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## SYSTEMS and COMPUTERS in JAPAN

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**A Translation of Denshi Joho Tsushin Gakkai Ronbunshi**

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# Acquiring Omnidirectional Range Information

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## SUMMARY

This paper describes a method of obtaining a precise omnidirectional view and coarse ranges to objects by rotating a single camera. The omnidirectional view is obtained by arranging image data taken through a vertical slit on the image plane while the camera rotates around the vertical axis. The omnidirectional view contains precise azimuth information determined by the resolution of the camera rotation. The range is obtained from two omnidirectional images taken through two slits when the camera moves along a circular path. This range estimate contains errors due to a finite resolution of the camera rotation system, while a conventional binocular stereo method contains errors due to quantization of images. The representation of an environment, "panoramic representation," by the omnidirectional view and range information is useful for a vision sensor of a mobile robot.

## 1. Introduction

A camera used for a vision sensor of a conventional mobile robot is mounted on the robot. To recognize an environment more flexibly, it is necessary to design a camera to have more active functions. To achieve this requirement, a camera should be able to sense the whole environment and its specific part.

Fixation of gaze upon the interesting object is used in the paradigm of "Active Vision" [1, 2] which is a current topic in Computer Vision. In the Active Vision, a camera gazes upon a particular feature point in an

environment while moving, and generates an environmental description with respect to the point.

Viewing the whole environment from an observation point is also important for a robot. It is necessary to build an accurate map when a robot works in an unknown environment. For this purpose, it is more efficient to use a wide view than integrating partial views of the whole environment by using a camera with a limited visual field. Since the conventional camera has a limited visual field, it is necessary to add extra facility to the camera to obtain an omnidirectional view field.

Yagi and Kawato [3] obtained an omnidirectional image by using a conic mirror which yields the image of the environment from the entire direction and by taking this image by a camera viewing from the top of the cone. Their method takes an omnidirectional image in real time and can analyze the image using a property whereby the optical flow of a point for a linear camera motion forms a curve. However, the angular resolution of their method is rather limited (the minimum resolution is about  $0.2^\circ$  in an image of  $512 \times 512$  pixels), the resolution being coarse near the vertex of the cone, since the image of the entire environment is projected onto a single image plane.

Morita et al. [4] obtained a wideview image by using a camera with a fisheye lens. The angular resolution of their method is also not very high, although they reconstruct a three-dimensional (3-D) structure using the vanishing point of straight lines in its environment and not directly using omnidirectional information.

Sarachik [5] has devised a method to obtain an omnidirectional image and the distance to a ceiling edge (a horizontal edge between a ceiling and a wall) by using two rotatable cameras on a robot. Her method can locate the robot in a room and estimate the camera direction.

By contrast to these passive methods, there have been active methods which project an optical pattern onto objects to measure their distances. Blais et al. [12] have constructed a compact stereo-based distance-measurement system by projecting a light onto the environment. By rotating their system, omnidirectional range information can be obtained. A disadvantage of the active method is that its environment is restricted by physical conditions, especially those of illumination.

The method proposed in this paper is a passive one without projecting a light pattern and uses a camera rotating around a fixed vertical axis, similar to Sarachik's system, to obtain an omnidirectional image. However, unlike her method which uses two cameras to obtain the distance information, the proposed method uses a single camera and can obtain both the view and range information with a high angular accuracy over  $360^\circ$ . Let us call this camera-centered 2.5-D representation containing both the visual information and the range information "panoramic representation." The method of Blais et al. [12] also can obtain both the omnidirectional view and range information. The difference of the proposed method from their method, other than the light projection, is the cause of errors in azimuth measurements. The error in their method depends on the resolution of its image sensor, and that in the proposed method depends on the angular accuracy of rotation of the camera around its axis (see section 2).

