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Error Recovery in the Assembly of a Self-Organizing Manipulator by Using Active Visual and Force Sensing

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Abstract. This paper deals with the assembly of a *S*elf-*O*rganizing *M*anipulator (*SOM*) by using the method of *Active Sensing*. We set a 6-axis force/torque sensor in the wrist of a manipulator and a CCD camera in the hand of another manipulator. By cooperation of hand and eye, human beings can do a variety of versatile work. The es guide the motion of the hand, while the hand moves to make the object easy to see. We try to construct a system working in the same way as a human being. We integrate a vision system, a manipulator, and a force/torque sensor into a hand-eye working system. The scene simplification is based on the controlled motion of camera and manipulator. A method of the *Average Visible Ratio* (*AVR*) is proposed to evaluate the viewpoint of the movable camera. A strategy for planning the assembly is presented. The efficiency of the system is illustrated by experiments.

Keywords: self-organizing manipulator (SOM), active sensing, hand-eye working system, average visible rate (AVR)

1 Introduction

Recent research on the *CE*LLULAR RO*BOT*ICS SYSTEM (*CEBOT*) (Fukuda & Nakagawa, 1988; Fukuda & Kawauchi, 1991; Fukuda & Xue, 1991) has shown that the robot can be decomposed into generic element parts (cells) and by combining these parts in different ways an adapt different kinds of work. We have proposed a kind of CEBOT that is called the *Self Organizing Manipulator System* in previous research (Fukuda & Xue 1991).

Different from the reconfigurable manipulator proposed in (Khosla, 1988), the reconfiguration of the cellular manipulator can be made automatically by other conventional manipulators. In Fig. 1, we show the concept of this system. The experimentally developed prototypes of cells and the assembled cellular manipulator are shown in Fig. 2. We have presented the off-line planning that generates the construction of a cellular manipulator according to a given task, and assembled this cellular manipulator by cooperation between two manipulators (Fukuda & Xue, 1991). Since the real environment is very difficult to be completely represented by a simple model, and because there may be unpredictable interferences due to unknown reasons, it is necessary for an intelligent robot system to have on-line planning functions based on sensor data.

Generally, there are mainly two kinds of sensor information being used in manipulation work. One is the force/torque sensor information that is often used in compliance control of manipulation, such as the peg-in-hole problem and so on (Hirai, 1988; Mason, 1981). The other one is the vision sensor information which is mainly used for localization of objects (Vernon, 1990). As we know, the accuracy and the reliability of sensors depend very much on their location. Recently research about task directed active sensing or sensor planning has been presented (Hager, 1991; Tsikos, 1991; Tarabanis, 1991; Sakane, 1987; Tsai, 1989). (Sakane, 1987) proposed a method to avoid occlusion of visual sensors. (Tarabanis, 1991) proposed a method to determine viewpoints for a robotic vision system for which object features of interest will simultaneously be visible.

Since vision information and force information are both necessary for human beings to carry out manipulation work, we try to use both of them in this research. Referring to the cooperation of hand and eye of human beings, we analyze the force information and vision information of an assembly task in a theoretical way,

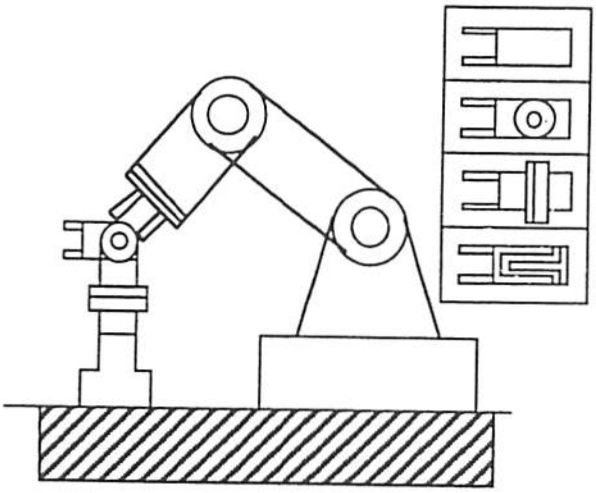


Fig. 1. Concept of self-organizing manipulator.

and illustrate it by experiment. The human's intuition about *Visibility* is defined as the *visible rate*, and the human's experience about manipulation work is used as a strategy in planning.

