A Stereo Vision System for Position Measurement and Recognition in an Autonomous Robotic System for Carrying Food Trays

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ABSTRACT

This paper describes a practical stereo vision system for position measurement and recognition in an autonomous food-tray-carrying robot. Our food tray carrying robot delivers and collects food trays in medical care facilities. The vision system must position and recognize tables and trays for the robot to manipulate the trays. We have developed edge detecting techniques for the position measurement of target objects that vary in terms of brightness using correlation operations. We fabricated a compact environmental perception unit using a real-time image correlation processor (the Color Tracking Vision) and had it installed on the food carrying robot. Tray delivery and collection experiments in a simulated environment show that the unit can position the tables and the food trays accurately enough to manipulate the trays in varying degrees of brightness (60 to 7200 lx) using video images from a pair of stereo cameras installed on the gripper of the manipulator.

1. INTRODUCTION

A rapidly aging population with fewer children is currently one of Japan's most important issues. A gradually decreasing work force is becoming a serious problem, particularly in medical care facilities because many routine tasks in these facilities have not been automated. Directly care tasks, such as changing attire or feeding patients, which are provided by hospital staff, should not be automated because they are important aspects of providing care services. Other tasks, however, such as collecting soiled garments or delivering food which do not require care-giver contact, can be replaced by robotic systems. Thus, it is necessary to automate indirect care-giving tasks in order to support care-giving staff in the facilities. With this in mind, we developed a food tray carrying robot that delivers and collects food trays in medical care facilities (Figure 1.) This robot navigates itself throughout the building and both delivers and collects food trays with its manipulator. This project is a joint venture with Yaskawa Electric Corporation, and sponsored by the New Energy and Industrial Technology Development Organization (NEDO.)

We developed this robot emphasizing safety, autonomy, and user-friendliness. The robot is designed with the safety of patients and care workers in mind. Because medical care facility environments are not as structured as industrial facilities, the device must be environmentally-responsive to complete its tasks autonomously. It must also be user friendly because it is operated in a patient oriented environment. To ensure these characteristics, this robot consists of six units: the manipulator, the mobile unit, the environmental perception unit, the navigation unit, the human interface unit, and the

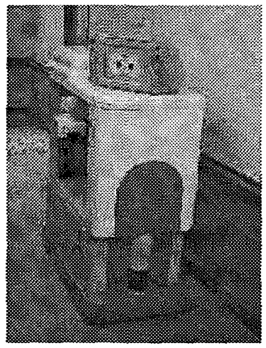

Figure 1. The food tray carrying robot

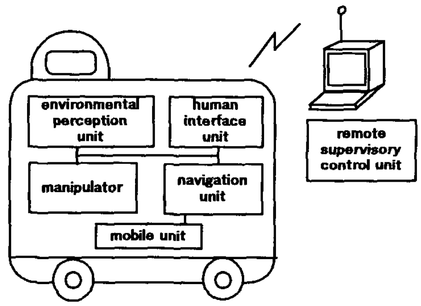

Figure 2. The components of the robot

remote supervisory control unit (Figure 2.) The environmental perception unit, which is the key to autonomous operation, has two sections: the navigation section and the manipulation section. The navigation section localizes the robot and detects obstacles placed in the path of the robot [1]. The navigation unit generates robot direction and navigates the mobile unit based on the location of obstacles. The manipulation section of the environmental perception unit positions the table and the tray for the manipulator to manipulate the food tray. The human interface unit provides a user friendly interface for robot operation. The operator can supervise the status of the robot through the remote supervisory control unit. Each unit was developed separately by either Yaskawa Electric Corporation or Fujitsu Limited. The manipulator and the mobile unit were developed by Yaskawa and the remaining units were developed by Fujitsu.

To deliver and collect food trays autonomously in a real-life environment, it is necessary for the robot to position and recognize food trays and tables in varying degrees of brightness. It is also necessary for the robot to

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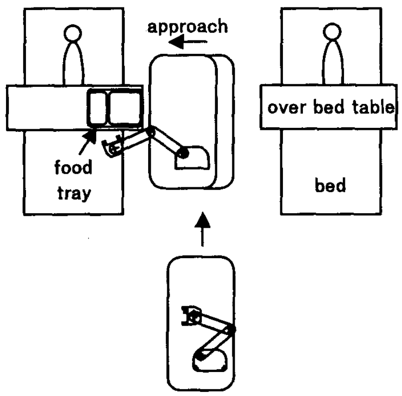
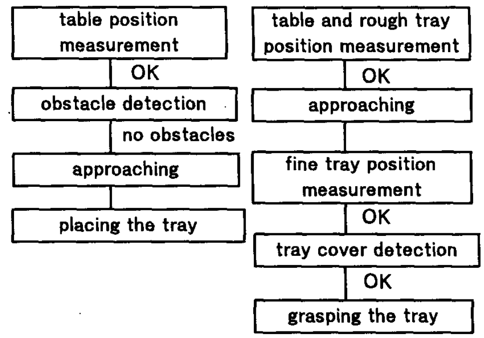
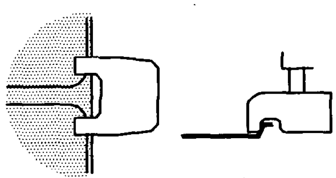