Advantages of the panoramic representation are as follows:

(A) Omnidirectional visual information has the following features:

- (1) When an omnidirectional image is taken in a rectangular room, four vanishing points appear every  $90^\circ$ .
- (2) When a camera moves on a straight line on a plane perpendicular to the rotation axis of the camera, two "foci of expansion" (FOE) of the optical flow of objects in its environment appear at an interval of  $180^\circ$  in the omnidirectional image.

- (3) The environmental structure is obtained by a set of two omnidirectional images.

By using feature (1) as a constraint, the vanishing points in an omnidirectional image can be determined more precisely; and this is useful in obtaining the rotation angle of a mobile robot. By using feature (2), the rotation angle and the direction of the robot motion can be obtained from the projection of the features onto a Gaussian sphere [6]. Feature (3) can be used for stereovision by using two omnidirectional images taken at different locations in an environment. The correspondence of the two images can be obtained by using "circular dynamic programming" [7] based on the structure of the omnidirectional image.

(B) Precise angular information

An image obtained by the proposed method has a resolution equal to that of the camera rotation; i.e., by using a precise camera rotation control system, the resolution of the angular information could be higher than that of a conventional method. This is an excellent feature of the proposed method. For example, the stereovision using a pair of two omnidirectional images (feature (3) in (A)) is useful for determining both the structure of the wide environment and positions of objects in it.

(C) Omnidirectional range information

The proposed method can obtain an omnidirectional view and at the same time the range information. The latter is useful in finding free regions in its environment, establishing the correspondence of a pair of two omnidirectional images, and determination of motion parameters of a robot.

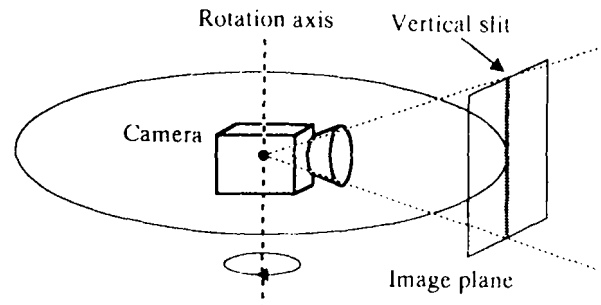


Fig. 1. Imaging method (omnidirectional view).

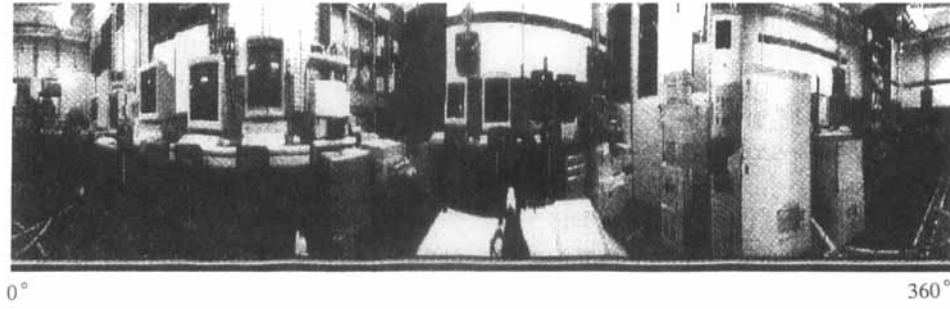


Fig. 2. Omnidirectional view.

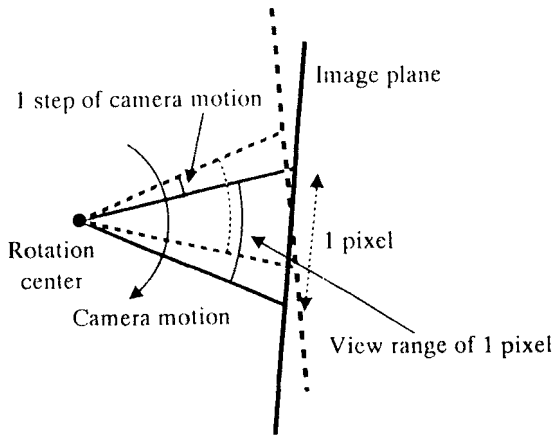


Fig. 3. Rotating angle and resolution of the image.

