LOCATION ESTIMATION FOR INDOOR AUTONOMOUS VEHICLE NAVIGATION BY OMNI-DIRECTIONAL VISION USING CIRCULAR LANDMARKS ON CEILINGS

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ABSTRACT

A novel approach to location estimation by omni-directional vision for autonomous vehicle navigation in indoor environment using circular landmark information is proposed. A circular-shaped landmark is attached on the ceiling and an omni-directional camera is equipped on a vehicle to be upward-looking, for the purpose of reducing occlusion and noise created by surrounding objects and humans. The perspective shape of the circular landmark is well approximated to be an ellipse by analytic formulas. The estimated position of the ellipse is then used to determine the location of the vehicle for navigation guidance. Both simulated and real images were tested and experimental results with good estimation precisions confirm the feasibility of the proposed approach.

Keywords: location estimation, autonomous land vehicle, omni-directional vision, omni-directional camera, omni-directional image, circular landmark, indoor environment, ceiling.

1. INTRODUCTION

Location estimation is essential for guidance of autonomous vehicles in many indoor navigation applications. A widely adopted approach is the vision-based technique. Most existing vision-based techniques deal only with front scenes and are easily interfered by unexpected objects around the vehicle. A feasible solution to solve this problem is to use an omni-directional camera, which has the unique advantage of providing wide-angle views. In this study, we propose further to set up the omni-directional camera to view upward the ceiling of the indoor environment and attach circular shapes on the ceiling as landmarks for the purpose of navigation guidance. By this way, it is expected that fewer objects around the vehicle will appear in the field of view of the upward-looking camera, thus reducing the guidance error coming from the influence of the surrounding objects in acquired images. An illustration of the navigation environment, including the vehicle, the ceiling, and the landmark, is shown in Figure 1.

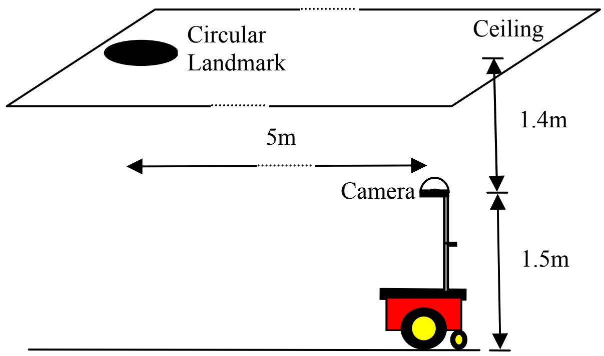

Figure 1: Relative positions of camera, ceiling, and circular landmark for providing sufficient field of view and avoiding unexpected objects appearing in acquired images.

Most ALV location estimation techniques using omni-directional images proposed up to the present can be grouped into three types: *triangulation*, *full-scene matching*, and *mirror-lens projection*, in accordance with the way of image information.

In triangulation techniques [1-2], a standard localization method is to identify surrounding landmarks in the environment and find their corresponding locations in the environment map built in advance. By the measured bearings of the landmarks [1], the location of an ALV can be obtained. Yagi [2] correlated the angle of the vertical edge in an omni-directional image to the

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environment map to acquire the location of the vehicle. However, sometimes it is difficult to find natural landmarks which can be identified stably from omni-directional images.

In full-scene matching techniques [3-4], a vehicle localizes itself by comparing images taken at its current location with the reference images stored in its memory. Full-scene matching provides more feasibility by the use of omni-directional cameras. However, it takes a lot of reference memory space to raise location precision. Gasper [3] showed that the qualitative position of the vehicle in the environment can be determined by comparing the vehicle's current view with previously learned images, using a low-dimensional subspace of the input images obtained from a principal component analysis process. Menegatti [4] simplified the location problem by using the Fourier components of the omni-directional image as the signatures of the acquired views.

The unique mirror-lens projection relation of the omni-directional camera also can be used to derive the location of an ALV by 3-D computer vision techniques [5-6]. In Koyasu [5], the range information from an omni-directional stereo vision system, which is composed of a pair of vertically-aligned omni-directional cameras, helps not only creating a 3-D map but also locating the vehicle itself. In [6], Cauchois compared synthetic landmark images with real landmark images taken from a calibrated omni-directional camera to accomplish absolute vehicle localization. However, these methods are unstable or inapplicable for locating a vehicle in a room crowded with people.

