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Stereo vision system on mobile robots for measuring road surfaces

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Abstract—Mobile robots need a visual sensing system. This paper proposes one type of visual sensing system for mobile robots which uses a stereo vision system for measuring road surfaces. The system uses the Laminated Difference Method which we developed and can measure depth in the direction of the field of view. The system changes the distance of depth measurement relative to three-dimensional space when set up diagonally across a road surface, using the system position and angle parameters. This paper explains the principles of operation and features, and proposes an environment map for mobile robots using the system. The paper also reports the experiments conducted, and investigates the effectiveness and feasibility of this visual sensing system for mobile robots.

1. INTRODUCTION

Mobile robots are now being studied intensively for a variety of applications, such as for automatic carrier systems in factories, guide dog robots for welfare use [1, 2] and self-contained automobiles [3–5].

Mobile robots are designed to move around. Thus, they have to obtain information on their environment and judge before moving whether they can move. External sensors for mobile robots to obtain this information on the environment are under development [6]. Some research on the sensor system to do high-speed movement in the maintained environment has been performed. However, this research aims at the development of the sensor system for autonomous movement in various environments. This system uses the passive-type visual system so that the active-type sensor may have the problem in coherence and limited of output. Moreover, this system is a system which can develop into not only the measurement of the road surface but also the lane detection and environment recognition by making the best use of the visual system.

The authors have already developed a visual system of avoiding collision and have proved it to be effective experimentally using mobile robots in a building [7, 8]. The system measures the positions of mobile obstacles. Based on the results of these developments, we have been studying autonomous field vehicles that can move in a self-controlled manner in the field [9, 10].

The visual system is an important element of mobile robots. This paper describes the system, especially in relation to measurements of the space above a road. The paper also shows how the system can be used to recognize the environment by representing a mobile robot on an environment map using the information obtained by the system. The paper finally describes the experiments performed using the system, and discusses the effectiveness and practicality of the system.

2. EXTERNAL SENSORS FOR MOBILE ROBOTS

Mobile robots use external sensors to measure distance. However, these sensors have certain problems [11].

(1) Sensors based on propagation time
- Ultrasonic waves — poor resolution.
- Laser beam, millimeter waves — gives a wide field of view, but requires large equipment.

(2) Sensors based on triangulation
- Stereoscopic vision (stereovision) — depends on how precisely the corresponding points are determined.
- Light projection — cannot sense distant objects.
- Pattern projection — requires pattern recognition.

(3) Sensors based on automatic focusing — cannot measure multiple points.

Each type of sensor has different features and the sensor with the most suitable features should be selected to match the working environment of the robot.

The mobile robots used in this study require external sensors with the following capabilities:

(1) Observation of objects over a wide field of view simultaneously, because both robots and obstacles move.
(2) Observation of objects several centimeters to several meters apart.
(3) Real-time data processing.
(4) Passiveness to avoid interference, because the workspace is used by both people and robots simultaneously.
(5) Compact, light and low power consumption with few mechanical moving parts.

To satisfy these conditions, we used mainly stereoscopic sensors because sensors for mobile robots must have a high resolution, a wide field of view, and must be passive for simplicity and to avoid interference. Studies are being conducted to integrate the functions of different sensors and the robot control system should be able to incorporate such combined sensors.

3. STEREOSCOPIC VISION IN THIS SYSTEM

3.1. General

Stereoscopic vision determines corresponding points in the right and left images, then calculates by triangulation the distances to the points using the field of view information on these points.

There are various ways of measuring the distances to corresponding points depending on how these points are determined [12, 13].

Processing by stereoscopic vision is difficult to perform quickly due to the time taken to determine corresponding points. The authors have therefore devised a high-speed processing system using the Laminated Difference Method to determine corresponding points [7, 14].

The stereoscopic vision described in this paper was developed by our research group to avoid collision of mobile robots. This visual system can determine the position of a mobile obstacle [7, 8].

3.2. Principle and features

The system consists of two CCD cameras. The stereoscopic measuring method is based on triangulation, calculating the direction and distance of an object by determining the parallax on a scanning line on which the epipolar surfaces of the right and left pixels match as independent fundamental units [15].

