Position/Force Control of Robot Manipulators for Geometrically Unknown Objects Using Fuzzy Neural Networks

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***Abstract*—In order to carry out the tasks of grinding, deburring, polishing, or wiping, the end-effector of the robot manipulator has to follow the contour of an object. In this paper, we propose a fuzzy vector method, which enables the controller to deal efficiently with force sensor signals which include noise and/or unknown vibrations caused by the working tool, to search the direction of the constraint surface of an unknown object.**

***Index Terms*—Force control, force measurement, fuzzy logic, fuzzy neural networks, intelligent control, robots.**

I. Introduction

POSITION/FORCE control has to be performed to realize sophisticated tasks such as grinding, deburring, polishing, or the wiping task by robot manipulators. Hybrid position/force control [1], [2] is one of the most effective methods to control the position and the force precisely. Most of the studies on hybrid position/force control, however, have been performed assuming that the shape of the object had been previously known. For research on the hybrid position/force control for a geometrically unknown object, Luo *et al.*[3] proposed the estimation method of the vector field model of an uncertain environment by integrating the information of sampled contact force and position vector data position and interaction force. It is not suitable for tasks such as deburring or grinding, since they require information about the contact force and position vectors at several locations on the object in advance. Yoshikawa and Sudou [4] proposed an unknown constraint estimation algorithm using reaction force from the environment, the current end-effector trajectory, and the virtual plane. Other researchers [5], [6] search the constraint surface of an unknown environment from the information from reaction force of the environment using force sensors, assuming that the friction force is negligible. However, the noise from the force sensor and/or the unknown vibrations from tools, such as grinders, are not mentioned in these studies. Friction force, noise, and unknown vibrations cannot be ignored practically in order to perform a task such as deburring or grinding. Furthermore, they assumed that the force control direction at the initial time was previously known, and have not mentioned the initial force control direction searching algorithm. In order to obtain the reaction force from a geometrically unknown object, somehow, initial force has to be applied to the object at first. The initial applied force should be small since it might not applied to the proper direction. When the applied force to the object is small, the force control direction might be changed in the wrong direction at every sampling time because vibrations from tools such as grinders and/or noise might dominate the signals from the force sensor. In this paper, we introduce an effective online force control direction adjustment algorithm for an unknown object. We propose a fuzzy vector method in order to deal with force sensor signals which include noise and/or unknown vibrations of the working tools.

It is difficult to decide the desired force and position (tool trajectory) to carry out tasks such as deburring, since it depends on the property of the object and the size of the burr. In this paper, the intelligent task planner [7] is applied to generate the desired force and the desired tool trajectory for the task. The fuzzy neural position/force controller [7], [8] is used to apply force to the unknown environment as it adjusts the force control direction using the fuzzy vector method, and to follow the geometrically unknown surface of the object.

In this study, an end-effector of a robot manipulator is assumed to be in contact with an object initially, although considering the approaching process is also an important topic practically. Therefore, impact force which might occur when the robot manipulator makes contact with the object is not considered. The effectiveness of the proposed method is evaluated by experiment with a two–degrees–of–freedom (2DOF) planar robot manipulator.

II. Position/Force Hybrid Control

In order to control force applied to an object and position on the surface of the object simultaneously with a robot manipulator, a hybrid position/force controller [1], [2], [7], [8] seems to be a proper controller. Considering the dynamic equation of the planar robot manipulator and the selection matrix S, which selects the directions for the force control that is normal to the constraint surface of the object and for the position control that moves along the constraint surface, the following equation can be written for the hybrid control:

$$\tau = M(q)J^{-1}\{E^{-1}[(I-S)u_p - \dot{E}J\dot{q}] - \dot{J}\dot{q}\} + h(q,\dot{q}) + F_c\,\mathrm{sgn}(\dot{q}) + J^TE^Tf + J^TE^TSu_f \quad (1)$$

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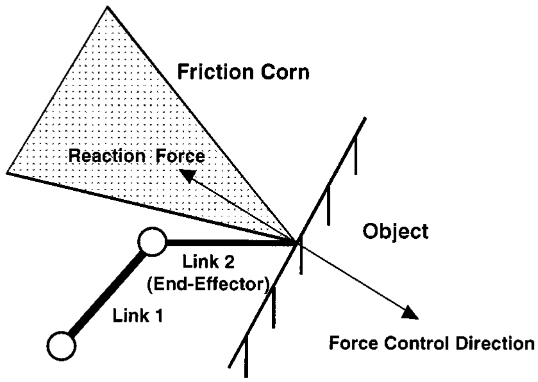


Fig. 1. Friction corn.

where u_p is a command vector for position control, u_f is a command vector for force control, and E is a transformation matrix from the Cartesian coordinate system to the constraint coordinate system. The transformation matrix E is adjusted at every sampling time during the control using the fuzzy vector method since the shape of the object is assumed to be unknown. In this paper, the fuzzy neural controller is applied to each control loop of the hybrid controller (see [7] for details).

