The 9th International Symposium on Automation and Robotics in Construction June 3-5, 1992 Tokyo, Japan

Gravity Center Control for Manipulator/Vehicle System for Man-Robot Cooperation

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Abstract

In this paper, we propose a **"center of gravity control(CGC)"** method to apply the manipulator/vehicle system, so that the system cannot fall down by controlling the center of gravity of the system. Different from the manipulator fixed on the floor/ground tightly, it is a very serious problem for the manipulator/vehicle system to avoid tumbling. Therefore, we consider the algorithm to control both the tip position of the endeffector and the center of gravity of the manipulator and the payload being carried by the manipulator. We applied this control algorithm to the manipulator with the vehicle for the man-robot cooperation. The trajectory of the manipulator is given by a human operator and the center of gravity is set so as not to tumble previously. We carried out the experiment to confirm the effectiveness of this control algorithm for the manipulator/vehicle system. In this experiment, we applied this control algorithm to a manipulator for the man-robot cooperation. This gravity center control algorithm can be applied to various types of manipulator/vehicle system.

1. Introduction

Recently, the robotic manipulators are used in many industrial fields, such as factory automation, construction and others. But most of their applications have been studied for known tasks or environments. That is to say, these robots are programmed in the off-line manner to execute known tasks. For these reasons, most of these conventional robots have difficulty in applying them to unknown tasks.

The demands for the robotic systems which can be used for completely unknown environments/tasks are rapidly increasing. The cooperative manipulator with a human operator is one of the solutions for the robot used in unknown environments/tasks from the view of the current robotic technology. The final goal of this research is to develop a manipulator for the man-robot cooperation, manipulator operated by a human operator directly. Several researches have been done concerned with the manipulator system for the man-robot cooperation.

G. Hirzinger and K. Landzettel have proposed a direct teaching method using the force/torque sensor mounted on a manipulator[1]. We have proposed a manipulator for the man-robot cooperation, which is designed for handing heavy objects by cooperation with a human operator[2]. H. Kazerooni has proposed the extender, robotic systems worn by human operators for material handing tasks[3][4]. None of the conventional method have dealt with the manipulator/vehicle system, which is controlled by a human operator. Figure 1 shows a concept of the manipulator for the man-robot cooperation work considered in this paper. Unlike the fixed base manipulator system, the manipulator/vehicle system does not have a fixed base, so that the control system must take into account the stability of the system not to fall down, when handling heavy payloads. This system consists of a manipulator with two force/torque sensors. One is the operational sensor, attached to the final link of the manipulator, while the other is the force control sensor, located between the final link of the manipulator and the endeffector of the manipulator. The operational sensor is used to command the manipulator's motion, while the force control sensor is used to control the interaction between the manipulator and the environment. A human operator can control the manipulator for the man-robot cooperation applying the operational force to the operational sensor. By using this system, we can perform the man-robot cooperation work for unknown environments/tasks.

Different from the conventional manipulators, in this system, a human operator exists in the same working space with the robot and the human operator executes the tasks by thinking what has to do and how to do following the task sequence. Since the human operator commands the manipulator by thinking of the tasks/environments continuously, the manipulator for the man-robot cooperation can be used in the various kinds of unknown tasks/environments without making the system complicated.

In this paper, we propose a control algorithm for the manipulator for the man-robot cooperation with a mobile mechanism. Compared with the manipulator fixed to the floor/ground, the manipulator mounted on a vehicle has many merits; because the manipulator/vehicle system can move anywhere we want to work, and the system realize a large working space without designing a large fixed base manipulator. But different from the manipulator mounted on the ground/floor, the manipulator mounted on the vehicle might be unstable and to tumble. That is why, we have to consider to control both the position of the endeffector and the center of gravity of the manipulator including a payload simultaneously, using the redundancy of the manipulator/vehicle system. Thus, we can avoid the system to tumble by controlling the center of gravity, so that the system will be much safer.

In the sequel, we first introduce a **center of gravity control(CGC)** method, that is, how to control the position of the endeffector and the center of gravity of the manipulator including payloads. Second, we discuss how to give the trajectory of the endeffector and the desired center of gravity. Finally, we show the experimental system and the experimental results, using the proposed **CGC** method.