Figure 3. Movement of the robot at bedside



a. tray delivery b. tray collection

Figure 4. Task sequence



a. top view b. front view

Figure 5. The gripper

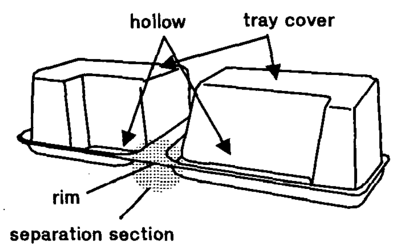


Figure 6. A food tray

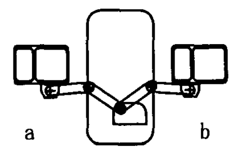


Figure 7. Grasping point

detect obstacles on the table before the food tray is placed. To recognize and position targets, active sensing, such as laser range sensing or sonar sensing, was not used because we feel it may adversely affect the patient. Visual sensing with active lighting was also not used because active lighting so close to the patient may also adversely affect the patient. Thus, we decided to develop a stereo vision system that positions and recognizes targets without using active lighting.

One of the practical techniques for visual sensing involves the preparation of target marks on target objects [2]. Preparing target marks, however, creates a target mark maintenance problem, that is, target marks on food trays may fall off or become unrecognizable during everyday use, thereby making it is difficult to maintain target marks on every food tray in a facility. To facilitate the introduction of a robot system, commercially available food trays and tables without marks should be used. Thus, we developed a vision system that positions and recognizes targets by outline of the outline of a target.

Many object recognition/manipulation techniques have been developed, some of which are applicable in varying degrees of brightness [3]. In this robot system, however, the visual perception unit must be installed in a mobile robot and the processing must be in real-time for practical use. It is also necessary to develop a compact and high-speed environmental perception unit. Thus, we utilized a high-speed one-board image correlation processor (the Color Tracking Vision [4]) that processes video images from a pair of stereo cameras.

Object recognition based on image correlation processing is, however, sensitive to changes in light and so we devised edge-detecting and object-recognition techniques that can be used in varying degrees of brightness using correlation processing. In this paper, we discuss position measurement and recognition techniques for tables and food trays based on correlation processing that are applicable in varying degrees of brightness in real-life environments. We also discuss obstacle and tray cover detecting techniques based on correlation processing.

Chapter 2 provides background of tray manipulation. Chapter 3 provides a list of targets of development of the environmental perception unit. Chapter 4 discusses problems and solutions. Chapter 5 provides details on table and food tray position measurement and recognition. Chapter 6 provides experimental results in simulated and real-life conditions. The vision system was proved that it can position and recognize food trays in degrees of brightness ranging 60 to 7200 lx. In conclusion, we shall demonstrate that the techniques can be applied to object manipulation tasks using an autonomous robot system in a real-life environment.

2. BACKGROUND OF TRAY MANIPULATION

2.1. Sequence of Tasks

The robot has two tasks: delivering trays and collecting trays. To carry out these tasks, the robot moves along the bed to the over bed table (Figure 3.) When delivering the tray, the environment perception unit measures position of the table, then detects obstacles there on. If no obstacles are detected, the robot approaches the table and places the tray there on (Figure 4-a.) When collecting the tray, the environmental perception unit measures position of the table and the tray. If the tray is placed on the table correctly, the robot approaches the table and the camera is targeted to the separation section on the tray (explained in the next section.) The environmental perception unit then measures position of the tray. If the tray position is measured correctly, the manipulator grasps the tray and moves it from the table to the robot container (Figure 4-b.)

2.2. Tray Grasping

In this project, actual hospital food trays were used. To grasp, the manipulator pinches the rim of the tray (Figure 5.), which is separated into two parts. When a tray is in a food-tray container before delivery, one part is kept

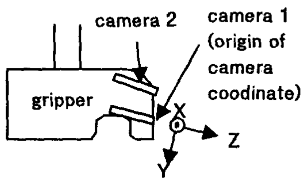


Figure 8. camera configuration

warm and the other part is kept cold to ensure correct food temperature. To ensure safety, the reach of the manipulator is limited. Because the separation section of the tray is not in the center (Figure 6), the grasping point is different depending on tray direction, i.e., the manipulator grasps the separation section when the separation section is close to the robot (Figure 7-b), and the manipulator grasps the non-separation section when the tray is in the opposite direction (Figure 7-a.)

