ y_C]^T$: position vector of P_C with respects to the world frame;
- ϕ_C : heading angle of the mobile robot with respects to the world frame;
- θ_i : rotational angles of the i-th joint of the arm $(i = 1, \ldots, 5)$;

The position vector of P_E in world coordinate frame is $\boldsymbol{r} = [x \ y \ z]^T$, and the driving joint vector is $\boldsymbol{\theta} = [\boldsymbol{\theta}_w^T \ \boldsymbol{\theta}_a^T]^T$. Here we call $\boldsymbol{r}$, $\boldsymbol{\theta}$ 'work-space', 'joint-space'

vectors respectively.

A. Kinematics

The position of the end-effector P_E is expressed geometrically from $\boldsymbol{x}$ and $\boldsymbol{\theta}_a$. By differentiating it, the velocity relation between the end-effector's position and the mobile manipulator's configuration can be described as Jacobian equation (1).

$$\dot{\boldsymbol{r}} = \boldsymbol{J}_{rx}(\phi_C, \boldsymbol{\theta}_a)\dot{\boldsymbol{x}} + \boldsymbol{J}_{ra}(\phi_C, \boldsymbol{\theta}_a)\dot{\boldsymbol{\theta}}_a \tag{1}$$

Though the relation between the vehicle's state $\boldsymbol{x}$ and the wheel's angles $\boldsymbol{\theta}_w$ cannot be expressed geometrically because of nonholonomic constraints, the kinematics of the vehicle can be expressed in velocity form (2)-(6).

$$\boldsymbol{v}_C = \boldsymbol{J}_{vw}\dot{\boldsymbol{\theta}}_w \tag{2}$$

$$\boldsymbol{J}_{vw} = \begin{bmatrix} \frac{R}{2} & \frac{R}{2} \\ \frac{R}{W} & -\frac{R}{W} \end{bmatrix} \tag{3}$$

where $\boldsymbol{v}_C = [v_C \ \dot{\phi}_C]^T$. and then,

$$\dot{\boldsymbol{x}} = \boldsymbol{J}_{xv}(\phi_C)\boldsymbol{v}_C \tag{4}$$

$$\boldsymbol{J}_{xv}(\phi_C) = \begin{bmatrix} \cos\phi_C & 0 \\ \sin\phi_C & 0 \\ 0 & 1 \end{bmatrix} \tag{5}$$

hence,

$$\dot{\boldsymbol{x}} = \boldsymbol{J}_{xv}(\phi_C)\boldsymbol{J}_{vw}\dot{\boldsymbol{\theta}}_w \tag{6}$$

By summarizing the previous matrix, the velocity relation between "work-space" and "joint-space" vectors can be described as equation (7).

$$\dot{\boldsymbol{r}} = \boldsymbol{J}_r(\phi_C, \boldsymbol{\theta}_a)\dot{\boldsymbol{\theta}} \tag{7}$$

where $\boldsymbol{J}_r(\phi_C, \boldsymbol{\theta}_a) = [\boldsymbol{J}_{rx}\boldsymbol{J}_{xv}\boldsymbol{J}_{vw} \ \boldsymbol{J}_{ra}]$.

B. New Coordinate of Joint-Space

In this part, new coordinate is defined with respect to "joint-space vector" of velocity level. $\dot{\boldsymbol{\theta}}_w$, a component of previous joint-space vector $\dot{\boldsymbol{\theta}}$, is not intelligible values for vehicle motion. Then, New coordinate $\dot{\boldsymbol{\theta}}_v$ is defined as follows:

$$\dot{\boldsymbol{\theta}}_v = [\boldsymbol{v}_C^T \ \dot{\boldsymbol{\theta}}_a^T]^T \tag{8}$$

where $\boldsymbol{v}_C = [v_C \ \dot{\phi}_C]^T$ are straight and rotational velocities of vehicle and they are significant value. By using this vector and new Jacobian matrix J_{rv}, the velocity relation between "work-space" and "new joint-space" can be described as equation (9), and the acceleration relation as equation (10).

$$\dot{\boldsymbol{r}} = \boldsymbol{J}_{rv}\dot{\boldsymbol{\theta}}_v \tag{9}$$

$$\ddot{\boldsymbol{r}} = \boldsymbol{J}_{rv}\ddot{\boldsymbol{\theta}}_v + \dot{\boldsymbol{J}}_{rv}\dot{\boldsymbol{\theta}}_v \tag{10}$$

where $\boldsymbol{J}_{rv} = [\boldsymbol{J}_{rx}\boldsymbol{J}_{xv} \ \boldsymbol{J}_{ra}]$.

