Distance Measurement Using Single Non-metric CCD Camera

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Abstract: - A novel measuring system based on a single non-metric CCD camera and a laser projector is proposed in this paper for measuring distance of a remote object. The setup of the measuring system is relatively easy, in which the laser pointer is positioned beside the CCD camera so that laser beam projected is parallel to the optical axis of the camera in a fixed distance. Based on a fast and effective algorithm proposed in this paper, the central position of the projected laser spot in images due to the laser beam can be accurately identified for calculating the distance of a targeted object according to an established formula. Because of the relationship of pixels counts of the diameter of the laser spot at different distances, processing of a sub-frame comprising a fraction of scan lines, rather than the whole image, is only required. Significant savings of computation time can therefore be achieved. Simulation results show satisfactory measurements can be obtained, where averaged absolute measurement errors via the proposed approach lie within 0.502% .

Key-Words: - Non-metric**,** Principal point, Distance measurement, CCD camera, Laser.

1 Introduction

The utilization of image information to conduct distance measurement is a common practice in photogrammetry and robot vision. However, photogrammetry requires the use of metric cameras and specific software to achieve the measuring functions. Despite of high resolution for analysis, this method can't deal with on-line process and relevant equipment is also costly. Robot vision on the other hand, is capable of obtaining measurement on a real-time basis. However, two or more cameras and complicated cooperation among high-speed DSP chips are required. If objects reside in a region with the same gray level, it will be extremely difficult to search corresponding points by all of block matching technology via area-based [1]-[2] or feature-based [3]-[4] approaches.

As an attempt to improve the performance of existing distance measuring methods, this paper proposes a simple method using a non-metric CCD camera and a laser projector set beside the CCD camera. The laser beam cast from the laser projector is parallel to the optical axis of the CCD camera. Based on a simple procedure, we can detect the position of the laser spot in images. From the calibration model of CCD camera, together with the identified position of the laser spot, we can measure the distance from an object of interest.

Unlike robot vision which requires complicated techniques, the proposed method with a simple structure and algorithm can be easily realized by FPGA for use in real-time processes.

The paper is organized as follows: Section 2 introduces the proposed distance measurement system based on images captured by a single camera. How intrinsic parameters of cameras can be obtained is also given in this section. A fast algorithm to identify the laser spot central from a sub-frame is also given in this section for calculating the distance from the targeted object. Experiment results and discussions are presented in Section 3. Conclusions are drawn in Section 4.

2 The proposed distance measuring system

Figure 1 shows the setup of the proposed distance measuring system, including a single non-metric CCD camera and a 10mW green-light laser projector set beside the CCD camera in a pre-specified distance *ds*. Laser beam from the projector is parallel with the optical axis of the CCD camera.

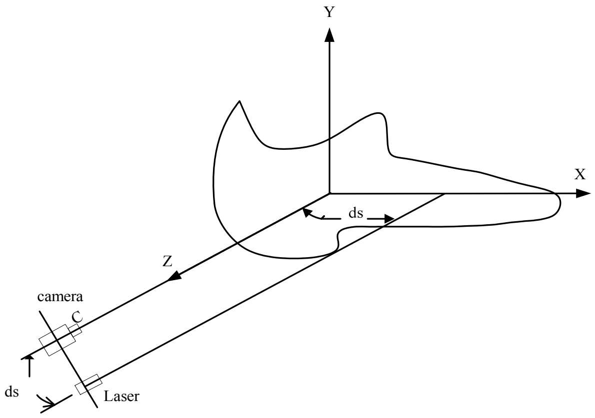

Fig. 1 Diagram illustrating the setup of the proposed distance measuring system.

Note that laser beam and optical axis of the camera are formed in parallel in a fixed distance irrelevant of the depth of the object in the real-world coordinates. For the 3-D space in the real-word environment, the projection reaches the 2-D formation of image in the camera frame. The pixel number between the principal point of the CCD and the laser spot projected from the laser project varies according to the distance of the targeted object. As shown in Fig. 2, the nearer the object, the more pixel counts in the image frame we can obtain. For objects in a farer distance, we have smaller pixel counts.

