Journal of Theoretical and Applied Information Technology
15th October 2012. Vol. 44 No.1

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

DEPTH ESTIMATION FOR MOBILE ROBOT USING SINGLE OMNIDIRECTIONAL CAMERA SYSTEM

[1] ZAKARIA EL KADMIRI, [2] OMAR EL KADMIRI, [3] LHOUSSAINE MASMOUDI
[1, 2]PhD. Std., LETS Laboratory, Physics Dept. Faculty of Science, Mohammed V University-Agdal, Morocco
[3]Prof., LETS Laboratory, Physics Dept. Faculty of Science, Mohammed V University-Agdal, Morocco
E-mail: [1] zakariaelkadmiri@gmail.com, [2]omar.elkadmiri@gmail.com, [3]masmoudi@fsr.ac.ma

ABSTRACT

Described here is a new method for depth estimation using a single omnidirectional visual sensor embedded on an autonomous mobile robot. This work is part of an on-going research project to study the visual guidance of autonomous robots. The method is based on a vertically aligned omnistereo configuration and laws of reflection applied on a geometric optics field. The proposed system yields a compact and cost-effective solution. Experimental results are satisfactory.

Keywords: *Depth Estimation, Omnidirectional Vision, Catadioptric Camera, Omnistereo, Mobile Robot.*

1. INTRODUCTION

The use of visual systems to control the movement of robots has attracted the interest of many researchers in recent years.

The Computer Vision is introduced in Robotic systems which provides the capacity for recognition and reconstruction of environments in which they operate without requiring the modeling of the environment. This is potentially important when the tasks have to be executed by the robot in unknown or dynamic environments. These systems are best suited for tracking applications, obstacle detection and autonomous navigation.

Autonomous robots need the ability to detect and track movements over a large 3-D space and must perceive and avoid obstacles which may not be in the field of view of conventional cameras.

Omnidirectional visual systems are useful in many application areas, such as automated video surveillance or recovery of 3-D structures of a large scene by offering a wide field of view (FOV).

There are many ways to enhance this field of view and obtain a larger one, such as replacing the classical optics of the camera by a very short focal length lens called fisheye lens [1], multiple-camera devices [2]-[4] and the moving camera systems [5]. All these systems have some advantages in typical applications and are limited in others [6]. However, a compromise has to be made, depending on the application, between high resolution images and real time processing or video rate. Yagi [7] described the different techniques for making wide field of view cameras, and Svoboda proposed in [8] several classifications of several omnidirectional cameras.

The catadioptric imaging is a common approach to the instantaneous acquisition of omnidirectional image providing 360° FOV. A convex mirror is aligned with a standard camera to obtain such a system. Spherical, conic, parabolic or hyperbolic mirrors [9]-[10] can be used in this case.

An obvious method for depth computation or omnidirectional stereo vision uses multiple omnidirectional cameras, making such a system relatively expensive and complicated compared to those using a single camera; this is due to the need for calibrating cameras for all imaging parameters. Other systems include the use of two coaxial revolution mirrors whose centers are collinear with the axis of the camera.

A major aim of this paper is to propose a new omnidirectional system which moderates the complexity implicated in designing special catadioptric systems. The device we use combines a camera and a spherical mirror located on a mobile robot. The proposed method allows calculating the depth of a target of an observed scene. The idea is to determine the distance between an object and the robot by taking two images of the same observed scene. The pair of images is obtained by simply fast-moving the camera-mirror system along the vertical optical axis of the camera. The mathematical algorithm that we developed allows us, through the extraction of information from the two obtained images, to calculate the depth of a target.

The paper is organized as follows. First, the proposed omnidirectional vision system and the mobile robot are briefly described in Section 2. Then, in Section 3, the mathematical fundament of depth estimation is presented. Depth accuracy is evaluated in Section 4. And experimental results from the application of this method on real images are analyzed in Section 5. Finally these results are discussed in Section 6.

2. HARDWARE DISCRIPTION

2.1. Omnidirectional Sensor:

A vision system is the richest source of information, but the narrow field of view offered by standard cameras limits the range of possible applications. The catadioptric sensor can solve this problem and it is a useful way for the acquisition of omnidirectional images.