As shown in Fig. 1, the perpendicular distance from the visual system to an object (measurement point) f, distance p and angle α between the line of sight and the object can be calculated as follows:

$$f = cw/s, \tag{1}$$

$$p = fx/c = xw/s, \tag{2}$$

$$\alpha = \tan^{-1}(x/c), \tag{3}$$

$$x = (i + j)/2, \tag{4}$$

$$s = i - j, \tag{5}$$

where c is a constant depending on the camera system, w is the distance between cameras and x is the average distance between corresponding points.

This system differs from conventional stereoscopic vision in the following respects. To match the two images, i.e. to find corresponding points in the right and left images, we compare only the lightness of each pixel without using the conventional edge extraction method in order to avoid occlusion and for quicker processing. We decreased the vagueness of matching introduced by this method by using our proposed Laminated Difference Arrangement. This method laminates the differences per pixel produced by shifting the arrangement of lightness of the corresponding right and left scanning lines. The sequence of lamination of this arrangement causes parallax corresponding to the distance to an object. Thus, the Laminated Difference Arrangement

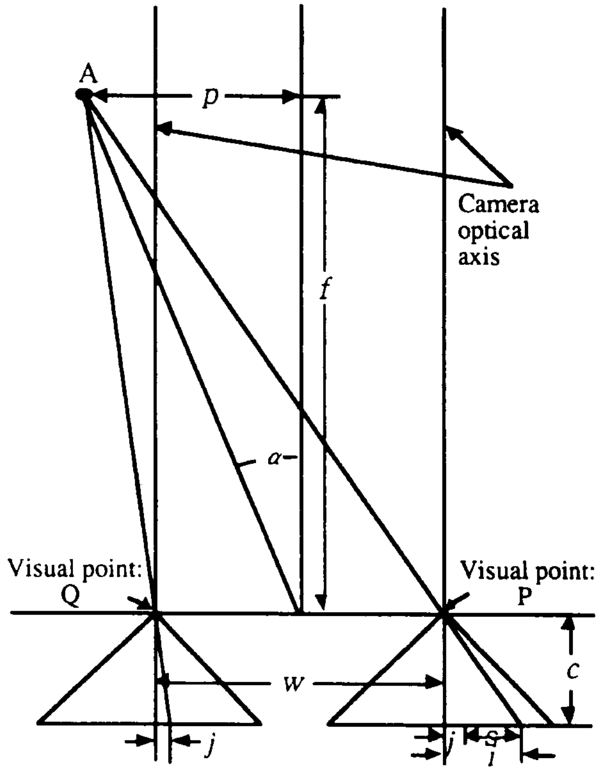


Figure 1. Principle of triangulation.

reveals information on the existence and position of the object in the space being observed. We then obtain constraints on corresponding points using the 'parallax plane' derived from the relationship between the positions of the difference laminated elements and the plane actually being observed. An example is the constraint condition that no object will be observed again behind an object in the direction in which an object was observed first. Such constraints increase the processing speed and allow us to find corresponding points that cause no geometric contradiction. Further, we use the parallax plane to interpolate corresponding points in the space where an occlusion has occurred, thereby solving the problem of correspondence to the real space.

We call this system Stereo Vision with the Laminated Difference Method, or LDM Stereo Vision. For a detailed explanation of the principle of operation and features of LDM Stereo Vision, see the literature [8, 14].

4. MEASUREMENT OF SPACE OVER A ROAD

4.1. System construction and three-dimensional position of measurement point

We developed the following system using LDM Stereo Vision for measuring the space over a road.

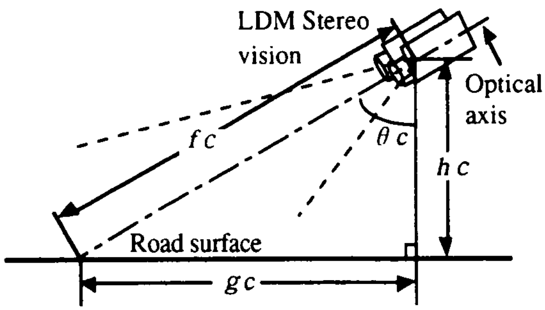


Figure 2. System installation.

