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Control of Manipulator/Vehicle System for Man-Robot Cooperation Using Fuzzy Logic

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Abstract

This paper proposed a control algorithm of the "Manipulator/Vehicle System for Man-Robot Cooperation". The manipulator/vehicle system has the redundant degrees of freedom. When the desired motion of the manipulator's end effector in the inertial coordinate system is given, the motion has to be decomposed into the motion of the manipulator and the motion of the vehicle. The motion of the end effector on the ground surface should be realized by the vehicle, if we want to move the system to another place, while the motion of the end effector should be realized by the motion of the manipulator, if we want to manipulate an object. The decomposition of the motion of the end effector should be done based on the operator's intention. How to decompose the motion of the end effector is one of the key issues of the manipulator/vehicle system for man-robot cooperation. The control algorithm, which we propose in this paper, controls the motion of the manipulator and vehicle based on the operator's intention modelled by fuzzy rules. The experimental results illustrates the effectiveness of the proposed control algorithm for manipulator/vehicle system for man-robot cooperation.

1. Introduction

According to the development of the robotic technology, many robots are used in many fields, such as factory, construction and so on. However most of these robots are used to execute fixed tasks, which are planned in advance. Conventional robots have difficulties for the changeable tasks. The manipulator, which can execute tasks in cooperation with the human operator, is one of the solutions for this problem.

G. Hirzinger has proposed the direct teaching method for the manipulator with force/torque sensor attached to it[1]. H. Kazerooni has proposed the extender. The human operator wears it and extends his power[2][3]. We have proposed a manipulator/vehicle system for man-robot cooperation, which is designed for handling heavy objects in cooperation with the human operator[4][5][6]. The manipulator/vehicle system for man-robot cooperation is the robot manipulator system for man-robot cooperation with mobile mechanism.

Figure 1 shows the concept of the manipulator/vehicle system for man-robot cooperation proposed in this paper. Unlike the conventional manipulators, a human operator exists in the same working space with the robotic system and the human operator commands the motion of the manipulator directly. The manipulator for man-robot cooperation can be used in various kinds of unknown environments/tasks.

In this paper, we propose a control method for manipulator/vehicle system for man-robot cooperation. We should design the motion of the manipulator considering the operational force and interaction between the manipulator and the environment to control the manipulator for man-robot cooperation proposed. In order to realize this motion of the manipulator, we use two impedance controllers. One is the human impedance controller and the other is the environmental impedance controller.

The manipulator/vehicle system is the robot manipulator system mounted on the mobile mechanism (vehicle). Compared with the manipulator fixed to the floor/ground, the manipulator/vehicle system has many merits; we can can move the system anywhere we want to execute tasks, and the system realizes a large working space without designing a large manipulator. The manipulator/vehicle system has redundant degrees of freedom and the motion has to be decomposed into the motion of the manipulator and the motion of the vehicle, when the desired motion of the manipulator's end effector in the inertial coordinate system is given. The motion of the end effector on the ground surface should be realized by the vehicle if we want to move the system to another location, while the motion of the end effector should be realized by the motion of the manipulator if we want to manipulate an object. The decomposition of the motion of the end effector should be done based on the operator's intention. How to decompose the motion of the end effector is one of the key issues of the manipulator/vehicle system for man-robot cooperation. Fuzzy inference system is used to decompose the motion based on the operator's intention.

In the sequel, we first introduce the control method of the manipulator for man-robot cooperation using the human impedance controller and the environmental impedance controller. Second we explain the decomposition of the motion of the end effector. Third we discuss how to decompose the motion of the end effector using the fuzzy logic which models human intention. Finally we carried out experiments to illustrate the effectiveness of the proposed control method for the manipulator/vehicle system for man-robot cooperation.

