A CALIBRATED PINHOLE CAMERA MODEL FOR SINGLE VIEWPOINT OMNIDIRECTIONAL IMAGING SYSTEMS

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ABSTRACT

This paper presents a perspective imaging model that is able to eliminate image deformations caused by non-linear lens distortion and to detect the location of the optical center respectively. By using a calibration pattern it can detect the optical center by tracking the optical rays generated by 3D points that have the same representation on the image plane. Calibration pattern is also used in order to generate normalized virtual screens on which captured images are back projected, thus eliminating the deformations. Experimental results for single viewpoint omni-directional cameras demonstrate the effectiveness of our method.

1. INTRODUCTION

Many applications in computer vision require mapping points in 3D world to corresponding points in an image. They employ either calibrated or uncalibrated cameras, perspective projection serving as the dominant imaging model. In our assumption, in a perspective projection imaging model, straight lines in the scene are projected as straight lines in the image, while in a non perspective projection model, straight lines in the scene appear as curved in the image.

This paper is presenting a perspective imaging model that enables a distortion free display on a virtual screen of the images captured with an uncalibrated singleviewpoint omnidirectional camera, supplemented by a precise detection of its optical center. Virtually, this imaging model can be regarded as a calibrated omnidirectional pinhole camera model.

An important feature of algorithms using uncalibrated cameras is that no knowledge of the poses and internal parameters of the camera are required. However, no lens is perfect and in the presence of nonlinear lens distortion the pinhole camera model is no longer valid and the technique breaks down. On the other hand, mathematical models of lens distortion developed for calibrated cameras compensated the errors but could not completely eliminate them.

A solution to this problems would be the geometric camera calibration. For example, by measuring the line-of-sight vector at each pixel in the image, a lookup table would be generated and then, given a pixel in an image, simple indexing would yield the line-of-sight vector. A complete geometric camera calibration includes the projection problem (given a point in space predict its location in the image) and the back-projection problem (given a pixel in the image compute the line-of-sight vector through the pixel).

In their work, Gremban et al[5] succeeded in offering a complete solution to the geometric camera calibration problem for the case of conventional cameras. Their method was based on a two-plane method of Martins et al[6] but was extended to include a solution to the projection problem too. Comparing with their work, our technique for detecting the optical center (the projection problem) uses the same principle of two calibration objects in order to find pairs of 3D points that are projected on the same pixel on the camera's image plane. The rays of light generated by these pairs of corresponding points converge to the optical center of the imaging model. The originality of our technique is related to the way the calibration patterns were generated and to the method of estimating the accuracy of the results. Moreover, our model allows a visualization of the rays of light and optical center too.

Based on a virtual modelling approach, we are subsequently building virtual screens that have the same structure and shape as the calibration objects. The images taken with the uncalibrated camera are then back-projected on these virtual screens based on our interpolation techniques. Because the virtual screens resembles exactly the shape of the calibration patterns, this back-projection process can be seen as an image plane normalization.

Recently, the developments in image sensing made the perspective model highly restrictive. In order to represent any arbitrary imaging system, Grossberg [1] introduced a new imaging model that was based on determining the locus of viewpoints (i.e. the caustic) of the imaging system by using the Jacobian method. While their method is determining the envelope of the reflected rays (i.e. the catacaustic), in our work we are estimating the point of intersec-

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tion of the incident rays. Also, in their calibration technique of the rotationally symetric imaging systems they neglected the deviation between the rotation axis and the location of the optical center. In a practical calibration, this deviation will obstruct the correct convergence of the reflected rays toward the optical center of the camera. Our paper presents an original method to compensate this deviation.

The projection of undistorted images on virtual screens was used by Yamazawa [2]. They used a grid pattern and by employing a bilinear interpolation process they projected the captured image on a perfectly rectilinear pattern. In this way they succeeded to eliminate the errors induced by lens artifacts. In order to perform the camera calibration they subsequently applied Tsai's method [3].