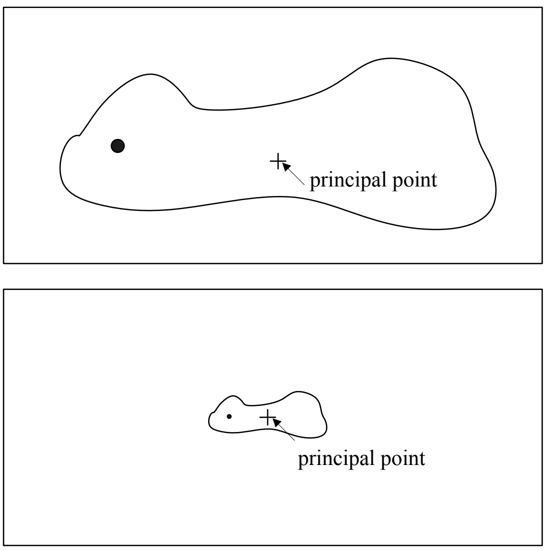

Fig. 2 The coordinate of the laser spot in CCD frames varies at different distances for an identical object.

Conversely, if we can determine the pixels counts between the laser spot and the principal point of the camera in the image frames, we can measure the distance between the object and the CCD camera. In short, the measurement method can be summarized as the following steps:

1. Obtain intrinsic parameters for the CCD camera adopted, including focal length, principal point, and radial distortion coefficient.
2. Establish a fast and effective algorithm for detecting the central position of the laser projected spot. Count the pixel number between the central position of the laser projected spot and the principal point of the CCD camera.
3. Calculate the distance from the targeted object based on the pixel counts obtained in Step 2.

For better clarity, the above-mentioned steps are described in more detail as follows:

2.1 Intrinsic parameters of cameras

CCD camera calibration is a fundamental task in photogrammetry and robot vision. In many cases, the overall performance of the machine vision system and photogrammetry strongly depends on the accuracy of camera calibration. A lot of methods have already been proposed [5-7] in this respect. Among them, the two-step method of Tsai [5] is the mostly used one. In the first stage, all extrinsic parameters except for different depth are computed by using the parallelism constrint. In the second stage, all missing parameters are evaluated by non-linear optimization techniques. Despite that fact that this method has solved the problem of non-coplanar calibration, the rotation matrix, however, failed to satisfy the orthogonal condition. In this paper, the four-step calibration procedures by J. Heikkila [6] are therefore adopted.

Generally speaking, camera calibration is to estimate a set of parameters that describes the camera's imaging process. With this set of parameters, a perspective projection matrix can directly link a point in the 3-D world reference frame to its projection (undistorted) on the image plane by:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = A[R\,|\,t]\begin{bmatrix} X^W \\ Y^W \\ Z^W \\ 1 \end{bmatrix} = \begin{bmatrix} f/D_u & 0 & u_0 \\ 0 & f/D_v & v_0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} X^C \\ Y^C \\ Z^C \end{bmatrix} \quad (1)$$

, where (u,v) is the distortion-free image point on the image plane; the matrix **A** fully depends on the camera's 4 intrinsic parameters (f, D_u, D_v, u_0, v_0) D_u and D_v being two scalars in the two image axes, (u_0, v_0) the coordinates of the principal point.

$\left[X^C, Y^C, Z^C\right]^T$ denotes a point in the camera frame which is related to the corresponding point $\left[X^W, Y^W, Z^W\right]^T$ in the world reference frame by $P^C = RP^W + t$ with (R,t) being the rotation matrix and the translation vector. Note that the unit of the image coordinates is pixel. Therefore, coefficients D_u and D_v, which are linearly dependent on the focal length f, are needed to change their metric units to pixels. By using the pinhole model, the projection of the point (x_i, y_i, z_i) to the image plane is expressed as:

$$\begin{bmatrix} u_i \\ v_i \end{bmatrix} = \frac{f}{z_i}\begin{bmatrix} x_i \\ y_i \end{bmatrix} \qquad (2)$$