When an ALV is used as a tour guide or a machine pet which must work with a crowd of people, a vision sensor system on the ALV should provide the vehicle location information even when the landmark is occluded by people next to it. Hence, continuous and precise location estimation is emphasized in this study. To achieve this goal, the first task in the proposed method is to mount an upward-looking camera on the ALV and attach circular landmarks on the ceiling. To estimate the ALV's location, an image of the ceiling, which includes the circular landmark, is taken and processed. An ellipse detection algorithm [7] is then applied to detect the projected shape of the circular landmark in the image. By applying the back-projection rule of the hyperboloidal omni-directional camera, the relative position of the vehicle is obtained for vehicle guidance.

The first contribution of this study is that circular landmark information is utilized for the first time in omni-directional vision. Furthermore, it is found in this study that the perspective circular landmark shape, complicated in geometry with no known shape descriptor, may be well approximated by an ellipse whose parameters can then be utilized for landmark location estimation. In this way, a constant, stable, and precise relative vehicle location can be obtained for navigation. This application is important for intelligence household robots such as a cleaning robot, a robot pet or a tour guide robot, which must work with humans at a close distance.

The remainder of this paper is organized as follows. In Section 2, we derive an equation of a circular landmark shape on the ceiling projected on an omni-directional image. In accordance with the landmark image equation, we describe in Section 3 in more detail about how to estimate the vehicle location from the acquired image. In Section 4, some experimental results are described to show the feasibility of the proposed method. Finally, conclusions are given in Section 5.

2. APPROXIMATION OF PERSPECTIVE CIRCULAR SHAPE IN OMNI-DIRECTIONAL IMAGE BY ELLIPSE

In this study, a circular shape is attached on the ceiling of the vehicle navigation environment for use as an artificial landmark for vehicle guidance. The circular shape becomes perspective with no mathematical descriptor in the omni-directional image taken with a hyperboloidal omni-directional camera. We propose to approximate the perspective shape by an ellipse. In this section, the equation of the elliptical shape in the image will be derived. The validity of this ellipse approximation will become clear in the derivation. Later, in Section 3, we will explain how this approximate elliptical shape can be used for vehicle location estimation.

In Section 2.1, the scene, camera, and image coordinate systems will be defined first. Then a formula from Koyasu, et al. [5] will be described to illustrate the projection transformation between the scene coordinates and image coordinates. In Section 2.2, the coordinate systems will be rotated horizontally to simplify the derivation of the equation of an ellipse. Finally, in Section 2.3 a simulated shape of the circular landmark computed with the derived equation will be compared with the perspective shape obtained by a projection based on [5] to show the effectiveness of the proposed shape approximation.

2.1 Projection Model of Hyperboloidal Omni-Directional Camera

The scene, camera, and image coordinate systems involved in this study using a hyperbolic omni-directional camera are depicted in Figure 2, with their coordinates specified by (X, Y, Z), (x, y, z), (u, v), respectively. The hyperbolical shape of the omni-directional mirror in the camera coordinate system may be described as:

$$\frac{R^2}{a^2} - \frac{Z^2}{b^2} = -1, \quad R = \sqrt{x^2 + y^2}, \quad c = \sqrt{a^2 + b^2}. \quad (1)$$