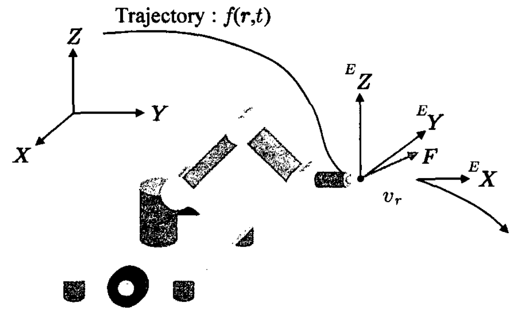

Fig. 2. A task and the end-effector coordinate frame

III. A Task for a Mobile Manipulator

In this section, we simply show the task for a mobile manipulator in this study.

First, an aim of task is that the end-effector exactly follows a continuous trajectory planned by time function. Here the end-effector coordinate frame ${}^EX -{}^E Y -{}^E Z$ is given as shown in Fig.2. A tangential direction of the trajectory is defined as x-axis of the end-effector frame, the vertical direction on a trajectory plane as y-axis and an alternative vertical direction from the trajectory plane as z-axis.

Next we consider the force influenced on the end-effector. In the task of a mobile manipulator, it is necessary to obtain the desired force response as well as the exact trajectory tracking with respect to end-effector's motion.

In the following section, we propose controller that both of force and position responses are simultaneously achieved.

IV. Scheme of Control System

A. Decoupling Force Controller

As the kinematics energies of both of joint-space and work-space are equivalent, an equation (11) is obtained as follows:

$$\frac{1}{2}\dot{\boldsymbol{\theta}}_v^T\boldsymbol{I}_v\dot{\boldsymbol{\theta}}_v = \frac{1}{2}\dot{\boldsymbol{r}}^T\boldsymbol{M}\dot{\boldsymbol{r}} \tag{11}$$

where $\boldsymbol{M}$ is equivalent mass matrix and $\boldsymbol{I}_v$ is inertia matrix in joint-space. By applying robust acceleration controller of joint-space based on disturbance observer, $\boldsymbol{I}_v$ can be set to virtual inertia matrix $\boldsymbol{I}_{vn}$. By substituting equation (9) into equation (11), the equivalent mass matrix (EMM) $\boldsymbol{M}_v$ is defined as follows:

$$\boldsymbol{M}_v = (\boldsymbol{J}_{rv}\boldsymbol{I}_{vn}^{-1}\boldsymbol{J}_{rv}^T)^{-1} \tag{12}$$

When the operational force $\boldsymbol{F}_n$ and the torque $\boldsymbol{\tau}$ of each joints are introduced for a mobile manipulator, the force relation between work-space and joint-space is obtained as follows:

$$\boldsymbol{\tau} = \boldsymbol{J}_{rv}^T\boldsymbol{F}_n \tag{13}$$

As the torque with respects to configuration is considered, joint-space acceleration reference are written as follows:

$$\ddot{\boldsymbol{\theta}}_v^{ref} = \boldsymbol{I}_{vn}^{-1}(\boldsymbol{\tau} + \boldsymbol{\tau}_n^{ref}) \tag{14}$$

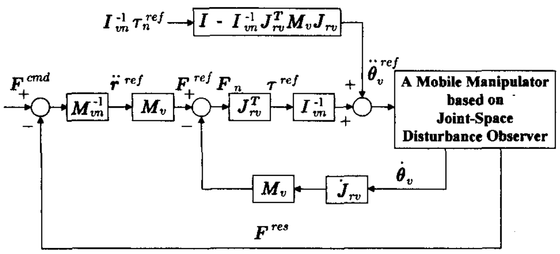

Fig. 3. Decoupling force controller

By substituting equation (12), (13) and (14) into equation (10), the motion equation is obtained as follows:

$$\boldsymbol{M}_v \ddot{\boldsymbol{r}} = \boldsymbol{F}_n + \boldsymbol{M}_v \dot{\boldsymbol{J}}_{rv} \dot{\boldsymbol{\theta}}_v + \boldsymbol{M}_v \boldsymbol{J}_{rv} \boldsymbol{I}_{vn} \boldsymbol{\tau}_n^{ref} \tag{15}$$