The corresponding image coordinates $(u_i^{'}, v_i^{'})$ in pixels are obtained from the projection (u_i, v_i) by applying the following transformation:

$$\begin{bmatrix} u_i^{'} \\ v_i^{'} \end{bmatrix} = \begin{bmatrix} D_u u_i \\ D_v v_i \end{bmatrix} + \begin{bmatrix} u_0 \\ v_0 \end{bmatrix} \qquad (3)$$

The pinhole model is only an approximation of the real camera projection. It is a useful model that enables simple mathematical formulation for the relationship between object and image coordinates. However, it is not valid when high accuracy is required and therefore, a more comprehensive camera model must be used. Usually, the pinhole model is a basis that is extended with some corrections for the systematically distorted image coordinates. The most commonly used correction is for the radial lens distortion that causes the actual image point to be displaced radially in the image plane. The radial distortion can be approximated using the following expression:

$$\begin{bmatrix} \delta u_i \\ \delta v_i \end{bmatrix} = \begin{bmatrix} u_i(k_1 r_i^2 + k_2 r_i^4 + k...) \\ v_i(k_1 r_i^2 + k_2 r_i^4 + k...) \end{bmatrix} \qquad (4)$$

, where $k_1, k_2, ...k$ are coefficients for describing radial distortion. Typically, one or two coefficients are enough to compensate for the distortion. A proper camera model for accurate calibration can be derived by combining the pinhole model with the correction for the radial components:

$$\begin{bmatrix} \tilde{u}_i \\ \tilde{v}_i \end{bmatrix} = \begin{bmatrix} D_u(u_i + \delta u_i) \\ D_v(v_i + \delta v_i) \end{bmatrix} + \begin{bmatrix} u_0 \\ v_0 \end{bmatrix} \qquad (5)$$

2.2 Determination of the laser spot central

One of the contributions of this research is the determination of the laser spot central via a fast and easily established algorithm. The proposed algorithm does not have to deal with full frame of CCD camera images. Processing of a sub-frame comprising a fraction of scan lines is only required. Fig. 3 shows the pixel counts of the laser spot from a 10mW laser projector at different distances. As shown in Fig. 3, the diameter of the laser spot is smaller than 10 pixels for the distances of interest. Therefore, we can just process about 17 scans lines for determining the laser spot central.

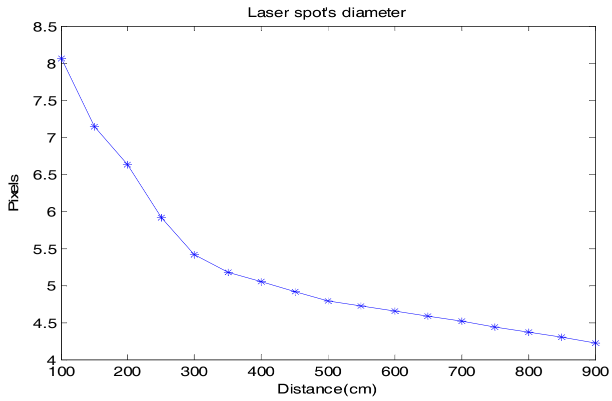

Fig. 3 Relationship of pixels counts of the diameter of the laser spot at different distances.

Because of the set up and precision of the measuring system, laser spots in images at different distances might deviate and span over several scan lines. At different distances, laser spot from the principal point of the CCD has a linear relation in terms of horizontal- and vertical-axis locations:

$$y = ax + b \qquad (6)$$

, where x and y stands for the x-axis position and y-axis position of the spot location in CCD frames, respectively, and a, b are constant coefficients. Fig. 4 shows a sub-frame of a CCD image, in which the laser spot may reside. Because of the linear relationship between x and y axis, we only need to process about 17 pixels in the y axis for different position along the x axis. Fig. 5 illustrates 17 scan lines in the sub-frame in Fig. 4 of a CCD image are to be processed.

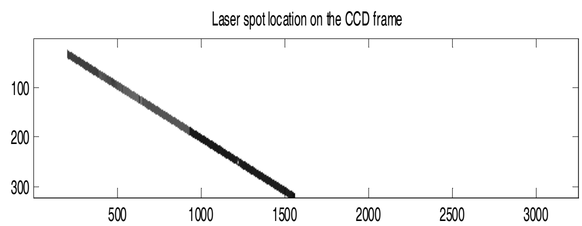

Fig. 4 Sub-frame of a CCD image containing the laser spot location.