2. CGC Method

2.1 CGC Features

In this chapter, we introduce the **"center of gravity control(CGC)"** algorithm for the manipulator/vehicle system. The manipulator/vehicle system consists of a mobile mechanism(vehicle) and a manipulator mounted on it. Different from the manipulator fixed on the ground, the manipulator/vehicle system is liable to be unstable and tumble. So we have to control the manipulator/vehicle system cooperatively in order not to tumble. In this **CGC** algorithm, we consider to control both the trajectory of the endeffector of the manipulator and the center of gravity of the manipulator including a payload. In this **CGC** algorithm, we define that the center of gravity is the projected position of the manipulator's and payload's center of gravity from the 3-dimensional space to the xy-plane/floor. The manipulator/vehicle system must not tumble if the center of gravity of the manipulator and payloads lies within the projected allowable area of the vehicle. We can prevent the manipulator/vehicle system from tumbling to control this gravity center.

In this control algorithm, we use two kinds of the coordinate systems as shown in fig. 2;
(1) **The inertial coordinate system**. The position of the endeffector of the manipulator is given in this coordinate system. The position of the vehicle is also given in this inertial coordinate system.
(2) **The vehicle coordinate system**. This coordinate system is fixed to the center of the vehicle. The center of gravity of the manipulator including a payload is given in this vehicle coordinate system.

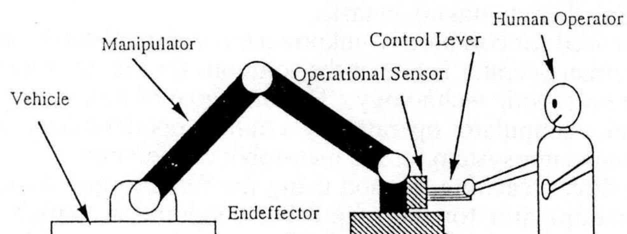

Fig. 1 Concept of Man-Robot Cooperation

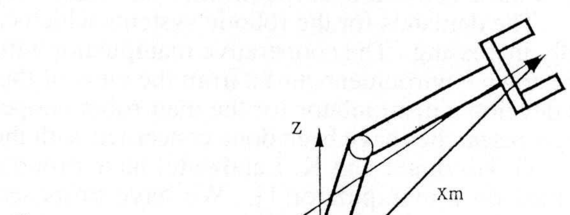

Fig. 2 Coordinate Systems

2.2 CGC Algorithm

It is well known that the velocity of the manipulator $\dot{x}$ with mobile mechanism can be expressed by both the manipulator's velocity itself $\dot{x}_m$ and the velocity of the vehicle $\dot{x}_v$, as follows;

$$\dot{x} = \dot{x}_v + \dot{x}_m \quad \in R^6 \quad . \qquad (1)$$

Using the Jacobian matrix of the manipulator $J_m \in R^{6\times6}$ and the manipulator's joint velocity $\dot{\theta}_m \in R^6$, the manipulator's velocity observed from the vehicle coordinate system is expressed by the following equation;

$$\dot{x}_m = J_m\dot{\theta}_m \quad \in R^6 \quad . \qquad (2)$$

As for the velocity of the vehicle, we assume that we can control the linear velocity in the x-axis direction v_x, the linear velocity in the y-axis direction v_y and the angular velocity around the z-axis ω_z, independently. That is to say, we can write the velocity of the vehicle observed from the inertial coordinate system;

$$\dot{x}_v = \begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix} \quad \in R^3 \quad . \qquad (3)$$

From eq. (1) with eqs. (2) and (3), the velocity of the endeffector of the manipulator in the inertial coordinate system is expressed by

$$\dot{x} = J_m\dot{\theta}_m + \begin{bmatrix} v_x \\ v_y \\ \omega_z \\ 0 \end{bmatrix} \quad \in R^6 \quad . \qquad (4)$$

As far as the center of gravity is concerned, the center of gravity in the vehicle coordinate system is expressed by the function of the variables of the manipulator's joint, that is,

$$x_g = f(\theta_m) \quad \in R \quad . \qquad (5)$$

Differentiating eq. (5) with respect to time, we obtain

$$\dot{x}_g = J_g\dot{\theta}_m \quad , \qquad (6)$$

where J_g is the Jacobian matrix of the center of gravity, and is defined as follows;

$$J_g = \frac{\partial f}{\partial \theta_m} \quad \in R^{1\times6} \quad . \qquad (7)$$