The panoramic representation proposed herein has features (B) and (C).

## 2. Method of Taking Images

### 2.1. Omnidirectional image

Figure 1 shows a mechanism to take an omnidirectional image. A camera rotates around the vertical axis passing through its focal point, the optical axis of its lens being perpendicular to the rotation axis.

The omnidirectional image is obtained by arranging the image through a vertical slit with a width of a single pixel along a horizontal line. Figure 2 shows an example

a horizontal line. Figure 2 shows an example of omnidirectional image ( $900 \times 265$  pixels) of a computer room obtained by rotating the camera with a step of  $0.4^\circ$ .

We can improve the resolution of the angular information by controlling the camera rotation with a finer step. If the resolution of camera rotation is reduced further, it becomes smaller than an angle corresponding to a single pixel (Fig. 3). For example, when a camera with the focal length of 600 pixels is used, the image angle corresponding to a single pixel is about  $0.1^\circ$ . However, the azimuth of each vertical edge of an object (which is parallel to the rotation axis of the camera) in a 3-D environment can be measured more accurately by rotating the camera with a smaller step than the azimuth information obtained by using a conventional image sensor. In an edge image made by a gradient operator (e.g., Sobel operator), an edge can be located where the edge strength is maximum. We confirmed experimentally that the edge image of an omnidirectional view taken with a very small rotation step also has a peak in each edge portion. From this result, it is expected that an omnidirectional image has a resolution equal to that of the camera rotation system.

### 2.2. Omnidirectional stereo method

Let us describe the method to obtain the omnidirectional view and distance information simultaneously by modifying the imaging method described already.

A stereovision system using two cameras is a well-known method to obtain the distance information from images. Sarachik [5] has obtained the distance information from a set of two omnidirectional images taken by two cameras (arranged in the upper and lower parts of the rotation system), and by finding the correspondence of the two images.



Figure 4 shows the imaging method for the omnidirectional stereo. A camera rotates at a distance  $R$  from the rotation axis. We set two vertical slits with a 1-pixel width symmetrically to the image center. By arranging the images through the slits, we acquire a pair of omnidirectional images, as shown in Fig. 5. A feature point in 3-D space appears in and passes through one slit and then appears in the other as the camera rotates. By measuring  $2\theta$  of the camera rotating the feature point from one slit to the other, we can estimate the range  $L$  of the point from the rotation center as

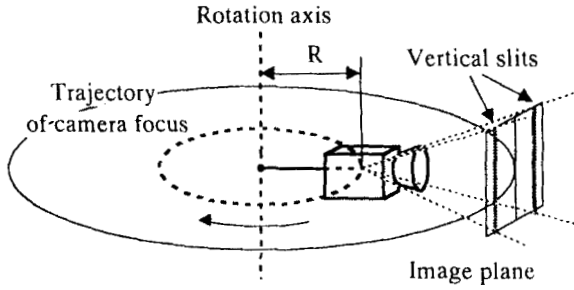


Fig. 4. Imaging method (omnidirectional stereo).

$$L = \frac{R \sin \varphi}{\sin(\varphi - \theta)} \quad (1)$$

where  $\varphi$  is a half of the view angle of the two slits or  $\varphi \approx \tan^{-1}(1/f)$ .

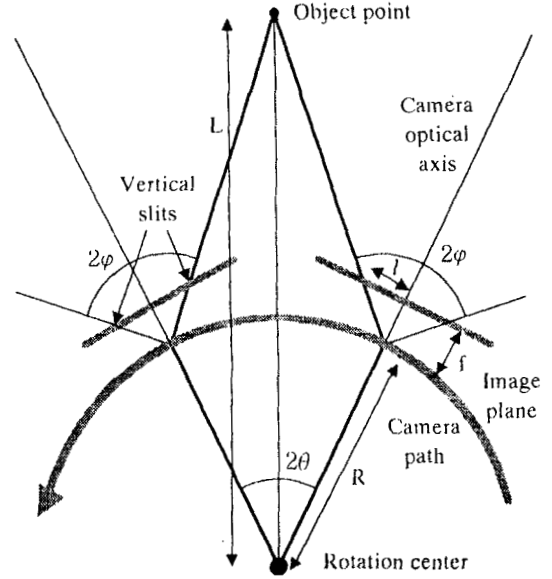


Fig. 6. Range estimation by omnidirectional stereo.