When the gripper grasps the separation section, the environmental perception unit detects the tray rim outline on the separation section so that the grasping point is positioned directly. However, when the non-separation section is grasped, the environmental perception unit cannot detect the grasping position directly because the non-separation section does not have characteristics for position measurement. In this case, the environmental perception unit measures the position of the separation section and the orientation of the tray rim and extrapolates the grasping point from the position of the separation section along the orientation of the tray rim. In this case, the grasping point is positioned indirectly and so is referred to as "indirect measurement".

A pair of tray covers, which have hollows for the gripper (Figure 6) is provided to stack the trays inside the robot container. During tray collection, the covers must be applied and the hollows must be faced in the direction of the gripper

3. TARGET OF DEVELOPMENT

3.1. Requirements

The required functions of the environmental perception unit are as follows.

A. Measurement accuracy

A-1. Table

Required table measurement accuracy when placing the tray on the table is: X ±35mm, Y ±15mm, Z ±15mm.

A-2. Tray

Required tray measurement accuracy when grasping the tray by the gripper is: X ±15mm, Y ±15mm, Z ±10mm.

Our goal is to obtain these accuracies with 99% reliability, i.e., tripled standard deviation of error (3 σ) does not exceed required accuracy.

B. Obstacle detection

Obstacles in the tray placing area on the table must be detected, including white and transparent obstacles, which provide the level of lowest contrast on a white table.

C. Tray cover detection

Tray cover and direction must be detected.

D. Processing time

Each process must be complete in a time that does not affect the total efficiency of the robot. The target time is 1s.

All processes must be performed in varying degrees of brightness in real-life environments. The target brightness range is 100 to 7000 lx.

3.2. Hardware Requirements

It is necessary to install the environmental perception unit on a mobile robot system. Thus, we devised a compact, high-speed, image correlation processor, the Color Tracking Vision, that can perform 500 local correlations on area comprising 8×8 or 16×16 pixels on color images in 33 ms. To take advantage of the Color Tracking Vision, we developed image processing techniques for edge detection and other functions that rely solely on correlation operation.

We determined to detect rim edges to measure position and orientation of tables and trays. In order to measure position and orientation from horizontal edges in input images, we installed a pair of vertically arranged calibrated stereo cameras on the gripper (Figure 8.)

4. PROBLEMS AND SOLUTIONS

4.1. Edge Detection Problems and Solutions

4.1.1. Changing Edge Contrast

One of the problems in detecting a target edge is the changing of edge contrast. The contrast of an outline edge changes significantly in terms of light source direction and brightness. When an edge detecting parameter, such as the threshold for the lowest contrast, is set in favor of dim (low contrast) conditions, the possibility of erroneous detection increases under bright (high contrast) conditions. We developed the following techniques to detect target edges under various conditions.

- Edge detection by edge tracing
- Adaptive edge threshold

4.1.2. Erroneous Edge Detection

Another problem associated with target edge detection is erroneous edge detection. The environmental perception unit must detect a target edge among the edges in the input image. We developed the following techniques to avoid erroneous edge detection.

- Edge verification using local features
- Verification by fitting models

4.1.3. Disappearing Target Edge

The final problem associated with target edge detection is the disappearance of a target edge under some conditions. For example, a tray rim edge is detectable in full length in the field of vision under some conditions but is detectable only in the separation section under other conditions. During indirect measurement, it is necessary to measure tray orientation accurately because the grasping point is extrapolated along tray orientation. If the tray rim edge is not detected completely, tray orientation cannot be measured accurately. We developed the following technique to solve this problem.

- Adaptive target edge selection

4.2. Camera Targeting Problem

We decided to measure the position of a target twice to improve measurement accuracy. For example, in table position measurement, a rough measurement of table position is taken before moving along the bed and a fine measurement is taken after moving along the bed. The former measurement is taken by the navigation section and the latter measurement is taken by the manipulation section of the environmental perception unit. Because the first measured position includes an error, the table is not always in the field of vision at the second position measurement. In tray position measurement, on the other hand, tray position is measured roughly before the robot approaches the table, and is measured accurately after approaching the

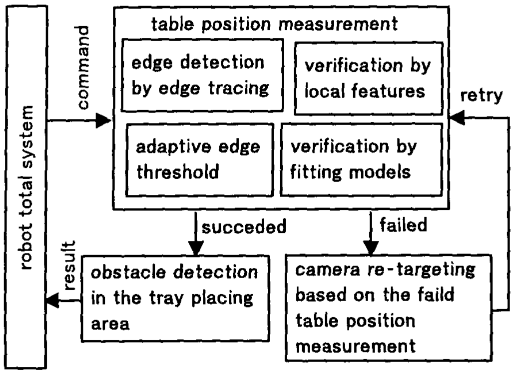


Figure 9. software configuration of table position measurement and obstacle detection

table. Because the first measured position includes an error, the tray is not always in the optimal position of the field of vision at the second position measurement. In this case, it is necessary to target the cameras to the object and measure the position again. We developed the following techniques to target the camera for retrying.