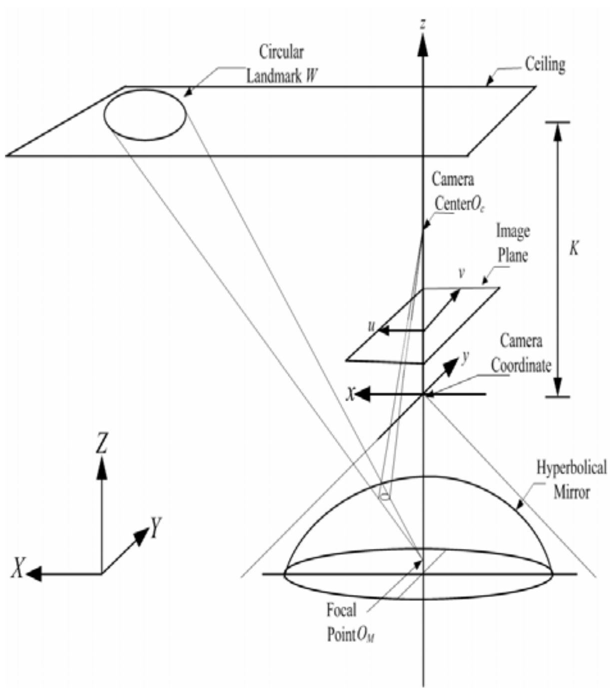

Figure 2: Coordinate systems.

The focal point O_M of the mirror is located at (0, 0, $-c$) and the camera center O_C at (0, 0, $+c$), in the camera coordinate system. The projection relationship between the image coordinates (u, v) and the camera coordinates (x, y, z) can be described [5] as follows:

$$u = \frac{xf(b^2 - c^2)}{(b^2 + c^2)(Z - c) - 2bc\sqrt{(Z - c)^2 + x^2 + y^2}},$$

$$v = \frac{yf(b^2 - c^2)}{(b^2 + c^2)(Z - c) - 2bc\sqrt{(Z - c)^2 + x^2 + y^2}}, \quad (2)$$

where f is the focal length of the camera.

2.2 Approximation of Circular Landmark in Omni-Directional Image by Ellipse

In Figure 2, the circular landmark with its normal vector parallel to the optical axis of the camera is denoted by W. Let its center and radius be denoted by P_w and R_w, respectively. Also, let (x_w, y_w, z_w) and (X_w, Y_w, Z_w) denote the camera and scene coordinates of P_w. To simplify the derivation described later, as shown in Figure 3 we rotate horizontally the camera coordinate system (x, y, z) and the image coordinate system (u, v) through a certain angle of θ_w where θ_w is defined as follows:

$$\theta_w = tan^{-1}\frac{y_w}{x_w}. \quad (3)$$

Then, the relation between the original camera coordinates (x, y, z) and the resulting ones (x', y', z') may be described by:

$$x' = x\cos\theta_w + y\sin\theta_w, \quad y' = y\cos\theta_w - x\sin\theta_w, \quad z' = z \quad (4)$$

and that between the original image coordinates (u, v) and the resulting ones (u', v') may be described by:

$$u' = u\cos\theta_w + v\sin\theta_w,\ v' = v\cos\theta_w -.\ u\sin\theta_w \quad (5)$$

Also, after this rotation, the circular shape of W in the new camera coordinate system may now be expressed by:

$$(x' - x_w')^2 + y'^2 = R_w^{\ 2},\ z' = z_w', \quad (6)$$

given that the center point P_w of W is located at (x_w', y_w', z_w') with $x_w' = x_w\cos\theta_w + y_w\sin\theta_w$, $y_w' = y_w\cos\theta_w - x_w\sin\theta_w$, $z_w' = z_w$ according to (4).

In the sequel, we will conduct the approximation of the circular shape of the landmark W in the omni-directional image by an elliptical shape in terms of the new image coordinates (u', v'). By optical geometry of the camera, we have

$$\frac{v'}{u'} = \frac{y'}{x'}, \quad (7)$$

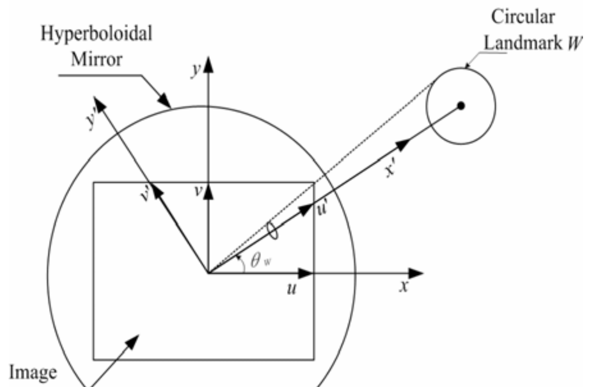

Figure 3: New image coordinate system (u', v') is obtained by rotating the u-axis through an angle of $\theta_w = \tan^{-1}(y_w/x_w)$ toward the center of the circular landmark W.

