Wide-Angle Vision Sensor with High-Distortion Lens*

(Detection of Camera Location and Gaze Direction Based on the Two-Parallel-Line Algorithm)

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The authors have conducted research into a vision sensor system which is functionally similar to the human eye. We have designed and manufactured a special lens to realize this function. The lens system provides an extensive 120-degree visual field, by optically enlarging an input image in the central area and compressing it in the peripheral area. In this paper, the authors propose a new method to detect a camera location and gaze direction based on two parallel boundary lines of a road projected in the peripheral area, and show that it works precisely and efficiently. Subsequently, we apply this method to a curved road and compare the location detected from the boundary lines with the actual camera location, and show that there is reasonable agreement between the detected and actual values.

Key Words: Vision Sensor, Foveated Image, Wide-angle Lens, Image Processing, Two-Parallel-Line Algorithm, Mechatronics and Robotics, Peripheral Vision, Measurement of Location and Posture, Moving Robot

1. Introduction

Many studies on visual navigation of mobile robots based on images obtained from CCD camera have been made. The mobile robot has to obtain various kinds of information from input images to decide its behavior in an environment. Therefore, generally, visual information with a wide-angle visual field and high resolution is desirable for navigation of a mobile robot. However, it is impossible to realize wide-angle visual field and high resolution simultaneously without increasing the number of pixels for each image. This trade-off between wide-angle visual field and high resolution is caused by conventional image input devices, e.g. a CCD camera attached with a conventional lens, which provides an almost undistorted image. In most of the published studies, visual navigation is carried out using such devices. The

increase in the amount of visual information makes real-time processing and transmission difficult. Therefore, these input devices are not necessarily suitable for robot vision.

In this paper, the authors propose a foveated vision sensor system for navigating a mobile robot. A special lens, which has been designed and manufactured in the authors' laboratory, plays a major role in this system⁽¹⁾⁻⁽⁴⁾. This lens provides wide-angle visual field and high resolution locally in the central area by distorting input image optically without increasing the amount of visual information. The major purpose of this study is to realize navigation of the mobile robot by using the foveated vision sensor system in a traffic environment such as inside a plant or on the street. This paper compares the proposed system and a conventional image input device, which provides an undistorted image, and considers the differences between them and advantages of the former. As an application to characterize this foveated system, we propose a method to detect the camera location and orientation (gaze direction) based on two parallel lines obtained from boundary lines of a road projected in the peripheral area of the input image.

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2. Vision Sensor System with Fovea

For robot vision, real-time operation is very much required. To realize both wide-angle vision and high resolution, however, makes real-time processing difficult, because it largely increases the amount of information for each image. Regarding this problem, recently, some attempts to decrease the amount of information and to realize high-speed processing by using foveated visual information mimicking the human eye have been reported^{(1),(5)-(8)}.

The human eye has a wide visual field with 120 degrees. The visual acuity is not uniform all over the visual field and is highest near a fovea and falls rapidly with increasing distance from the fovea. Wide-angle and as detailed information as possible can be obtained by changing the gaze direction with minimum amount of information from an observed environment. As other methods to realize the foveated vision, a method to reconstruct foveated image from input image with uniform resolution by log-polar mapping^{(5),(6)}, a method to use a special CCD chip whose density is variable⁽⁷⁾, and so on have been proposed.

In our laboratory, we have designed and manufactured a special super wide-angle lens which provides 120 degrees visual field and whose distribution of magnification is similar to that of human visual activity. We acquire the foveated image optically by using a commercially available CCD camera attached with this special lens. We call this lens Wide Angle and High Distortion lens (WAHD lens). Figure 1 shows the characteristics of the WAHD lens by image height with incidence angle. For comparison, we assume a pinhole camera with the same amount of information and the same range of visual field, and show also characteristics of this pinhole camera, which provides an ideal undistorted image. The gradient of these curves represents the resolution in the radial direction of visual field. This figure shows that the magnification factor of the WAHD lens is larger in the central area of the visual field and smaller in the peripheral area than that of the pinhole

Fig. 1 Image height of WAHD lens and pinhole camera

camera.