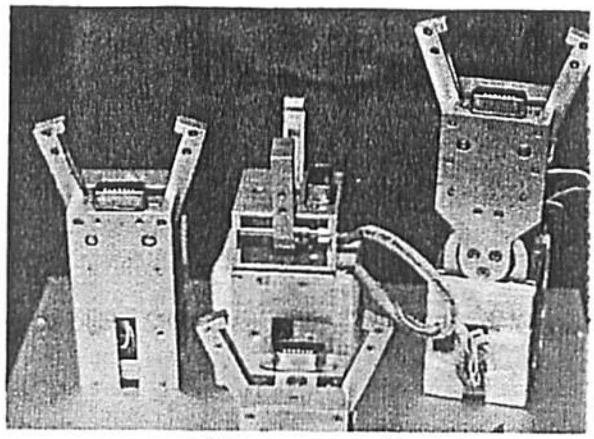
2 Hand Eye Cooperation

It is very difficult for human beings to carry out a manipulation task without the cooperation of hand and eye. We cannot know the location of an object if there is no guidance from the eyes, and, if there is no force information from hand, the manipulation cannot be carried out flexibly either. We human beings can perform a lot of versatile work by cooperation of hand and eye because the hand works for the eye, and the eye works for the hand. To us, *the hand for eye* is interpreted as equally important as *the eye for hand.* By now, research concerning *the eye for hand*, such as stereo vision measurement has been presented, while research that concerns *the hand for eye* has rarely been studied (Tsikos, 1991).

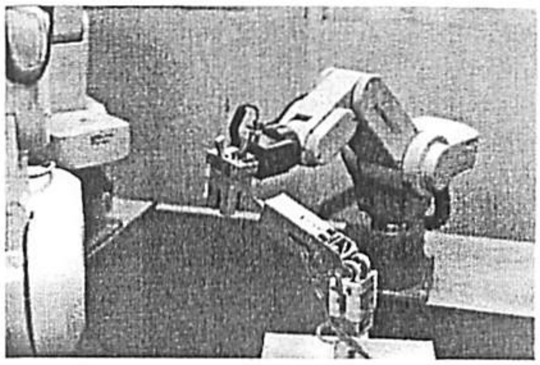
In our system, we take both of them into account, and the role of hand (manipulator and force/torque sensor) is shown as follows:

1: Pick and place cells
2: Estimate the contact state of cells
3: Change the contact state of cells as required by the eye
4: Follow the result of the vision system and move cells

The role of the eyes (the camera set at the end-effector of manipulator) is as follows:



(a) Prototypes of cells



(b)Assembled Cellular Manipulator

Fig. 2. Manipulator cells: (a) prototypes of cells, (b) ass cellular manipulator.

1: Choose the best viewpoint for measuring
2: Analyze the result from several viewpoints, late the error of connection of cells
3: Guide the motion of the manipulators

3 Contact State and the Best Viewpoint

In this paper, we modeled cells as solid rectangle can analyze the contact state to a certain degree ing force/torque information obtained from the sensor, but it is not enough to measure the positi ror. By using the vision system, we are able to the position error, but 3-dimensional vision mea ment is still a difficult problem in a real enviror and actually with lower precision. Usually, in h work, instead of performing 3-dimensional vision surement from a given viewpoint by the eyes, we change the viewpoint to where it is easy to under and easy to measure. It is natural for humans, an a good idea for our work. Here we present an e nation of the viewpoint.

In the past, viewpoint selecting has been determined by considering such criteria as occlusions, field-of-view, depth-of-field, and/or camera spatial resolution off-line (Cowan & Bergman, 1989; Tarabanis, 1991). Khosla presented research about visual tracking, visual servo (Khosla, 1992), that also took the manipulator configuration into account. Most of these researchers used 3-dimensional camera parameters to process complicated images.

In this paper, we try to treat a 3-dimensional work using a 2-dimensional method if possible, and simplify the processing. Here we propose a criterion to select viewpoints.

3.1 Definition

To a polyhedral solid object, in a visible area, from the viewpoint Θ, the ratio of a visible surface's area projected to the normal to the line of sight to its actual area is defined as the *visible ratio* of this surface in the viewpoint Θ. The average of visible ratios of all surfaces in the visible area of viewpoint Θ is defined as *Average Visible Ratio* (AVR) ω of viewpoint Θ.

$$\omega = \frac{1}{N}\sum_{i=1}^{i=N}\frac{Sz(i)}{S(i)} \tag{1}$$

where,

N is the number of visible surfaces from viewpoint Θ.
$Sz(i)$ is the normal or perpendicular visible area of surface number i from this viewpoint.
$S(i)$ is the original area of surface number i from this viewpoint.
In the following we refer to $Sz(i)$ as the "projected area."