(a) Omnidirectional view from left slit



(b) Omnidirectional view from right slit

Fig. 5. Two omnidirectional views for stereo method.

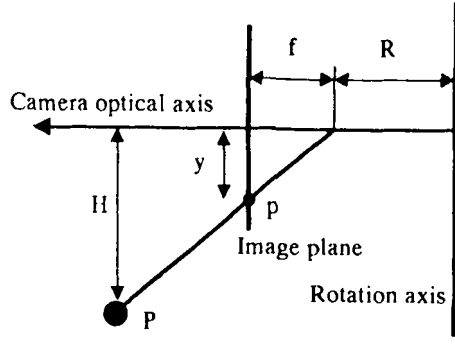


Fig. 7. Height estimation by omnidirectional stereo.

To measure a distance to an object, a conventional stereo method uses its parallax between a pair of images. Instead, the proposed method uses the difference of two angles viewing the same object through the two slits (i.e., this corresponds to the parallax in the conventional stereo method).

Referring to Fig. 7, the height of an object  $H$  in an omnidirectional stereo image is given by

$$H = (L \cos \theta - R) \frac{y}{f} \quad (2)$$

This shows that the vertical position  $y$  of the object in the image and the focal length of the camera  $f$  are needed for estimating the height of the object.

The correspondence of an object in a set of two omnidirectional images can easily be found by tracking it between the two slits. This tracking is robust since the direction of movement is known and its amount is very small. If an object is hidden by another, its distance can be obtained by the rotation angle of the camera before occlusion. We use a conventional method [10] for finding correspondence.

Another advantage of the proposed method is ease of equipment setting. Unlike a conventional stereo method using two cameras which requires calibrations of many parameters related to the cameras, the proposal using a single camera reduces such procedures.

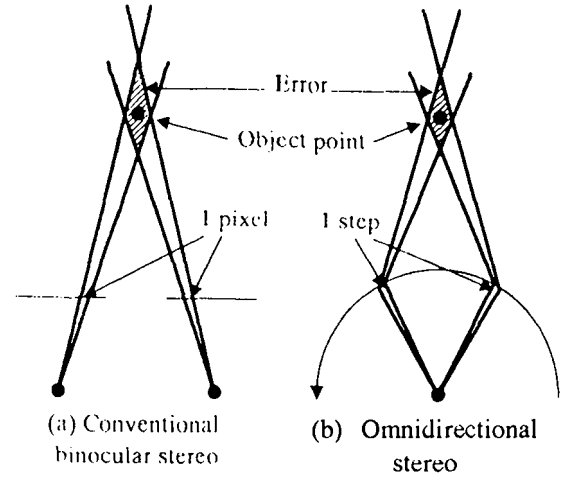


Fig. 8. Conventional binocular stereo vs. omnidirectional stereo.

### 2.3. Errors in omnidirectional stereo

A distance measured by a conventional binocular stereo method contains an error caused by its quantization. This is equivalent to the resolution  $\Delta\theta$  of the camera rotation system in the proposed omnidirectional stereo method as shown in Fig. 8. When the camera rotation system has an error of  $\Delta\theta$ , the error in the distance to a feature point is given by

$$\Delta L = \frac{\sqrt{1 - \left(\frac{R \sin \varphi}{L}\right)^2}}{R \sin \varphi} L^2 \Delta \theta \quad (3)$$

This shows that  $\Delta L$  is proportional to the square of the distance  $L$  between the camera rotation center and the object if the object is sufficiently far ( $L \gg R \sin \varphi$ ); and this is inversely proportional to  $R \sin \varphi$  which corresponds to the distance between the two cameras in a conventional binocular stereo system.