Combining eqs. (4) and (6) leads to

$$\begin{bmatrix} \dot{x} \\ \dot{z} \\ \dot{x}_g \end{bmatrix} = \left[\begin{array}{c:c} J_m & \begin{matrix} 1 \\ 0 \end{matrix} \\ \hdashline J_g & 0 \end{array}\right] \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ v_x \end{bmatrix} \quad . \qquad (8)$$

Now we define J as follows;

$$J = \left[\begin{array}{c:c} J_m & I \\ & 0 \\ \hdashline J_g & 0 \end{array} \right] \in R^{7\times 9} \qquad (9)$$

Without losing the generality for this problem, we assume that the matrix has a full rank, that is rank(J)=7. From eq. (9), we can obtain the pseudo inverse matrix $J^{+} \in R^{9\times 7}$. Multiplying this pseudo inverse of matrix J on both sides of eq. (8), we obtain

$$\begin{bmatrix} \dot{\theta}_m \\ v_x \\ v_y \\ \omega_z \end{bmatrix} = J^{+} \begin{bmatrix} \dot{x} \\ \dot{x}_g \end{bmatrix} \qquad (10)$$

From eq. (10), we can calculate both the velocity of the vehicle and the manipulator's joint velocity. We can realize the **CGC** method by feeding the velocity calculated by eq. (10) to the manipulator/vehicle system. Therefore, we can control both the position of the endeffector of the manipulator in the inertial frame and the center of gravity of the manipulator and the payload, simultaneously

2.3 How to Give Trajectory of Endeffector and Center of Gravity

Trajectory of Endeffector of Manipulator

At first, we describe how to give the trajectory of the endeffector of the manipulator in the inertial coordinate system. As shown in fig. 3, the control loop for the manipulator is designed by considering the operational force applied by a human operator and the interaction between the environment and the endeffector of the manipulator. That is, the motion of the manipulator is determined by both the contact force and the operational force[5][6][7]. We can give the velocity of the endeffector of the manipulator as follows;

$$\dot{x} = \dot{x}_h + \dot{x}_e \ , \qquad (11)$$

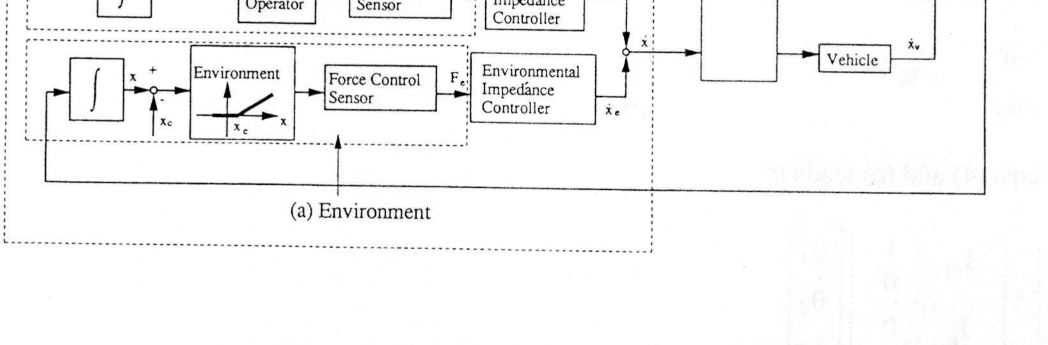

Fig.3 Control System

where $\dot{x}_h \in R^6$ is calculated by the human impedance controller with the operational force applied by a human operator, and $\dot{x}_e \in R^6$ is also calculated by the environmental impedance controller with the contact force between the environment and the endeffector.

The human impedance controller gives the relation between the operational force and the motion of the manipulator. On the other hand, the environmental impedance controller describes the relation between the contact force and the motion of the manipulator. We can derive these relations in the discrete system from the first order approximation as follows;

$$\begin{bmatrix} x_h(k+1) \\ \dot{x}_h(k+1) \end{bmatrix} = \begin{bmatrix} I & I\Delta T \\ -M_h^{-1}K_h\Delta T & -M_h^{-1}D_h\Delta T+I \end{bmatrix} \begin{bmatrix} x_h(k) \\ \dot{x}_h(k) \end{bmatrix} + \begin{bmatrix} 0 \\ M_h^{-1}\Delta T \end{bmatrix} F_h(k) \quad , \quad (12)$$