The gaze direction of the CCD camera can be controlled by a camera mover which has been manufactured in the authors' laboratory. Figure 2 shows a sketch of Wide Angle Vision Sensor System with Fovea. This system makes it possible to obtain information from an arbitrary environment with as less a space as possible and as much detail as possible.

3. Navigation on Streets Using Vision Sensor System with Fovea

We apply the proposed system to navigation of the mobile robot in a traffic environment. Figure 3 (a) shows a foveated image of a street obtained from the WAHD lens, which is drawn by computer simulation. For estimating the foveated system, we assume a pinhole camera which provides the same amount of information and the same range of visual field, and compare the foveated image with an undistorted image obtained from the pinhole camera shown in Fig. 3(b). In these figures the gaze direction is in the direction of a vanishing point determined from the boundary lines of the road. The small and large circles drawn in each image show visual angles of 10

Fig. 2 Schematic of Wide Angle Vision Sensor System with Fovea

(a) Image obtained from WAHD lens (b) Image obtained from pinhole camera

Fig. 3 Computer simulation images in a traffic environment

degrees and 30 degrees, respectively. The area of the small circle (from 0 to 10 degrees) is 14% of the whole visual field in Fig. 3(a) although only 1% in Fig. 3(b). On the other hand, the peripheral area from 30 to 60 degrees is 40% of the whole in Fig. 3(a) although 90% in Fig. 3(b). Since the image obtained from the WAHD lens has more information for central vision than that obtained from the pinhole camera, this system can obtain detailed information in the front of the mobile robot earlier, where it might pass. Moreover this system can obtain information of a closer place to the camera, which is projected in the outer area of visual field, because the input image obtained from this system has a wide-angle visual field with 120 degrees. On these sides, the information obtained from the WAHD lens has advantages while navigating the mobile robot in unknown environments.

Foveated visual information is utilized by classifying into two levels, i.e. central vision and peripheral vision. The central area in the visual field with high resolution has adequate information for tasks of central vision, i.e. to specify an object, a traffic sign and a traffic signal by their characteristic such as shape. On the other hand, although the peripheral area has lower resolution and does not have so large amount of information, this area covers a wider visual range. Therefore, this area seems to be suitable for tasks of peripheral vision, where high speed is required, i.e. to recognize a remarkable change of the environment, to extract obstacles which come into the visual field, to detect the camera location and orientation by using boundary lines of a road to obtain information around the mobile robot or of the robot itself in the environmental space and so on.

Figure 4 shows the resolution in the radial and tangential directions by the WAHD lens. As shown in Fig. 4, compared with the resolution by the pinhole camera, the magnification distribution makes the resolution in radial direction higher in the central area and lower in the peripheral area. On the other hand,

Fig. 4 Resolution in visual field

the resolution in tangential direction by the WAHD lens is kept higher all over the visual field than that by the pinhole camera. This characteristic is observed only when the foveated image is obtained optically. In the case of the other methods, the resolution in tangential direction is lower than that by the pinhole camera. Therefore, it is possible to detect the camera location and orientation with less information and more precision, based on the boundary lines of a road projected in the peripheral area when camera gaze direction is closely parallel to the boundary lines.

This paper proposes a method suitable for detecting the location and gaze direction of the camera equipped with the mobile robot.

4. Detection of Camera Location and Gaze Direction Based on Boundary Lines of a Road

4.1 Camera calibration

The entrance-pupil, the intersection point of the optical axis and an incident principle ray, of the WAHD lens is assumed to be at a fixed position as a visual point (origin of coordinates, O_c), although its position varies slightly with the incidence angle of each principle ray as shown in Fig. 5. Moreover, it is assumed that the optical axis of the lens is perpendicular to the image (CCD) plane and that the lens characteristics are symmetrical with respect to the optical axis. The camera is calibrated experimentally as follows. A laser spot is projected onto an object plane at a reasonable distance (2 meter) from the camera and the camera is rotated by a constant step angle (0.72 degree) about the vertical axis and horizontal axis, each of which is at a right angle to the optical axis and passes through the entrance-pupil point. The position of the centroid of the laser spot projected on the image plane with each angle is recorded into data tables with respect to deflected angle. The dot aspect ratio of this input device, K , and the image center position (I_u, I_v) on the CCD plane are determined from the data tables. The approximated function of image height r with reference to the incident angle is determined from these data tables by using the least square method.