- Camera re-targeting based on failed table position measurement
- Camera re-targeting based on failed tray position measurement

4.3. Detection of Obstacles on the Table

Before the robot places the tray on the table, obstacles on the table must be detected. The problem is detecting an object out of the tray placing area as an obstacle. We developed the following technique to solve this problem.

- Obstacle detection in the tray placing area in the input image

4.4. Detection of the Tray Cover and its Direction

When the robot collects the tray on the table, the tray cover must be applied correctly in order to stack the trays in the container. The hollow of the tray cover must face the gripper. Thus, it is necessary to detect the tray cover and its direction. The problem is that the tray cover has no detectable characteristics in terms of input image. We developed the following techniques to detect the tray cover and its orientation without depending on additional marks.

- Tray cover detection based on pixel values
- Detection of the tray cover direction based on pixel values

4.5. Software Configuration

We organized these techniques to develop a robust environmental perception unit having the following advantages.

- Detecting specific target edges having various contrasts.
- Selecting target edges according to conditions with robustness improving under various conditions
- Re-targeting cameras, which improves robustness against camera positioning.

Figure 9 shows the software configuration of table position measurement and obstacle detection. The environmental perception unit performs table position measurement using edge detection techniques in accordance with commands from the robot total system. If table position is measured successfully, the unit completes

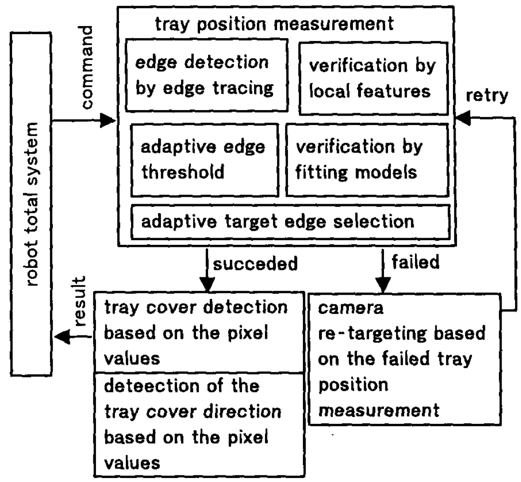


Figure 10. software configuration of tray position measurement and tray cover detection

obstacle detection and returns the position and orientation of the table and obstacle detection results. If the table position measurement fails, the unit targets the cameras and takes another the measurement.

Figure 10 shows the software configuration of tray position measurement and tray cover detection. The environmental perception unit performs tray position measurement using edge detection techniques in accordance with commands from the robot total system. If the tray position is measured successfully, the unit completes tray cover detection and returns the position and orientation of the tray and tray cover detection results including the direction of the tray cover. If the tray position measurement fails, the unit targets the cameras and takes another measurement.

Retrial of position measurement is repeated a maximum of five times. If position measurement fails on the fifth attempt, the unit returns the error to the total system.

5. METHODS

5.1. Edge Detection Methods

5.1.1. Methods for Detecting Changing Contrast Edges

5.1.1.1. Edge Detection by Edge Tracing

Because our target edges are horizontal edges in the input images, we developed an edge detecting technique that is specified to detect horizontal edges. The technique consists of the following steps.

- Edge fragment detection
- Edge tracing
- Line fitting of local areas

An edge fragment is a local area (8×8 or 16×16 pixel) that is on the edge in the input image. To detect an edge fragment, we used input image differentiation using correlation operations with a standard horizontal edge template (Figure 11), which has a white upper half and a black lower half. A correlation operation between an input image and the standard horizontal edge template reflects vertical differentiation of the input image. Thus, a local area having a peak output value in the center indicates a possible edge fragment.

The next step involves tracing the edge that is connected to the detected edge fragment using a correlation operation between the detected edge fragment and adjacent local areas. The most correlated local area is selected

Figure 11. a standard edge template

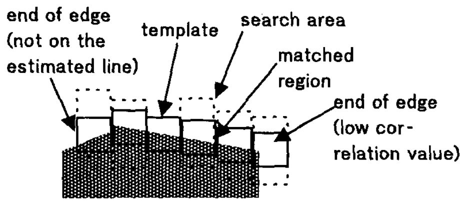
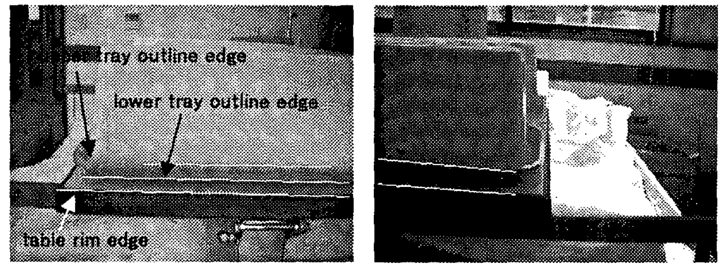