$$\begin{bmatrix} x_e(k+1) \\ \dot{x}_e(k+1) \end{bmatrix} = \begin{bmatrix} I & I\Delta T \\ -M_e^{-1}K_e\Delta T & -M_e^{-1}D_e\Delta T+I \end{bmatrix} \begin{bmatrix} x_e(k) \\ \dot{x}_e(k) \end{bmatrix} + \begin{bmatrix} 0 \\ M_e^{-1}\Delta T \end{bmatrix} F_e(k) \quad , \quad (13)$$

where $F_h \in R^6$ is the operational force applied by a human operator and $F_e \in R^6$ is the contact force. We assume that the operational force can be measured by the operational sensor and the contact force can be measured by the force control sensor. M_h, D_h and $K_h \in R^{6\times6}$ are the human impedance parameter matrixes and M_e, D_e and $K_e \in R^{6\times6}$ are the environmental impedance parameter matrixes, respectively. ΔT is a sampling time of the control system and k=1,2,3,4.... We can calculate the velocity of the manipulator in the inertial coordinate system by eq. (11) with eqs. (12) and (13).

Desired Position of Gravity Center

In this section, we discuss how to give the desired center of gravity of the manipulator including a payload to avoid tumbling. As shown in fig. 4, we can prevent the manipulator/vehicle system from tumbling, if we can control the center of gravity within the no-tumbling area. We can obtain the no-tumbling area from fig. 4;

$$L\cdot w_v = (\bar{x} - L)\cdot(w_m + w_p) \quad (14)$$

$$L\cdot(w_m + w_p) + L\cdot w_v = \bar{x}\cdot(w_m + w_p) \quad (15)$$

$$\bar{x} = \frac{w_v + w_m + w_p}{w_m + w_p}\cdot L \quad , \quad (16)$$

where

w_v: the weight of the vehicle
w_p: the weight of the payload
w_m: the weight of the manipulator
L : the length from the center of the vehicle to the wheel axis
$\bar{x}$: the length from the center of the vehicle to the no tumbling position .

In this control system, we have considered the **CGC** method statically. In the practical use of this **CGC** algorithm for the manipulator/vehicle system to avoid tumbling, we have to take account of the vibration of the system and the collision between the endeffector and the environment and so on. That is to say, the no-tumbling area is more narrow than the area which we can obtain from eq. (16). Considering the safety ratio, 0<S<1, eq. (16) leads to

$$\bar{x} = S\cdot\frac{w_v + w_m + w_p}{w_m + w_p}\cdot L \quad . \quad (17)$$

Considering the tumbling phenomena of the manipulator/vehicle system, we can divide the no-tumbling area into four areas as shown in fig. 4. If the center of gravity of the manipulator and the payload in the vehicle coordinate system lies in the area(a), the system will tumble around the I_{aa} axis. As described in the above, the center of gravity for the no-tumbling area is calculated as the function of the rotation angle of the gravity center θ_g. In this way, we can calculate the no-tumbling area in advance.

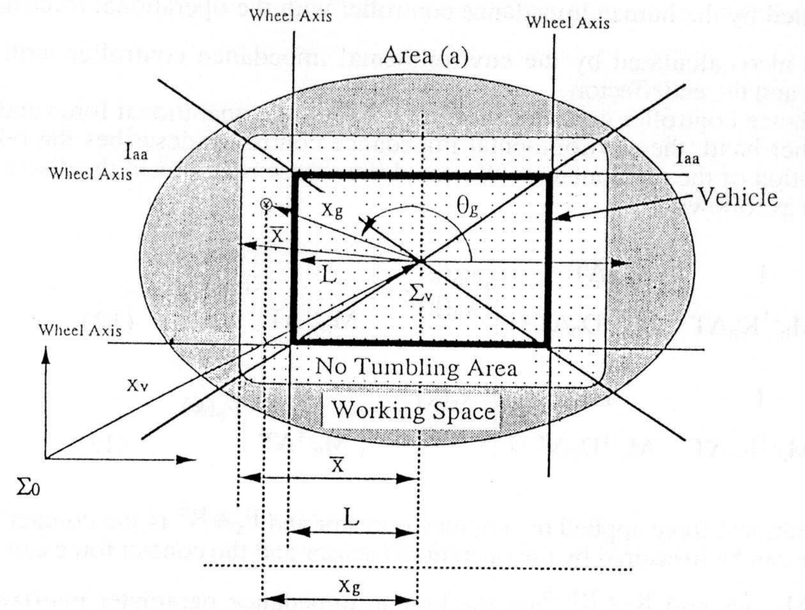

Fig. 4 No-Tumbling Area

Using the method of the resolved motion rate control of the manipulator system[8], we composed the control system. The velocity of the center of gravity is given as follows;