or equivalently,

$$v' = \frac{u'}{x'}y'. \quad (8)$$

Under the assumption that the horizontal distance from the origin of the camera coordinate system to the landmark is much larger than the radius of the landmark, variables x' and u' in (8) can be replaced approximately by x'_w and u'_w since $x' \approx x_w'$ and $u' \approx u_w'$, resulting in

$$v' \approx \frac{u_w'}{x_w'} y',$$

or equivalently, in

$$y' \approx v' \frac{x_w'}{u_w'}. \quad (9)$$

The other coordinate u' of each shape pixel of the circular landmark can also be derived by approximation, but in a different way. Under the same assumption mentioned above that the radius of the landmark is relatively very small with respect to the horizontal distance from the origin of the camera coordinate system to the landmark, the magnitudes of the x's of all shape pixels of the circular landmark in the camera coordinate system are much larger than those of the y's. Therefore, we may neglect the influence of the magnitude of y' in the computation of u'. For this, we define a new function F such that $u' = F(x')$ and use the first two terms of the Taylor expansion series of F, $F(x') = F(x_w') + (x' - x_w')F'(x_w') + (x' - x_w')^2F''(x_w') + \ldots$, to approximate $F(x')$ in the following way:

$$u' = F(x') \approx F(x_w') + (x' - x_w')F'(x_w'). \quad (10)$$

We then substitute u_w' into $F(x_w')$ and L into $F'(x_w')$ in (10), resulting in:

$$u' \approx u_w' + (x' - x_w')L$$

or equivalently,

$$x' \approx x_w' + (u' - u_w')/L \quad (11)$$

with L, denoting $F'(x_w')$, being computed by:

$$L = F'(x_w') = \frac{u_b' - u_w'}{x_b' - x_w'} \quad (12)$$

where, as illustrated in Figure 4, the variable x_b' is the x' coordinate of P_b' which is the nearest point of the landmark W to the origin of the camera coordinate system; u_b' is the u' coordinate of point I_b' which is the image of P_b'; u_w' is the u' coordinate of P_w' which is the center of the W; and x_w' is the x' coordinate of I_w' which is the image of P_w'. To compute L by (12), we have $x_b' = x_w' - R_w$ as seen from Figure 4; and also we can get u_b' by substituting (x_b', y_b') into (2).

Now, substituting (9) and (11) into (6) and rearranging the result, we can accomplish the approximation of the landmark shape W by the following equation which specifies *exactly* an elliptical shape centered at $(u_w', 0)$ with axis lengths R_wL and $R_w(u_w'/x_w')$:

$$\frac{(u' - u_w')^2}{R_w^2 L^2} + \frac{v'^2}{R_w^2 (\frac{u_w'}{x_w'})^2} = 1. \quad (13)$$

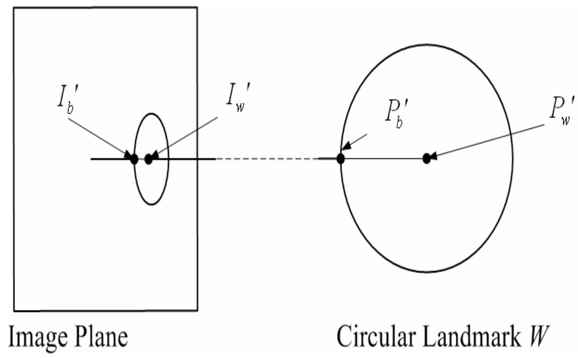

Figure 4: Illustration of correspondence between landmark points and image points where P_b' is the nearest point in landmark W to the origin of the camera coordinate system, and I_b' is the corresponding point of P_b' in the image plane.