As shown in Fig. 2, the LDM Stereo Vision is installed facing downwards. Assuming that the ground is flat, the distance f_c along the optical axis to the ground can be calculated in advance by the following equation:

$$f_c = h_c / \cos\theta_c \tag{6}$$

where h_c is the height of the camera above the ground and θ_c is the camera angle (angle of horizontal scanning line to the optical axis).

Similarly, the angles of scanning lines above and below the scanning line along the optical axis can be calculated from the angle covered by the lens. Thus, the distance from each scanning line on a screen to the flat ground can be calculated in advance. By calculating these, we can know in advance the space that the system can measure. Thus, when constructing the system for a mobile robot, we can determine the height and angle of the camera by the reverse calculation according to the space to be measured.

As explained in Section 3, LDM Stereo Vision can reveal the perpendicular distance f from the visual system to an object (measurement point), and the distance p and angle α between the line of sight of the visual system and an object on any point on a screen (Fig. 3). Thus, the 3D position of a measurement point can be represented by the following equation:

$$g = f \sin\theta, \tag{7}$$

$$h_p = f \cos\theta, \tag{8}$$

$$h_g = h_c - h_p, \tag{9}$$

where θ is the value obtained in advance from the direction of the scanning line and the angle of view of the lens, and h_g is the relative height of the system above the ground using the height of this visual sensing system as the reference.

The system can measure the space over the ground three-dimensionally using the LDM Stereo Vision measurements if the system orientation is determined with a gyroscope and corrected appropriately.

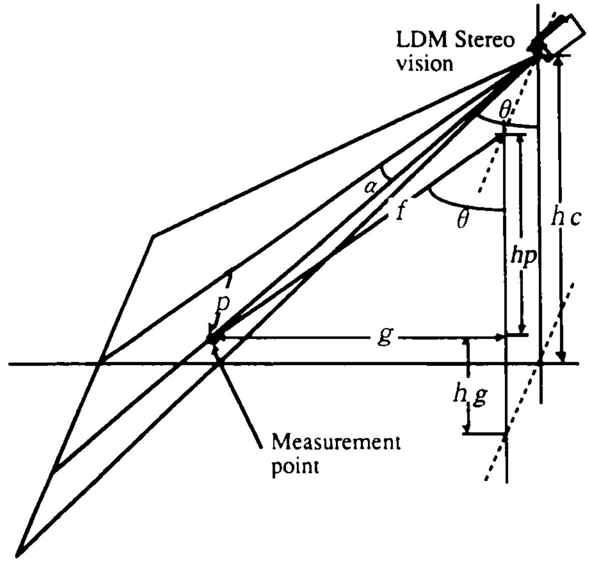


Figure 3. 3D position of measurement point.

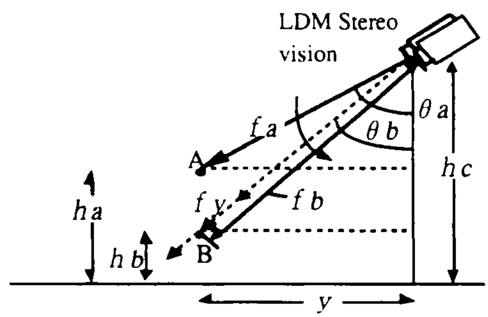


Figure 4. Judging the effectiveness of measured values.

4.2. Features

This system uses LDM Stereo Vision as a sensor to measure the space over the ground and has the following features:

When the values measured by LDM Stereo Vision are applied to a space as a 3D position over the ground surface using the height of the visual system as the reference, geometric restraints are introduced which result in a faster search time for corresponding points and errors. Further, certain facts hold true for the measurement results. We will explain how the distance is measured from the scanning line at the top of the screen as shown in Fig. 4.