The AVR shows the visible extent of an object. Clearly, for a viewpoint, the larger the AVR is, the better it is for measurement. For understanding the concept of the AVR, first we show an example of a two dimensional problem. As shown in Fig. 3(a), the AVR can be calculated as (2) and (3).

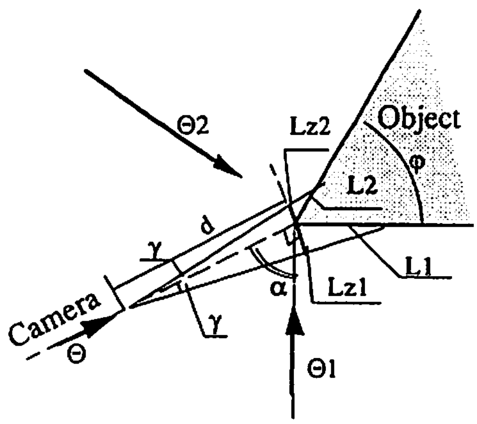
$$\omega_1 = \frac{Lz_1}{L_1}, \omega_2 = \frac{Lz_2}{L_2} \tag{2}$$

$$\omega = \begin{cases} \dfrac{|\cos(\alpha+\gamma)|}{|\cos(\gamma)|} & \alpha \le \dfrac{\pi}{2} - \varphi \\ \dfrac{|\cos(\alpha+\gamma)| + |\cos(\alpha+\varphi-\gamma)|}{2|\cos(\gamma)|} & \dfrac{\pi}{2} \ge \alpha > \dfrac{\pi}{2} - \varphi \\ \dfrac{|\cos(\alpha+\varphi-\gamma)|}{|\cos(\gamma)|} & \alpha > \dfrac{\pi}{2} \end{cases} \tag{3}$$

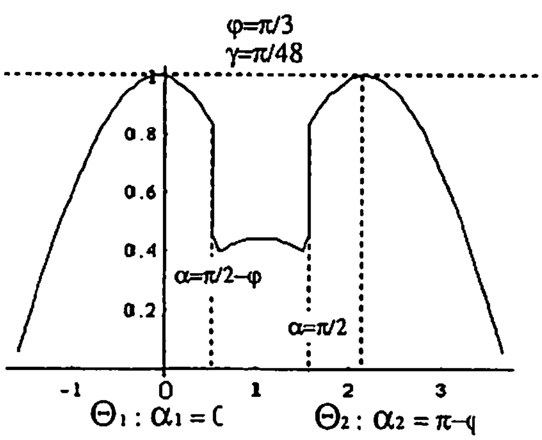
where

γ is the visible angle of the camera.
φ is the angle of the 2-dimensional object facing the camera.
α is the angle between the axis of the camera and the object.
L_1, L_2 are the actual lengths of the object.
Lz_1, Lz_2 are the projected visible lengths of the object.

The result of this example is shown in Fig. 3(b). At the point where $\alpha = 0$ or $\alpha = \pi - \varphi$, AVR $\omega = 1(\Theta 1, \Theta 2$ shown in Fig. 3(a)). Considering the human's viewpoint in this case, we can understand that the result agrees with our intuition. Conversely, at the point where $\alpha = \pi/2 - \varphi$, the AVR declines