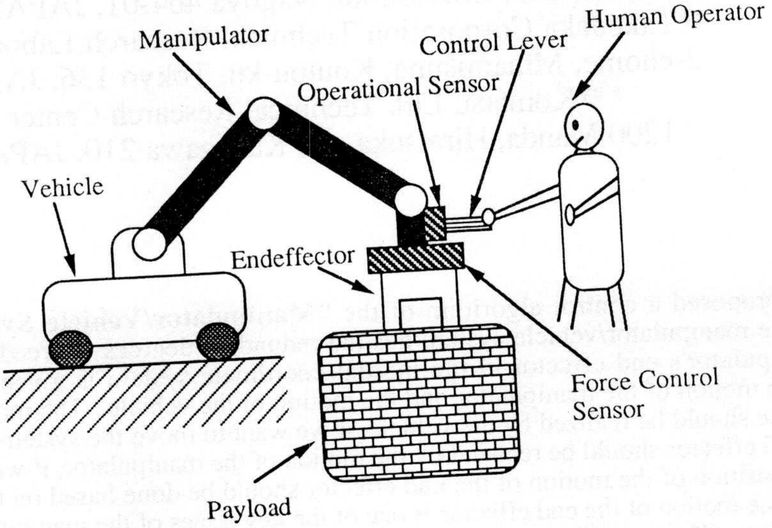

Fig. 1 Concept of Man-Robot Cooperation

2. Motion of End Effector for Man-Robot Cooperation

Figure 2 shows the control system for the manipulator/vehicle system for man-robot cooperation proposed in this paper. We have to design the control system of the manipulator for man-robot cooperation considering the operational force by the human operator and the contact force between the manipulator and the environment[7][8][9][10]. We assume that the operational force can be measured by the operational force sensor which is attached to the final link of the manipulator and the contact force can be measured by the environmental force sensor which is located between the final link of the manipulator and the end effector of the manipulator. The human impedance controller relates the motion of the manipulator and the operational force applied by the human operator, while the environmental impedance controller relates the contact force and the motion of the manipulator. The final motion of the manipulator is determined by both the motion calculated by

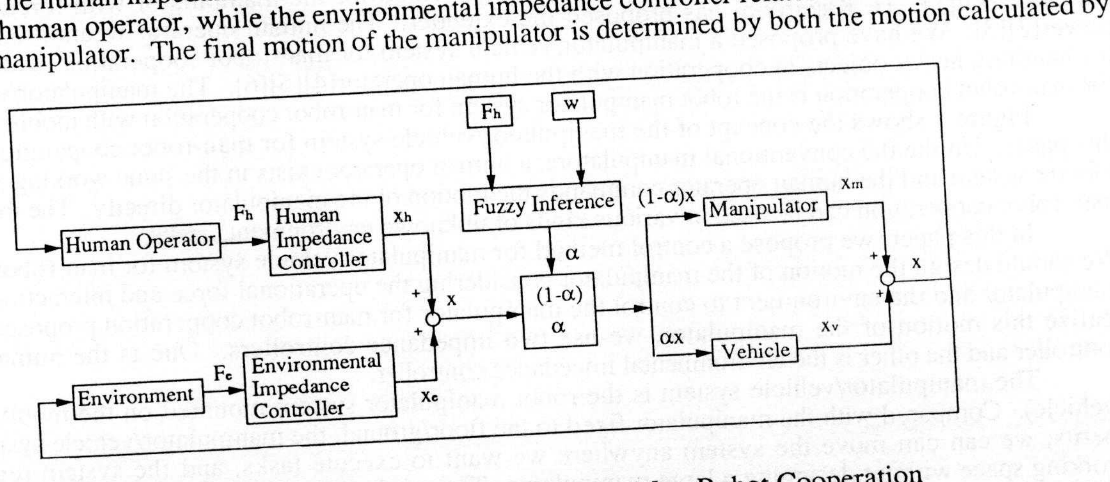

Fig.2 Control System of Manipulator/Vehicle for Man-Robot Cooperation

the human impedance controller and the motion calculated by the environmental impedance controller as follows:

$$X_h = H^{-1} \cdot F_h \quad (1)$$

$$X_e = E^{-1} \cdot F_e \quad (2)$$

$$X = X_h + X_e \quad (3)$$

where H is the human impedance controller, E is the environmental impedance controller, Xh is the motion of the manipulator determined by the human impedance controller H and Xe is the motion of the manipulator calculated by the environmental impedance controller E. X is the final motion of the manipulator. We determine this final motion of the manipulator by both Xh and Xe.