From equation (15), the operational force $\boldsymbol{F}_n$ is written as follows:

$$\boldsymbol{F}_n = \boldsymbol{F}^{ref} - \boldsymbol{M}_v \dot{\boldsymbol{J}}_{rv} \dot{\boldsymbol{\theta}}_v - \boldsymbol{M}_v \boldsymbol{J}_{rv} \boldsymbol{I}_{vn} \boldsymbol{\tau}_n^{ref} \tag{16}$$

$\boldsymbol{F}^{ref}$ is the force reference, and given as equation (17)

$$\boldsymbol{F}^{ref} = \boldsymbol{M}_v \ddot{\boldsymbol{r}}^{ref} = \boldsymbol{F}^{cmd} - \boldsymbol{F}^{res} \tag{17}$$

From equation (17), the decoupling force response is not always obtained because the EMM is not diagonal. To realize decoupling force response, $\boldsymbol{F}^{ref}$ is given as follows:

$$\boldsymbol{F}^{ref} = \boldsymbol{M}_v \boldsymbol{M}_{vn}^{-1} (\boldsymbol{F}^{cmd} - \boldsymbol{F}^{res}) \tag{18}$$

By using equation (18), the EMM $\boldsymbol{M}_v$ in equation (17) is replaced as $\boldsymbol{M}_{vn}$.

$$\boldsymbol{M}_{vn} \ddot{\boldsymbol{r}}^{ref} = \boldsymbol{F}^{cmd} - \boldsymbol{F}^{res} \tag{19}$$

where the mass matrix $\boldsymbol{M}_{vn}$ is an arbitrary one. When $\boldsymbol{M}_{vn}$ is a diagonal matrix, the force responses of each motion direction are decoupled. From previous equations, the joint-space acceleration reference is derived as follows:

$$\begin{aligned} \ddot{\boldsymbol{\theta}}_v^{ref} &= \boldsymbol{I}_{vn}^{-1} \boldsymbol{J}_{rv}^T \boldsymbol{M}_v (\ddot{\boldsymbol{r}}^{ref} - \dot{\boldsymbol{J}}_{rv} \dot{\boldsymbol{\theta}}_v) \\ &\quad + (\boldsymbol{I} - \boldsymbol{I}_{vn}^{-1} \boldsymbol{J}_{rv}^T \boldsymbol{M}_v \boldsymbol{J}_{rv}) \boldsymbol{I}_{vn}^{-1} \boldsymbol{\tau}_n^{ref} \end{aligned} \tag{20}$$

On the other hand, the joint-space acceleration reference is obtained by the inverse kinematics including the null-space vector as follows:

$$\ddot{\boldsymbol{\theta}}_v^{ref} = \boldsymbol{J}_{rv}^{+} (\ddot{\boldsymbol{r}}^{ref} - \dot{\boldsymbol{J}}_{rv} \dot{\boldsymbol{\theta}}_v) + (\boldsymbol{I} - \boldsymbol{J}_{rv}^{+} \boldsymbol{J}_{rv}) \ddot{\boldsymbol{\theta}}_{vnull}^{ref} \tag{21}$$

$$\boldsymbol{J}_{rv}^{+} = \boldsymbol{W}^{-1} \boldsymbol{J}_{rv}^T (\boldsymbol{J}_{rv} \boldsymbol{W}^{-1} \boldsymbol{J}_{rv}^T)^{-1} \tag{22}$$

where $\boldsymbol{J}_{rv}^{+}$ is a weighted pseudo inverse matrix of Jacobian. To compare equation (22) with equation (20), it is found that the weight matrix $\boldsymbol{W}$ has the same effect with the virtual inertia matrix $\boldsymbol{I}_{vn}$ physically. Then, $\boldsymbol{I}_{vn}$ is regarded as $\boldsymbol{W}$. So coefficients of $\boldsymbol{W}$ should be decided by considering the physical meaning.