2.3 Effectiveness of Shape Approximation

To check the effectiveness of the approximation of the circular shape of the landmark by the elliptical shape using Equation (13), we show in Figure 5 an example of our simulation results in which both the original circular and the approximate elliptical shapes are drawn and overlapped: the former shape being drawn by Equation (6) and then projected into the image plane by Equation (2), and the latter being drawn directly by Equation (13). The outer big circle in the figure marks the field of view of the camera. Inside the outer circle, the former circular shapes of W at different positions are drawn and shown by white pixels. Then, the latter approximate elliptical shapes are computed using the coordinates of the white pixels, and drawn by black pixels which are then superimposed on the white ones. From the figure, we can see that each black ellipse overlaps the corresponding perspective white circle quite well. This shows that the circular landmark in our application circumstance may really be approximated by the ellipse described by Equation (13). This discovery gives a great help, as found in this study, in using this kind of circular landmark to provide the location information for vehicle guidance, as described in the following section.

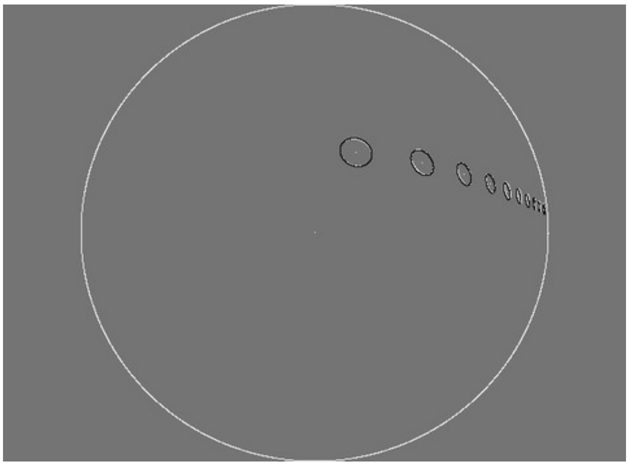

Figure 5: A simulation of a serious of circular landmark shapes at different places, showing that the perspective landmark shape may be approximated well by ellipses. The white pixels are simulated landmark shape points and the black pixels are approximate ellipse points computed by (13).

3. IMAGE PROCESSING AND VEHICLE LOCATION ESTIMATION

With the aid of image processing techniques, we propose in this section a method to detect the circular landmark stably from the omni-directional image. Also proposed here is a method for vehicle location estimation using the detected landmark, considered as a known reference point.

More specifically, from each acquired image of the ceiling, we extract a circular landmark by some image processing techniques, including thresholding, edge detection, and ellipse detection. The circular landmark contrasts well with the background in the image since it is originally an artificially-made visual aid attached on the ceiling. It is reasonable to pre-select a threshold value to segment the circular landmark in the image. A Sobel edge detector is applied next to extract edges in the image. Then, according to Section 2, it is known that the circular landmark on the ceiling can be regarded as an ellipse in the image. Therefore, an ellipse detection algorithm [7] is employed to extract the landmark, yielding the coordinates (u_w, v_w) of the center point I_w of the landmark. With the ceiling height K known in advance, the location (x_w , y_w , z_w) of the landmark in the camera coordinate system can be computed by substituting (u_w , v_w) and K into Equation (2) and manipulating the resulting equations:

$$x_w = \frac{(b^2-c^2)\sqrt{u_w^2+v_w^2}\,(K-c)}{(b^2+c^2)f-2bc\sqrt{u_w^2+v_w^2+f^2}} \times \frac{u_w}{\sqrt{u_w^2+v_w^2}},$$

$$y_w = \frac{(b^2-c^2)\sqrt{u_w^2+v_w^2}\,(K-c)}{(b^2+c^2)f-2bc\sqrt{u_w^2+v_w^2+f^2}} \times \frac{v_w}{\sqrt{u_w^2+v_w^2}},$$

$$z_w = K. \qquad (14)$$

On the other hand, we know that the circular landmark center is located in the scene coordinate system at (X_w, Y_w, Z_w) which can be measured in advance. With the camera coordinates (x_w, y_w, z_w) of the circular landmark computed by ellipse detection, let the translation and rotation relations between the scene and camera coordinate systems be denoted by (X_d, Y_d, Z_d) and φ, which describe the location of the camera on the vehicle. For simplicity, we may take the origin of the camera coordinate system to be that of the vehicle coordinate system, such that (X_d, Y_d, Z_d) and φ can be considered as the location and orientation of the autonomous vehicle in the scene coordinate system. And they can be computed as follows:

$$X_d = X_w - x_w;$$

$$Y_d = Y_w - y_w;$$

$$Z_d = Z_w - z_w;$$

$$\varphi = \tan^{-1}\frac{Y_d}{X_d}. \qquad (15)$$

4. EXPERIMENTAL RESULTS

In this section, we show the effectiveness of the proposed location estimation method described in Sections 2 and 3 by experimental results. The experiments include two parts: (1) using computer simulations to test if the circular landmark shape in the acquired images taken with omni-directional cameras with different shapes of hyperboloidal mirrors can be detected by the proposed ellipse approximation method; (2) using real images to determine the precision of the estimated vehicle location.

4.1 Simulations

In the first experiment designed to examine if the landmark shapes can be detected by an ellipse detection algorithm [7] stably, the first step is to create landmark shapes at different locations. A series of virtual circular landmarks with a radius of 20 cm are created and projected onto the image plane by [2], in which the centers of these landmarks are located in a range of 300 cm in intervals of 50 cm with azimuth angles θ ranging from 0^o to 360^o in intervals of 5^o. Second, an ellipse detection algorithm is used to detect these landmarks. Third, we computed the rate of successful detection. At last, we repeated the three steps to compute the detection rate for different kinds of omni-directional cameras which were created virtually only by changing the parameters of their hyperboloidal reflection mirrors. More specifically, we only change the mirror parameter b in (1) while maintaining c invariant since the position and the focus of the cameras need not be changed. The smallest value of b was taken to be 146mm since otherwise the landmark image will exceed the range of the image plane. And the biggest value of b was taken to be 158mm because otherwise the detection rate will drop dramatically owing to the shrinking of the landmark shape to a point in the image. The results are shown in Table 1. An example of successful detection is shown in Figure 6.

This simulation shows that, with a proper shape size, almost all landmarks can be successfully detected from the omnidirectional images, even when the images are taken with cameras with different hyperboloidal reflecting mirrors.

4.2 Experimental Results of Real Images for Vehicle Location Estimation

The proposed method was also applied to two sets of real images. As shown in Figure 7, both sets of images were taken by an autonomous land vehicle quipped with an upward-looking omni-directional camera mounted on an expandable shaft. The relative position of the camera, ceiling, and landmark are illustrated in Figure 1. When the vehicle is performing location estimation, the shaft will lift the camera to the height of 1.5m and start detecting the landmarks which were attached on the ceiling with a height of 2.9m from the ground. The relative height difference of 1.4m allows the landmarks to be clearly observed by the camera within a range of 10m horizontal distance. Out of this range, the camera will not be able to provide sufficient resolution. In the first set, the images were taken separately at the same orientations but with different distances from the landmark to the camera for the purpose of investigating the relation between the landmark distance and the estimation error. The results of this experiment are shown in Table 2 and some examples are demonstrated in Figure 8. In the second set, using one circular landmark, a sequence of images were taken by the ALV while the navigation process was being carried out. A self-location estimation result of the ALV is shown in Figure 9 and the average error is about 5% in a real navigation. The processing time for each cycle is within 100 milliseconds using a personal computer of Pentium 2.4GHz. These experimental results not only satisfy the needs of guidance accuracy but also computational speed.