Figure 12. edge detection using adjasent correlation operation



a. regular (non-back-light) condition b. back-light condition

Figure 13. input image of a table and a tray

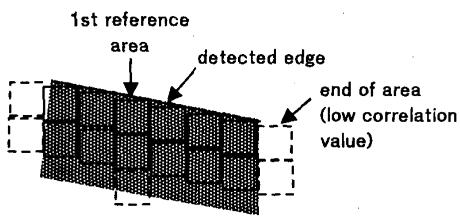


Figure 14. parallelogram area detection using adjasent correlation operation

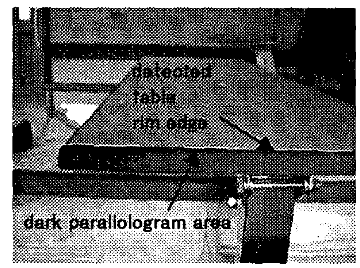


Figure 15. input image of a table

among search areas next to the edge fragment (Figure 12.) A correlation value between the edge fragment and the most correlated local area smaller than the threshold indicates that the border of these areas is the end of an edge. The threshold is determined during edge detection experiments under various degrees of brightness. If the most correlated local area is found, next correlation operation is performed between the edge fragment and the local area of the most correlated local area found. By repeating this process, an array of local areas lying along the edge is detected. In each correlation process, the vertical position of the most correlated area is compared with the position that is estimated from an extension of previously found local areas. A vertical position of a newly correlated local area found apart from the estimated vertical position indicates the end of the edge (Figure 12.)

The last step is to perform a line fitting with the correlated local areas. We used the least squares method to perform the line fitting. The results of this edge detection method show the ends and the angle of the edge.

An advantage of using this method is that only one template is required and so space and over-head time can be minimized. This method also does not require many operation steps or image pre-processing, and so applicable to a mobile robot system.

5.1.1.2. Adaptive Threshold

The contrast of edges changes significantly depending on the direction and the brightness of the light source so that a single threshold value is not appropriate for all brightness. Thus, we prepared several threshold values and applied them individually from a critical threshold to an insignificant threshold. For example, we use the highest threshold first to detect the edge fragment of a target edge. If the target edge is not found, second highest threshold is then applied. If the target edge is found, the edge detecting process is completed and the process proceeds to the next step. A target edge not found when the lowest threshold is applied indicates that there is no target edge in the input image. In this case, the environmental perception process provides a warning that no target objects are found.

Figure 13 provides examples of detected table rim and tray rim edges during tray collection. Under normal (non-back-light) conditions, three edges can be detected, i.e., an upper tray outline edge, a lower tray outline edge, and a table rim edge (Figure 13-a.) Under back-light conditions, on the other hand, a lower tray outline edge almost disappears because of a shadow of the tray itself and so two edges can be detected (Figure 13-b.)

5.1.2. Avoiding Erroneous Edge Detection

5.1.2.1. Edge Verification Using Local Features

We utilized local area features adjacent to a target edge to verify a detected edge. For example, the table we used has a white top face and a black side face. The table rim edge in the input image is a border of an upper bright area and a lower dark area. Thus, the table rim edge can be verified so as to detect a dark parallelogram area along the lower side of the edge. To find a parallelogram area along the edge, we used a correlation operation among adjacent areas along the edge (Figure 14.) The first reference area is defined arbitrarily in lower areas on the detected edge. The referenced area and an adjacent local area are then compared through a correlation operation. The adjacent local area is located by moving the reference area in parallel along the detected edge. If a high correlation value is found, next correlation operation is performed between the adjacent local area as a new reference area and the next adjacent local area. If a low correlation value is found, the end of a parallelogram area is found. This process is similar to edge tracing, but the correlation process is performed only one time during each step and the vertical position of the most correlated area is not relevant. The correlation process is performed toward both sides of the first reference area. If both ends of the parallelogram area are found, the parallelogram area is then extended downward by performing a correlation operation between the first reference area and the downward adjacent area. The threshold value that defines the correlation results as high or low is determined during experimentation.

Figure 15 provides an example of the detected table rim edge using this technique. The table rim is characterized by a high contrast edge with a dark

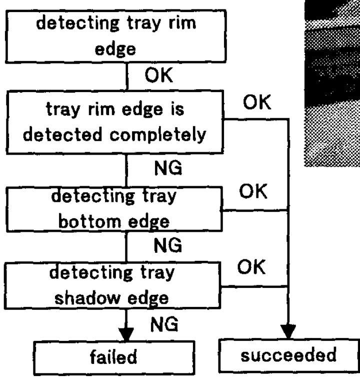


Figure 16. sequence of adaptive target edge selection

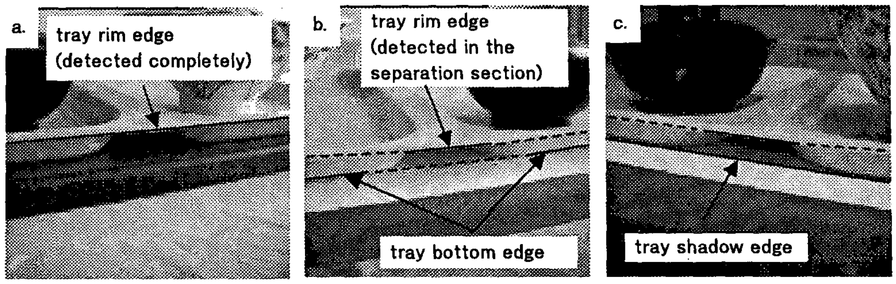


Figure 17. Tray images in three conditions
(solid line: detected edge, broken line: non detected edge)