B. Hybrid Controller

In this study, we apply the hybrid control for the force operated by the end-effector. Then, the force is parted to components with respect to the end-effector frame. In the hybrid control, the force and position is controlled for the x, z-axis respectively and the force is only controlled for the y-axis.

B.1 Rotation Transformation of Work-Space Frame

In this part, the rotation of work-space with respect to end-effector frame is presented. As the rotational transformation, decoupling controller is also transformed. The position of end-effector in new frame is given as follows:

$${}^{E}\boldsymbol{r} = {}^{W}\boldsymbol{R}_E(\boldsymbol{\phi}_E)^{-1} \boldsymbol{r} \tag{23}$$

where ${}^{W}\boldsymbol{R}_E({}^{E}\boldsymbol{\phi})$ is a rotation matrix, and superscript "E" means in end-effector frame.

B.2 ^{E}Y-axis Controller

The force controller with respect to ${}^{E}Y$-axis is constructed as follows:

$${}^{E}\ddot{y}^{ref} = \frac{1}{M_{vn,y}} ({}^{E}F_y^{cmd} - {}^{E}F_y^{res}) + K_I ({}^{E}\dot{y}_{obj} - {}^{E}\dot{y}^{res}) \tag{24}$$

where K_I is speed feedback gain of the force controller, and the subscript "*obj*" means with respect to the environmental object.

B.3 ^{E}X, ^{E}Z-axis Controller

The force and position controller with respect to ${}^{E}X$, ${}^{E}Z$-axis is constructed as follows:

$$\begin{aligned} {}^{E}\ddot{x}^{ref} &= K_{P,x}({}^{E}x^{cmd} - {}^{E}x^{res}) \\ &\quad + K_{V,x}({}^{E}\dot{x}^{cmd} - {}^{E}\dot{x}^{res}) \\ &\quad + {}^{E}\ddot{x}^{cmd} + \frac{1}{M_{vn,x}} ({}^{E}F_x^{cmd} - {}^{E}F_x^{res}) \end{aligned} \tag{25}$$

This controller (25) is considered as the impedance controller in (26).

$$\begin{aligned} {}^{E}\ddot{x}^{ref} &= \frac{1}{M_{vn,x}} \{K'_{P,x}({}^{E}x^{cmd} - {}^{E}x^{res}) \\ &\quad + K'_{V,x}({}^{E}\dot{x}^{cmd} - {}^{E}\dot{x}^{res}) + ({}^{E}F'^{cmd}_x - {}^{E}F_x^{res})\} \end{aligned} \tag{26}$$

C. A Total Control System

Finally, we show a structure of the whole control system in Fig.4.

Here, because the trajectory of task is given in world coordinate frame, the position of end-effector $\boldsymbol{r}$ must be also obtain in world frame. $\boldsymbol{r}$ is derived by both of arm's configuration and vehicle position $\boldsymbol{x}$. The arm's configuration is exactly obtained by the information from rotary encoders of each joint. The vehicle position $\boldsymbol{x}$, however, can not be obtained with the internal sensors, as rotary encoder, because of its nonholonomic constraints. Then, $\boldsymbol{x}$ is estimated in real time with

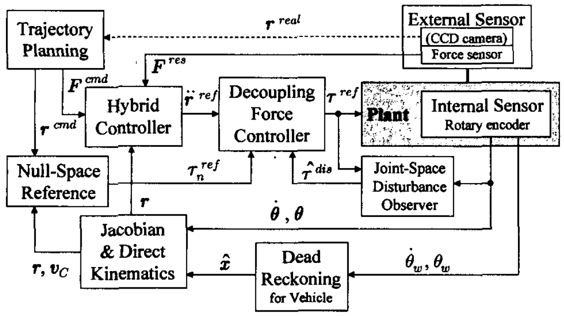

Fig. 4. A Total Control System

rotary encoders of wheels by using a dead-reckoning method. By using estimated values $\hat{x}$, r is obtained as follows:

$$r = \hat{x} + {}^V R_W(\phi_C)^V r \tag{27}$$

where ${}^V R_W(\phi_C)$ is a rotation matrix, and the superscript "V" means in vehicle frame. Because the absolute position error is accumulated, it should be compensated with the external sensors, as visual, supersonic sensor and so on. Moreover, the system should stably correspond to the error between the real position and the desired trajectory. In following section, we propose the configuration control to obtain a desired response.