Table 1: Successful detection rate of landmark shapes taken by cameras with different shapes of hyperboloidal reflection mirror

b (unit mm)	Detection rate
146	100%
147	100%
148	100%
149	100%
150	100%
151	100%
152	100%
153	100%
154	100%
155	100%
156	100%
157	100%
158	95%
159	<66%

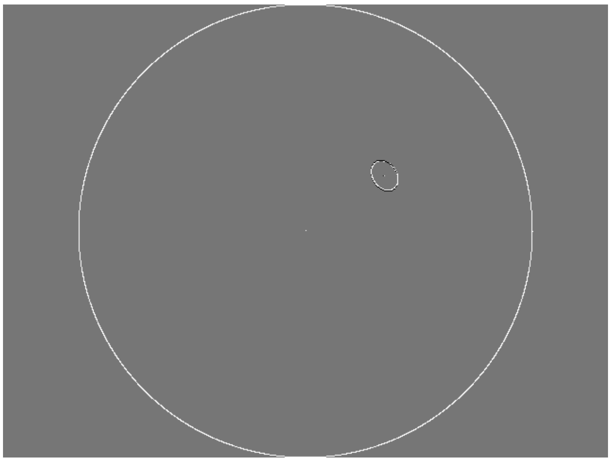

Figure 6: An example of successful detection of elliptical shapes.

Figure 7: All the experimental images were taken by an autonomous land vehicle quipped with an upward-looking omni-directional camera.

Table 2: The average of errors in location estimations with the landmarks located in the same directions but at different distances.

Horizontal distance	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**
Average error (%)	1.8	2.1	2.5	2.65	2.45	3.4	3.5

5. CONCLUSION

In this study, a new approach to location estimation of a moving ALV for navigation in indoor environment using landmark information by 3D computer techniques has been proposed. In the proposed approach, we attach a single circular-shaped landmark on the ceiling and acquire its images with an upward-looking omni-directional camera, to avoid noise or occlusion created by unexpected objects around the vehicle. It has been found that the perspective shape of the circular landmark can be approximated well by an elliptical shape. The orientation and position of the ALV can be computed from the parameters of the approximating ellipse. The computation is analytic, thus speeding up the estimation process and so the navigation cycle time. Both simulated and real images were tested and good experimental results prove the effectiveness of the proposed approach.

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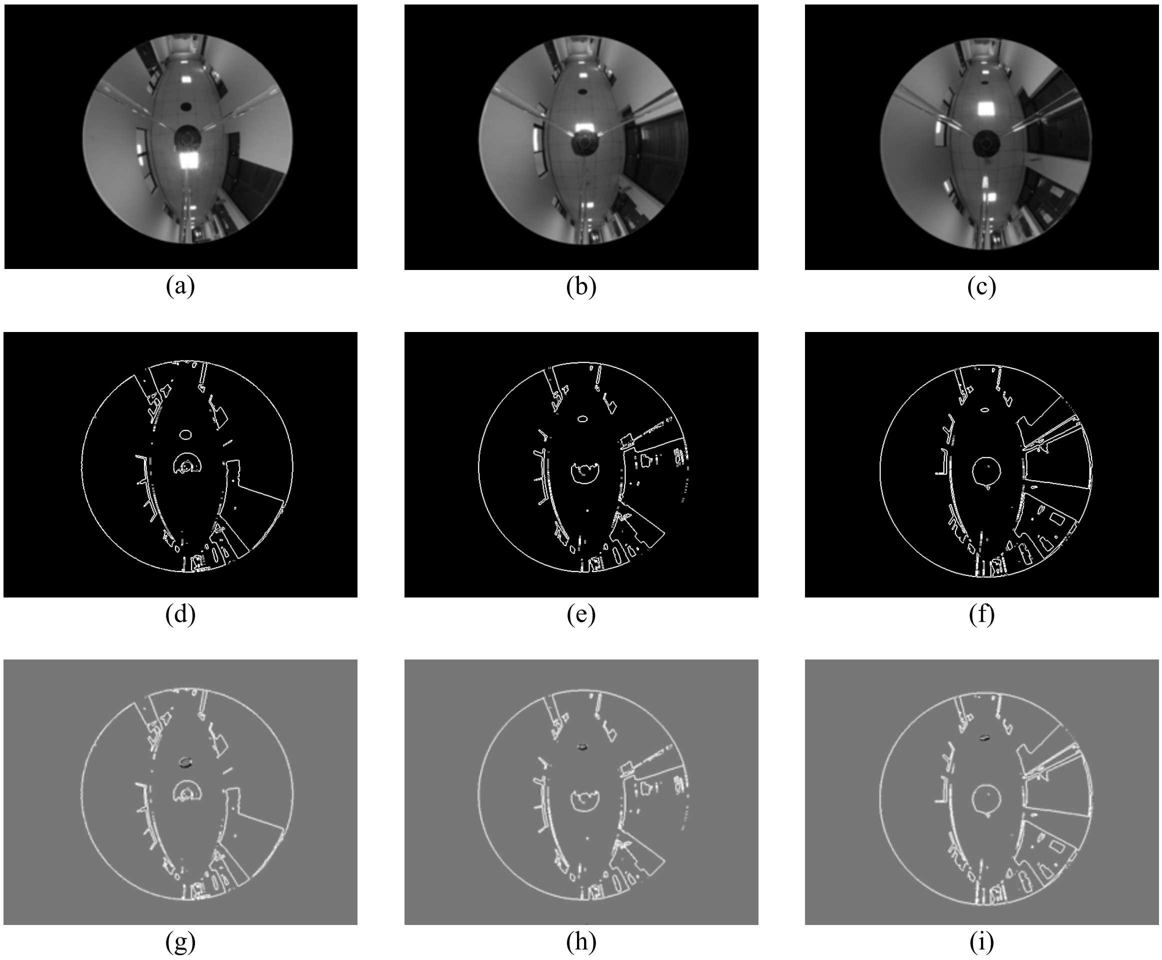