Figure 9 shows the relationship between the rotation radius  $R$ , the distance and the error, when the resolution of the camera rotation system  $\Delta\theta$  is  $0.4^\circ$ . Although the error reduces when  $R$  is large, there is a practical limit in its maximum value when the system is mounted on a mobile robot. In the experiment to be described herein, the focal length of the camera  $f = 600$  pixels,  $R = 0.2$  m, and the distance of 200 pixels from the central line of the



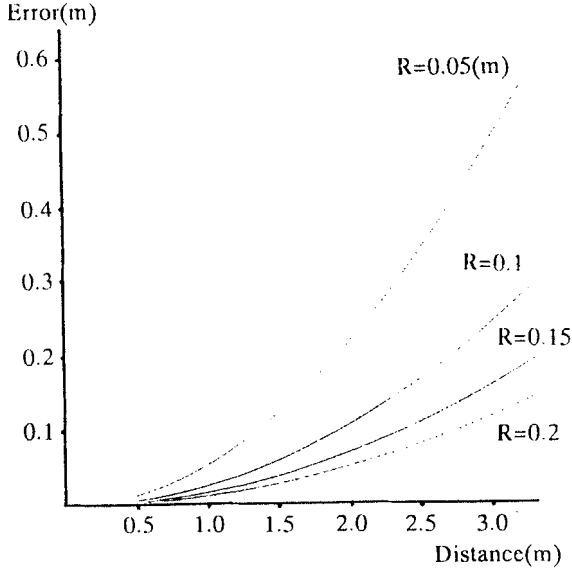


Fig. 9. Relationship between radius  $R$  and error.

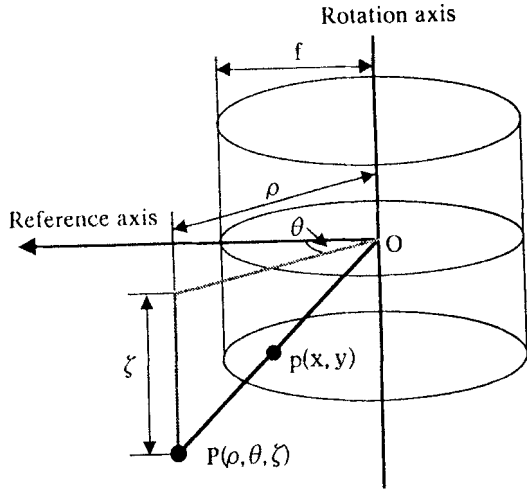


Fig. 10. Imaging model (omnidirectional view).

of the image plane to each slit are used. Despite the forementioned limit of  $R$ , the resolution of the camera rotation system  $\Delta\theta$  can be very small (i.e., the error in distance measurement can be small) in the proposed method, since the azimuth of an object can be determined with an accuracy equal to that of the camera rotation

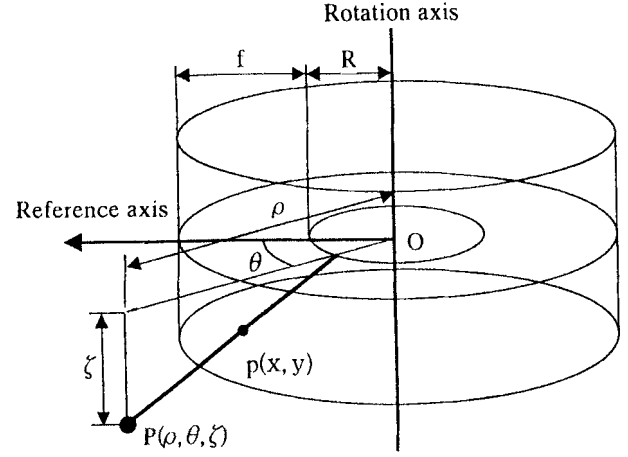


Fig. 11. Imaging model (omnidirectional stereo).

system. The camera rotation system used for the experiment has a solution of  $0.005^\circ$ . Therefore, assuming that the system is operated with  $0.003^\circ$  step and that the error depends solely on the resolution of the rotation system, the error in the distance to an object separated from the rotation center by 1.0 m will be about 0.0014 m.