V. Configuration Control of a Mobile Manipulator

A. Weight Matrix

As shown in section (IV. A), the weight matrix W is should be decided by considering the physical meaning. In general, W has been set to unit matrix I. However, the dynamic characteristics of the mobile manipulator are much different between vehicle and arm. So it may be necessary to decide W in proportion to the characteristics or a kind of motion. In following simulation, we present some patterns of the weight matrices, and compare them with respect to the end-effector's responses. As one of pattern, W is determined as follows:

$$\begin{aligned} W &= diag\{\frac{J_{n,v}}{\tau_{lim,v}}, \frac{J_{n,\phi}}{\tau_{lim,\phi}}, \frac{J_{n,1}}{\tau_{lim,1}}, \cdots, \frac{J_{n,5}}{\tau_{lim,5}}\} \quad (28) \\ &\approx diag\{\ \ddot{\theta}_{lim,v}, \ddot{\theta}_{lim,\phi}, \ddot{\theta}_{lim,1}, \cdots, \ddot{\theta}_{lim,5}\ \}^{-1} \end{aligned}$$

where J_n is the nominal self inertia, τ_{lim} is the torque limit and $\ddot{\theta}_{lim}$ is the acceleration limits of joint. As for τ_{lim} of vehicle and arm, the wheel's slip and the influence of gravity are considered respectively.

$$\frac{1}{R}\tau_{lim,w} \simeq F_{slip,w}, \qquad \tau_{lim,i} \simeq \tau'_{lim,i} - \tau_{g,i}$$

where $F_{slip,w}$ is the initial force that the wheel begin to slip, and from $\tau_{lim,w}$ and $J_{n,w}$, W_v and W_ϕ are obtained. $\tau_{g,i}$ is the gravity torque.

B. Utilization of Null-Space Motion

Here the second term at the right hand side of equation (20) is null-space function that can control configuration torque reference τ_n^{ref} without influence on work-space. When a cost function is $g(\theta_v)$, the configuration control is given by the following equations.

$$\begin{aligned} u &= \frac{\partial g}{\partial \theta_v} \\ I_{vn}^{-1}\tau_n^{ref} &= -K_{Pn}u - K_{Vn}\dot{\theta}_v \end{aligned} \tag{29}$$

The second term at the right hand side of equation (29) is damping factor for stable configuration.

B.1 Equivalent Mass Matrix

For the performance indices related to null-space reference, we consider the equivalent mass matrix (EMM) M_v, and it is represented as follows:

$$M_v = \frac{1}{\det(J_{rv}W^{-1}J_{rv}^T)}\begin{pmatrix} m_x & & \mathrm{m_{int}} \\ & m_y & \\ \mathrm{m_{int}} & & m_z \end{pmatrix} \tag{30}$$

where $\omega_w = \det(J_{rv}W^{-1}J_{rv}^T)$ is defined as a weighted manipulability measure.

In the mobile manipulator, however, much calculation effort is required to obtain M_v, so we consider M_v as arm $M_{v,a}$, vehicle and one link part $M_{v,v1}$ indepently.

EMM in Arm part

For arm part, to utilize the dexterous performance of arm, we consider to keep the small EMM for all direction. Then, $\omega_{w,a}$ is decided as performance index for arm's configuration to keep high manipulability. Then, null-space torque references are given by the following equitation.

$$\tau_{n,i}^{ref} = w_i[K_{Pn,i}\frac{\partial \omega_{w,a}}{\partial \theta_v} - K_{Vn,i}\dot{\theta}_i] \tag{31}$$

EMM in Vehicle & One Link part

For vehicle and one link part (Fig.5), we investigate the relation between $M_{v,v1}$ and configuration as shown in Fig.6. From the results, it is found that $M_{v,v1}$ has singular points in different motion direction. To avoid the singular point in the arbitrary motion, it is preferable that EMM is not directly utilized for the cost function of null-space. Then, we determine a selection of $M_{x,v1}^{ref}$, $M_{y,v1}^{ref}$, which is suitable as the reference for