Assume that the height and distance of point A is located at height h_a above the ground and at a distance f_a from the camera, which is at height h_c and is used as the reference. The point is measured using LDM Stereo Vision in the direction of the line of sight on the scanning line of angle θ_a. Next, let us study the distance of f_y to a point to be measured in the direction of the scanning line with an angle of θ_b. The distance f_y can be longer than, equal to or shorter than f_b in Fig. 4. If f_y is smaller than f_b, the measurement point exists before point A. If f_y is equal to f_b, the distance f_y from the system installation point to B is equal to that to A. The height h_a of A, which is higher than B, should be used because, for a mobile robot, the height of an object is used to judge whether the object is an obstacle. If f_y is larger than f_b, the object is lifted or has a hole, or the measurement contains an error. Since we are interested in whether the mobile robot can pass along a route, we can decide whether the object is an obstacle only if we know the height of the top (or the bottom when the robot travels over a hollow) of the object. Thus, we can ignore f_y in practice if f_y is larger than f_b based on the measured values of point A. Similarly, this also applies when the measurement point is observed at a position lower than the ground surface with the camera height h_c as the reference. In this case, the object will be an obstacle for the robot if it is lower than the ground. Thus, this system can measure only the values in space over the road surface, which are effective for judging whether the robot can travel along the route. One method of measuring the distance using the location parameters of the camera installation, just like this system, is the inverse perspective transform [16] by monocular vision. This method is based on the secondary correspondence between the pixels on a screen and the ground. Thus, it can measure the position of an object on the ground but cannot measure the precise position of an object floating in space. If we calculate the distance to the measurement point using LDM Stereo Vision in advance, the system proposed in this paper can measure the precise position of an object floating in space.

One method of obtaining stereo vision is to extract the edges of an object to find the correspondence between the right and left images. This method, however, has the disadvantage that it recognizes a mark on an upward slope as being floating in space. The system gives a similar result on a road with small variations in lightness, but can nevertheless determine the road surface information precisely because it matches corresponding points pixel-to-pixel. We have been studying a system that projects random patterns on a road surface with small variations in lightness in order to provide a measurement space with greater variations in lightness [17]. This is an active sensing system which also removes interference by projecting random patterns.

5. MAP REPRESENTATION AND ENVIRONMENT RECOGNITION OF A SPACE OVER A ROAD

A mobile robot can be represented on a mobile environment map in various ways. This study uses the values of a 2D arrangement converted from the relative heights of an object above the road surface obtained from the position of this visual system. It represents the coordinates on the 2D plane at constant intervals as elements of the 2D arrangement. The size of area that this method can represent can be varied according to the number of elements of the arrangement and the intervals of scaling the actual space. In this case, the scale should be determined by considering the performance and size of the mobile robot. In this system, the 2D arrangement representing the height is called an elevation arrangement map.

Using this elevation arrangement map, mobile robots can easily judge by the arrangement figures on the route whether they can move. The judgment is made by determining the threshold depending on the step height that a mobile robot can cross. This elevation arrangement map can represent the environment precisely.

By measuring and representing the space over the ground precisely, the mobile environment can be recognized, including upward slopes, the shapes of obstacles and the sizes of cars. The same techniques can also be used to identify the position of mobile robots.

6. BASIC EXPERIMENT

6.1. Overview of the experimental system

An experimental apparatus was constructed to determine whether the proposed visual system is effective for measuring the space over a road. Figure 5 outlines the apparatus.

The system uses two 2/3 in. monochrome CCD cameras equipped with a wide-angle lens (4.8 mm). The images from the two cameras are synchronized and converted from analog to digital signals simultaneously. The signals are then automatically switched every eight scans by the image switching unit and stored in one frame of memory (Fig. 6). An image converted to a digital signal can be resolved to 256 pixels in the horizontal direction and each pixel has a resolution of 64 tones. The cameras are spaced 15 cm apart.

6.2. Outline of experiment

The system did not match all the images in a picture but measured five scanning lines at random.

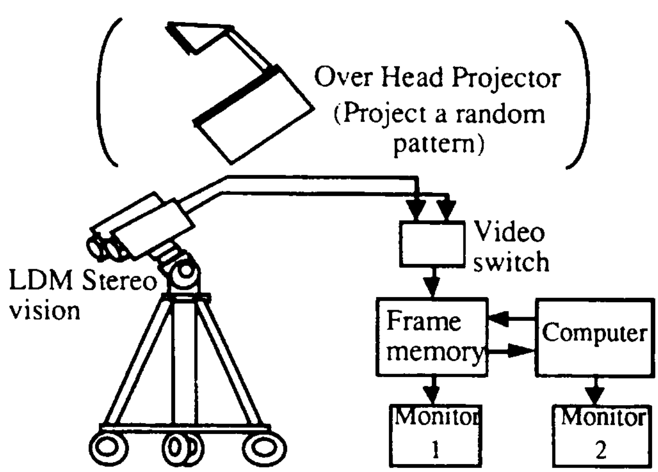


Figure 5. Outline of the experimental apparatus.

