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Where physically is the optical center?

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Abstract

A simple and fast method of determining the position of the optical center without any specialized equipment is presented. The position of the optical center is a depth determining parameter in a panoramic depth imaging system [Peer, P., Solina, F., 2002. Panoramic depth imaging: single standard camera approach. Internat. J. Comput. Vision 47 (1/2/3), 149–160; Peer, P., Solina, F., 2005. Multiperspective panoramic depth imaging. In: Computer Vision and Robotics. Nova Science Publishers]. The reconstructed distances correspond well to the actual measured distances on the scene.

Keywords: Camera; Optical center; Computer vision

1. Introduction

Camera manufacturers seldom list a number of important details about cameras, which are sometimes required if the camera is used in computer vision applications. Examples of such information are the size of the CCD chip, the precise position of the principal point, the physical position of the image plane within the camera, the physical position of the optical center within the camera etc. Some of this information can be obtained with well-known calibration methods (e.g., Bouguet, 2005), but some, such as the position of the optical center, cannot be obtained easily without specialized optical equipment. Although it seems that the optical center is easy to infer for most cameras it is not self-evident, especially for recent vertical zoom optics in ultra-compact digital cameras. In general, we want to design computer vision methods to be as autonomous as possible, without the need if possible to tune or set various system parameters. For example, methods that do not require camera calibration are therefore preferred over the methods that require camera calibration. Our system for panoramic depth imaging which works by rotating a single standard camera, however, requires the precise position of the optical center to obtain correct depth values (Peer and Solina, 2002, 2005).

The optical center within the camera represents the point in which all the light rays that form the image intersect if the lens is approximated with a single thin lens. The distance between the center of camera rotation and the optical center is needed to compute the depth information. Since we used in our panoramic depth imaging system several different cameras, sending them all to an optical company which could determine their optical center by photogrammetrical methods (using special equipment) (Clarke and Fryer, 1998; Ray, 2002) was not an option. Therefore, we designed a simple and fast method to determine the optical center for a given camera lens without any specialized equipment.

Generally, in the process of establishing the position of the optical center we are dealing with three coordinate systems. The first one is that of the imaging system, the second one is that of the camera body and the third one is that of the calibration object. Standard calibration finds

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the relation between the first and the third system. In our case, we need the relation between the first and the second system. We find this relation by first establishing the relation between the second and the third system and then use all gathered information (the relation between the first and the third coordinate system and the relation between the second and the third coordinate system) to obtain the relation between the first and second coordinate system.

In the next section we outline the proposed method for establishing the position of the optical center. In Section 3 we perform the evaluation of the results. We use the resulting optical center position in our panoramic depth imaging system and compare in selected points the obtained depth with the actual distance measurements. Finally, in Section 4, we summarize the paper.

2. Method

The depth recovery system, for which the information about the physical location of the optical center is needed, is assembled in such a way that the optical center is offset from the system's rotational center. In Fig. 1 r represents the distance between the rotational center R of the system and the optical center C of the camera. Both points lie on the optical axis of the lens. Since the exact position of the optical center is normally not given by the manufacturer, we have to somehow estimate its position to get the value of r. To simplify measurements we mark a fixed point P on the camera body so that the optical center C can be determined relative to that point. To be more exact, we determine the optical center C relative to the projection of point P on the axis $\overline{RC}$, marked with P' in Fig. 1. But as we see in the continuation, the measurements involved in the calculations can be determined from point P.

We implicitly make the following assumptions: The points R, C and P' in Fig. 1 are aligned. The orientation and position of the line $\overline{RC}$ is known, and only the position of C along this line is to be estimated (and not the three coordinates of this point). Furthermore, the millimeter (mm) grid plane is placed orthogonal to $\overline{RC}$.

First, we calibrate the camera with a well-known calibration technique based on a check board pattern (Bouguet, 2005). It gives us the following information: precise focal length f, principal point, radial coefficients, tangential coefficients, skew and pixel error. The principal point is the point where the optical axis intersects the image plane. Since our method needs the camera horizontal view angle α, we actually need only the precise focal length information. If we assume that the lens distortion parameters are negligible, which also means that we can assume that the principal point is in the middle of the captured image, we can calculate the horizontal view angle of the camera from

$$\alpha = 2\arctan\frac{l/2}{f},$$

where l is the width of the captured image used in the calibration process and f is the focal length, both in pixels.