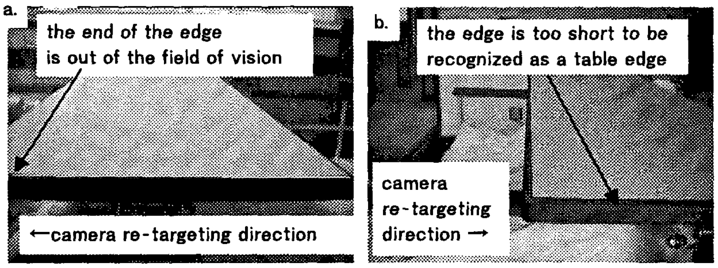


Figure 18. examples of failed camera targeting

parallelogram area underneath.

5.1.2.2. Edge Verification by Fitting Models

By applying the processes described above, target edge candidates can be detected from input images of cameras 1 and 2. To perform stereo matching, we used correlation operations between edge fragment areas in camera 1 and 2. Edge fragments in two input images are correlated in a round robin manner and most correlated (matched) area pairs are selected. 3D position and orientation of an edge is then calculated based on the pair of matched edges.

The calculated line is then verified using a simple 3D model of the target object. For example, the distance between the camera and the table ranges from 150 to 550 mm, thereby ensuring that the calculated edge is verified if the distance is between 150 to 550 mm. This process eliminates non-target edges such as patterns on the wall.

5.1.3. Adaptive Selection of Target Edges

We developed an adaptive target edge selection technique to solve this problem. A flow chart of this technique is shown in Figure 16. During tray position measurement, the environmental perception unit first attempts to detect the tray rim edge. A tray rim edge that is detected completely, indicates that the tray rim edge is detected in both the separation section and in the non-separation section and that tray orientation can be measured accurately (Figure 17-a.) If a tray rim edge is detected in the separation section only, however, tray orientation cannot be measured accurately. In this case, the tray bottom edges on both sides of separation section are detected (Figure 17-b) and tray orientation is measured based on the connected tray bottom edges. If the tray bottom edges cannot be detected, the environmental perception unit attempts to detect the edge of the tray shadow (Figure 17-c.)

5.2. Camera Re-Targeting

5.2.1. Camera Re-Targeting Based On A Failed Table Position Measurement

A camera targeting failure during a table position measurement occurs when the table is located too far to the right of the cameras or too far to the left of the cameras. Figure 18-a shows the table is located too far to the left of the cameras. In this case, the end of the table edge is out of the field of vision. Thus, the edge starting at the end of the input image indicates the table end is too far to the left. The cameras are then panned to the left and a position measurement is retried. Figure 18-b shows the table is located too far to the right to the cameras and the table position measurement has failed because the detected edge is too short for a table edge. In this case, the cameras are panned to the right and position measurement is retried.

5.2.2. Camera Re-Targeting Based On A Failed Tray Position Measurement

Although environmental perception unit targets the cameras to the separation section of the tray with 100% reliability, the distance between the cameras and the separation section is occasionally too far. When the cameras are located too far from the separation section, the position of the tray can be measured roughly but cannot be measured accurately enough to grasp the tray. Thus, if the unit determines that the tray distance is out of optimal range (160 to 220mm), the cameras are re-targeted to the optimal position based on the latest results and a position measurement is retried.

5.3. Obstacle Detection in the Tray Placing Area

We developed the following obstacle detection technique. The environmental perception unit re-calculates the tray placing area in the input image based on the previously measured table position and orientation and performs input image differentiation in this area (Figure 19.) Differentiation is performed using a correlation operation with a standard edge template (Figure 11.) The

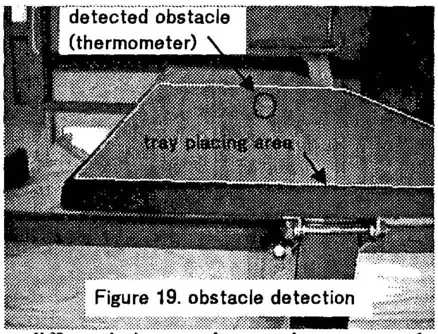


Figure 19. obstacle detection

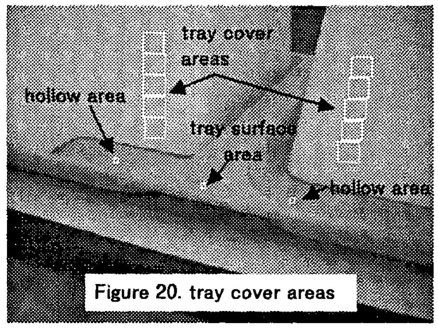


Figure 20. tray cover areas

peaks in the differentiation results are then extracted and absolute peak values are compared with the threshold. A peak value larger than the threshold indicates the presence of an obstacle. The threshold is determined during experimentation at the lowest brightness level in which the contrast of edge of obstacle represents the lowest value.

