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

GUOQING XUE
TOSHIO FUKUDA
fukuda@mein.nagoya-u.ac.jp

Dept. of Mechano-Informatics and Systems, Nagoya Univ. 1 Furo-cho, Chikusa-ku, Nagoya, 464-01 Japan

HAJIME ASAMA
RIKEN, 2-1, Hirosawa, Wako-shi, Saitama, 351-01 Japan

Abstract. This paper deals with the assembly of a Self-Organizing Manipulator (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. These 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 CELLULAR ROBOTICS SYSTEM (CEBOT) (Fukuda & Nakagawa, 1988; Fukuda & Kawauuchi, 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,
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:

3 Contact State and the Best Viewpoint

In this paper, we modeled cells as solid rectangles. We can analyze the contact state to a certain degree by force/torque information obtained from the sensor, but it is not enough to measure the position. By using the vision system, we are able to get the position error, but 3-dimensional vision measurement is still a difficult problem in a real environment with lower precision. Usually, in human work, instead of performing 3-dimensional vision measurement from a given viewpoint by the eyes, we change the viewpoint to where it is easy to understand and easy to measure. It is natural for humans, and a good idea for our work. Here we present an explanation 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 $\Theta$, 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 $\Theta$. The average of visible ratios of all surfaces in the visible area of viewpoint $\Theta$ is defined as Average Visible Ratio (AVR) $\omega$ of viewpoint $\Theta$.

$$\omega = \frac{1}{N} \sum_{i=1}^{N} \frac{S_z(i)}{S(i)}$$  \hspace{3cm} (1)

where,

$N$ is the number of visible surfaces from viewpoint $\Theta$. $S_z(i)$ 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 $S_z(i)$ 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).

$$\omega_1 = \frac{Lz_1}{L_1}, \omega_2 = \frac{Lz_2}{L_2}$$  \hspace{3cm} (2)

$$\omega = \begin{cases} 
\left[\cos(\alpha + \gamma)\right] & \alpha \leq \frac{\pi}{2} - \varphi \\
\left[\cos(\gamma)\right] & \frac{\pi}{2} - \varphi \leq \alpha \leq \frac{\pi}{2} - \gamma \\
\left[\cos(\alpha + \varphi - \gamma)\right] & \alpha > \frac{\pi}{2} - \gamma \\
\left[\cos(\gamma)\right] & \alpha > \frac{\pi}{2} 
\end{cases}$$  \hspace{3cm} (3)

where

$\gamma$ is the visible angle of the camera.
$\varphi$ is the angle of the 2-dimensional object facing the camera.
$\alpha$ 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

---

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

\[
\vec{S}_1, \vec{S}_2, \ldots, \vec{S}_n, \vec{S}_\Theta
\]

\[
\theta_i = \cos^{-1} \left( \frac{\vec{S}_i \cdot \vec{S}_\Theta}{|\vec{S}_i||\vec{S}_\Theta|} \right)
\]

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

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

\[
C_i = \begin{cases} 
1 & \frac{\pi}{2} \leq \theta_i \leq \frac{3\pi}{2} \\
0 & -\frac{\pi}{2} \leq \theta_i \leq \frac{\pi}{2} 
\end{cases}
\]

\[
N = \sum C_i
\]

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 object shown in Fig. 4(a), the calculation result of AVR shown in Fig. 4(b).

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

4 Visibility and Contact State

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

Data from "TST17.DAT"

![Graph showing experimental force data.](image)

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

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

The experiments shown here consist of two parts:
1: Use the Force/Torque sensor to change the state of the cells to make them easily visible on the calculation result of AVR.
2: Set the movable camera at the best viewpoint to measure the connection error by image processing.

The results of the two parts of the experiment are described below.

5.2 Transition of Contact State

The transition of contact state of cells is simplified shown in Fig. 5, the experimental force/torque data shown in Fig. 10. It is clear that when the monoblock 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.

References


Guoqing Xue graduated from Shanghai JiaoTong University Shanghai, P.R. China in 1985. From 1985 to 1988, he was a assistant professor of Department of Ship and Marine-Engineering, Shanghai JiaoTong University. He received Master degree from the Nagoya University in 1992. Now he is a Doctor Course Student of Mechanical Engineering Department of Nagoya University. His Interests are Self-Organizing Manipulator, Sensor Fusion, and Assembly. He is a student member of IEEE.

Toshio Fukuda graduated from Waseda University, Tokyo, Japan in 1971 and received the Master of Engineering degree and the Doctor of Engineering degree both from the University of Tokyo
1973 and 1977, respectively. In 1977, he joined the National Mechanical Engineering Laboratory in Japan. From 1979 to 1980, he was a Visiting Research Fellow at the University of Stuttgart, West Germany. At present, he is Professor of Mechanical Engineering Department of Nagoya University, Japan, mainly engaging in the research fields of intelligent robotic system, self-organizing system, micro robotics. He is the Vice President of IEEE Industrial Electronics Society (1990–).

Hajime Asama graduated from the University of Tokyo. 1982 and received the Master and the Doctor of Engineering degree both from the University of Tokyo, 1984 and 1986, respectively. From 1986, he joined the Institute of Physical and Research (RIKEN) in Japan and he is currently a research at the Institute. His main interests are distributed autonomous systems and intelligent bioprocess systems. He is a member of the New York Academy of Science.