### 3. Projection to Omnidirectional Image

Mathematical properties of projection onto an omnidirectional image are described here. An omnidirectional image has features of cylindrical projection of a 3-D space. Referring to Figs. 10 and 11, let us represent a 3-D space by using a cylindrical coordinate system. The  $\zeta$  axis is taken along the camera rotation axis, the origin  $O$  is a point on the  $\zeta$  axis at the height of the focal point of the camera, and  $\theta$  is an angle on a horizontal plane crossing with the origin and measured from an arbitrary reference direction.

#### 3.1. Omnidirectional image taken by method shown in Fig. 1

Figure 10 shows a model of projection onto an omnidirectional image taken by the method described in section 2.2. Point  $P = (\rho, \theta, \zeta)$  in a 3-D environment

is projected as point  $p = (x, y)$  in the omnidirectional image plane by

$$x = \theta, \quad y = \frac{f\zeta}{\rho} \quad (4)$$

where  $f$  is the focal length of the camera.

A line in the 3-D space is projected on an ellipse which appears when the cylinder is cut by a plane containing this line and the origin. This line appears as a sinusoidal curve in the omnidirectional image which is an expanded plane of the cylindrical surface. For example, a simple case where a straight horizontal line (height  $H$ , distance from the  $\zeta$  axis  $D$ ) perpendicular to the reference axis, i.e.,

$$\rho = \frac{D}{\cos \theta}, \quad \zeta = H \quad (5)$$

is represented by

$$y = \frac{fH \cos x}{D} \quad (6)$$

and this is projected as a sinusoidal curve.

As shown in Fig. 2, an object taken by this method is distorted when it is projected onto an omnidirectional image. It is easy to reconstruct the original image from the distorted image. Considering this, an omnidirectional image taken by the proposed method contains all the information of an environment around the camera.

### 3.2. Omnidirectional image using method shown in Figure 4

Figure 11 shows the omnidirectional imaging through the vertical slit passing the center of the image when the method shown in Fig. 4 is used. Point  $P = (\rho, \theta, \zeta)$  in the environment is projected onto point  $p = (x, y)$  using

$$x = \theta, \quad y = \frac{f\zeta}{\rho - R} \quad (7)$$

where  $f$  is the focal length of the camera.

When a horizontal straight line in a 3-D space represented by Eq. (5) is projected onto a cylindrical

plane, this does not form an ellipse but a more complex pattern given by

$$y = \frac{fH \cos x}{D - R \cos x} \quad (8)$$

However, a vertical line in the 3-D space appears also as a vertical.

Almost all the information taken by the camera in this configuration can be extracted by some means. For example, in the omnidirectional stereo method (section 2.2), the angle difference produced by the rotation of the camera initially is extracted; and then this is converted into the range information. Note, this angle difference is equivalent to "parallax" in a conventional stereo method.

## 4. Experimental Results

The experiments were carried out in an indoor environment. The camera is arranged so that its optical axis is always parallel to the floor of the room and the axis rotates at a height of 1.0 m. The camera (from Matsushita) has a color CCD with a lens (focal length 16 mm). The camera control system has a dc motor with worm-gear speed-reduction mechanism for the camera rotation. An optical encoder is connected directly to the shaft of the motor to form a feedback circuit so that the rotation of the camera is controlled accurately with  $0.005^\circ$  step.

The input image has  $512 \times 512$  pixels. The focal length of the lens is calibrated as 591 pixels. The Nexus 6000 was used for image digitization, an Epson laptop computer was used for camera control, and a Sun 4 Workstation was used for the host computer in this experiment.

Vertical straight lines were used as the feature lines in the environment. Almost all the indoor environments have many vertical lines, and it is practical to choose them as features for the robot navigation.