$$\dot{x}_g = \dot{x}_{gd} + K(x_{gd} - x_g) \quad , \qquad (18)$$

where

$\dot{x}_g$:the actual velocity of the center of gravity

x_g :the actual position of the center of gravity

$\dot{x}_{gd}$: the desired velocity of the center of gravity

x_{gd} : the desired position of the center of gravity

K : the feedback gain .

From eq. (18), we can calculate the velocity of the center of gravity . In order for the manipulator/vehicle system not to tumble, we must set the desired center of gravity within the no-tumbling area.

3. Experiment

3.1 Experimental System

The manipulator/vehicle system for the man-robot cooperation has been developed experimentally for the pick-and-place operation of a heavy object. Figure 5 shows the structure of the manipulator/vehicle system built for our laboratory use. The manipulator has a parallel link mechanism with four degrees of freedom and each degree of freedom is driven by a DC motor through reduction gear (Harmonic drives). It has a vacuum sucker attached at the tip of the endeffector to hold loads. The manipulator has two force sensors made by Hitachi Construction Machinery Co., Ltd.; one is the "operational sensor", while the other one is the "force control sensor". The operational sensor is attached to the end of the final link, while the force control sensor is attached between the endeffector and the final link.

3.2 Experiment of CGC Method

In chapter 2, we introduced the **CGC** algorithm for the manipulator/vehicle system in order to avoid tumbling. In this section, for simplicity, we show the experimental result applying the proposed **CGC** algorithm to the manipulator/vehicle system for the man-robot cooperation. In this experiment, we used one-degree-of vehicle, which can move to the x-axis direction freely, and two-degree-of-freedom manipulator as shown in fig. 6. In the following section, we show the equations for this specific experimental system. The center of gravity of the manipulator and the payload in the vehicle coordinate system is calculated by the following equation;

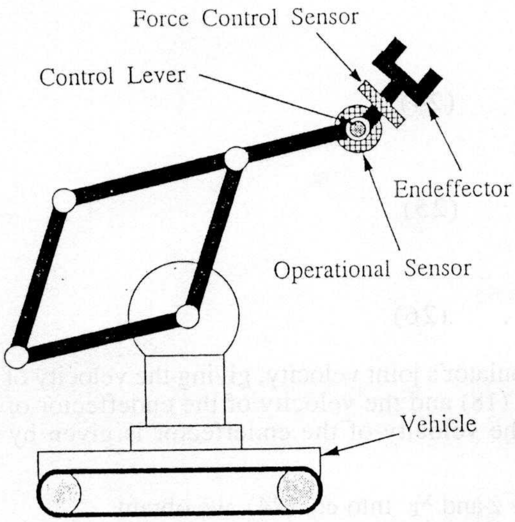

Fig. 5 Structure of System

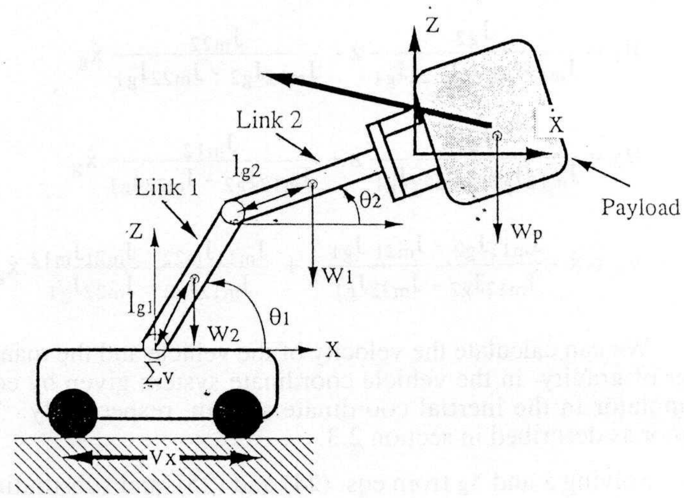

Fig. 6 Experimental Method

$$x_g = \frac{1}{w_1+w_2+w_p}\{(w_1 l_{g1}+w_2 l_1+w_p l_1)\cos(\theta_1) + (w_2 l_{g2}+w_p l_2)\cos(\theta_2)\} \quad \in R \qquad (19)$$

where

w_1, w_2: the weight of each link,

l_1, l_2 : the length of each link ,

l_{g1}, l_{g2}: the length between the center of gravity of each link and the joint .