Next, we consider the coordinate systems shown in Fig. 6. In the visual point coordinate system $O_c - X_c Y_c Z_c$, the optical axis coincides with the Y_c axis.

Fig. 5 Camera calibration model

Fig. 6 Coordinate systems

The coordinates (u', v') of the input image are revised into visual point coordinates (u, v) based on the dot aspect ratio K . Each point on the image with these coordinates corresponds to an incidence direction (θ, ϕ) , respectively. From the experiment for camera calibration, we obtain the following equation.

$$r = 125.1022\theta^3 - 408.1315\theta^2 + 466.1757\theta \quad [\text{pixel}] \quad (1)$$

The incidence direction (θ, ϕ) to the visual point is defined by the visual point coordinates as per the following equations.

$$\theta = \tan^{-1} \frac{\sqrt{X_c^2 + Z_c^2}}{Y_c} \quad (2)$$

$$\phi = \tan^{-1} \frac{Z_c}{X_c} \quad (3)$$

A point of the object with the incidence direction (θ, ϕ) is projected to a point (u', v') on the input image based on Eqs. (1) to (5).

$$\begin{cases} u = I_u + r \cos \phi \\ v = I_v + r \sin \phi \end{cases} \quad (4)$$

$$\begin{cases} u' = u \\ v' = I_v + K(v - I_v) \end{cases} \quad (5)$$

4.2 Two-parallel-line algorithm

Now, we propose a method to detect the camera location $(w/W, h/W)$ and the gaze direction (ϕ_1, ϕ_2) based on considering the boundary lines of a road approximately as two parallel lines with a width w . The boundary lines of a road, close to the visual point, are projected in the peripheral area of the input image which has a 120 degrees wide visual field. We assume here that the camera does not rotate about the optical axis. The proposed method is as follows.

At first, the edge image of boundary lines of a road is obtained with gray-scale from the input image. By scanning the peripheral area of this image in the tangential direction, a series of sectional peak points along each edge line is acquired. The position of the sectional peak is assumed to be that of an axis of a quadratic function fitted with the sectional shape of the edge line in the scanning direction.

The image obtained from the WAHD lens is so highly distorted that this image is not necessarily suitable for usual image processing methods. Therefore, we introduce the perspective coordinates in order to remove the distortion from the input image. To reduce the amount of calculation, only the peak points along each edge line are transformed from the visual field coordinates (u, v) into the perspective coordinates (u_{per}, v_{per}) or (r_{per}, ϕ) . These values are used for calculation hereafter. In this transformation into the perspective coordinates, r_{per} is calculated from the value θ , which is determined by using Eq. (1) from the image height r , using Eq. (6).

$$r_{per} = \frac{r_{\max}}{\sqrt{3}} \tan \theta \quad (6)$$

where $r_{\max}$ is the maximum radius of the visual field. The value in the tangential direction, ϕ , is kept constant before and after this transformation.

Equation (7) shows two straight lines, which are calculated approximately by the least square method from the series of peak points along each of two boundary lines transformed into the perspective coordinates.

$$\begin{cases} v_{per} = m_1 \cdot u_{per} + n_1 \\ v_{per} = m_2 \cdot u_{per} + n_2 \end{cases} \quad (7)$$

The vanishing point (V_u, V_v) is calculated from Eq. (7).

$$\begin{pmatrix} V_u \\ V_v \end{pmatrix} = \begin{pmatrix} -m_1 & 1 \\ -m_2 & 1 \end{pmatrix}^{-1} \begin{pmatrix} n_1 \\ n_2 \end{pmatrix} \quad (8)$$

where the subscripts 1, 2 denote the two parallel lines.