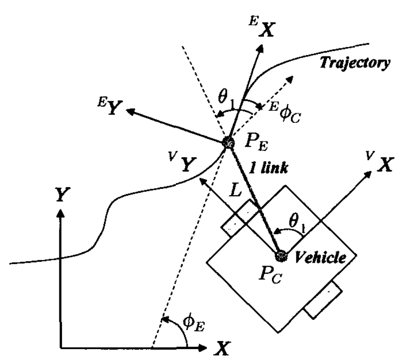

Fig. 5. EMM for vehicle and one link part

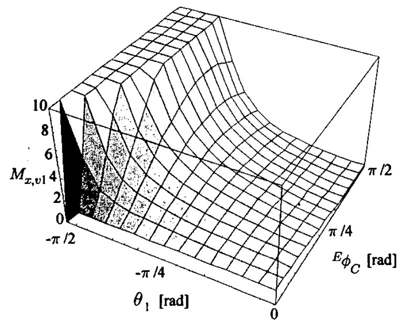

Fig. 6. Relation between EMM and configuration

TABLE I
PARAMETERS FOR CONTROLLER

PD controller in work-space	
Position feedback gain	$K_P = 400.0$ [rad^2/sec^2]
Velocity feedback gain	$K_V = 40.0$ [rad/sec]
Force controller in work-space	
Virtual mass in ^EYaxsis	$^EM_{vn,y} = 20.0$ [kg]
Integral feedback gain	$K_I = 60.0$ [rad/sec]

the equivalent mass matrix, according to the preknown work for mobile manipulator. The configuration torque reference in null-space $\boldsymbol{\tau}_n^{ref}$ is given by the configuration of the vehicle &`1 link that correspond to $\boldsymbol{M}_{v,v1}^{ref}$.

$$\tau_{n,v}^{ref} = w_v K_{Vn,v}(v_C^{cmd} - v_C) \tag{32}$$

$$\tau_{n,\phi}^{ref} = w_\phi[K_{Pn,\phi}(\phi_C^{cmd} - \phi_C) - K_{Vn,\phi}\dot{\phi}_C] \tag{33}$$

$$\tau_{n,1}^{ref} = w_1[K_{Pn,1}(\theta_1^{cmd} - \theta_1) - K_{Vn,1}\dot{\theta}_1] \tag{34}$$

B.2 Variable Null-Space Gains by Equivalent Mass Matrix

In the proposed approach, the weight matrix $\boldsymbol{W}$ has large inertia $\boldsymbol{W}_p$ to avoid the slip effect of vehicle. Then, the end-effector easily approaches to its singular configuration since the controller make force the correct tip trajectory motion even if the vehicle does not move active. This means that there is a trade-off to select the weight gain between the avoidance motion of slip and singular configuration. From this point of view, we introduce the variable null-space gain according to the change of configuration.

$$K_{Vn,v}^{var} = (\omega_{w,a}^{max} - \omega_{w,a})K_{Vn,v} \tag{35}$$

$$K_{Pn,\phi}^{var} = |M_{x,v1} - M_{x,v1}^{ref}|K_{Pn,\phi} \tag{36}$$

Here $\omega_{w,a}^{max}$ is the maximum value of dynamical manipulability and $K_{Vn,v}^{var}$, $K_{Pn,\phi}^{var}$ are variable null-space gains.

VI. Experimental Results

To confirm the effectiveness of proposed controller, several experiments are implemented.

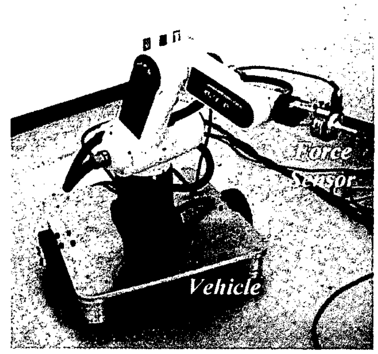

Fig. 7. The mobile manipulator for experiment

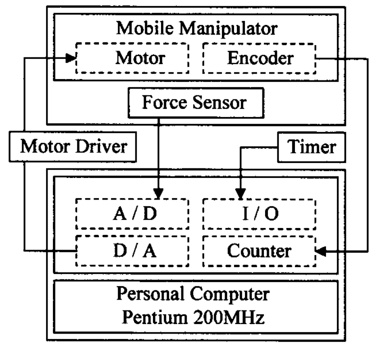

Fig. 8. Signal flow diagram of control system

A. Experimental Conditions

The mobile manipulator and the signal flow diagram of the experiment system are shown in Fig. 7. and Fig. 8. respectively.