III. Force Control for a Geometrically Unknown Object

In this section, an online force control direction adjustment algorithm is proposed to coincide with the opposite direction of the normal vector of the constraint surface using the fuzzy vector method. One direction in the Cartesian coordinate system is decided to be an initial temporal force control direction assuming it is not parallel to the constraint surface of the unknown surface. Then, the temporal force control direction is adjusted based on the reaction force information from a six-axes force sensor (a strain-gauge-based sensor), which is located between link1 and link2 (end-effector) of the 2DOF planar robot manipulator, at every sampling time. Therefore, the force control direction is adjusted to coincide with the opposite direction of the normal vector, assuming it is the same direction as the reaction force. In this case, however, the direction of the reaction force might not be perpendicular to the unknown surface since it is affected by the frictional force between the robot manipulator and the object. Consequently, the obtained direction of the reaction force is located somewhere in the friction corn, as shown in Fig. 1. If the manipulator is already moving on the unknown constraint surface, the direction of the normal vector not affected by the frictional force might be obtained by removing the frictional force component from the reaction force, assuming the moving direction of the end-effector is the tangential direction of the constraint surface [4]. However, the moving direction of the end-effector does not exactly coincide with the tangential direction of the object when the object is deformed by the applied force. Therefore, this method is not applicable for a deformable object.

There might exist some problems if the force control direction is changed exactly to the direction which is opposite to the reaction force vector, since the direction of the reaction force is calculated from the force sensors which include noise and/or unknown vibrations of the working tool. If the current force control direction is much different from the obtained opposite direction of the reaction force, the next force control direction can be changed to the same direction as the obtained opposite direction of the reaction force. However, if the current force control direction is almost the same as the obtained opposite direction of the reaction force, the amount of force control direction adjustment should be less than the obtained angle difference in order to reduce the adverse effects of noise and/or unknown vibrations. Otherwise, the noise and/or unknown vibrations might cause major changes in the force control direction at every sampling time. Furthermore, the noise and/or unknown vibrations might dominate the signals from the force sensor when the applied force is small. In this case, also, the amount of force control direction adjustment should be less than the obtained angle difference in order to prevent the force control direction from being changed to the wrong direction, because accuracy of the obtained direction is low. Therefore, the amount of force control direction adjustment should be changed according to the amount of applied force and the difference between the current force control direction and the obtained opposite direction of the reaction force. In this paper, a fuzzy vector method is proposed to express the magnitude of the accuracy and coincidence of the vectors, and applied for the force control direction adjustment algorithm during tasks such as deburring or grinding.

A. Fuzzy Vector

In this section, we will discuss the fuzzy vectors, in other words, inaccurate vectors. Since the obtained vector of the reaction force contains an error caused by noise and/or unknown vibrations from the working tools, it is convenient if it is dealt with as a fuzzy vector whose magnitude and direction are fuzzy. It is possible to express the accuracy of the vector according to the magnitude of the vector, and the similarity of the direction of the vectors. We assume that the six-axes force sensor is located to measure the force component along the end-effector length and the force component that is perpendicular to the end-effector length by overlapping the sensor axis with the end-effector length. Therefore, the force component of only the x-axis and y-axis of the force sensor are supposed to be used for measuring reaction force from an environment for the 2DOF planar robot manipulator. Since both of these force components are effected by noise and/or unknown vibrations, the magnitude and direction of the calculated normal vector of the unknown surface using these force components are inaccurate. The fuzzy vector is depicted in Fig. 2(a) and (b). The ellipse is used instead of the arrow to express the pointed end of the component vector since the magnitude of the measured force component is not accurate. Therefore, the pointed end of the component of the fuzzy vector is located somewhere in the ellipse. In Fig. 2(a) and (b), the pointed end of the fuzzy vector that is calculated from the measured force components is located somewhere within the square, and the direction is located somewhere in the blackened area. Comparing the fuzzy vector of Fig. 2(a) with that of Fig. 2(b), we can see that the fuzzy vector composed of a bigger force component has less fuzziness if the amount of error caused