Figure 19 shows that a white thermometer is detected on a white table with a brightness of 100 lx, that is a condition that provides the lowest contrast.

5.4. Detection of the Tray Cover and its Direction

5.4.1. Tray Cover Detection Base on the Pixel Values

We developed the following technique to detect the tray cover. The tray cover area in the input image is re-calculated based on the position and orientation of the tray (Figure 20.) A correlation operation is then performed between tray cover areas and a reference area having zero pixel value in each color. This operation provides average pixel values in tray cover areas. Red, green, and blue pixel values are calculated respectively. The pixel values of all tray cover areas are then evaluated if included in tray cover colors. The tray cover colors are defined as follows.

$$R:G \fallingdotseq B:G \fallingdotseq 1$$

$$G > G_{thresh}$$

Where R, G, B represent red, green, blue pixel values, respectively. G_{thesh} represents a threshold for the minimum pixel value of a tray cover. G_{thesh} is determined through experimentation.

5.4.2. Detection of the Tray Cover Direction Based on Pixel Values

We developed the following technique to detect tray cover hollow. The tray cover hollow areas and a tray surface area in the input image are re-calculated based on the measured position and orientation of the tray (Figure 20.) The pixel values of the hollow area (R_1, G_1, B_1) and those of the tray surface area (R_2, G_2, B_2) are then calculated using the same method as described in 5.4.1. The pixel values are then compared. The pixel value similarities are defined as follows.

$$R_1 : G_1 \fallingdotseq R_2 : G_2$$

$$B_1 : G_1 \fallingdotseq B_2 : G_2$$

6. EXPERIMENTS

6.1. The Environmental Perception Unit

We fabricated the environmental perception unit for installment on the food-tray-carrying robot (Figure 21.) We used micro color CCD cameras (TOSHIBA SM-40,) that are calibrated and installed on the gripper. The video signals (NTSC) from the cameras are input to one of the four Color Tracking Vision boards, which are on the VME bus with the CPU board (110-MHs, microSPARC-2) and one of which is used by the manipulation section. The environmental perception unit and the manipulator communicate through TCP/IP LAN installed on the robot frame.

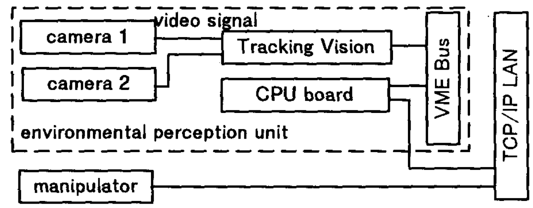


Figure 21. system configuragion of the environmental perception unit

6.2. Evaluation in A Simulated Environment

We completed an evaluation of all target functions in our simulated environment, which simulates a hospital room in a medical care facility. The experiments were carried out under various conditions as follows. The brightness level on the over bed table ranged from 60 to 7200 lx.

- Daytime on a sunny day without a window shade, no direct sunlight
- Twilight without a ceiling light
- Evening with a ceiling light

A. Position measurement accuracy evaluation

We evaluated position measurement accuracy by comparing measurement results with relative distances to the target. The prior relative distance between the camera and the target is measured directly. Experiments are performed using a range of distances by moving the manipulator.

A-1. Table

Figure 22 shows the distance-measurement result curve for a table position measurement. A tripled standard deviation (3σ) of error for a table position measurement in X, Y, and Z directions are $\pm$31.0mm, $\pm$6.2mm, and $\pm$14.5mm, respectively. Each value satisfies target accuracy (Table 1.) These results illustrate that this unit can position the table successfully 99% of the time.