The parameters on this control scheme are shown in TABLE I.

B. Experimental Results

To make clear the effect of the proposed approach, the following three case experiments are implemented.

Experiment 1

Fig.10. shows the position step response (0.8[cm] in the direction of X-axis) under the condition that weight matrix $\boldsymbol{W}$ are $\boldsymbol{I}$ and $\boldsymbol{W}_p$ respectively.

Experiment 2

Fig.11. shows the end-effector response of a sine curve reference (amplitude 1.0[m], cycle 10[sec]) under the condition of the variable null-space gain and constant one. Then, weight matrix is $\boldsymbol{W}_p$.

Experiment 3

Fig.12. shows the result of pushing task ($\boldsymbol{W} = \boldsymbol{W}_p$). Here the end-effector follow the tangental direction of the wall (position control: lamp input 0.1[m/sec]) and performs force task in the vertical direction of the wall (force control: 30[N]). Then, the surface condition of wall changes and its height difference is about 3.0[cm].

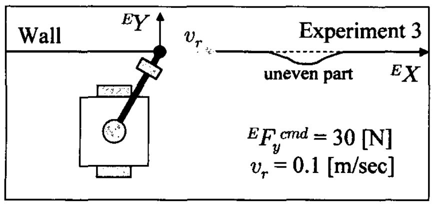

Fig. 9. Wall pushing task in experiment 3

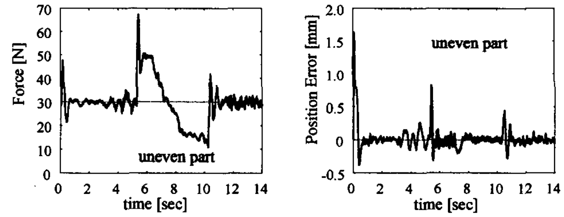

Fig. 12. Response of force and position error in experiment 3

C. Consideration

Fig.10. shows that both of the desired position and velocity is achieved by using the proposed approach with weight matrix . Fig.11. shows that using the variable gain, the dynamical manipulability keeps desirable condition and manipulability (configuration) without deteriorating the trajectory response. Fig.12. shows that decoupling force and position controller in workspace is realized.

VII. Conclusions

Considering a task oriented motion by the mobile manipulator, it is important to cooperate with the subsystems efficiently and to make its motion keep the adequate configuration for the task. When the mobile manipulator is considered as a unified system of the vehicle and the arm, it is easy to satisfy the above condition. In this paper, in order to obtain the desired hybrid control with respect to the end-effector's tasks, the performance indices, which is based on the equivalent mass matrix, are introduced to increase both of the manipulability of the arm and the stability of the vehicle motion. Furthermore, the weight matrix is proposed to obtain the adequate torque's distribution. The validity of the proposal approach is confirmed by several experiments.

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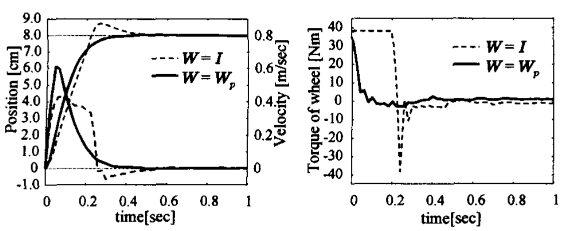

Fig. 10. Response of end-effector's position / velocity and wheel's torque in experiment 1

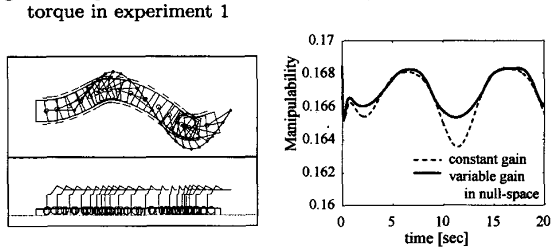

Fig. 11. Trajectory tracking and dynamical manipulability in experiment 2