Next, we capture n images of the mm grid paper at several distances to the grid paper. The optical axis is perpendicular to the paper surface. For each image i we measure the distance p_i in mm from a fixed point P on the camera body to the grid paper using a tape measure. Note that this distance is equal to the one we would obtain if we could measure the distance from point P'. For each captured image we read its corresponding width w_i in mm by counting the mm marks on the imaged grid paper. Now, we can calculate the distance c_i between the optical center C and the grid paper:

$$c_i = \frac{w_i/2}{\tan(\alpha/2)}.$$

Because we know the distances p_i and c_i, we also know the position of the optical center C with respect to the point P':

$$\overline{CP'_i} = c_i - p_i.$$

We select point P on the camera body so that this difference is positive.

Since the process of establishing the position of the optical center C involves measuring the physical distance p_i, a better result is obtained by repeating the process m times.

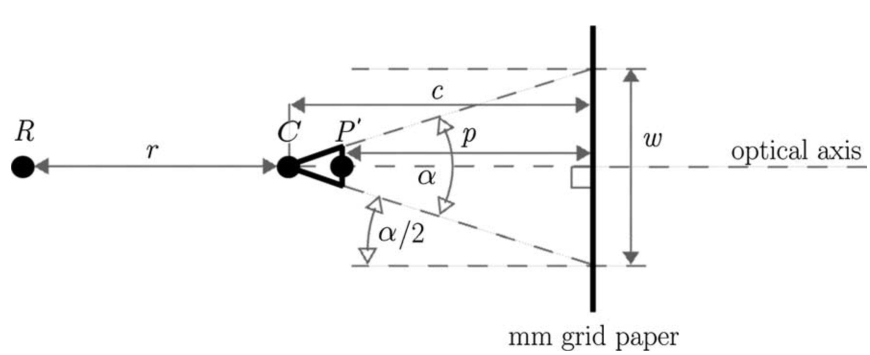

Fig. 1. Relation between the parameters, which are required for determining the physical position of the optical center C and consequently the radius r: R is the panoramic depth imaging system rotational center; c is the distance from the optical center to the grid paper; P' is a projection of a fixed point, that lies on the camera body, on the optical axis selected so that the difference $c - p$ is positive; p is the distance from point P' to the grid paper; w is the width of the imaged grid paper in mm; α is the horizontal view angle of the camera.

In our case m was typically 3. In the end, the position of the optical center with respect to the point P' is calculated as an average over all estimated values:

$$\overline{CP'} = \frac{\sum_{i=1}^{m} \overline{CP'_i}}{m}.$$

To summarize, the input parameters to our method of determining the position of the optical center C are the camera horizontal view angle α (estimated by using a calibration technique based on a check board pattern (Bouguet, 2005)), measurements of the distance p_i between a fixed point P on the camera body and the target mm paper, and width of the corresponding captured image w_i. The only value which is measured manually is the distance of the millimeter paper to the point P on the camera body. Therefore, several measurements of this distance are made when the target mm paper was set at different distances from the camera. The length of the millimeter paper that is seen on the captured image can be established manually or by a computer program that counts the number of mm marks along the selected axis.

Finally, r is computed as

$$r = \overline{RC} = \overline{RP'} - \overline{CP'},$$

where $\overline{RP'}$ is the distance between two points, R and P'.

The position of the optical center C established in this way can be further refined as suggested in the next section.

3. Evaluation of the method

We did not have any means to establish the position of the optical center by an independent method so that the results could be compared directly.

3.1. Background

As we stated in the introduction, we need the position of the optical center to compute the radius r of our system for panoramic depth imaging (Fig. 2). Here, we first briefly outline this system.