Basic principles of our approach are shown in the Section 2 while in Section 3 we concisely describe the 3D solution for estimating the convergence point of the rays of light. Finally, Sections 4 and 5 give our experimental results and conclusion.

2. GEOMETRIC OMNIDIRECTIONAL CAMERA CALIBRATION

We used a catadioptric system consisting of a perspective camera looking into a hyperbolic mirror. In order to generate a distortion free image representation, we performed an image plane normalization by using a calibration object. This process consists of building a virtual screen that had to had the same shape and structure as the calibration object, followed by a back-projection of the captured images on to the virtual screen. Because the omnidirectional camera had a 360 degrees field of view, we built a cylindrical shaped calibration object by placing an LED bar (consisting of 72 LEDs) at a certain distance from the omnidirectional camera and computed the locations of each LED for intermediate positions from 15 to 15 degrees (Fig. 1).

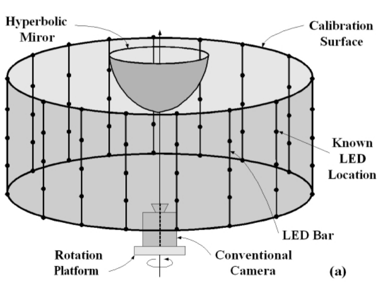


Fig. 1. Cylindrical shaped calibration object.

Further, we built our virtual screen as a scaled representation of the generated cylinder shaped calibration object. Back-projection task was performed by employing a local linear and circular interpolation that computed a corresponding image pixel for each point on the virtual screen

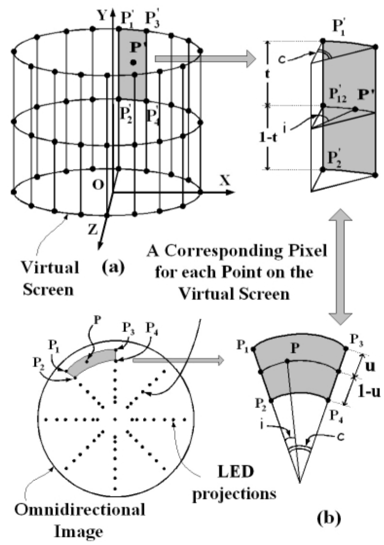


Fig. 2. Back-projection performed by local interpolation: (a) on virtual screen; (b) on omnidirectional image

(see Fig. 2a). In order to detect the location of the optical center, we generated two cylinder shaped calibration surfaces and detected 3D corresponding points that are projected on the same pixel on the image plane (Fig. 3).

The ray $\mathbf{p}_1$ proceeding from the camera is reflected by the mirror as a ray $\mathbf{p}_1^{'}$. In the case of catadioptric systems with hyperbolic mirrors, all the reflected rays $\mathbf{p}^{'}$ intersect at the focal point of the mirror $\mathbf{F}^{'}$ and the camera center of projection $\mathbf{C}$ coincides with the second focal point of the mirror, $\mathbf{F}$. Because of the uniqueness of the projection center $\mathbf{C}$, if two 3D points from the surrounding environment have the same representation on the image plane we can say that they lie on the same reflected ray that will include also the mirror's focal point. Our purpose is to find the optical center which is represented by the mirror's focal point.

Knowing the 3D coordinates of the LEDs on the calibra-

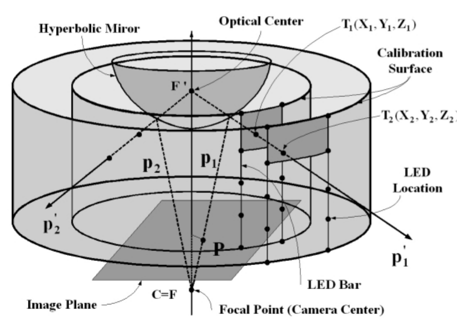


Fig. 3. Optical center detection for Single Viewpoint Omnidirectional Camera

tion pattern and the coordinates of their projections on the image plane, and by using similar interpolation function, a correspondence between each pixel in the image plane and 3D points on the calibration pattern could be found. For each intermediate distance, we built a lookup table that matched the pixels in the image plane with the corresponding 3D points located on the calibration pattern. By iterating a search process on the resulting two tables, 3D points that correspond to the same pixels could be detected.