We can express these impedance controllers as follows;

$$H = M_h \cdot s^2 + D_h \cdot s + K_h \quad (4)$$

$$E = M_e \cdot s^2 + D_e \cdot s + K_e \quad (5)$$

where s is a Laplace operator,Mh is the mass matrix of the human impedance controller,Dh is the damper matrix of the human impedance controller,Kh is the stiffness matrix of the human impedance controller,Me is the mass matrix of the environmental impedance controller,De is the damper matrix of the environmental impedance controller and Ke is the stiffness matrix of the environmental impedance controller. With these two impedance controllers, we can control both the motion of the end effector of the manipulator based on the operator's intentional force and the interaction between the end effector and the environment.

3. Motion Decomposition of End Effector

To model the manipulator/vehicle system, we introduce two coordinate systems used in the as shown in fig. 3.

(1) **The inertial coordinate system**(Oo-xoyozo). The position of the end effector of the manipulator and the position of the vehicle are given in this coordinate system.

(2) **The vehicle coordinate system**(Ov-xvyvzv). This coordinate system is fixed to the vehicle. The center of gravity of the manipulator including a payload is given in this vehicle coordinate system.

The manipulator/vehicle system for man-robot cooperation is the robot manipulator system mounted on the mobile mechanism. The manipulator/vehicle system has redundant degrees of freedom. When the desired motion of the manipulator's end effector in the inertial coordinate system is given, the motion has to be decomposed into the motion of the manipulator and the motion of the vehicle. That is; the desired position of the manipulator's end point is decomposed as follows:

$$X = X_m + X_v \quad (6)$$

$$X_m = (1-\alpha) \cdot X \quad (7)$$

$$X_v = \alpha \cdot X \quad (8)$$

where X is the desired motion of the manipulator's end point in the inertial coordinate system and the motion is determined by equation (3). Xm is the motion of the manipulator in the vehicle coordinate system and Xv is the motion of the vehicle in the inertial coordinate system. α is the decomposition ratio of the motion of the end effector in the inertial coordinate system; if the decomposition ratio α is set nearly equal to zero, the motion of the end effector is realized by the motion of the manipulator and if the ratio α is set nearly equal to unity, the motion of the end effector is realized by the motion of the vehicle.