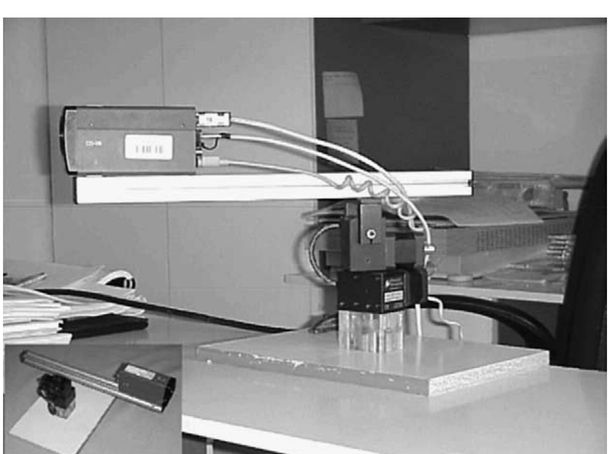

Fig. 2. The system for capturing panoramic depth images.

In Fig. 2, the hardware of our system for panoramic imaging can be seen: a color camera is mounted on a rotational robotic arm so that the optical center of the camera is offset from the vertical axis of rotation. The camera is looking outward from the system's rotational center. Panoramic images are generated by repeatedly shifting the rotational arm by an angle that corresponds to a single pixel column of the captured image. By assembling the center columns of these images, we get a mosaic panoramic image. One of the known drawbacks of mosaic-based panoramic imaging is that dynamic scenes are not captured adequately.

Symmetric pixel columns on the left and on the right-hand side from each captured image center column are assembled into a mosaic stereo pair. The column from the left-hand side of the captured image is mosaiced in the right eye panoramic image and the column from the right-hand side of the captured image is mosaiced in the left eye panoramic image. For so defined stereo pair, the basic equation for depth estimation e is $e = (r \cdot \sin\varphi)/\sin(\varphi - \theta)$. This equation implies that we can estimate depth e only if we know three parameters: φ, θ and r. φ defines the offset of symmetric pixel columns in each direction from the image center column expressed as a rotation centered in the optical center C, and can be easily calculated from the camera's horizontal view angle α. To calculate θ, we have to find corresponding points in panoramic images. And last, the calculation of r, which is the subject of this paper. At this point we should emphasize the main conclusion that addresses the magnitude of errors in the estimated depths coming from the stereo matching algorithm itself: the bigger e, the smaller the confidence in the estimated depth. We come back to this at the end of Section 3.2. More about the system, including exhaustive analysis of the system's capabilities and a number of experiments, can be found in (Peer and Solina, 2002, 2005).

To perform the stereo reconstruction, we need to know the radius r which is determined by the position of the optical center C. The actual physical distances a from the center of our system R to selected points on the scene can be measured with a tape measure. If the results of stereo depth reconstruction would differ too much from the actual distances, the estimated value of r would not be correct since the values of all other parameters needed in stereo reconstruction are known or can be measured directly. Therefore, the measured distances are the ground truth information that help us evaluate if the distance r between the rotational center R and the optical center C is correctly determined and, in consequence, if the proposed method for determining the position of the optical center C is correct. In a number of experiments that we made, we achieved depth reconstruction which corresponded well to actual distance measurements of selected points (Peer and Solina, 2002, 2005). In the next subsection we analyze an experiment to prove that the method for determining the position of the optical center C works.

3.2. Results

The normalized error of the estimated depth e in comparison to the actual distance a (in % of a) for the scene point i is given as

$$\mathrm{ERR}_{\%,i} = \frac{|e_i - a_i|}{a_i} \cdot 100.$$

Furthermore, the average error over n scene points is calculated as

$$\mathrm{AVG}_{\%} = \frac{\sum_{i=1}^{n} \mathrm{ERR}_{\%,i}}{n}.$$

The standard deviation,

$$\mathrm{SD}_{\%} = \sqrt{\frac{\sum_{i=1}^{n} (\mathrm{ERR}_{\%,i} - \mathrm{AVG}_{\%})^2}{n-1}},$$

shows how tightly the various estimated depths are clustered around the average error in the set of data.

Correspondences for each feature point on the scene used in the evaluation were determined with a *normalized correlation* procedure (Faugeras, 1993) and rechecked manually for consistency.

In the experiment the following cameras were used: *camera #1* with the horizontal view angle $\alpha = 34°$, *camera #2* with $\alpha = 39.72°$ and *camera #3* with $\alpha = 16.53°$. The number of feature points on the scene n used in the evaluation was 21.