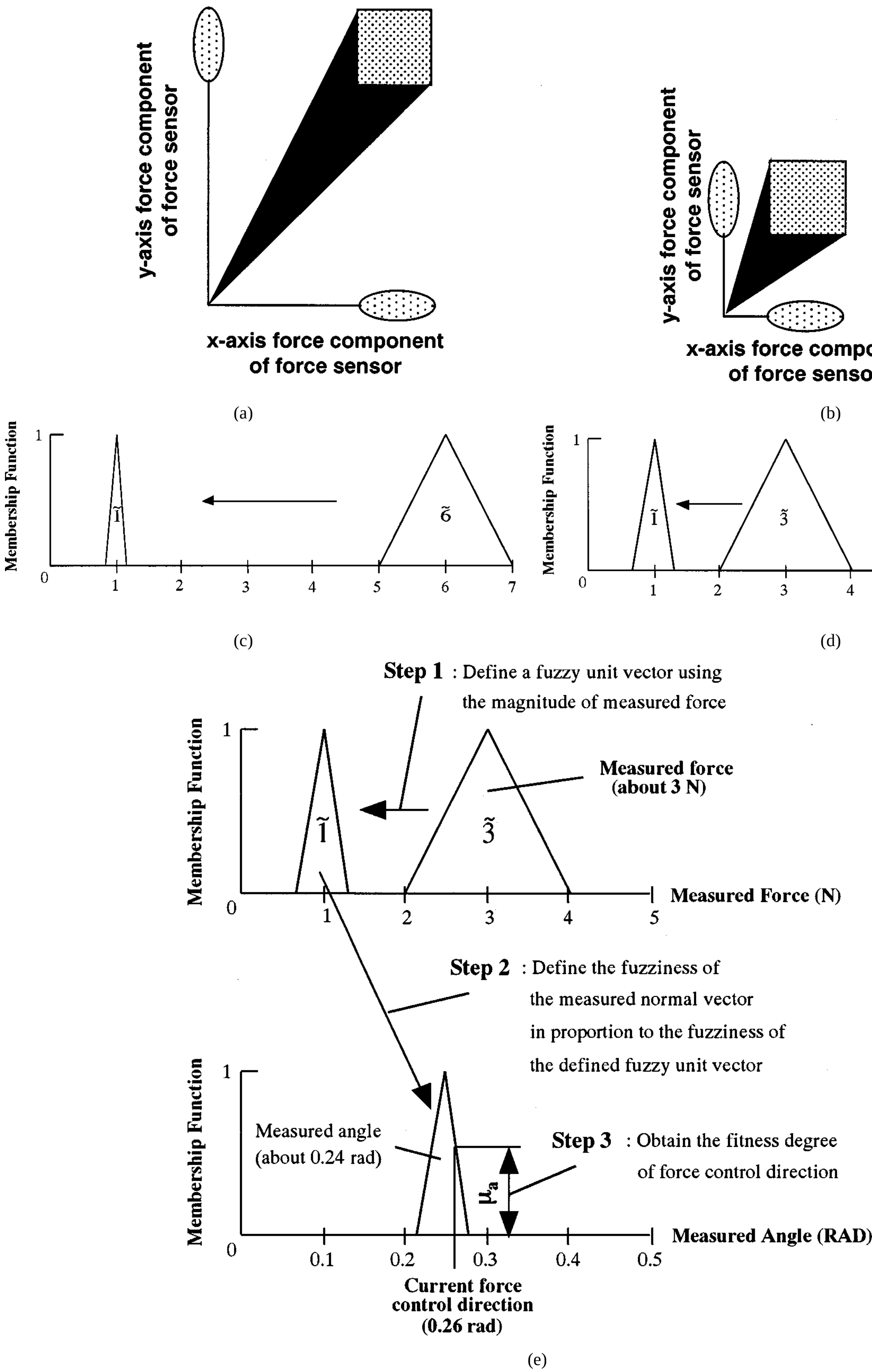


Fig. 2. Fuzzy vectors.

by noise and/or unknown vibrations in the force component is at the same level. Consequently, if the applied force is smaller, the calculated normal vector is fuzzier.

The magnitude of the fuzzy vector is dealt with as a fuzzy number. If we convert a vector whose magnitude is expressed by a fuzzy number to a fuzzy unit vector, then a smaller magnitude vector is converted to a fuzzier unit vector. For example, if we divide the fuzzy number $\tilde{6}$ (about 6) and $\tilde{3}$ (about 3) by the crisp numbers 6 and 3, respectively, the membership function of the fuzzy number $\tilde{1}$ which is calculated from the fuzzy number $\tilde{3}$ becomes wider, as shown in Fig. 2(c) and (d). The number whose membership function is wider is a fuzzier number. The fuzziness of the calculated unit vector indicates the fuzziness of the calculated normal vector.

The amount of force control direction adjustment is controlled according to the degree of coincidence between the current force control direction and the opposite direction of the obtained normal vector of the unknown constraint surface applying the concept of fuzzy control.

B. Force Control Direction Adjustment Algorithm (Fuzzy Vector Method)

The membership function that expresses the fuzziness of the fuzzy normal vector direction is defined according to the magnitude of the fuzzy normal vector, as shown in Fig. 2(c) and (d). Therefore, a bigger magnitude vector is considered a more accurate vector. In other words, a bigger magnitude vector contains lower fuzziness in the direction of the obtained normal vector.

The amount of angle adjustment for the next force control direction is written as

$$\Delta\alpha_f = (1-\mu_a)(\alpha_n - \alpha_f) \tag{2}$$

where μ_a is the fitness of the angle between the current force control direction and the opposite direction of the obtained normal vector, α_f is the angle of the current force control direction, and α_n is the angle of the opposite direction of the obtained normal vector of the unknown constraint surface. It becomes possible to control the amount of force control direction adjustment according to the degree of coincidence of the angle between the current force control direction and the opposite direction of the obtained normal vector. Each step of the proposed algorithm (fuzzy vector method) is explained below. Fig. 2(e) shows an example of the process of this algorithm in the case where the current force control direction is 0.26 rad, the magnitude of the measured reaction force is about 3 N, and the angle of the measured normal vector is about 0.24 rad.

Step 1: Transfer the normal vector of the unknown constraint surface which is obtained from the force sensor to a fuzzy unit vector to obtain the fuzziness of the fuzzy unit vector. Here, a larger amount of fuzziness makes a wider shape of membership function [see Fig. 2(c) and (d)].