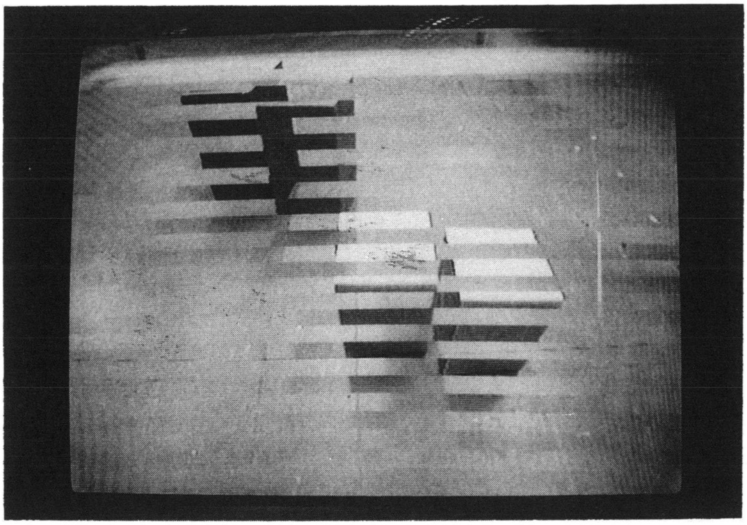
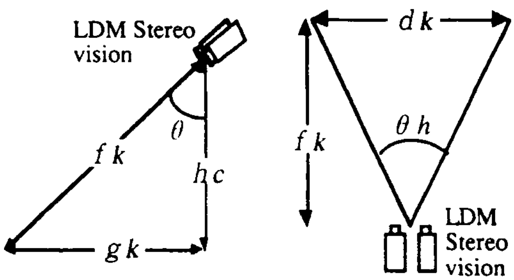


Figure 6. Image of a frame of memory.



Scanning Line	1	2	3	4	5
θ (degree	37.0	43.0	49.5	54.5	59.0
f k (cm)	125.2	136.7	154.6	172.2	194.2
g k (cm	75.3	93.3	117.1	140.2	166.4
d k (cm)	76.6	83.6	94.2	105.3	118.7

Figure 7. Correspondence between scanning lines and angles.

The details of the experimental apparatus are:

Camera installation angle θ_c	45°
Camera height h_c	100 cm
Horizontal angle θ_h	34 (range over which the measured values are effective experimentally; the camera lens covered about 74°)

Figure 7 shows the correspondence between the scanning lines and angles.

The mobile robot is intended to be used for an electric car about the size of an ordinary passenger car. Thus, the experiment represents the space on the road on an elevation arrangement map of depth 10 cm by width 20 cm for each arranged value.

6.3. Experimental environment

The measuring system was tested for a virtual indoor space, and for a road environment including a flat paved road, a flower bed and a stepped area. The experiment indoors was conducted under the following conditions:

(1) Flat floor.

(2) Upward slope, downward slope.

(3) Wall.

(4) Obstacles.

Random patterns were projected using an OHP during measurement to supplement insufficient variations in lightness in the indoor experiment.

The outdoor experiment was conducted under the following conditions:

(1) Flat brick paved road.

(2) Flower bed.

(3) Stepped area.

(4) Flat asphalt road.

6.4. Experimental results

In the indoor experiment in which variations in lightness were intensified by projecting random patterns, the system was able to record the measured values on the elevation arrangement map clearly. It represented on the map the slope inclination and the positions and sizes of the walls and obstacles although with some errors. For details of the errors, see Section 6.5.

The outdoor experiment was conducted in natural light without projecting random patterns. Roads with some variations in lightness gave satisfactory results and the system showed the road space on the elevation arrangement map. However, when the lightness only varied up to 7–9 of the 64 tones in the experiment, satisfactory results were not obtained because exact corresponding points could not be found. LDM Stereo Vision was unable to measure corresponding points due to its principle of operation.