3. ESTIMATING THE OPTICAL CENTER

Two lines in 3D generally don't intersect at a point. They may be parallel (no intersection) or they may be coincident (infinite intersections) but most often only their projection onto a plane intersect. When they don't exactly intersect at a point they can be connected by a line segment, the shortest line segment is unique and is often considered to be their intersection in 3D.

In order to find the point that is located at the shortest distance to all of the generated rays of light, we resorted to the use of a linear least squares method that computes an approximate solution by minimizing the sum of all the distances from an arbitrary point to all the rays (we omit the details here).

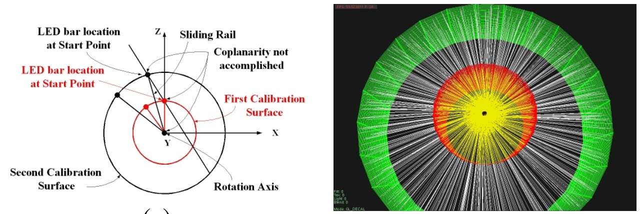
4. EXPERIMENTAL RESULTS

The calibration setup consisted of: (1) a calibration pattern (an LED bar whose lighting was controlled by software), (2) an analog color camera with a resolution of 640 x 480 pixels, (3) a catadioptric attachment (paraboloid mirror), (4) a sliding rail, (5) a Pan-Tilt Unit (controlled by software). For both experiments we used a 2GHz PC with 2GB memory, a video capture board and a flat panel display.

In the experiments, the sliding rail was oriented perpendicular towards the rotation axis of the omnidirectional camera that was marked by the manufacturer of the catadioptric attachment. The origin of the world coordinate system was placed inside of the calibration patterns, its equivalent virtual representation being built with the XOZ plane parallel with the ground (see Fig. 2a). The measurements were performed by placing the calibration pattern at 13cm and 33cm respectively from the camera.

The generated rays of light will include the optical center if the vertical axes of the LED bar for a certain rotation angle are coplanar with the rotation axis of the camera (Fig. 4a). If this condition is not accomplished and if a deviation angle is inserted, the 3D coordinates of the LEDs will be wrongly estimated and the location of the optical center will be missed (Fig. 4b).

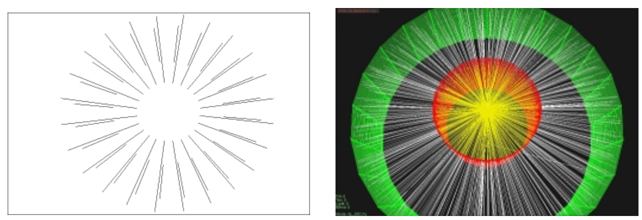
In order to detect the deviation angle we applied the following method. Firstly, we determined the parameters of



(a) (b)

Fig. 4. (a) Coplanarity is required in order to have convergent rays of light.(b) Erroneous placement of the Calibration Pattern generates a locus of the Optical Center on the circumference of a circle.

the lines generated by the projections of LEDs on the image plane for two different distances camera-LED bar (Fig. 5a). We used least-squares minimization method to approximate the best fitted lines. Further, we detected their crossing points and the results obtained confirmed that they were identical.



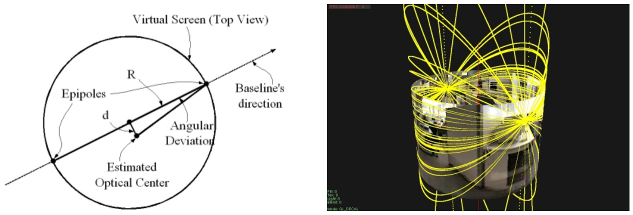
(a) (b)

Fig. 5. (a) Lines through the sets of pixels representing the projections of LEDs for two consecutive distances. (b) After proper correction, the locus of the Optical Center will be a point.