In [12] several interesting configurations of omnidirectional stereo (omnistereo) have been discussed and compared. Binocular omnistereo is one of the possible configurations where two omnidirectional cameras are aligned. In the case of horizontally-aligned omnistereo, the depth accuracy of the H-binocular omnistereo is non-isotropic and for a given baseline the best depth estimation is achieved when the disparity Δφ is maximum. The depth accuracy of the H-binocular omnistereo is proportional to the square of the depth, and inversely proportional to the baseline length. In such a system, the two cameras will occlude each other in the direction of the baseline, so no information is available in the mutually occluding regions.

For this study we adopted vertically-aligned omnistereo with a single catadioptric camera able to move along the vertical axis powered by a fast DC motor. The depth accuracy of this system is isotropic in all directions. One of the advantages of our system is the simple epipolar geometry. For omni-views, the epipolar lines are radial lines. For panoramic images the epipolar lines are vertical parallel lines (see Fig. 1). In addition, there are no mutual occlusions by the sensors in both images.

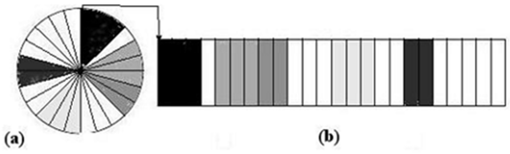

Figure 1. Epipolar geometry. (a) Omnidirectional image. (b) Panoramic image.

The catadioptric camera has been mounted on a mobile robot to acquire the omnidirectional images. This sensor is designed by combining a high resolution CCD camera with a convex mirror. The sensor used shown in Fig. 2 has the following specifications:

The sensor is wrought using a spherical stainless steel mirror with a radius of 6cm, and a Logitech C310 HD CCD camera with this specific configuration:

The resolution is 1280 x 720 pixels, interface is USB 2.0, the ratio of video stream is 30 fps, color depth is 24 bits, and the focal distance is variable. The optical axes of the camera and the mirror are aligned vertically.

Figure 2. The catadioptric omnidirectional vision system.

2.2. Vehicule:

The vehicle used for this research has a mass of approximately 31kg and overall dimensions of 90 x 53 x 30cm (see Fig. 3). It has three kinematic degrees of freedom: two independently controlled motors turn the main tracks on the sides of the vehicle as well as the tracks on the flippers, and two synchronized motors turn both of the flippers about a pivot point at the front of the vehicle.

The design of this robot is part of our research project that aims to develop and test new algorithms for object tracking and servoing using an omnidirectional camera. The choice of the PackBot concept is amply justified by the need to have a vehicle capable of crossing small obstacles, and even greater mobility in reduced environments.

The tracking target process can be summarized in the four following steps: detection and identification of the target, orientation of the robot to the target, depth estimation, and servoing according to the estimated position. These steps are schematized in Fig. 4.

In this work, we propose a new depth-estimation method which yields a compact and cost-effective solution.

Figure 3. View of the ESCALADE360 Robot and the embedded omnidirectional camera system.

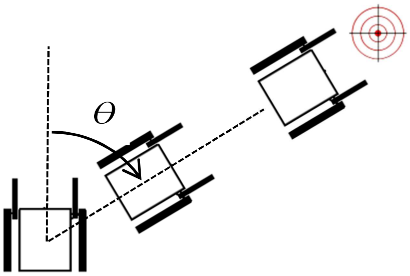

Figure 4. Target tracking process

3. MATHEMATICAL FUNDEMENTALS OF DEPTH COMPUTATION

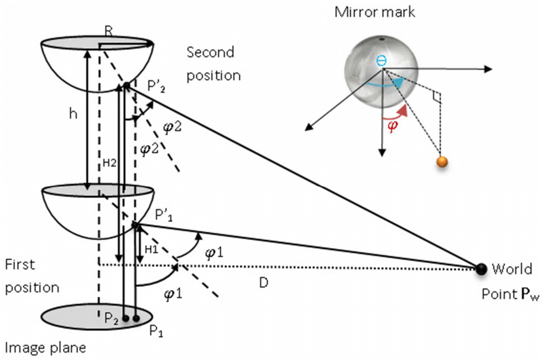

Figure 5. Triangulation and depth computation

The depth computation uses optical reflection laws. Let P_w be a world point of the observed surrounding scene, with a distance D from the catadioptric system, and P_1, P_2 their corresponding image points in the pair of images plan.

φ_1, and φ_2 denote successively half angles formed by the incident rays at down and up positions and the reflected ones. H_1 and H_2 are the distances between the reflection points (P'_1, P'_2) and their orthogonal projection on the horizontal plan containing the world point P_w (see Fig. 5).