The comparison of results for all cameras is given in Table 1. The results show that similar overall accuracy can be achieved if we use different cameras, which implies that (1) repeatability is assured and (2) since the depth estimations e correspond well to the measured actual distances a, the proposed method of determining the optical center works. Obviously, it is harder to estimate the location of the optical center in this way if the view angle is smaller. The problem is even bigger if the camera cannot focus well on near objects.

We also investigated the sensitivity of the stereo depth reconstructions e with respect to the changes of parameter r. In this experiment we made the assumption that each stereo depth reconstruction e is equal to the actual distance a for a given depth point. In this way we tried to eliminate the influence of the error of the stereo matching algorithm ($\mathrm{ERR}_{\%,i} = 0\%$ for correct r). Thus, all calculations in which we changed only the value of parameter r should reveal only the sensitivity of the process with respect to the changes of parameter r. We focused on two extremes, the nearest and the farthest actual reconstructed scene points (two different values of θ with fixed φ). Now, we varied the value of the parameter r and obtained different values of the stereo depth reconstructions e with respect to the changes of parameter r. Table 2 gives an example: For $\Delta r = -1$ cm the difference Δe at the nearest point was 2.0 cm and at the farthest point 7.8 cm. With $\mathrm{ERR}_{\%,i}(\Delta r)$ we marked the normalized error $\mathrm{ERR}_{\%,i}$ that follows mentioned assumption at varied value of parameter r. The error $\mathrm{ERR}_{\%,i}(\Delta r)$ was 3.36% at the nearest point and 3.30% at the farthest point, but the difference in the percentages is due to the usage of rounded values in the calculations. The results can be summarized as follows: The difference between reconstructions in centimeters is much bigger at the farthest point, but the error $\mathrm{ERR}_{\%,i}(\Delta r)$ is constant. Furthermore, Fig. 3 shows that with bigger r we get smaller $\mathrm{ERR}_{\%,i}(\Delta r)$. To conclude, we can say that the sensitivity is in all cases rather small, but not negligible.

In Fig. 3 we can see that for a fixed r the relation between Δr and $\mathrm{ERR}_{\%,i}(\Delta r)$ is linear. Moreover, $\mathrm{ERR}_{\%,i}(\Delta r) = \mathrm{ERR}_{\%,i}(-\Delta r)$. Let us compare this with the magnitude of errors in the estimated depths coming from the stereo matching algorithm itself (parameter θ): Fig. 4 reveals that for a fixed θ the relation between $\Delta\theta$ and $\mathrm{ERR}_{\%,i}(\Delta\theta)$ is not linear, and $\mathrm{ERR}_{\%,i}(\Delta\theta) > \mathrm{ERR}_{\%,i}(-\Delta\theta)$. With respect to the changes of parameter θ we can conclude that the bigger e, the smaller the confidence in the estimated depth (Peer and Solina, 2002, 2005). Thus, the reconstruction process is more sensitive to the errors in parameter θ than in parameter r.

Table 1
Reconstruction results

	Camera #1	Camera #2	Camera #3
$\mathrm{AVG}_{\%} \pm \mathrm{SD}_{\%}$	$3\% \pm 2\%$	$2.7\% \pm 2.3\%$	$5.9\% \pm 2.5\%$

Table 2
Sensitivity of the stereo depth reconstructions e with respect to the changes of parameter r

r	e_{near}	e_{far}
30 cm (correct)	59.6 cm	236.2 cm
29 cm	57.6 cm	228.4 cm
Δe	2.0 cm	7.8 cm
$\mathrm{ERR}_{\%,i}(\Delta r)$	3.36%	3.30%