Differentiating eq. (19) with respect to time, we obtain the Jacobian matrix of the center of gravity as follows;

$$J_g = \left[\; -\frac{w_1 l_{g1}+w_2 l_1+w_p l_1}{w_1+w_2+w_p}\sin(\theta_1) \quad -\frac{w_2 l_{g2}+w_p l_2}{w_1+w_2+w_p}\sin(\theta_2) \;\right] \in R^{1\times 2} \qquad (20)$$

On the other hand, we have the Jacobian matrix of the manipulator as follows;

$$J_m = \begin{bmatrix} -l_1\sin(\theta_1) & -l_2\sin(\theta_2) \\ l_1\cos(\theta_1) & l_2\cos(\theta_2) \end{bmatrix} \in R^{2\times 2} \qquad (21)$$

Using eq. (8), we can obtain the following equation;

$$\begin{bmatrix} \dot{x} \\ \dot{z} \\ \dot{x}_g \end{bmatrix} = \left[\begin{array}{c:c} J_m & \begin{matrix} 1 \\ 0 \end{matrix} \\ \hdashline J_g & 0 \end{array}\right] \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ v_x \end{bmatrix} \qquad (22)$$

Now, we define the Jacobian matrixes as follows;

$$J_m = \begin{bmatrix} J_{m11} & J_{m21} \\ J_{m12} & J_{m22} \end{bmatrix} \quad , \; J_g = [\; J_{g1} \quad J_{g2} \;] \qquad (23)$$

Solving eq. (22) with eq. (23), we obtain

$$\dot{\theta}_1 = \frac{J_{g2}}{J_{m12}J_{g2} - J_{m22}J_{g1}}\dot{z} - \frac{J_{m22}}{J_{m12}J_{g2} - J_{m22}J_{g1}}\dot{x}_g \quad , \tag{24}$$

$$\dot{\theta}_2 = \frac{J_{g1}}{J_{m12}J_{g2} - J_{m22}J_{g1}}\dot{z} + \frac{J_{m12}}{J_{m12}J_{g2} - J_{m22}J_{g1}}\dot{x}_g \quad , \tag{25}$$

$$v_x = \dot{x} - \frac{J_{m11}J_{g2} - J_{m21}J_{g1}}{J_{m12}J_{g2} - J_{m22}J_{g1}}\dot{z} + \frac{J_{m11}J_{m22} - J_{m21}J_{m12}}{J_{m12}J_{g2} - J_{m22}J_{g1}}\dot{x}_g \quad . \tag{26}$$

We can calculate the velocity of the vehicle and the manipulator's joint velocity, giving the velocity of the center of gravity in the vehicle coordinate system given by eq. (18) and the velocity of the endeffector of the manipulator in the inertial coordinate system, respectively. The velocity of the endeffector is given by the operator as described in section 2.3.

Solving $\dot{z}$ and $\dot{x}_g$ from eqs. (24) and (25), and substituting $\dot{z}$ and $\dot{x}_g$ into eq. (24), we obtain

$$v_x = \dot{x} - (J_{m11}\dot{\theta}_1 + J_{m21}\dot{\theta}_2) \quad , \tag{27}$$

where $(J_{m11}\dot{\theta}_1 + J_{m21}\dot{\theta}_2)$ is the velocity of the end point of the manipulator observed in the vehicle coordinate system.
From eq. (27), we can understand that the vehicle velocity v_x is given as the relative velocity between the end point velocity of the manipulator in the inertial coordinate system and the velocity of the manipulator itself in the vehicle coordinate system. Under the condition that $v_x = 0$, we can obtain $\dot{x}_g$ from eq. (26). Substituting $\dot{x}_g$ into eqs. (24) and (25), we can obtain the same result of the manipulator fixed on the ground.