By simple inspection of the obtained geometric configuration we determine:

$$\tan(2\varphi_1) = \frac{D_1}{H_1} \quad (1) \qquad \tan(2\varphi_2) = \frac{D_2}{H_2} \quad (2)$$

Where R is the radius of the spherical mirror, then $D_i = D - R\sin(\varphi_i)$, i=1, 2.

And: $H_2 = H_1 + h - \lambda$ (3)

With:

$$\lambda = R(\cos(\varphi_2) - \cos(\varphi_1))$$

h is the baseline parameter, which corresponds to the stroke movement of the catadioptric system on the vertical axis.

By exploiting equations (1) and (2) we obtain:

$$\tan(2\varphi_2) = \frac{(D - R\sin(\varphi_2))}{\dfrac{(D - R\sin(\varphi_1))}{\tan(2\varphi_1)} + h - \lambda}$$

From which we deduce the estimated depth as:

$$D = \varepsilon + \frac{(h-\lambda) \times \tan 2\varphi_1 \times \tan 2\varphi_2}{\tan(2\varphi_1) - \tan(2\varphi_2)} \quad (4)$$

With:

$$\varepsilon = \frac{R(\tan(2\varphi_2)\sin(\varphi_1) - \tan(2\varphi_1)\sin(\varphi_2))}{\tan(2\varphi_2) - \tan(2\varphi_1)}$$

It can be seen that the depth accuracy is strongly related to the baseline parameter h. So the best choice of this parameter is necessary.

4. DEPTH ACCURACY

In order to evaluate the proposed approach, a study of the error variation is presented below.

Given two corresponding points P_1, P_2 of the stereo pair respectively related to φ_1 and φ_2, of the 3D world point P_w.

Since $\lambda << h$ and $\varepsilon << \frac{h \times \tan 2\varphi_1 \times \tan 2\varphi_2}{\tan(2\varphi_1) - \tan(2\varphi_2)}$

Then the depth equation can be expressed as follows:

$$D \approx \frac{h \times \tan 2\varphi_1 \times \tan 2\varphi_2}{\tan(2\varphi_1) - \tan(2\,\varphi_2)} = -\frac{h\sin(2\varphi_1)\sin(2\varphi_2)}{\sin(\varphi)} \quad (5)$$

Where $\varphi = 2\varphi_1 - 2\varphi_2$ is the vertical disparity.

The depth error depending on the disparity can be estimated as:

$$\frac{\delta D}{\delta \varphi} = \frac{D}{h\sin(2\varphi_1)\sin(2\varphi_2)}\sqrt{D^2 - (h\sin(2\varphi_1)\sin(2\varphi_2)} \quad (6)$$

As h<<D the depth error is given by:

$$\delta D \approx \frac{D^2}{h\sin(2\varphi_1)\sin(2\varphi_2)}\,\delta\varphi \qquad (7)$$

Where $\delta\varphi$ is the vertical error disparity.

The depth error of the proposed system is proportional to the square of the distance D and inversely related to the baseline parameter h.

5. EXPERIMENTAL RESULTS

Our prototype device is designed to acquire omnidirectional image sequences, by moving up and down only the catadioptric system. The optical axes of the camera and the mirror are adjusted to be aligned vertically, according to the following manner: once the optical axis of the camera is perfectly vertical, we move the spherical mirror horizontally, until the projection image of the sphere is centered, which constraints all vertical edges in the omniview to pass through the image center. Finally, we adjust the focal length of the camera until getting the best image sharpness. Once the system is set, there is no need to check its adjustment again, as it remains mechanically unchanged.

The target has been chosen as a visible laser spot in the scene; thus P_w is representing the world point at a given depth. At the first step of the depth computation process, we take one image of the pair of omniview images at the down or up catadioptric system position. The next step consists of taking the second image at the opposite position, as shown below:

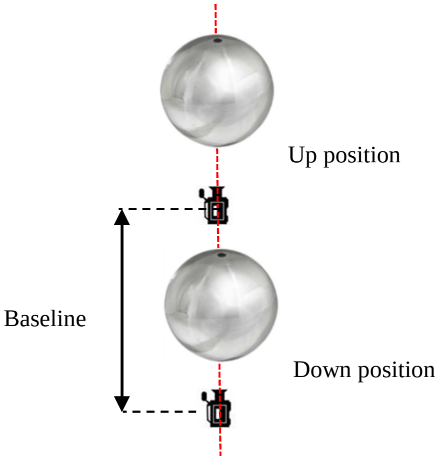

Figure 6. Pair of Omniview images acquisition

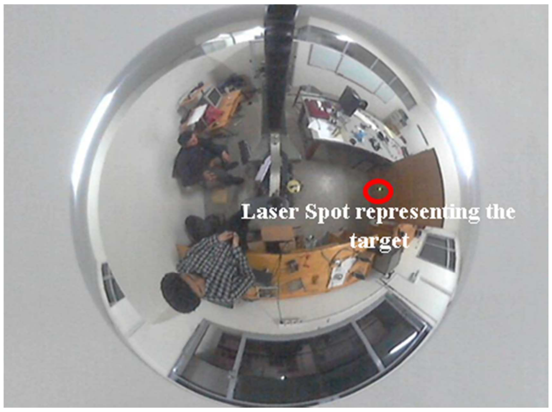

Figure 7. Omniview image at up position

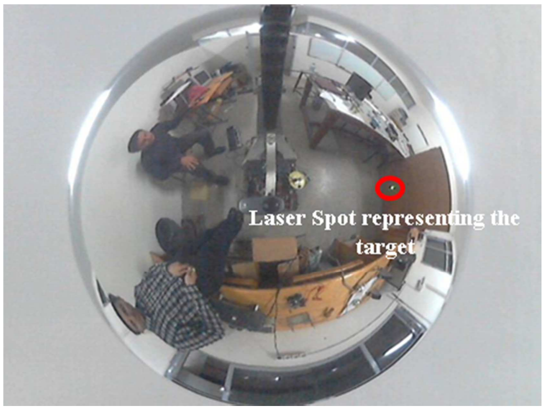

Figure 8. Omniview image at down position

After the acquisition of the two omnidirectional images containing P_1 and P_2, which represents the word point P_w, we calculate φ_1 and φ_2. By replacing them in equation (4), the estimated depth D is obtained.

5.1. Experimental Error Evaluation:

To illustrate the mathematical expression of error given in section 4, several experiments have been conducted. As shown in tables 1, 2, and 3, we studied the variation of the error depending on of the baseline length h for different given real distances D.

TABLE 1: Depth error variation for a given distance D=2.18m.

Real Depth (m)	2.18						
Baseline h (m)	0.80	0.90	1.00	1.10	1.20	1.30	1.04
Estimated Depth (m)	2.38	2.37	2.32	2.28	2.23	2.19	2.13
Depth error (m)	0.2	0.19	0.14	0.1	0.05	0.01	-0.05
Depth error (%)	9.17	8.72	6.42	4.59	2.29	0.46	2.29

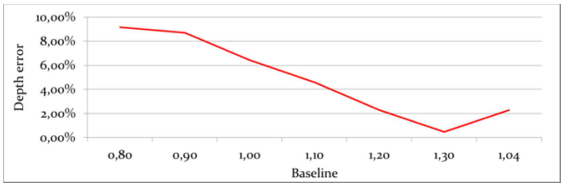

Figure 9. Error variation curve (D=2.18m).

TABLE 2: Depth error variation for a given distance D=3.18.

Real Depth (m)	3.18						
Baseline h (m)	0.30	0.35	0.40	0.425	0.45	0.50	0.60
Estimated Depth (m)	3	2.91	3.15	3.17	3.1	3	3.08
Depth error (m)	-0.18	-0.27	-0.03	-0.01	-0.08	-0.18	-0.1
Depth error (%)	5.66	8.49	0.94	0.31	2.52	5.66	3.14

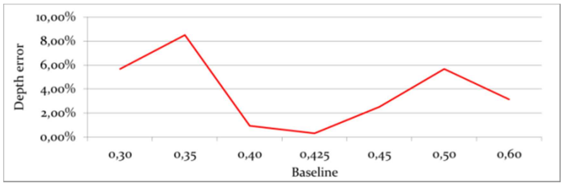

Figure 10. Error variation curve (D=3.18m).

TABLE 3: Depth error variation for a given distance D=4.18.