### 4.1. Acquisition of accurate azimuth information

Figure 2 shows an example of omnidirectional view obtained by using the proposed method in the configuration shown in Fig. 1 with a single vertical slit at the center of the image plane, and this contains the

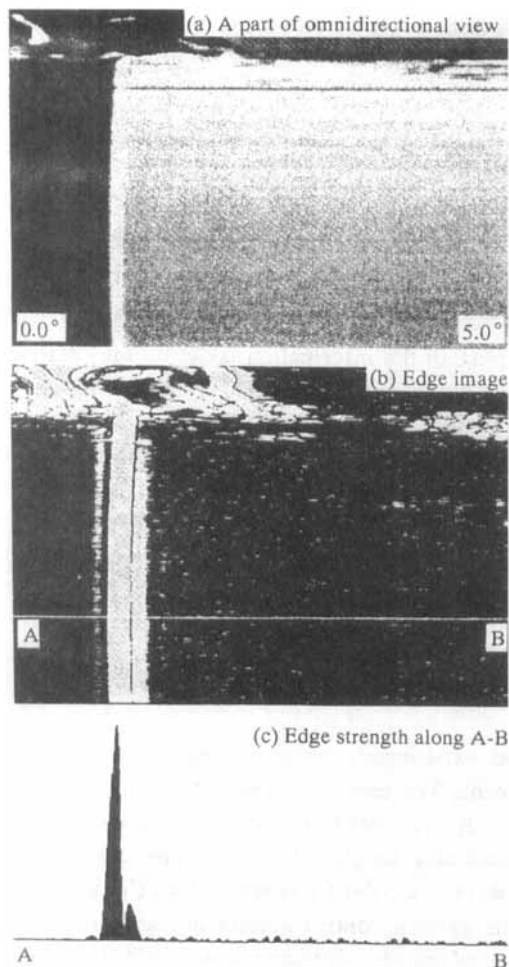


Fig. 12. Precise azimuth information.

information of an omnidirectional view. The image is taken by rotating the camera at  $0.4^\circ$  step over  $360^\circ$ . The image consists of  $900 \times 512$  pixels (the image is reduced vertically to one-half).

It is not certain, however, that this image contains a full azimuth information, considering that even in an image taken by a conventional method with a focal length of 600 pixels, the azimuth per pixel is about  $0.1^\circ$  ( $= \tan^{-1}(1/600)$ ). To confirm this point, the accuracy of the azimuth was checked experimentally by rotating the camera with  $0.01^\circ$  step.

Figure 12(a) shows a part of an omnidirectional image obtained by rotating the camera degrees with  $0.01^\circ$  step over  $5.0$ . Figure 12(b) shows an edge emphasized by applying Sobel's gradient operator. Figure 12(c) shows

the intensity of the edge sampled along a line A-B in Fig. 12(b).

The intensity of the edge shown in Fig. 12(c) indicates that its maximum occurs at the position where the vertical edge is in Fig. 12(a). As this example shows, the azimuth of a vertical edge in an environment can be detected with the accuracy of the camera rotation by detecting the position of the maximum intensity of the edge image.

Even in a conventional image, the position of an edge can be determined with a sub-pixel accuracy by using the blur of the edge as the linear mixing model [11]. In the proposed method, the shape of a blur can be determined accurately by moving the camera, as the forementioned experiment shows, and this can be applied to a difficult case where even the linear mixing model is not applicable.

Although Fig. 12(a) was obtained by the method described in Fig. 1, the azimuth in an image obtained by the method shown in Fig. 4 can also be measured with accuracy equal to that of the camera rotation.

## 4.2. Acquisition of distance information

Experiments to obtain the omnidirectional distance information around the camera were carried out.

The camera rotation axis (vertical) must cross its optical axis (horizontal) perpendicularly. This condition is achieved by adjusting the camera position so that both feature points on a horizontal line through the cross point, and in directions separated by  $180^\circ$ , are seen respectively, on the center of the image plane when the camera is rotated by  $180^\circ$ . The rotation radius of the camera  $R$  was measured by using an object with a known distance.