This outcome gave us the common element that was needed in order to compare the two sets of lines. The deviation between the lines corresponding to different distances represents actually the deviation inserted by erroneous placement of the LED bar. Once the deviation angle was detected, we built the calibration surfaces accordingly, the final result being presented in Fig. 5b.

The new results of the calibration process placed the optical center inside of the virtual screen with a slight deviation from the rotation axis. In order to measure the error of optical center estimation, we checked the deviation of the optical center from the baseline generated by recording two images at different locations with the camera placed at the same height from the ground.

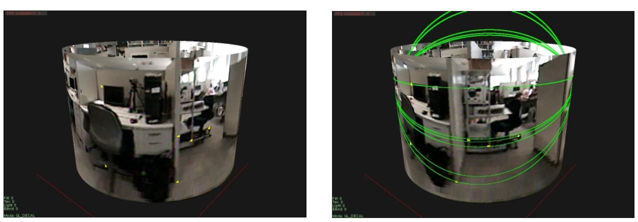
Taking into account that in the case of omnidirectional camera, the image plane is represented by the cylindrical virtual screen, the intersection of the baseline with each corresponding virtual screen will generate two epipoles. Therefore, the direction of the baseline will coincide with the line generated by the epipoles on each virtual screen and our initial task will be reduced to computing the angular deviation of the estimated optical center with regard to the line generated by the epipoles that belong to the same virtual screen (Fig.6a).



(a) (b)

Fig. 6. (a) Computing the deviation from the baseline of the estimated optical center. (b) Optical Center Estimation.

We computed the coordinates of the two epipoles as the intersection points of the epipolar curves generated by using a set of 50 feature points placed uniformly on the surface of the virtual screen. We used a method that eployed the epipolar constraint equation and Kanatani's [4] algorithm for computing the essential matrix (we omit here the details). Epipolar curves and their epipoles are presented in Fig.6b. In order to check the corectness of the epipolar curves we had to measure if the feature points in one image reside on the curves generated by the corresponding feature points from the other image. In order to keep the clarity of the image, Fig. 7 presents six of the corresponding feature points (white dots in the image) and the corresponding epipolar curves generated in the second image by feature points in the first image.



(a) (b)

Fig. 7. (a) Feature Points on First Image. (b) Corresponding Feature Points and Epipolar Curves on the Second Image.

Based on our calculations (knowing the radius of the cylinder and computing the distance from the estimated optical center to the line generated by the epipoles) we obtained an angular deviation in the range of 0.316 degrees.

By combining back-projected images with the converging rays we get the final representations of the virtual screens and the optical center (Fig. 8). As can be noticed, the objects in the normalized image are keeping their proportions.

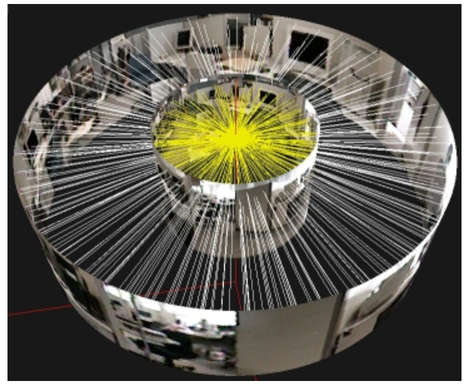


Fig. 8. Converging rays for single viewpoint omnidirectional camera.

5. SUMMARY AND CONCLUSIONS

The main contribution of this paper was the presentation of a pinhole camera model that can be used to represent an omnidirectional single viewpoint imaging system. This model uses a calibration object in order to build a virtual screen on which undistorted images are projected. Supplementary, it can detect and visualize the optical center by performing optical rays tracking. In the experiments, results for omnidirectional cameras demonstrated the effectiveness of our method. In the future we would like to extend our work towards the simultaneous 3D reconstruction and localization tasks that are suitable for intelligent mobile robots.

6. REFERENCES

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