Real Depth (m)	4.18						
Baseline h (m)	0.10	0.20	0.25	0.30	0.35	0.40	0.50
Estimated Depth (m)	4.76	4.56	3.95	4.26	4.12	4.03	3.9
Depth error (m)	0.58	0.38	-0.23	0.08	-0.06	-0.15	-0.28
Depth error (%)	13.88	9.09	5.50	1.91	1.44	3.59	6.70

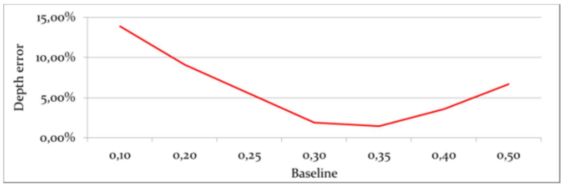

Figure 11. Error variation curve (D=4.18m).

5.2. Experimental Results:

The table below illustrates the results of some experiments of our approach comparing the estimated depth to the real one with a fixed baseline length.

TABLE 4: Estimated depth versus real one.

Baseline h (m)	0.425			
Real Depth (m)	1	1.975	2.95	3.97
Estimated Depth (m)	0.92	2.055	2.964	3.91
Depth error (m)	0.08	0.08	0.014	0.06

6. DISCUSSION

Equation (7) proves that the error generated while estimating depth is inversely proportional to the baseline h. So we can conclude that the longer the baseline, the better the estimation accuracy, which was verified in the experimental study of error. However, those experiments demonstrate that the depth accuracy is limited. Once the baseline exceeds a certain threshold, the error increases again. This can be interpreted mathematically by the fact that once the threshold is reached, the approximation h<<D is no longer verified.

This study has also validated our choice of a motorized catadioptric system allowing adjustment of the baseline as required.

7. CONCLUSION

It is perceptible that the use of 360 degree images and of scene-depth information is ideal for robot navigation tasks. For this purpose, we have presented here a novel approach allowing depth estimation for mobile robot navigation a using single omnidirectional camera. Based on the theory described in section 3 and regarding the results in the previous section, we can conclude that the proposed approach has been validated and its results are satisfactory.

REFRENCES:

[1] Y. Xiong, K. Turkowski, "Creating image based vr using a selfcalibrating fisheye lens", In *CVPR97*, pages 237--243, 1997.

[2] F. Kangni et R. Laganière, "Epipolar Geometry for the Rectification of Cubic Panoramas", *Third Canadian Conference on Computer and Robot Vision*, CRV 2006.

[3] T. Sato et N. Yokoya, "Omni-directional Multi-baseline Stereo without Similarity Measures", *IEEE Workshop on Omnidirectional Vision and Camera Networks* (OMNIVIS 2005), October, 2005.

[4] R. Cutler, Y. Rui, A. Gupta, J. Cadiz, I. Tashev, L. wei He, A. Colburn, Z. Zhang, Z. Liu, et S. Silverberg, "Distributed Meetings: A Meeting Capture and Broadcasting System", *ACM Multimedia*, 2002.

[5] R. Benosman et S. B. Kang, "Panoramic Vision: Sensors, theory and applications", *Ed Springer Verlag*, 2001.

[6] C. Fermüller et Y. Aloimonos, "Geometry of Eye Design: Biology and Technology", *Theoretical Foundations of Computer Vision* 2000: pp 22-38.

[7] Y. Yagi. "Omnidirectional sensing and its aplications", *IEICE Trans on Information and Systems*, E82-D(3): 568–578, 1999.

[8] Tomas Pajdla Tomas Svoboda. "Panoramic cameras for 3d computation", *Proceedings of the Czeck Pattern Recognition Workshop*, pages 63–70, February 2000.

[9] S.Baker and S. Nayar, "A theory of Single-Viewpoint Catadioptric Image Formation", *Int'l Journ. Of Computer Vision*, vol. 35, no. 2, pp 175-196, 1999.

[10] S. Nayar, "Catadioptric Omnidirectional Camera", *Proc. of IEEE Conf. on Computer Vision and Pattern Recognition*, pp.4820488, 1997.

[11] D. Southwell, A. Basu, M. Fiala and J. Reyda,"Panoramic Stereo", *Proc. of ICPR'96*, pp. 378-382, 1996.

[12] Zhigang Zhu, "Omnidirectional Stereo Vision", *Workshop on Omnidirectional Vision, in the 10th IEEE ICAR*, August 22-25, 2001, Budapest, Hungary.