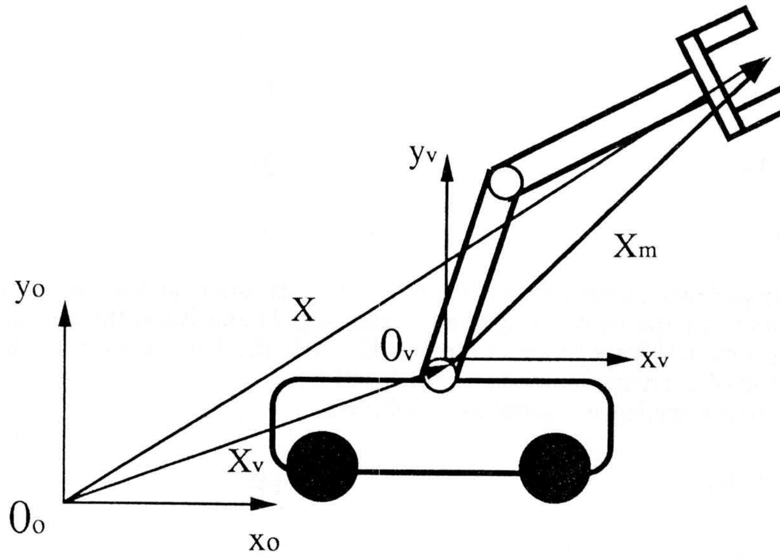

Fig. 3 Coordinate Systems

4. Control of Manipulator/Vehicle System Based on Human Intention

The decomposition of the motion of the end effector should be done based on the operator's intention. How to decompose the motion of the end effector is one of the key issues of the manipulator/vehicle system for man-robot cooperation. In this section, we propose a control system of manipulator/vehicle system for man-robot cooperation based on the human intention. Fuzzy logic is used to decompose the motion based on the operator's intention, that is, we determine the decomposition ratio of the motion of the system using fuzzy logic. In this fuzzy logic system, we use two kinds of the fuzzy rules; the rules based on the operational force detected by the operational force sensor and the rules based on the manipulability of the manipulator. The first one is used to take the operator's intention into account. One may apply the large operational force when he wants to move the vehicle, while one may apply the small operational force when he wants to manipulate an object. The second one is to avoid the singular point of the manipulator and to realize the large working area.

The manipulability ω of the manipulator proposed by T. Yoshikawa [11] is calculated as follows.

$$\omega = \sqrt{\det\left\{J(\theta)J(\theta)^T\right\}} \tag{9}$$

where $J(\theta) \in R^{m \times n}$ is the Jacobian matrix of the manipulator and θ is the joint coordinate vector. In the case of m=n, we can calculate the maneuverability of the manipulator as follows:

$$\omega = \left|\det\left\{J(\theta)\right\}\right| \tag{10}$$

The manipulability of the manipulator has the relation with the distance between the singular point of the manipulator and the end point of the manipulator. If the manipulability is small, the end point of the manipulator is close to the singular point of the manipulator, that is, the manipulator is hard to be manipulated. On the other hand, if the manipulability is large, the end point of the manipulator is far from the singular point of the manipulator, that is, the manipulator is easy to be manipulated.

We have to consider the singular point of the manipulator when we control the manipulator/vehicle system cooperatively. Unless we take the singular point of the manipulator into account, the system can not move anymore when the manipulator reach the singular point. For these reasons, we decide the fuzzy rules for the singular point of the manipulator with respect to the manipulability of the manipulator system as follows.

If the manipulability of the manipulator is small then the vehicle should move. On the other hand, if the manipulability of the manipulator is large then the manipulator should move.

5. Experimental System

The manipulator/vehicle system for man-robot cooperation has been developed experimentally for pick-and-place operation of a heavy object. Figure 4 shows the photograph of the experimental system and fig. 5 shows the structure of the manipulator vehicle system, which we have developed. The manipulator has a parallel link mechanism with four degrees of freedom and each joint is driven by a DC motor through reducers (Harmonicdrives). It has a vacuum sucker attached to the end of the arm to manipulate the heavy object. The manipulator has two force/torque sensors. One is "the operational force sensor", which is attached to the end of the final link of the manipulator. The other is "the environmental force sensor, which is attached to the position between the end effector and the final link of the manipulator. We can measure the operational force and the contact force by these two sensors.

The vehicle is driven by two DC motors through reducers. The vehicle can do the rotary motion and the straight motion with these two DC motors.