The experiment carried out here is to move a payload to the slant direction as shown in fig6 and to observe how the manipulator and the vehicle move cooperatively. Figure 7 illustrates a cooperative movement of the manipulator and the vehicle by applying the **CGC** algorithm. According to the backward movement of the center of gravity, the vehicle moves backward to control the center of gravity of the manipulator, including a payload. From this experimental result as shown in figs 7, 8 and 9, it is clear that we can control both the position of the manipulator in the inertial coordinate system and the center of gravity in the vehicle coordinate system by the proposed **CGC** method.

Table 1 Parameters Used in Experiments

W_V	30	N
W_P	5	N
W_1	1	N
W_2	1	N
l_1	0.4	m
l_2	0.4	m
l_{g1}	0.2	m
l_{g2}	0.2	m
x_{gd}	0.24	m
$\overline{x}$	0.3	m

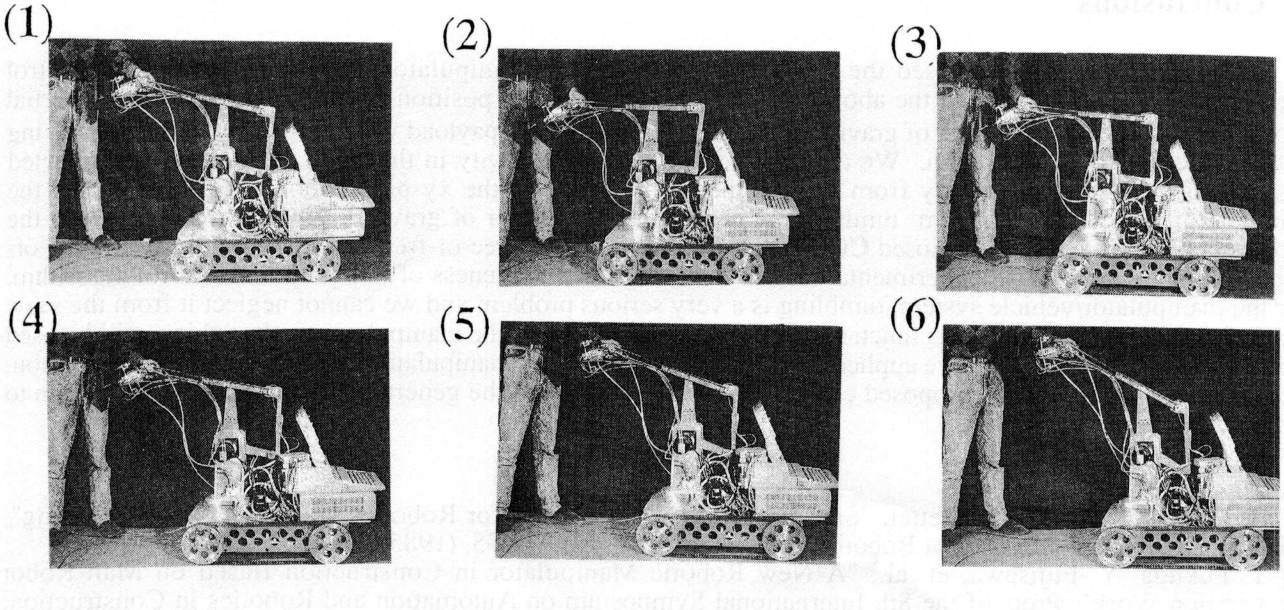

Fig. 7 Experimental Result (1)