A-2. Tray

Figure 23 shows the distance-measurement result curve for an indirect tray position measurement. A tripled standard deviation (3σ) of error for a tray position measurement in X, Y, and Z directions are $\pm$ 11.3mm, $\pm$ 6.8mm, $\pm$ 10.4mm, respectively. Each value satisfies target accuracy (Table 1.) Measurement accuracy in the Z direction exceeds target accuracy by 0.4mm, and is verified through experimentation that this excess can be absorbed in the grasping movement of a manipulator. These results illustrate that this unit

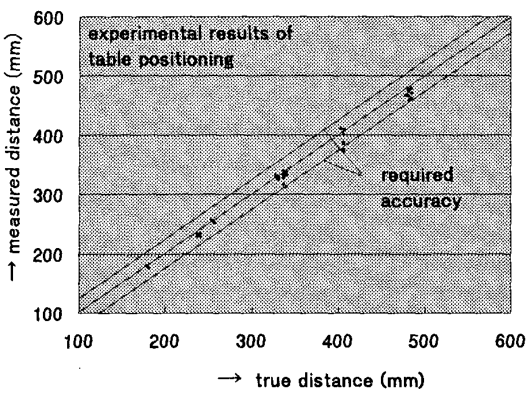


Figure 22. experimental results of table positioning

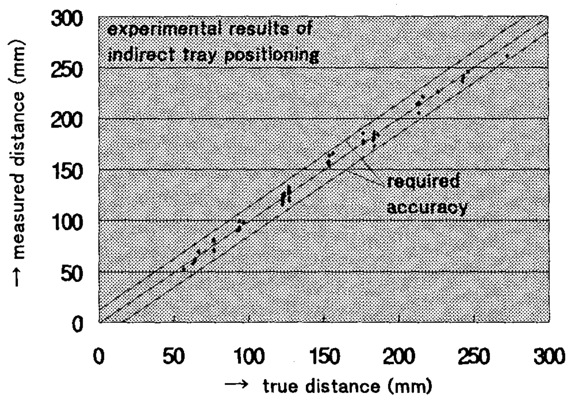


Figure 23. experimental results of tray positioning

can position the tray successfully 99% of the time.

B. Obstacle detection evaluation

We evaluated the obstacle detection function in 60 to 7200 lx of light. We used a thermometer and a glass as obstacles because these objects show the smallest degrees of contrast on a white table surface and are most difficult to detect. The results of the experiment illustrate that these obstacles can be detected within the full range of light levels.

C. Tray cover detection evaluation

We conducted a tray cover detection experiment in 60 to 7200 lx of light. The results of the experiment illustrate that the tray cover and its direction are detected within the full range of light levels.

D. Processing time evaluation

The average processing time of table position measurement and obstacle detection is 418ms. The average processing time of tray position measurement and tray cover detection is 237ms. These results are in accordance with the goal processing time (Table 1.)

Table 1. Experimental Results

		required	result
measurement accuracy (mm)	table	X: ±35.0	±31.0
		Y: ±15.0	±6.2
		Z: ±15.0	±14.5
	tray (indirect measurement)	X: ±15.0	±11.3
		Y: ±15.0	±6.8
		Z: ±10.0	±10.4
brightness range (lx)		100 - 7000	60 - 7200
process time	table	1 s	418 ms
	tray	1 s	237 ms

6.3. Evaluation in a Real-life Environment

We conducted a total system evaluation in a real-life environment in a medical care facility. The robot delivered and collected food trays successfully in about 100 trials.

7. CONCLUSION

We developed an environmental perception unit for an autonomous food-tray-carrying robot. We also developed the following new environmental perception techniques.

- Recognizing commercially available trays and tables in a real-life environment
- Measuring position and orientation of trays and tables accurately enough for the manipulator to manipulate the trays
- Detecting obstacles on the table in a real-life environment

We developed these techniques using a compact high-speed local image correlation processor (the Color Tracking Vision.) We fabricated a compact environmental perception unit and installed the unit in our food-tray-carrying robot. Our environmental perception unit has following advantages.

- Sufficiently compact to be installed in a mobile robot
- Applicability in varying degrees of brightness in a real-life environment (60-7200 lx)
- High-speed processing for practical use (<0.5s)

We conducted food tray delivery and collection experiments in a simulated environment and a real-life medical care facility. The experiments verified that our techniques are effective in a real-life environment and can be applied to practical object-manipulation tasks.

8. ACKNOWLEDGEMENT

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9. REFERENCES

[1] Masayoshi Hashima, Fumi Hasegawa, Shinji Kanda, Tsugito Maruyama, and Takashi Uchiyama, "Localization and Obstacle Detection for a Robot For Carrying Food Trays," Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'97,) Vol.1 pp.345-351, 1997.

[2] Yoshiro Hada, Kunikatsu Takase, "Task Level Feedback Control of a Robot Based on the Integration of Real-time Recognition and Motion Planning," Journal of the Robotics Society of Japan, Vol.15 No.2 pp.134-143, 1997.

[3] Kohtaro Ohba, Yoichi Sato and Katsushi Ikeuchi, "Visual Learning and Object Verification with Illumination Invariance," Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'97,) Vol.2 pp.1044-1050, 1997.

[4] Naoyuki Sawasaki, Toshihiko Morita, and Takashi Uchiyama, "Design and Implementation of High-Speed Visual Tracking System for Real-Time Motion Analysis," Proc. International Conference on Pattern Recognition, Vol.3 pp.478-483, 1996.