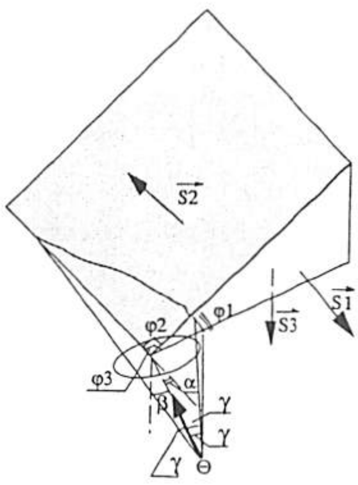


(a) A Two-Dimensional Object

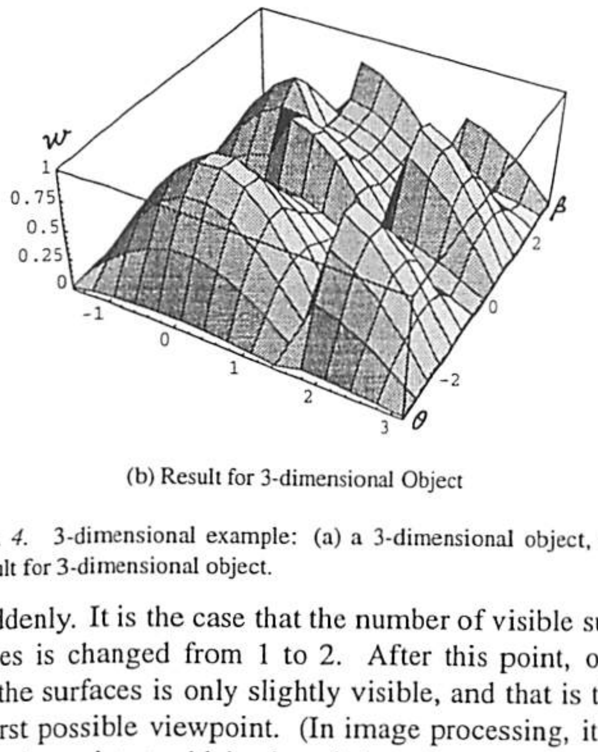


(b)Result of Two-Dimensional Object

Fig. 3. A 2-dimensional example: (a) a two-dimensional object, (b) result of 2-dimensional object.



(a) A 3-Dimensional Object



(b) Result for 3-dimensional Object

Fig. 4. 3-dimensional example: (a) a 3-dimensional object, (b) result for 3-dimensional object.

suddenly. It is the case that the number of visible surfaces is changed from 1 to 2. After this point, one of the surfaces is only slightly visible, and that is the worst possible viewpoint. (In image processing, it is the viewpoint at which edges fade out.)

Now, let's consider the case when the camera moves along a sphere in 3-dimensional space. To the object shown in Fig. 4(a), the direction vector of each surface is shown in (4), and the direction of the viewpoint to the surface is (5)

$$\vec{S_1}, \vec{S_2}, \ldots, \vec{S_n}, \vec{S_\Theta} \tag{4}$$

$$\theta_i = \cos^{-1}\left(\frac{\vec{S_i} \cdot \vec{S_\Theta}}{|\vec{S_i}||\vec{S_\Theta}|}\right) \tag{5}$$

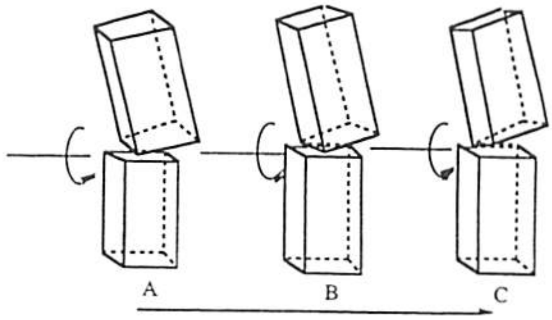


Fig. 5. Relation of contact state and viewpoint.

Whether, from a given viewpoint a surface is vis or invisible is determined by (6), and the numbe visible surfaces is given by (7)

$$C_i = \begin{cases} 1 & \frac{\pi}{2} \le \theta_i \le \frac{3\pi}{2} \\ 0 & -\frac{\pi}{2} \le \theta_i \le \frac{\pi}{2} \end{cases}$$

$$N = \sum C_i$$

The visible rate of each surface and the AVR shown in (8), (9)

$$\omega_i = \frac{\cos(\theta_i + \gamma)}{\cos(\gamma)}$$

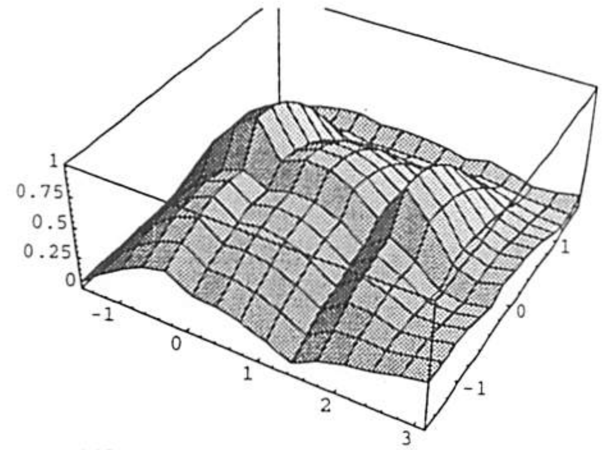
$$\omega = \frac{1}{N}\sum_{i=1}^{N} C_i \cdot \omega_i$$

Applying the definition related above to the ob shown in Fig. 4(a), the calculation result of AVI shown in Fig. 4(b).