The distance between the vanishing point and the image center, r_{per} , is calculated as follows.

$$r_{per} = \sqrt{(V_u - I_u)^2 + (V_v - I_v)^2} \quad (9)$$

The gaze direction (θ, ϕ) is derived from Eq. (6) and the following equation.

$$\phi = \tan^{-1} \frac{V_v - I_v}{V_u - I_u} \quad (10)$$

The gaze direction is also represented by pan angle ϕ_1 and tilt angle ϕ_2 based on the structure of the camera mover.

$$\begin{cases} \phi_1 = \tan^{-1}(\tan \theta \cos \phi) \\ \phi_2 = \sin(\sin \theta \sin \phi) \end{cases} \quad (11)$$

The camera location (visual point location), $(w/W, h/W)$, is calculated by two planes including the visual point and each of two boundary lines. Now, we introduce the coordinate system $O_c - X'_c Y'_c Z'_c$ of which the origin is the same as that of the visual point coordinate system $O_c - X_c Y_c Z_c$. The Y'_c axis is parallel to the two boundary lines and the X'_c axis is parallel to the plane including the two lines in the coordinate system $O_c - X'_c Y'_c Z'_c$. These planes are expressed as Eq. (12).

Fig. 7 Two-parallel-line algorithm

$$Z'_c = a_i X'_c \quad (i=1, 2) \quad (12)$$

The coefficient, a_i , of each plane is determined from Eqs.(13) and (14).

$$\sqrt{3} n_i Y_c = \left(\frac{-Z_c}{X_c} - m_i \right) r_{\max} \sqrt{X_c^2 + Z_c^2} \times \cos(\tan^{-1} \frac{-Z_c}{X_c}) \quad (13)$$

$$\begin{pmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{pmatrix} = \begin{pmatrix} \cos \psi_1 & \sin \psi_1 \cos \psi_2 & \sin \psi_1 \sin \psi_2 & 0 \\ -\sin \psi_1 & \cos \psi_1 \cos \psi_2 & \cos \psi_1 \sin \psi_2 & 0 \\ 0 & -\sin \psi_2 & \cos \psi_2 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} X'_c \\ Y'_c \\ Z'_c \\ 1 \end{pmatrix} \quad (14)$$

The camera location (w/W , h/W) is represented by using a_i as

$$\begin{cases} w/W = \frac{a_1}{a_1 - a_2} \\ h/W = \frac{a_1 a_2}{a_1 - a_2} \end{cases} \quad (15)$$

When the gaze direction is parallel to the boundary lines, the gradient m_i of a straight line calculated in the perspective coordinate system can be regarded directly as the value of $-a_i$.

We refer to the proposed method as Two-parallel-line algorithm (2PL algorithm) and show its flow chart in Fig. 7.

5. Experiments

5.1 Experimental equipment

The gaze direction of CCD camera with the WAHD lens is controlled by the camera mover with two stepping motors. The image recorder operates at the video rate and has 512×512 pixels in each frame. The image processing and the control of the gaze direction are executed by a 32-bit personal computer.

5.2 Detection of the camera location and the gaze direction from two parallel lines

We have manufactured a box, named the 3 dimen-

Fig. 8 Three dimensional test pattern

Fig. 9 Results of location w and error influence of image center

sional pattern (3D test pattern), which provides four parallel boundary lines as shown in Fig. 8. By using two parallel boundary lines included in the base of the 3D test pattern, we have carried out experiments to detect the camera location and gaze direction from the peripheral parts of the two lines.

Figure 9 shows experimental results of the horizontal location w/W when the gaze direction is kept parallel to the boundary lines and the height h/W of the camera location is fixed at 0.5. In this figure, the horizontal axis shows a true value of location w/W and the vertical axis shows a centesimal error of the detected location w/W , which is plotted with a black dot (The other signs are explained later). The error of location is normalized by the width W between the two lines. In the above experiment, the gaze direction is kept parallel to the boundary lines so that the intersection point of two lines (the vanishing point) and the image center coincide with each other. As shown in Fig. 9, the maximum error of the location w/W is about 0.2%.

Figure 10 shows experimental results for the pan

Fig. 10 Results of pan angle ψ_1 and influence of image center error

angle ψ_1 when the camera location is fixed at (0.5, 0.5) and the gaze direction is kept horizontal to the base of the 3D test pattern (the tilt angle is fixed at 0 degree) and the pan angle ψ_1 rotates about the vertical axis which passes through the visual point. In Fig. 10, a black dot shows the absolute error of detected ψ_1 by this experiment. As shown in this figure, it is found that the detected value ψ_1 coincides with the measured value in the range of small pan angles. On the other hand, the error becomes larger as the pan angle increases.