This paper reports only the results of the indoor experiment for a space with two obstacles. Figure 8 shows the experimental environment, while Fig. 9 shows the dimensions. Figure 10 shows the elevation arrangement map of the measured results. The arrangements are spaced at a depth of 10 cm and width 20 cm. The value of 999 represents an unmeasured area. Dots and arrows show the positions and directions of the visual system.

Figure 11 shows a stereoscopic graph of the arrangement map data. To make the graph easy to understand, the value of each point on the elevation arrangement map is represented by a plane consisting of four points. Thus, an arrangement value of

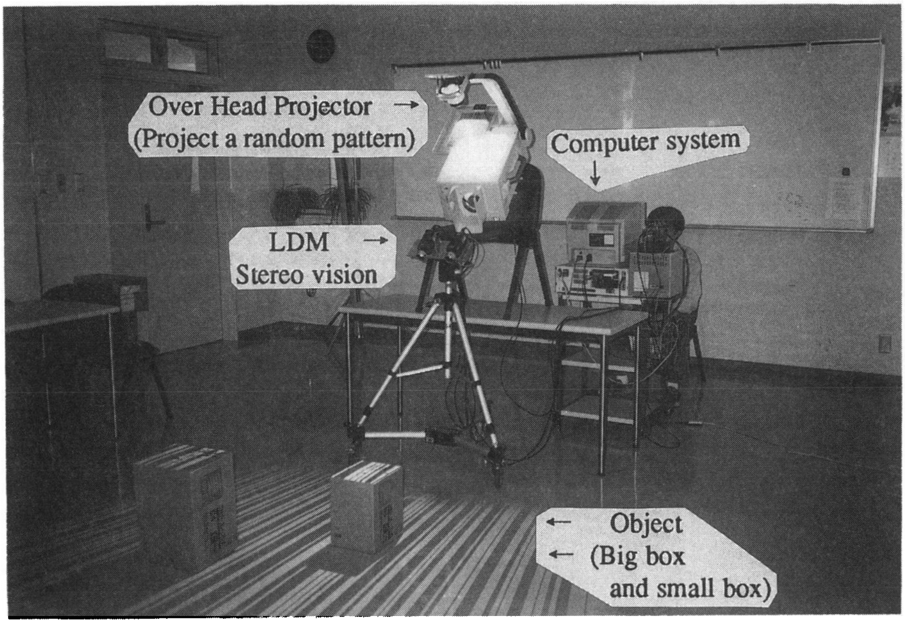


Figure 8. Experimental environment.

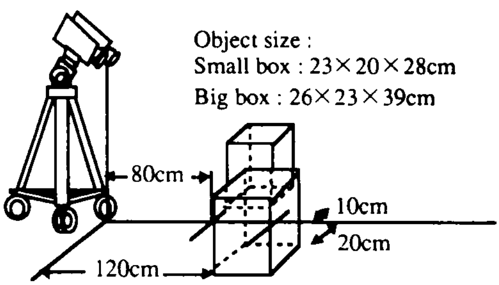


Figure 9. Dimensions of the experimental environment.

10 cm (depth) × 20 cm (width) is represented by a plane of 5 × 10 cm. In Fig. 10, underlined 999 shows unmeasured areas; these are just in front of the system and are treated as a plane with zero height within the field of view, assuming that the system has already advanced and has measured the areas. The areas behind the object, areas which remained unmeasured due to the inconvenient layout of the scanning lines, and areas which are out of the field-of-view angle and coverage of the system are marked as unmeasured areas on the stereoscopic graph.