Figure 5 shows an example of a pair of two omnidirectional images taken by the method shown in Fig. 4. The image has  $900 \times 512$  pixels (reduced vertically to one-half). The camera was rotated with  $0.4^\circ$  step over  $360^\circ$  with  $R = 0.2$  m, and the two slits were set with the distance of 200 pixels from the image center. The correspondence between the two images was obtained by tracking vertical lines in the environment between the two slits [13].

Figure 13 shows the positions on the room floor of vertical lines in the environment estimated by the omnidirectional stereo method. This shows that the error

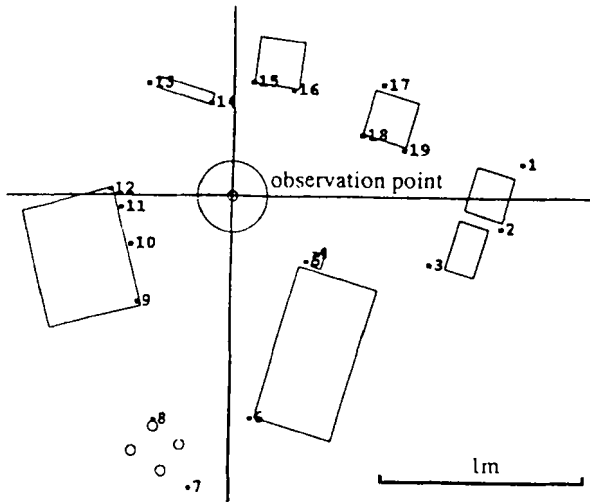


Fig. 13. Position of 3-D vertical lines.

of positions of vertical lines within a radius of 1.0 m around the camera rotation center is about 0.05 m. This error can be reduced further by improving the resolution of the camera rotation system which can be controlled with a resolution of  $0.005^\circ$ .

Figure 14 shows errors in the height measurements of the lower ends of the vertical edges, which are within about 0.1 m. The accuracy of height measurements is poorer than that of position measurements, since Eq. (2) contains parameter  $y$  whose resolution yields additional error.

## 5. Conclusions

This paper describes a method to obtain both the accurate azimuth and distance information in omnidirection simultaneously by rotating a camera. The features of the method are described including the accuracy in the distance information and the projection of objects in an environment. Experiments were carried out to confirm the usefulness of the method. The features of the method are summarized as follows:

- (1) A distance measurement using a conventional binocular stereo method has errors due to quantization of its image; in contrast with this the proposed method has errors due to the resolution of the camera rotation system. The resolution of a camera rotation system can easily be improved so that a distance can be

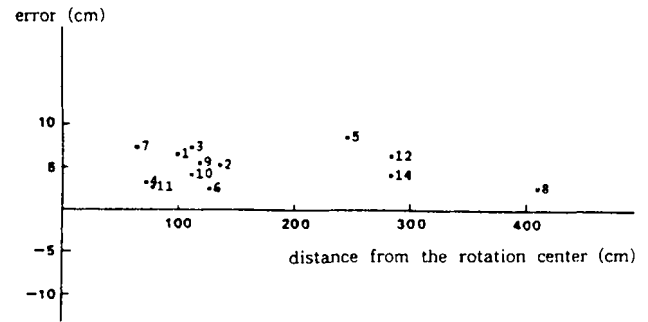


Fig. 14. Error of heights.

measured with a higher accuracy even in a small azimuth. Note that an azimuth in the proposed method corresponds to a parallax in a conventional stereo method.

- (2) The correspondence problem between a set of two images in the proposed method can be established by tracking features between the two slits.
- (3) Setting of the camera system is easier in the proposed method.

A disadvantage of the proposed method is its relatively slow imaging. This problem can be improved by development of a custom-designed hardware in the future and by limiting the sensing direction depending on each application.

An application of the method to an indoor mobile robot is currently under study.

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