5.3 Influence of camera calibration error on detected values

The influence of the camera calibration error on the detection of the location and gaze direction is investigated by computer simulation where a pixel size is taken into consideration. In the computer simulation used here, a distorted picture is drawn based on Eq. (1) and an ideal boundary line in which the jaggies are removed by anti-aliasing processing. In the following, we simulate the case that the image center is determined with a certain value of locational error and estimate the accuracy of the camera calibration in the above experiments.

In Fig. 9 of the detected error of camera horizontal location w/W , signs of double circles, circle and triangle respectively mean the cases when there is no locational error (difference) between a real image center and the determined image center, when there is the difference with 1 pixel in the u axis direction in the visual coordinates and when there is the difference with 1 pixel in the v axis direction. These errors are calculated by adding the locational difference consciously to the true image center and using the boundary lines drawn by the computer simulation in each of camera horizontal locations.

Figure 9 shows that a difference of the order of 1 pixel in the v axis direction hardly influences the detected horizontal location of the visual point.

Additionally, the error of location is within 0.4% when there is the difference of 1 pixel in the u axis direction. As the experimental error is much less than the simulation result, the difference between the determined image center and the true image center in the u axis direction is expected to be within 1 pixel in this experiment.

In Fig. 10, a sign of circle means the error of gaze direction about the pan angle ψ_1 detected when the image center has a locational difference of 1 pixel in the u axis direction. It is found that the influence on ψ_1 is within 0.2 degree when the difference is of the order of 1 pixel. In this calibration, it is supposed that other factors cause the detected error in addition to the locational difference of the image center, since the experimental result is slightly larger than this simulated result. For example, the WAHD lens may have optical radial-asymmetry about the optical axis regarding the characteristics of image height, because the WAHD lens consists of seven lenses and the optical axis may not be vertical to the image plane. In addition, the entrance-pupil position is determined approximately as a point of the visual point. Therefore, we guess that the characteristic of image height also causes the detected error. The influence of variation of entrance-pupil position can be ignored by using boundary lines far enough from the camera.

Under the assumptions that image center has no locational error and the image height is radial-symmetric to the optical axis, it is said that when the gaze direction is parallel to the boundary lines, the image height does not influence the detected value of camera location, even if the determined image height function represented by Eq. (1) includes some error. In such cases the camera location can be detected from the information about only the tangential direction. As previously stated, the resolution in the tangential direction of the image obtained from the WAHD lens is always higher than that obtained from a lens without distortion such as the pinhole camera. Therefore, to use the peripheral area of the image obtained from the WAHD lens makes it possible to detect the camera location more precisely than that obtained from the pinhole camera, when the gaze direction is parallel to the boundary lines.

5.4 Application of Two-Parallel-Line algorithm to curved road

Generally, boundary lines of a road are not always two straight parallel lines but often have a curvature. The proposed system is advantageous in detecting camera location from curved boundary lines, because this system has such a super wide angle lens with 120 degrees to acquire boundary lines physically close to the visual point onto the peripheral area.

Fig. 11 A curved road drawn by WAHD image simulator

Figures 11(a) to (c) show wide-angle distorted images of curved roads obtained from the WAHD lens, drawn by the computer simulation. Two crosses in these figures show the image center and the vanishing point detected from the two boundary lines drawn in the peripheral area, respectively. As shown in Fig. 11, it is found that the larger the radius of curvature R becomes, the closer is the interval between the image center and the vanishing point. Therefore, when the radius of curvature is large enough, the boundary lines of a curved road projected in the peripheral area can be regarded approximately as two parallel lines. By using the images drawn by the computer simulation, it is investigated how much the radius of curvature of a road influences the detected error of camera location in the case when the proposed 2PL algorithm is applied to curved boundary lines. It is assumed here that the road is a flat plane and the gaze direction is in the tangential direction of the curved road and parallel to the road plane. As shown in Fig. 11(d), the radius of curvature is based on a central line of a road and the camera horizontal location w is defined as a distance from the left boundary line.