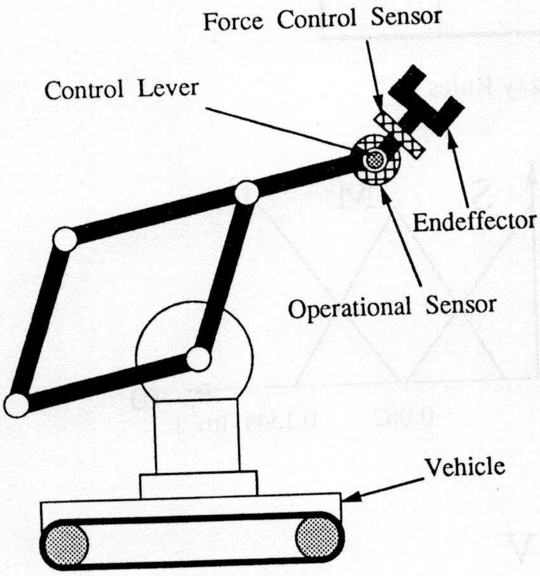

Fig. 4 Structure of Experimental System

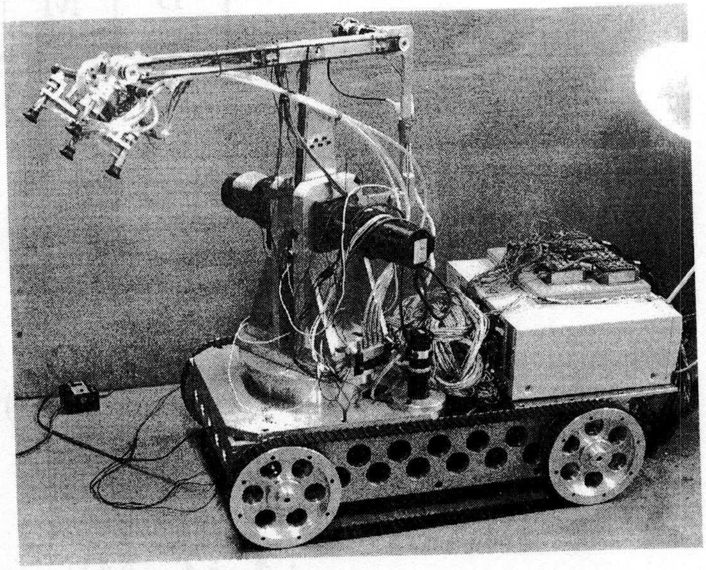

Fig. 5 Photograph of Experimental System

6. Experiments

We used the experimental system as two degrees of freedom manipulator and one degree of vehicle. Figure 6 shows the fuzzy rules used for the manipulator/vehicle. F_h means the operational force applied by a human operator and the force can be measured by the operational force sensor. ω means the manipulability of the manipulator. B represents big, M represents medium and S means small, respectively.

Figure 7 shows the membership function used in this fuzzy logic. The manipulability of the manipulator in this experimental system ω is calculated as follows;

$$\omega = \left|\det(J(\theta))\right| = \left| l_1 \cdot l_1 \cdot \sin(\theta_2) \right| \qquad (11)$$

$$J = \begin{bmatrix} -l_1 \cdot \sin(\theta_1) - l_2 \cdot \sin(\theta_1 + \theta_2) & -l_2 \cdot \sin(\theta_1 + \theta_2) \\ l_1 \cdot \cos(\theta_1) + l_2 \cdot \cos(\theta_1 + \theta_2) & l_2 \cdot \cos(\theta_1 + \theta_2) \end{bmatrix}$$

The link parameters of this experimental manipulator system is as follows;

$l_1 = 0.32$[m], $l_2 = 0.42$[m]