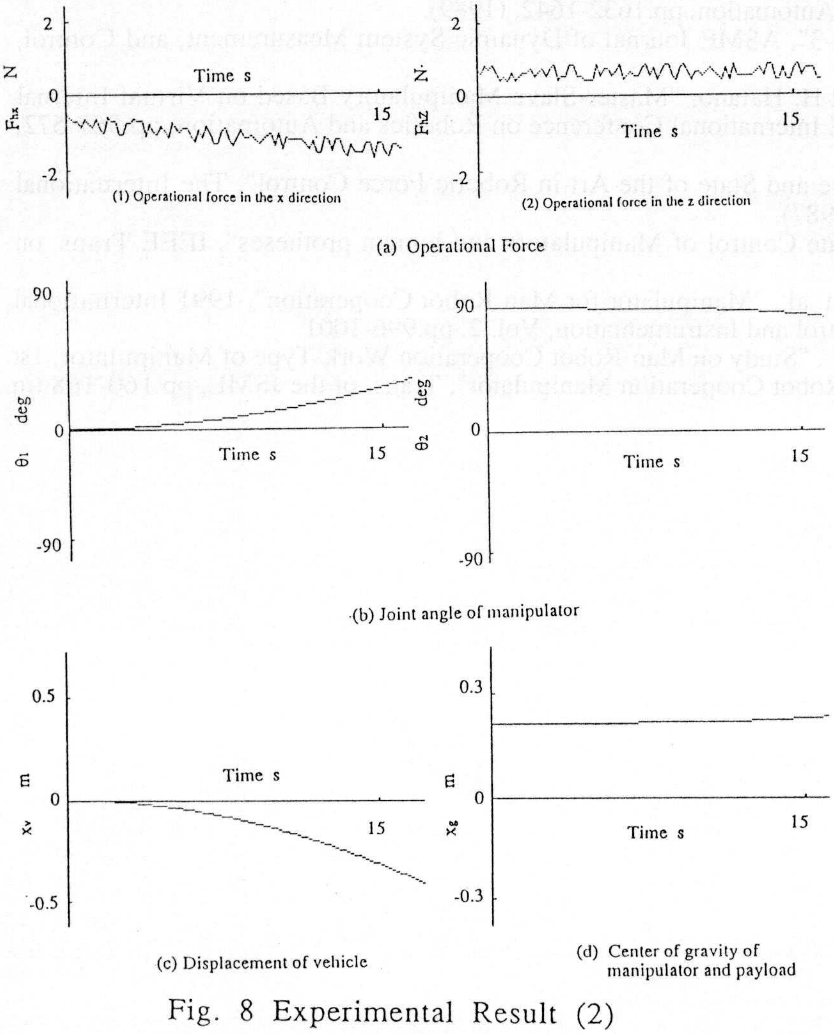

Fig. 8 Experimental Result (2)

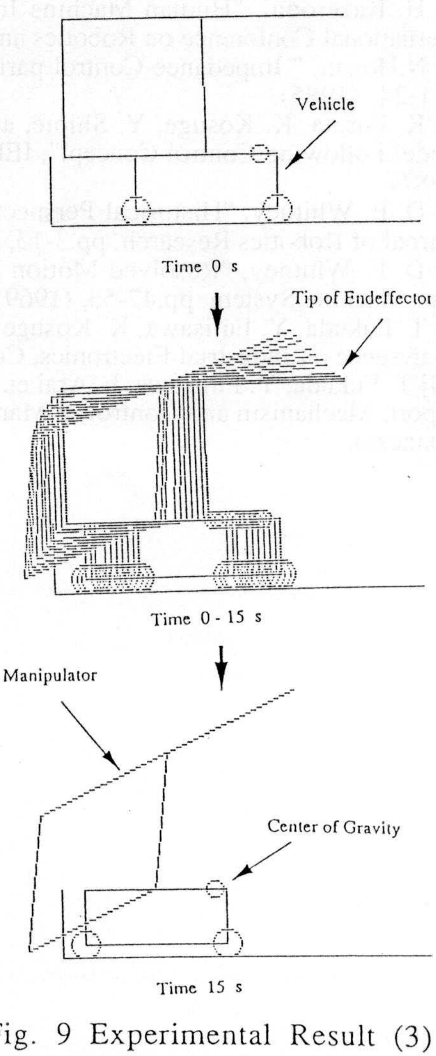

Fig. 9 Experimental Result (3)

4. Conclusions

In this paper, we proposed the **CGC** algorithm for the manipulator/vehicle system. This control algorithm was, as mentioned in the above, verified to control the tip position of the endeffector in the inertial coordinate system and the center of gravity of the manipulator and the payload which the manipulator is carrying in the vehicle coordinate system. We defined that the center of gravity in the **CGC** method is the projected position of the center of gravity from the 3-dimensional space to the xy-plane/floor. We can prevent the manipulator/vehicle system from tumbling by controlling the center of gravity. Finally, we carried out the experiment according to the proposed **CGC** method by using one-degree-of-freedom vehicle and two-degree-of-freedom manipulator. This experimental result validated the effectiveness of this proposed control algorithm. For the manipulator/vehicle system, tumbling is a very serious problem and we cannot neglect it from the view point of the safety. To extend the function of the manipulator system, the manipulator on the vehicle will be used more and more. In this paper, we applied this **CGC** algorithm to the manipulator for the man-robot cooperation. It is needless to say that this proposed control algorithm is useful to the general manipulator/vehicle system to avoid tumbling.

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