Step 2: Define the fuzziness of the angle of the fuzzy normal vector in proportion to the fuzziness of the fuzzy unit vector. In other words, transfer the shape of membership function of the fuzzy unit vector to that of the angle of the fuzzy normal vector according to the transfer rate defined by human experts, as shown in Fig. 2(e). (Therefore, if the shape of membership function of the fuzzy unit vector is narrow, the shape of the membership function of the angle of the fuzzy normal vector also becomes narrow.)

Step 3: Obtain the opposite direction of the fuzzy normal vector and calculate the fitness of the angle between the current force control direction and the opposite direction of the obtained normal vector.

Step 4: Adjust the force control direction in accordance with the amount calculated in (2).

This force control direction adjustment is carried out not only in the beginning, but also during tasks.

IV. Position Control for a Geometrically Unknown Object

In order to follow the unknown contour of the object to perform tasks, the position control direction which is perpendicular to the force control direction has to be adjusted based on the shape of the objects surface. Using the proposed algorithm (fuzzy vector method), the force control direction will stay in the friction corn (see Fig. 1). However, this algorithm does not guarantee that the force control direction will be perpendicular to the object's surface, since the friction force exists. Therefore, the position control direction that is supposed to be tangential to the object's surface might not be obtained accurately. In the case where the summed vector of the driving force vector for force control and that for position control stays in the friction corn, because of the control direction error, as shown in Fig. 3(a), the end-effector does not move, even though the driving force for position control exists. In this case, the opposite direction of the summed vector of the driving force vectors is the reaction force from the object. Then, the reaction force from the object is used for changing the force control direction according to the proposed force control direction adjustment algorithm. On the other hand, in the case when the summed vector of the driving force vector for force control and that for position control goes out from the friction corn, as shown in Fig. 3(b), the end-effector moves along the object's surface because of the effect of the driving force for the force control, even though the current position control direction is incorrect. In this case, the desired position might not be realized since the position control direction is not always correct. However, the position error caused by the position control direction error can be compensated for by the fuzzy neural network position controller [7], [8].

It is difficult to generate the desired trajectory to perform some tasks like deburring or grinding with a geometrically unknown object. The surface following algorithm used by Kraft [9] and Bossert *et al.*[5] can be utilized to cope with the change of the position control direction, although the friction between the end-effector and the object, noise, and/or unknown vibrations from tools were ignored in their study. Each step of this algorithm, which is illustrated in Fig. 3(c), is written as follows.

Step 1: Obtain the position of the end-effector and the tangential direction based on the measured force control direction using the proposed force control direction adjustment algorithm at time t_0, and define the position as position X_0.

Step 2: Define the desired position (x_{dx1}, x_{dy1}) in the tangential direction in the Cartesian coordinate with a