Fh / ω	S	M	B
S	V	V	V
M	M	MV	V
B	M	M	M

Fig. 6 Fuzzy Rules

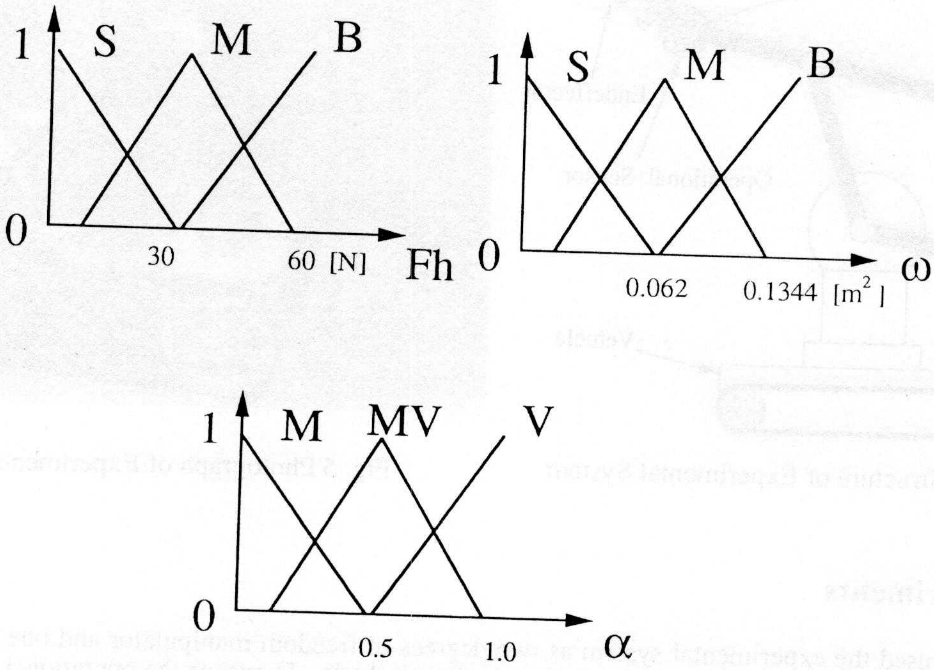

Fig.7 Membership Functions

The largest manipulability of the experimental manipulator system ω_{max} is equal to 0.1344[m^2] when the joint angle θ_2 equals ±90 deg., while the smallest manipulability of the experimental manipulator ω_{min} is equals to zero when the joint angle θ_2 equals ±180 deg.

We applied the proposed fuzzy logic system to the manipulator/vehicle system for man-robot cooperation, which consists of a manipulator with two degrees of freedom and vehicle with one degree of freedom.

Figure 8 illustrates the experimental results without fuzzy logic system. It is an example of the experimental results when the decomposition ratio α is equal to 0.5. Figure 9 also illustrates the experimental results with fuzzy logic system proposed in this paper. X is the desired position of the end point of the manipulator, x_m is the position of the manipulator's end point in the x-axis direction with respect to the vehicle coordinate system, y_m is the position of the manipulator's end point in the y-axis direction in the vehicle coordinate system and x_v is the position of the vehicle in the inertial coordinate system.

From fig.8(x), the manipulator/vehicle system can not move anymore when the system reach 0.25 [m], because both the manipulator and the vehicle try to move in spite of the manipulator's end point reaches the singular point. From fig. 9(x), the system can move over the position 0.25 [m], because the decomposition ratio α is determined with respect to the manipulability of the manipulator ω. As discussed in section 4, when the manipulability of the manipulator is small then the decomposition ratio is determined close to unity and the manipulability of the manipulator is large then the decomposition ratio is determined close to zero. From these experimental results, we can understand that the manipulator/vehicle system for man-robot cooperation can extend the working area using the proposed fuzzy logic system.

7. Conclusions

The manipulator/vehicle system has redundant motion degrees of freedom on the ground. How to decompose the motion of the system on the ground into the motion of the vehicle and the motion of the manipulator has discussed, and a control algorithm using fuzzy logic was proposed in this paper. We designed the motion of the end effector using two impedance controllers, so that the end effector is controlled based on the operator's intention and the interaction with the environment. The motion of the end effector was decomposed into the manipulator motion and the vehicle motion modelled by a set of fuzzy rules. The proposed control algorithm extends the working space of the system, which keeping the manipulability of the system. Finally experimental results illustrated the effectiveness of the proposed control system.