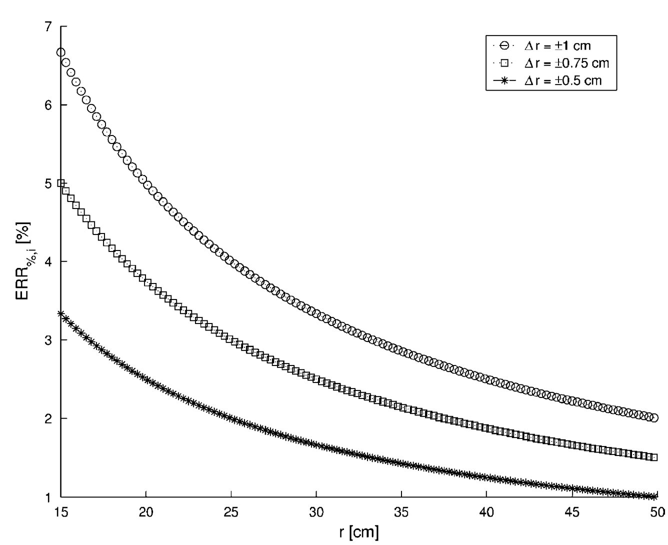

Fig. 3. Sensitivity of the stereo depth reconstructions e with respect to the changes of parameter r at different values of Δr.

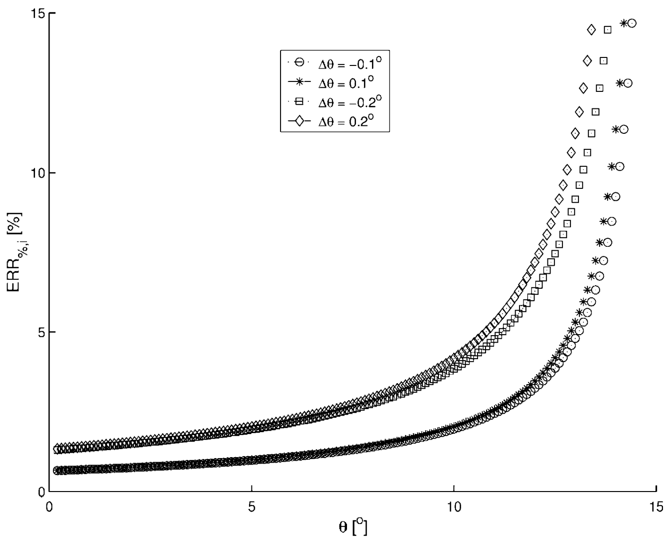

Fig. 4. Sensitivity of the stereo depth reconstructions *e* with respect to the changes of parameter θ at different values of $\Delta\theta$.

3.3. Possible further improvement

We could even further improve the estimation of *r* by minimizing $AVG_{\%}$. By letting *r* go through an interval of possible values around the estimated value and calculating $AVG_{\%}$ for each value of *r*, we select that particular value of *r* that minimizes $AVG_{\%}$. This optimization step was not done in the experiment presented above.

Therefore, in respect to the optimization step, we can present an extended method for determining the physical location of the optical center, which optimizes the location of the optical center: (1) Execute the method in Section 2 to get the first approximation of the optical center location. (2) Calculate $AVG_{\%}$ for a pair of panoramic images using the system presented in Section 3.1. (3) Optimize *r* by minimizing $AVG_{\%}$, which gives you the optimal location of the optical center.

With this extended method the improvement of results $AVG_{\%}$ was significant only for *camera #3* (Peer and Solina, 2005), which could not focus well on near objects. Consequently, the counting of the mm marks on the imaged grid paper is harder. This is most likely the reason why the stereo reconstruction results obtained with *camera #3* in Table 1 are not as good as the results obtained with the other two cameras.

The remaining error in determining the position of the optical center could be attributed to

- the error in estimations of other parameters (e.g., α);
- the error due to the lens distortion;
- the principal point does not lie precisely in the middle of the captured image and/or
- the human factor (e.g., the distances to the features on the scene are measured manually).

4. Conclusion

We presented a simple method of determining the optical center of a camera without the need of any specialized equipment. Since we did not have independent measurements of the optical center for our lenses to confirm our results, we tried to verify our results in another way. We used our estimates of the optical center position in our system for panoramic depth imaging (Peer and Solina, 2002, 2005).

One of the parameters of our panoramic depth imaging system is the distance between the center of rotation and the optical center of the single camera. Without this information all estimated depths would only be in the right ratio among each other, i.e., the depths would be estimated only up to a scalar factor. However, we are interested in actual depths given in mm, since we would like to use our system in autonomous mobile robot localization and navigation tasks. The described method for establishing the optical center of a camera gave in our panoramic depth imaging system depth results consistent with actual measurements on the scene.

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