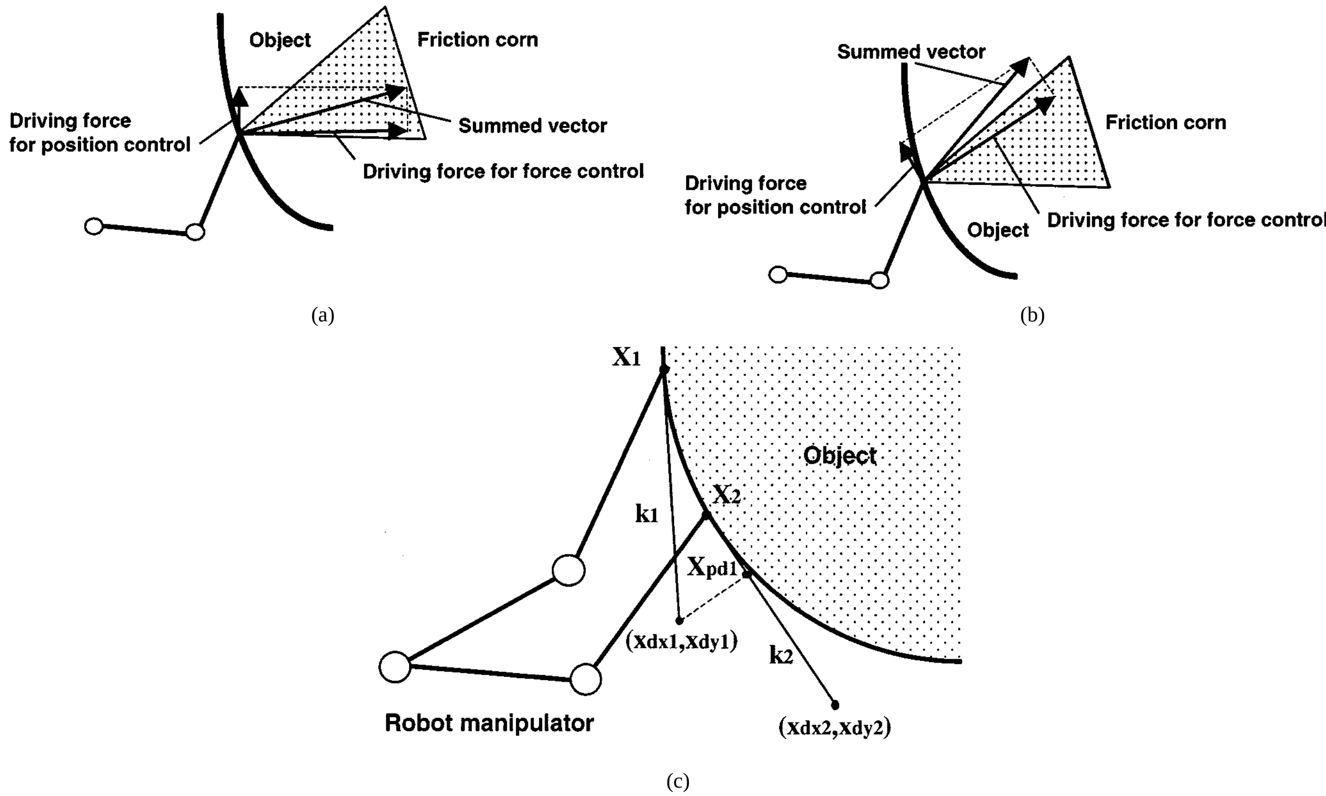


Fig. 3. Robot manipulator in contact with an object.

distance k_1 which is generated by the intelligent task planner at time t_0.

Step 3: At time t_1, one sample period after t_0, obtain the new position of the end-effector and the new tangential direction based on the measured force control direction using the proposed force control direction adjustment algorithm, and define the position as X_1.

Step 4: The previous desired position (x_{dx1}, x_{dy1}) is then projected onto the new tangential line; define the position X_{pd1}.

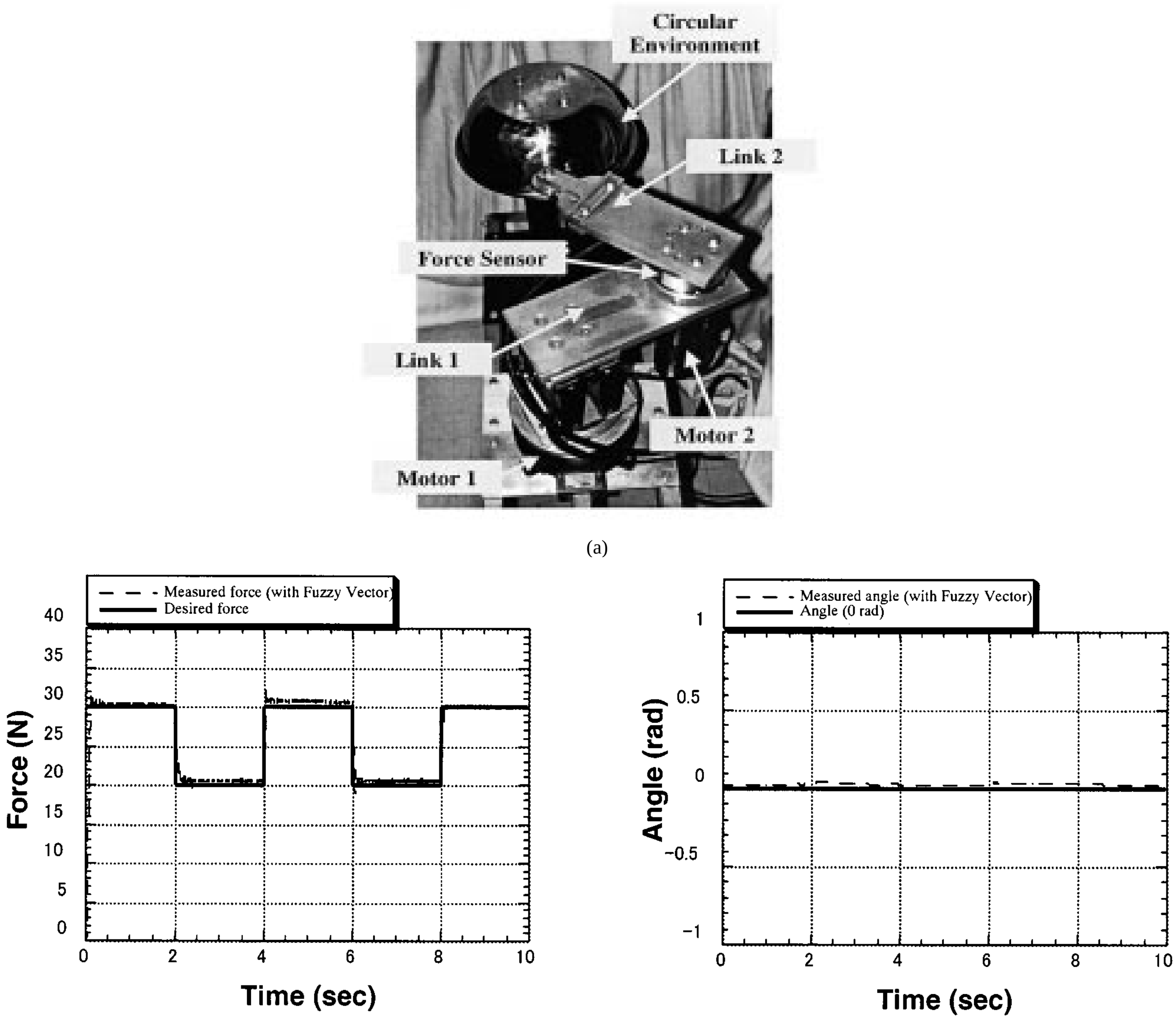
Step 5: The next desired position (x_{dx2}, x_{dy2}) is located at distance k_2, which is generated by the intelligent task planner at time t_0, from X_{pd1} along the new tangential direction.