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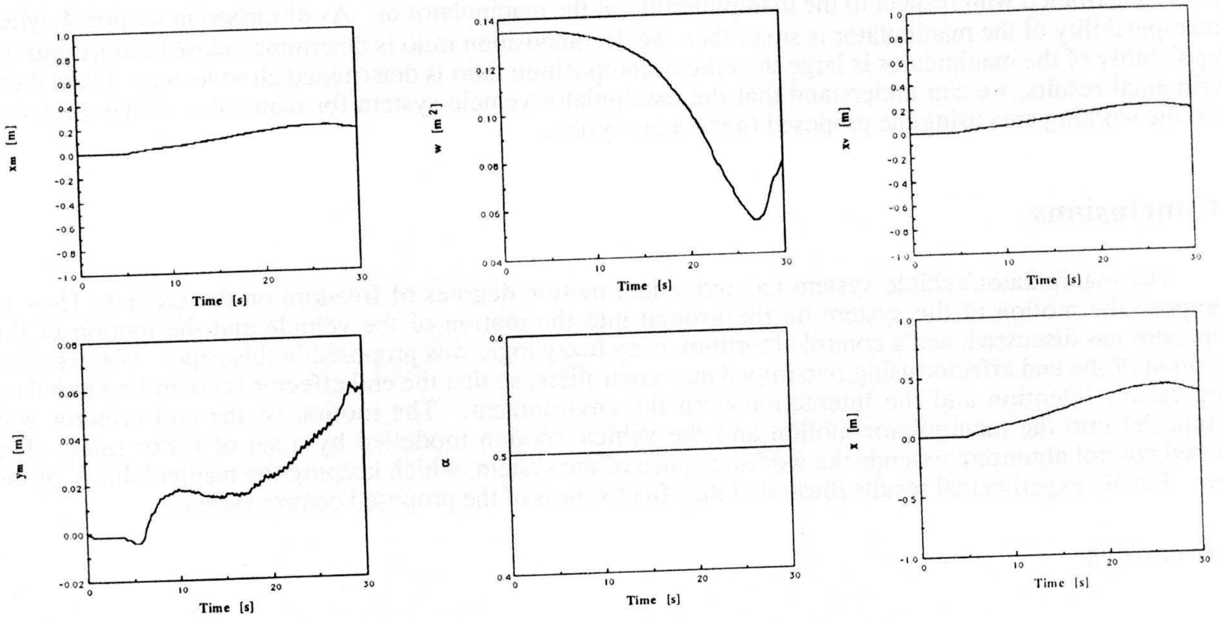

Fig. 8 Experimental Results (Without Fuzzy Logic System.)

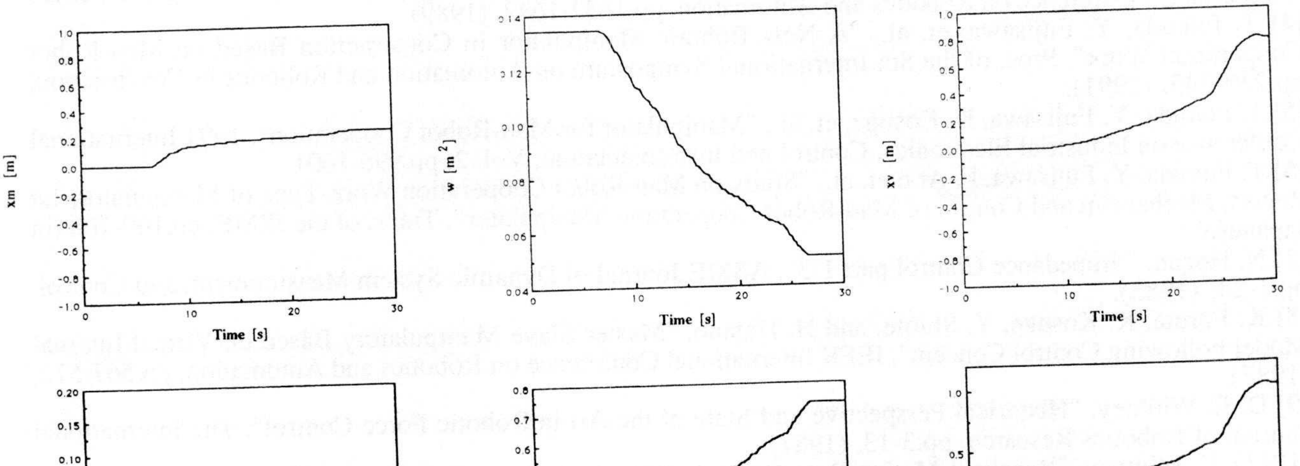

Fig. 9 Experimental Results (With Fuzzy Logic System.)