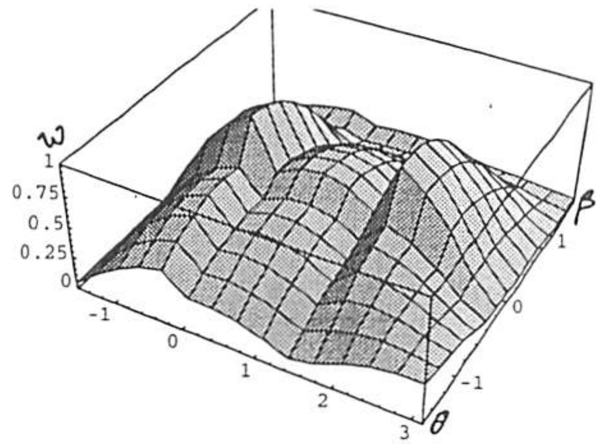
Here, at the points $\alpha = 0, \beta = 0$ and $\alpha = 0,$ $-\pi/2$ and $\alpha = \pi/2, \beta = \pi/2 - \varphi$, the maximum A is obtained ($\omega = 1$). This result also agrees with hur intuition. In this case, the information amount nee for measurement is maximized, and useless infor tion amount is minimized, and thus it can be conside as the best condition for measurement.

4 Visibility and Contact State

When two or more objects are in contact with e other, according to the state of contact, there may no viewpoint for which the AVR is 1. For exam in the case of the point-surface contact state show Fig. 5-A, the calculation result of AVR is showr Fig. 6(a). From this we see that wherever the cam



(a)Result of AVR Before State Transition



(b)Result of AVR After State Transition

Fig. 6. Result of AVR: (a) result of AVR before state transition, (b) result of AVR after state transition.

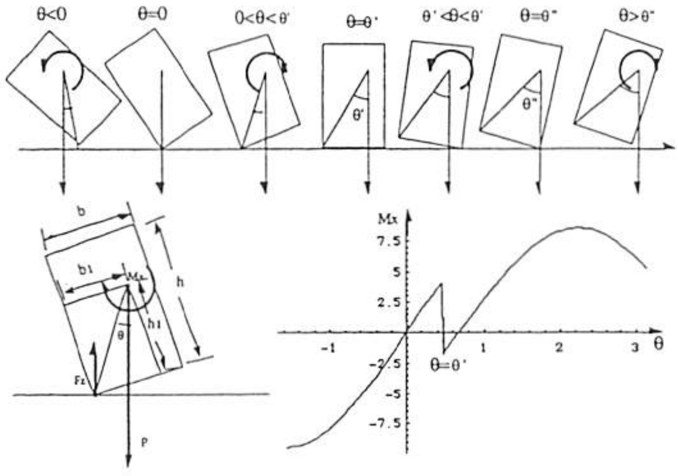


Fig. 7. Force analysis during state change.

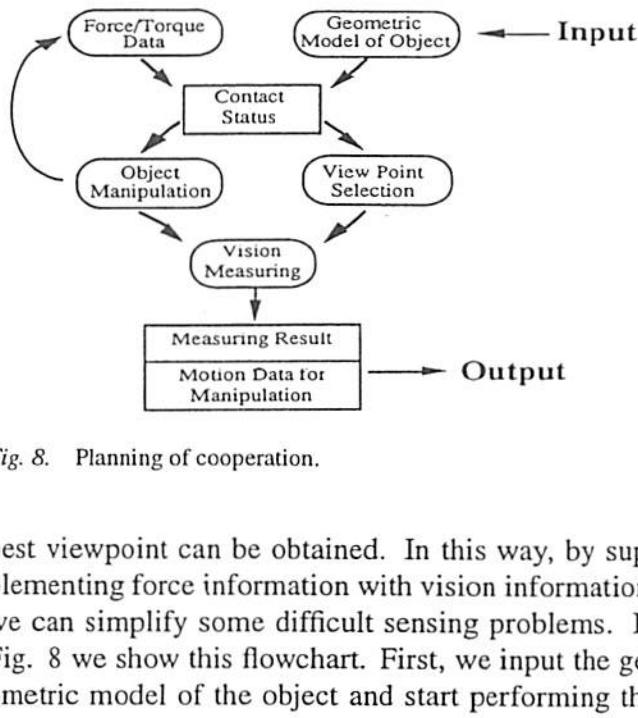


Fig. 8. Planning of cooperation.

moves, there exists no viewpoint for which $\omega = 1$. To obtain the best viewpoint, it is necessary to do state transition by manipulation.