This process is repeated during the hybrid position/force control. The desired tool trajectory generated to carry out the required task can be realized by the adaptation ability of the fuzzy neural network position controller. The objective of this adaptation is to make the position error between X_{pd1} and X_1 zero.

V. Intelligent Position/Force Controller [7]

The desired force and position (tool trajectory) for the task are generated by the intelligent task planner, and then they are realized by the fuzzy neural position/force controller, as we introduced in [7]. The intelligent task planner [7] consists of the fuzzy property estimator and the fuzzy neural planner. The fuzzy property estimator evaluates the hardness of an unknown object and generates the desired force for the force control and the desired tool trajectory (the desired position at each control step) coefficient for the position control according to the hardness of the object. The other role of the fuzzy property estimator is generating the input adjustment coefficients for the fuzzy neural force controller according to the hardness of the object. The fuzzy rules of this estimator have been designed based on the knowledge and the experience of the human experts. The fuzzy neural planner generates the desired tool trajectory depending on the size of the burr. The input variable to the fuzzy neural planner is the size of the burr. The generated desired tool trajectory according to the burr size is multiplied by the desired tool trajectory coefficient generated from the fuzzy property estimator. Therefore, both burr size and hardness of the object are taken into account to decide the desired tool trajectory in the planner. The rules in the fuzzy neural planner are adjusted online by monitoring the performed task.

The fuzzy neural position/force controller [7], [8], in which fuzzy neural networks are incorporated into hybrid control, is applied for control of the robot manipulator to realize the desired force and position (tool trajectory). Controller adaptation is carried out for both position and force control laws at every sampling time. However, the controller should not be adjusted until the position control direction becomes close to the tangential direction of the objects surface. Consequently, we suggest multiplying the amount of weight adjustment by μ_a (the fitness of the angle between the current force control direction and the opposite direction of the obtained normal vector shown in (2)). The fuzzy neural force control law is adjusted online to realize the desired force with an unknown object. The position control law consists of a fuzzy neural network division for trajectory control and a specialized neuron division for friction compensation. The position error mainly caused by the friction force can



(a)

(b)

(c)

Fig. 4. Experiment. (a) Experimental setup. (b) Force response at 0 rad (with the proposed method). (c) Angle of the tangential direction at 0 rad (with the proposed method).

be compensated for by learning the friction coefficient between the end-effector and the object with the specialized neuron division for friction compensation, and that caused by other effects such as the position control direction error can be reduced by the learning (adaptation) of the fuzzy neural network division for trajectory control.

VI. Experiment

An experiment has been performed with a 2DOF planar robot manipulator to confirm the effectiveness of the proposed method for the geometrically unknown object, as shown in Fig. 4(a). The sampling time for the experiment is set to 2 ms for every experiment. In order to reduce the friction between the end-effector and the object, a roller was attached to the tip of the end-effector. A direct-drive motor (NSK: YS2020FN001) is used for motor 1 and a harmonic geared dc motor (Harmonic Drive Systems: RHS-14-3003-E050D0) is used for motor 2. A six-axes force sensor (NITTA Universal Force-Moment Sensor System UFS-3512A25-FS5) is located between link1 and link2 (end-effector). The digital signal processor (DSP) is used to control the robot manipulator. The signals from the force sensor are filtered by a low-pass filter at 150 Hz. It is possible to use signals filtered at lower frequency for the fuzzy vector method. However, it is not recommended to use signals filtered at lower frequency for the real-time force control adjustment, since the filtering causes the time lag. A circular object [see Fig. 4(a)], whose radius is about 0.1 m, is prepared as an unknown object. The end-effector is assumed to be in contact with the object in advance.

For the first evaluation, force control has been performed at different points on the object in order to confirm the effectiveness of the proposed force control direction adjustment algorithm which searches the normal direction of the unknown constraint surface and adjusts the force control direction to its opposite direction. The angle of the tangential direction at one contact point is 0 rad and that at the other contact point is 0.8 rad from