Figures 10 and 11 show an object 20 cm wide lying 10 cm to the left and 80 cm in front of the visual system. There is another object 30 cm wide, 20 cm to the right and 120 cm in front of the system. Because the arrangements are spaced, a position at 10 cm means an area of 10–20 cm. Since only five scanning lines were used this time, the top of the obstacle could not be measured, but the height can be measured

999	999	999	999	999	999	999	999	999	999	999	999	999	999	999
999	999	999	999	999	999	999	999	999	999	999	999	999	999	999
999	999	999	999	999	999	999	999	999	999	999	999	999	999	999
999	999	999	999	999	999	999	999	0	999	999	999	999	999	999
999	999	999	999	999	999	999	0	0	999	999	999	999	999	999
999	999	999	999	-9	999	999	0	999	999	999	999	999	999	999
999	999	999	-4	22	999	999	0	0	999	999	999	999	999	999
999	999	999	-4	22	0	999	0	0	999	999	999	999	999	999
999	999	999	0	0	0	999	0	0	999	999	999	999	999	999
999	999	999	0	0	0	999	5	0	999	999	999	999	999	999
999	999	999	4	0	0	999	0	999	999	999	999	999	999	999
999	999	999	0	0	0	21	0	999	999	999	999	999	999	999
999	999	999	0	0	0	21	0	999	999	999	999	999	999	999
999	999	999	-4	0	0	17	0	999	999	999	999	999	999	999
999	999	999	999	999	999	999	999	999	999	999	999	999	999	999
999	999	999	999	999	999	999	999	999	999	999	999	999	999	999
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Position and derection of stereo vision

Figure 10. Elevation arrangement map. Environment measurements are shown in Fig. 8.

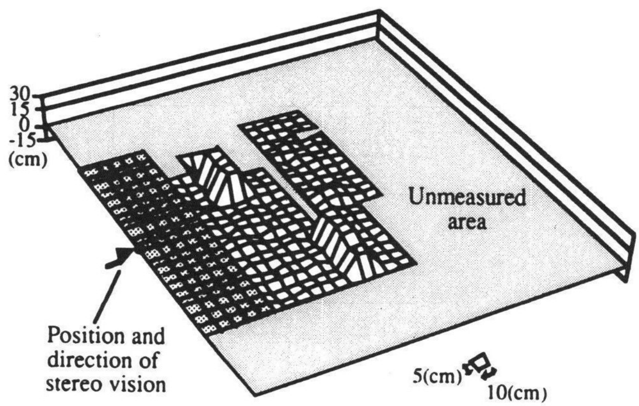

Figure 11. Stereoscopic graph of space over the road.

more precisely by using more scanning lines. The results agree closely with the actual size and position of the object.

6.5. Considerations

The measurement results are almost satisfactory, and we have demonstrated the effectiveness and feasibility of the proposed visual system for measuring the space over a road.

We did not increase the processing speed of the system because the experiments were designed to test the principle only. The current system takes about 5 s to measure one space with five scanning lines on an NEC 9801VX personal computer (286 10 MHz). The processing speed can be increased by using a high-speed computer or parallel processing transputer. Data could be processed in real-time by using a dedicated processor and hardware.

The picture was distorted at the corners because of the wide-angle lens and distances could not be measured precisely; measured values were effective in a narrow range only. Factors which affect the measuring range such as the lens used and assignment of scanning lines should be investigated further.

We used a monochrome CCD camera in this experiment, but this could not measure at all a road surface with a simple pattern such as an asphalt road. In this case, a projection system is effective. To judge the terrain in the field, color information would be more effective than variations in lightness because color contains more information. We are now studying a stereo vision system based on the Laminated Difference Method using color information.

The measurement errors must also be considered, using the errors in the values in Fig. 2, Section 2 as an example. The quantization errors for direction K and for distance M are given by the following equations:

$$K = \beta / n, \tag{10}$$

$$M = f^2 / (c \cdot w), \tag{11}$$

where β is the angle of view and n is the resolution of angle of view.

As shown by (10), the quantization error increases as the distance increases. The maximum error of the system was within $\pm 10\%$ when measuring an object at a distance of 2 m. Because the measurements are made with the camera placed at an angle, the horizontal plane is stored as a square in the frame memory after being converted to a digital signal, although it is actually a trapezoid. This also explains why the quantization error increases as the distance from the camera increases. Furthermore, when the environment is represented using the elevation arrangement map, the measured values are stored discretely according to the scale of this arrangement map, thus introducing a further error. The scale of the arrangement map should be considered carefully to suit the mobile robot.

7. CONCLUSION

This paper has described a visual system for measuring the space over a road as an external sensor for mobile robots. The authors devised a Laminated Difference Method and represented the measured values on the environment map for mobile robots, and proved that the system can be used to recognize an environment. Experiments showed that the proposed system is an effective sensor for measuring the space over a road and a practical system is likely to be developed.