Figures 12 and 13 show the error of the camera location versus the radius of curvature R , by varying the camera height h and the range of the peripheral area used for the detection, respectively. The error of the detected location is normalized based on the width of the road W . These figures indicate that the errors

Fig. 12 Influence of height h on detecting location when w/W is 1/2 and peripheral area size is in the range 0.85~1

Fig. 13 Influence of peripheral area size on detecting location when $(w/W, h/W)=(1/2, 1/6)$

get smaller as the radius of curvature increases. The error of the camera height h is considerably smaller than that of the camera horizontal location w . It is noted that the errors of camera location decrease as the camera height is reduced or as the peripheral area used for the detection is limited to the outer part of visual field. However, as shown in Fig. 13, if the peripheral area is too small, the detected values have large fluctuations. It is inferred that the number of data on the boundary line is not large enough for a precise approximation to a linear equation by the least square method. Sufficient range of the peripheral area must be used for the approximation in navigating the mobile robot, because the number of data is not always obtained from the actual input image as surely as that obtained from the simulated image. On the other hand, as to the camera height, a physical limit to detect the camera location precisely is supposed to exist.

5.5 Detection of camera location from real road images

Figure 14 shows the real images of a curved road whose radius of curvature, R/W , is about 15, obtained from the WAHD lens. Here the camera location w is detected from the real images of the curved roads

(a) Curved road when (b) $(w/W, h/W)=(0.25, 0.2)$
 $(w/W, h/W)=(0.5, 0.2)$

Fig. 14 Images of actual curved road

including Fig. 14 and straight road. The camera location has been detected within a 3% error from the straight roads and within a 6% error from the curved roads when the range of the peripheral area used for the detection is from 0.75 to 1.0.

The error of camera location detected from the real image is larger than that from the experiment using 3D test pattern or that from the computer simulation on curved roads in the previous section. It is, however, supposed that the detected error can be reduced by improving on detection of edge lines from an input image and setting up the camera in the experimental environment.

6. Conclusion

In this paper, the authors have proposed a wide-angle vision sensor system with fovea, which utilizes the WAHD lens manufactured in our laboratory, and have investigated to apply this system in order to navigate the mobile robot in a traffic environment. The results of this study are summarized as follows.

(1) The advantages of applying the proposed system to visual navigation are pointed out in respect of the amount of information and resolution, in comparison with the conventional system with a pinhole camera.

(2) An algorithm for detecting the camera location and gaze direction precisely from two boundary lines of a road in the peripheral area of the visual field by regarding the lines as two parallel straight ones has been proposed, called the 2PL algorithm. The experimental results using a 3D test pattern prove that the 2PL algorithm works with fair accuracy.

(3) The 2PL algorithm has been applied to curved roads to investigate the influence on the detected camera location by computer simulation. It has been found that the error is small enough when the radius of road curvature, R/W , is larger than about 20.

References

- (1) Suematsu, Y. and Hayase, T., An Advanced Vision Sensor with Fovea, Proc. of IECON90, Vol. 1(1990), p. 581-585.
- (2) Suematsu, Y. and Yamada, H., A Wide Angle Vision Sensor with Fovea (Design of Distortion Lens), Trans of SICE (in Japanese), Vol. 31, No. 10(1995), p. 1556-1563.
- (3) Shimizu, S. and Suematsu, Y., Vision Sensor with Wide Angle and High Distortion Lens, ICRA Video Proceedings(1995), p. 3.
- (4) Shimizu, S., Suematsu, Y. and Yahata, S., A Wide Angle Vision Sensor with High Distortion Lens (Detection of Camera Location and Gaze Direction Based on Two-Parallel-Line Algorithm), Proc. of IECON96, Vol. 3(1996), p. 1600-1605.
- (5) Baron, T., Levine, M. D. and Yeshurun, Y., Exploring with a Foveated Robot Eye System, Proc. of 12th International Conference on Pattern Recognition, (1994), p. 377-380.
- (6) Yamamoto, H., Yeshurun, Y. and Levine, M. D., A Foveated Vision System with Attentional Mechanisms, Trans. of EiC(D-II), (in Japanese), Vol. J77-D-II, No. 1(1994), p. 119-130.
- (7) Sandini, G., Dario, P. and Fantini, F., A Retina Like Space Variant CCD Sensor, SPIE 1242 (1990), p. 133-140.
- (8) Kuniyoshi, Y., Kita, N. and Sugimoto, K., A Foveated Wide Angle Lens for Active Vision, Proc. of ICRA95(1995), p. 2982-2988.