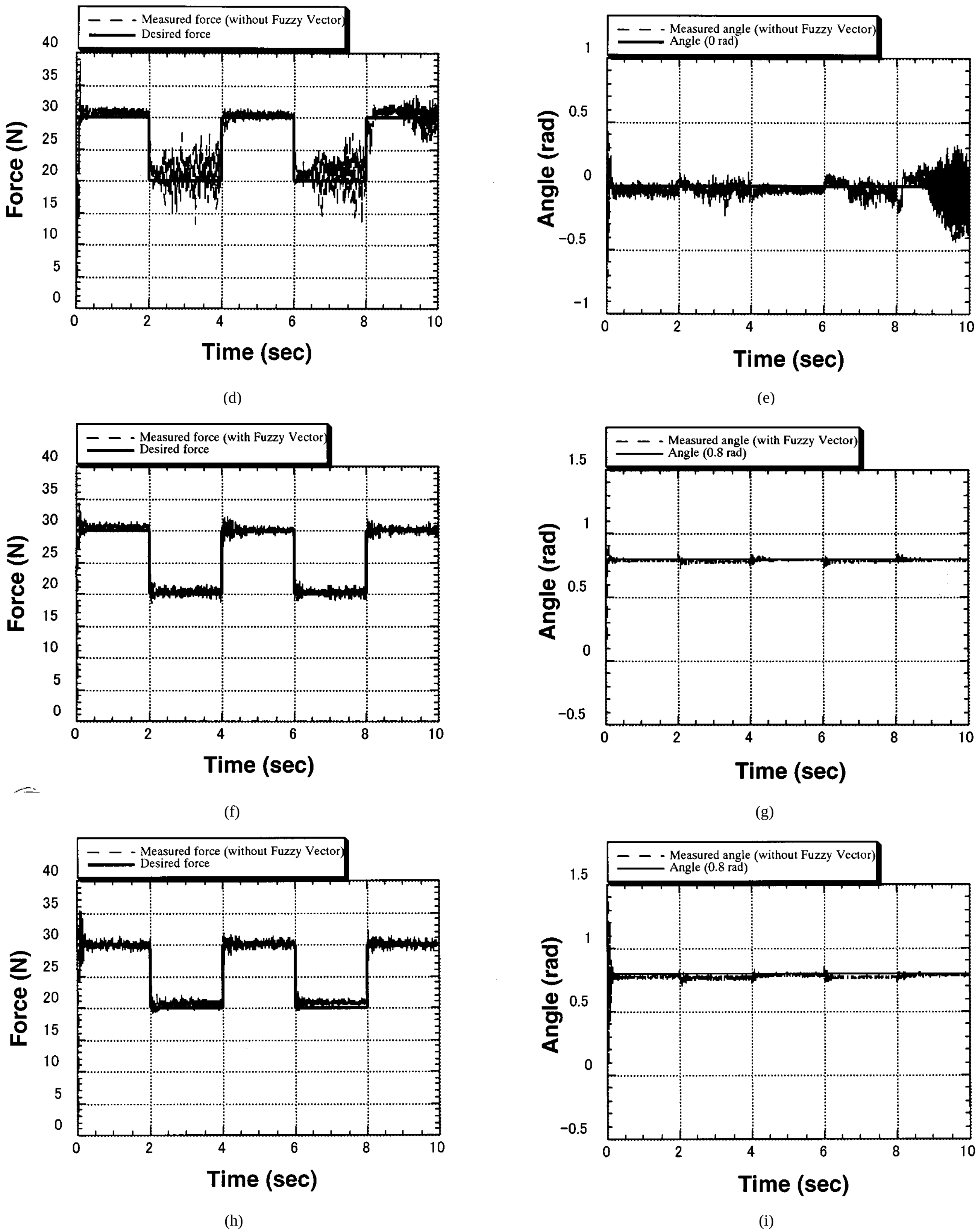
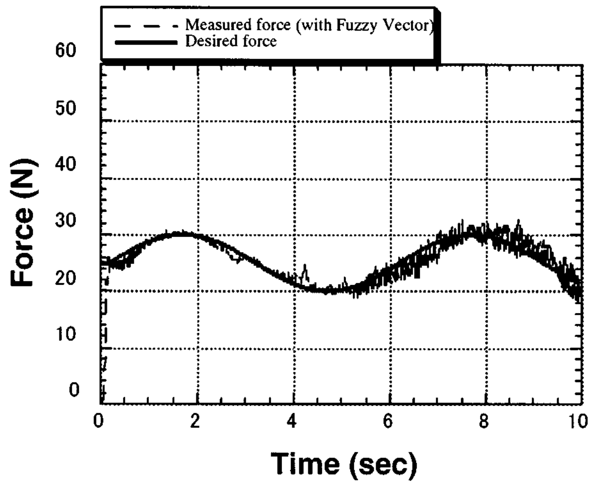
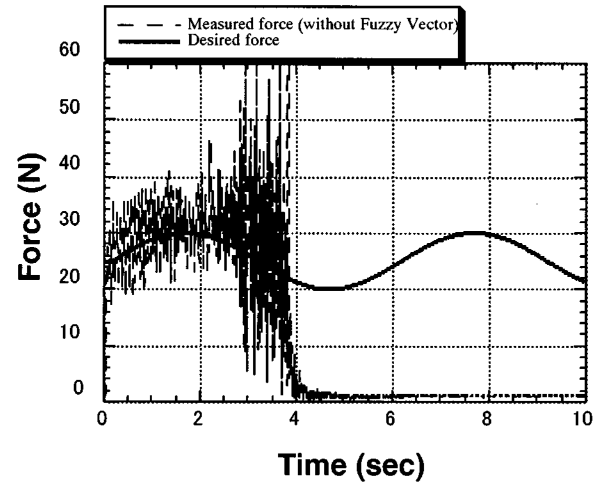


Fig. 4. *(Continued.)* Experiment. (d) Force response at 0 rad (without the proposed method). (e) Angle of the tangential direction at 0 rad (without the proposed method). (f) Force response at 0.8 rad (with the proposed method). (g) Angle of the tangential direction at 0.8 rad (with the proposed method). (h) Force response at 0.8 rad (without the proposed method). (i) Angle of the tangential direction at 0.8 rad (without the proposed method).