Figure 8: A circular landmark was successful detected in real images at different horizontal distances. (a) (b) (c): images of the landmark pictured at distances 1.5, 2.5, and 3.5m separately. (d) (e) (f): image processing results corresponding to (a) (b) (c). (g) (h) (i): detection results which the black pixels indicting elliptical shapes of the landmark.

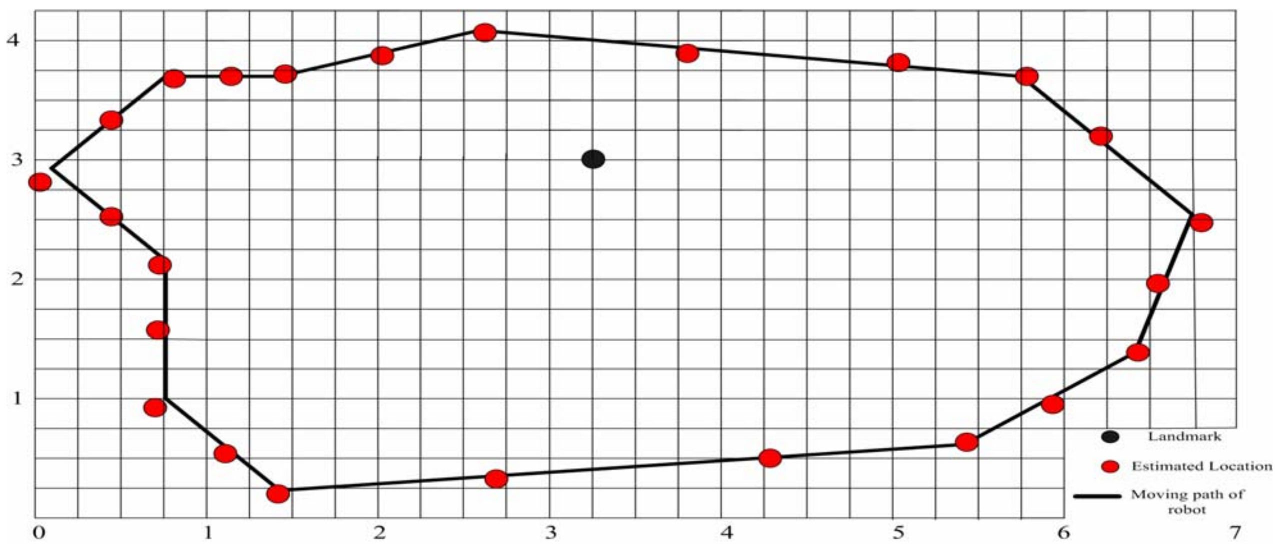

Figure 9: Results of location estimations in an real indoor environment (unit: m).