If we change the state from A shown in Fig. 5 (point-surface) to state B (line-surface), then the AVR will be changed to the shape shown in Fig. 6(b). Now we see that the viewpoint p (2 visible surfaces, axis of camera is vertical to both two surfaces), the viewpoint with $\omega = 1$ can be obtained. Therefore, the obvious viewpoint can be obtained. In Fig. 7, we show the variation of torque while doing state transition. Here, the force Fz is kept as a constant while changing the angle θ, and parameters are shown in the figure.

From Fig. 7, we can see that at the point $\theta = \theta'$, the moment is changed suddenly. Accordingly, take the contact point as the center, rotate the above cells while pushing it down with an unchanged force, stop at the point where the torque in the direction of the rotating axis declines suddenly (where the contact point is changed, $\theta = \theta'$ in Fig. 7); the contact state is then changed to line-surface contact state. Therefore, the best viewpoint can be obtained. In this way, by supplementing force information with vision information we can simplify some difficult sensing problems. In Fig. 8 we show this flowchart. First, we input the geometric model of the object and start performing the assembly task, then we conjecture the contact state of the cells based on the Force/Torque data. According to the contact state, the system tries to select a viewpoint for measurement or performs a manipulation of cells. After the viewpoint is selected, vision measurement is carried out to detect the error between cells, and the results of measuring data are outputted for controlling the motion of the manipulator.

5 Experimental Results

5.1 *Construction of System*

The hardware of the system model is shown in Fig. 9. We have 3 manipulators (5 DOF, movemaster

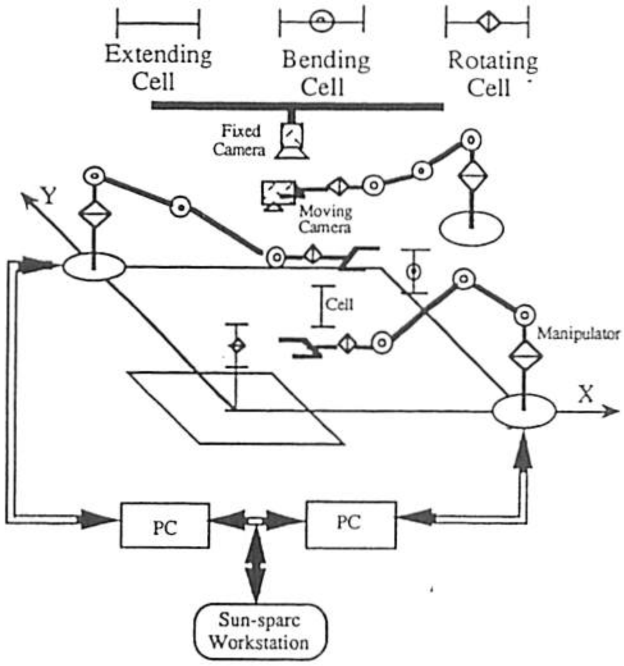


Fig. 9. Model of the system.