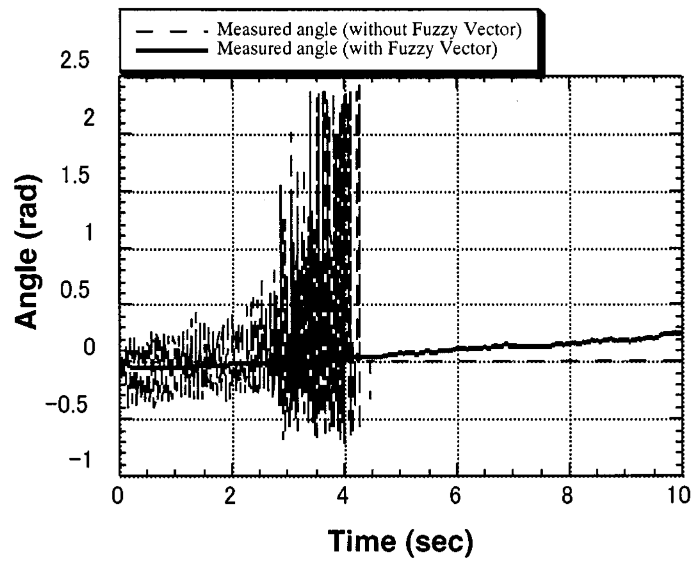
the y axis of the Cartesian coordinate system. In this experiment, the robot manipulator applies force at the same position on the object. The desired contact force to an object is a combination of step signals changed between 30–25 N every 2 s.



(j)



(k)



(l)

Fig. 4. *(Continued.)* Experiment. (j) Force response (with the proposed method). (k) Force response (without the proposed method). (l) Angle of the tangential direction.

Every experiment has been performed with and without the proposed algorithm. The results (the force response and the measured angle of the tangential direction) with the proposed algorithm where the angle of the tangential direction at the contact point is 0 rad, in other words, the results where force control direction is already coincident with the opposite direction of the normal vector of the constraint surface from the beginning, is shown in Fig. 4(b) and (c). It is seen that the desired force can be realized precisely. The amount of force control direction change is little during the control since the direction has been coincident with the opposite direction of the normal vector of the constraint surface from the beginning. The results without the proposed algorithm where the angle of the tangential direction at the contact point is 0 rad is shown in Fig. 4(d) and (e). It is seen that the force control direction changes much at every sampling time because of the effect of the noise, even though the direction is coincident with the opposite direction of the normal vector of the constraint surface at the beginning. It is also seen that the direction change is affected by the magnitude of the applied force, in particular, in the beginning of control. Consequently, it can be stated that the better force response is obtained with the proposed algorithm.

The result with the proposed algorithm when the angle of the tangential direction at the contact point is 0.8 rad is shown in Fig. 4(f) and (g), and that without the proposed algorithm is shown in Fig. 4(h) and (i). It is seen in Fig. 4(g) that the force control direction is settled to the opposite direction of the normal vector of the constraint surface from the beginning of the control. On the other hand, it is seen in Fig. 4(i) that the force control direction is changed to the wrong direction in the beginning of the control and then settled around the right direction, since the noise dominates over the force components when the magnitude of the applied force is small. It can be said, again, that the better force response can be obtained with the proposed algorithm, although the effect of the proposed method in this experiment is not as obvious as that in the previous experiment because the direction of the reaction force in this experiment is almost the same as the x axis of the force sensor under this configuration of the robot manipulator.

For the second evaluation, position/force control has been performed on the unknown object. In this experiment, the end-effector is supposed to move in the y direction in the Cartesian coordinate as it applies the force to the object. The desired contact force, which is supposed to be generated by the intelligent task planner, is set to be a sinusoidal signal $25.0 + 5.0\sin(\pi t/3)$ N in this experiment. The desired position (obtained from the tool trajectory), which is also supposed to be generated by the intelligent task planner, is set to be sinusoidal signal $0.1\sin(\pi t/75)$ m in this experiment.

The experimental result of the force response with the proposed method is shown in Fig. 4(j), and the result without the proposed method is shown in Fig. 4(k). The experimental results of the adjusted angle of force control direction with and without the proposed method are shown in Fig. 4(l). It is seen from the result with the proposed method in Fig. 4(l) that the force control direction is changed to be almost the same as the actual force control direction just after the start of the control, and it keeps being changed to be the same as the actual direction without being affected by the change of the magnitude of applied force after that. We can verify that the desired force can be realized with the proposed method from the result shown in Fig. 4(j). On the other hand, it is seen from the result without the proposed method in Fig. 4(l) that force control direction is not stable from the beginning, and then becomes out of control after all. Although position/force control without the proposed method was tried many times, it could not complete the task because of noise and other unknown vibration mainly caused by the rotation of the roller attached to the end-effector.

VII. Conclusion

The concept of the fuzzy vector method has been proposed to obtain the normal vector of the unknown constraint surface effectively from the force sensor signals, which include the noise and/or the unknown vibrations caused by tools such as grinders. The effective online force control direction adjustment algorithm is introduced using the proposed fuzzy vector method. The effectiveness of the proposed method has been verified by experiment with a 2DOF planar robot manipulator.

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