Future tasks include increasing the processing speed of the system, studying possible applications for environment recognition and implementing the system in a mobile robot.

REFERENCES

1. S. Tachi, K. Komoriya, K. Tanie, T. Ohno and M. Abe, "Guide dog robot — freasibility experiments with MELDOG Mark III," in *Proc. 11th Int. Symp. Industrial Robots*, 1981, pp. 95–102.
2. Y. Yamamoto, K. Nishikawa and H. Mori, "Development of guide dog robot 'HITOMI' — Application of HARUNOBU-5," in *Proc. 8th Lecture Meeting of Robotics Society of Japan*, 1990, pp. 151–154.

3. M. Turk, D. Morgenthaler, K. Gremban and M. Marra, "Video road-following for the autonomous land vehicle," in: *Proc. 1987 IEEE Int. Conf. Robotics and Automation*, vol. 1, pp. 273–280, 1987.
4. C. Thorpe, S. Shafer and T. Kanade, "Vision and navigation for the Carnegie Mellon NAVLAB," *IEEE Trans, Pattern Analysis Machine Intell.*, vol. PAMI-10, no. 3, pp. 362–373, 1988.
5. A. Hattori, S. Ueki and E. Nakano, "Steering control of an autonomous vehicle," in *Proc. 8th Lecture Meeting of Robotics Society of Japan*, 1990, pp. 141–142.
6. H. Mori, "Road environment understanding and navigation," *J. SICE*, vol. 30, no. 1, pp. 21–26, 1990.
7. S. Hachiyama and J. Takeno, "Fundamental studies on robot collision avoidance problem for moving obstacles — study 10. A 2nd experiment on a robot collision avoidance problem for a moving obstacle using a visual system," in *Proc. 6th Lecture Meeting of Robotics Society of Japan*, 1988, pp. 527–530.
8. J. Takeno, S. Kato and S. Hachiyama, "Fundamental studies on robots' collision avoidance problem for moving obstacles — study 14. A complete self-contained collision avoidance robot with a vision system and controlling three sensors to detect moving obstacle," in *Proc. 9th Lecture Meeting of Robotics Society of Japan*, 1989, pp. 13–16.
9. S. Kato and J. Takeno, "A real time stereo vision system for autonomous field vehicle," in *Proc. 17th Lecture Meeting of SICE*, 1992, pp. 23–31.
10. S. Kato, S. Nishiyama and J. Takeno, "Research of autonomous vehicle on the field using a 3D vision system — Part 1. Proposition of an autonomous vehicle on the field and environment recognition for moving on the field," in *Proc. 9th Lecture Meeting of Robotics Society of Japan*, 1991, pp. 293–296.
11. Y. Shirai, *Pattern Recognition*. Ohm-sha, 1987.
12. H. K. Nishihara and T. Poggio, *Stereo vision for robotics. Robotics Research: The 1st Int. Symp.* Boston, MA: The MIT Press, pp. 489–505, 1984.
13. Y. Ohta, Y. Masai and K. Ikeda, "Interval matching method of stereo images using dynamic programming," *Trans. Inst. Electron. Commun. Eng. Jpn*, vol. J68-D, no. 4, pp. 554–561, 1985.
14. J. Takeno and S. Hachiyama, "New technology on stereo vision for mobile robots," in *Proc. Int. Conf. Advanced Robotics (ICAR'91)*, 1991, pp. 1383–1391.
15. R. M. Haralick and L. G. Shapiro, *Computer and Robot Vision*. Addison-Wesley, 1992.
16. M. Yachida, "Robot vision," *J. Robotics Soc. Jpn*, vol. 10, no. 2, pp. 140–145, 1992.
17. K. Sakai, S. Nishiyama and J. Takeno, "Studies on a visual system for mobile robot study 1. Proposing a stereo vision with random pattern projection (SVRP)," in *Proc. 9th Lecture Meeting of Robotics Society of Japan*, 1991, pp. 181–182.

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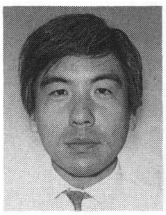

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