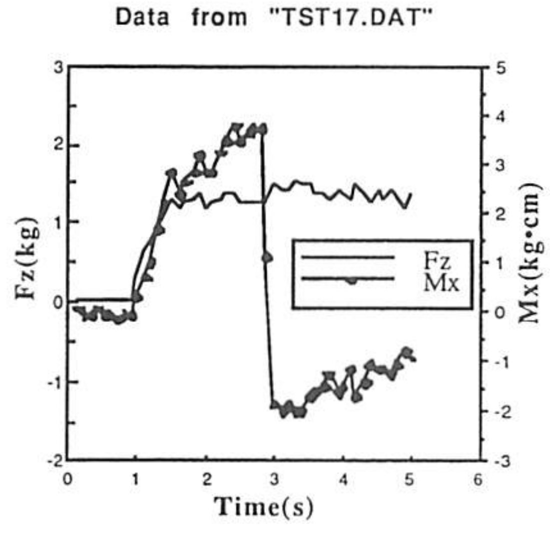
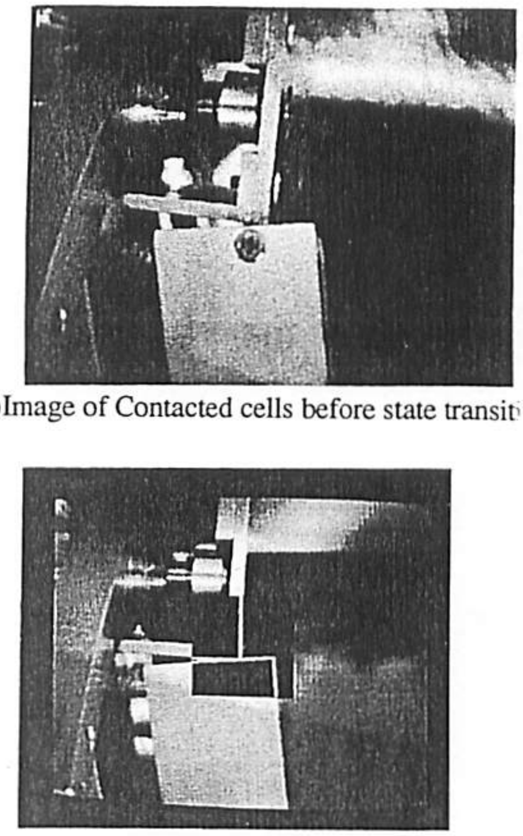


Fig. 10. The experimental force data.

precision 0.1 mm), 2 CCD cameras, 2 personal computers, 1 workstation (SPARC Station 10) and some manipulator cells in our system. A CCD camera is set at the end-effector of a manipulator, another is fixed on top of the working system. A 6-axis Force/Torque sensor is attached to the wrist of a manipulator. The cells are controlled by a personal computer through a D/A converter, and the Force/Torque sensor data is read through an A/D converter. The D/A, A/D converter, image processing board, LAN communication board, and RS232c interface that is used to control manipulators are put in the expansion slots of the personal computer. Personal computers are linked to the



(a)Image of Contacted cells before state transiti

(b) Image Processing Result After State Transi

Fig. 11. Result of image processing: (a) image of contact before state transition, (b) image processing result after stat tion.

workstation through a LAN communication bo this system, complicated calculations such as processing are performed by the workstation, a results are transmitted to the PC for controlling r ulator, camera and cells.

The experiments shown here consist of two p

1: Use the Force/Torque sensor to change the c State of the cells to make them easily visible on the calculation result of AVR.
2: Set the movable camera at the best viewp measure the connection error by image proc

The results of the two parts of the experime described below.

5.2 *Transition of Contact State*

The transition of contact state of cells is simpli shown in Fig. 5, the experimental force/torque d shown in Fig. 10. It is clear that when the mon the direction of x axis is changed suddenly from to plus (or plus to minus), the contact state of also changed at that point. This result agrees with the theoretical analysis shown in Fig. 7. By analyzing the data from the force/torque sensor, we can obtain the point of state-transition.

5.3 Using the Image Processing of the Movable Camera to Detect the Connection Error of Cells

In this experiment two manipulators and one CCD camera are used. The image of the contracted cells before state transition is shown in Fig. 11(a). From Fig. 11(a), we can see that it is very difficult to process this image. Actually, the edges of cells can not be extracted sharply.

Fig. 11(b) shows the result of image processing that is done at the best viewpoint after contact state transition. Image processing consist of noise processing, differencing, thresholding, line-thinning, and line approximation.

By using this method, we are able to measure the error with an accuracy of 0.2 mm without using expensive devices or 3-dimensional image processing. This result is good enough to be used in the assembly of the Self-Organizing Manipulator.

6 Conclusions

In this research, to make the self-organizing manipulator system intelligent, we presented an on-line planning system which uses the method of active sensing with a 6-axis force/torque sensor and a movable camera. We obtained the following results.

1. By changing the contact state of cells, we can get simpler images for measuring the error between cells.
2. We proposed the concept of *Average Visible Rate* (AVR), and by evaluating the viewpoint based on this concept and selecting the obvious viewpoint for vision measurement, we can simplify the processing of the image of a polyhedral solid object.
3. By changing the viewpoint, and doing vision measurement at the best viewpoint, we acquired an accurate result.

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