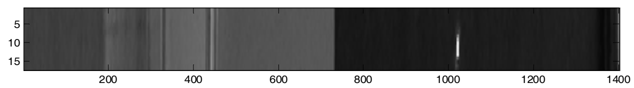

Fig.5 17 scan lines in the sub-frame of a CCD image for pocessing.

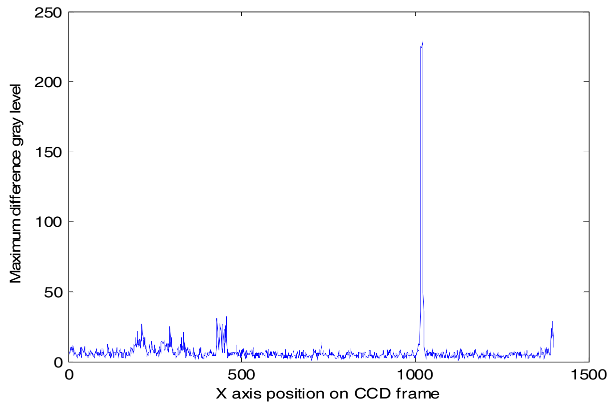

Fig. 6 Maximum difference in gray level for pixels contained in the subframe of a CCD image.

The next procedure is to accurately identify the laser spot in the sub-frame of a CCD image. We only need to deal with signals of 17 pixels in the subframe for every position in the *x* axis. Note that luminous intensity of the laser spot is far greater than that of the background of images. The gray level of the laser spot might even reaches the saturation level. As a result, very large gray-level difference between the laser spot and the background occurs. We define the maximum difference in gray level for pixels in the subframe of a CCD image as l_i below：

$$l_i = \max(y_i) - \min(y_i) \quad (8)$$

, where *i* is the position in the *x* axis.

Figure 6 shows the maximum difference in gray level for pixels in the subframe of a CCD image in Fig. 5, based on which we can identify the location of the laser spot. Note that the size of the laser spot in the real-world coordinate will vary, depending on the photographing distances between the CCD camera and the targeted object. When there are sufficient power for projecting the laser beams, dispersion phenomenon due to laser beam occurs, which counteracts the relationship between the pixel counts of the area of the laser spot and the photographing distances illustrated in Fig. 3. As a result, the larger the distance from the targeted object, the shorter the distance between the laser spot to the principal point. There are fewer pixels in the *x* axis in this case. Close-range measurement of object, however, the laser spot is farer away from the principal point. However, there are more pixels in the *x* axis in this case. This is one of the salient characteristics for distinguishing the laser spot. As a conclusive remark, there are three important critical conditions to identify the location of the laser spot central:

1. Gray level exceeds a threshold value, for example, 220 of gray level in green color in images.
2. The position corresponds to a maximum difference in gray level.
3. Pixel counts of the diameter of the laser spot meet the relationship described in Fig. 3.

By doing so, *x*-axis position meeting the above-mentioned criteria can then be identified as the central of the laser spot.

2.3 Distance measurement via the proposed method

Intrinsic parameters of a CCD camera can be obtained based on the descriptions in Sec. 2.1. From the establishment of the proposed distance measuring system in Fig. 1, distance between the CCD camera and the laser projector, alternatively the distance between the optical axis of the CCD and the laser beam projected, can be arranged and known as a priori ds . Based on the position of the laser spot in the CCD frame, we can measure the distance of a targeted object from the camera. This paper adopts a 10mW green-light laser [8] source, projecting laser beam as close as much to the horizontal scan line (x axis) that the optical principal point resides of the CCD image. Certainly, making laser beam totally orthogonal to the CCD plane is difficult to realize in practice. Fortunately, the condition needs not to be strictly followed as will be illustrated in Fig. 7. We position the laser beam perpendicular to the CCD plane as much as we can, and the real angle can be obtained from the calibration procedure. Because of set up procedure, the laser beam might not be totally parallel with the optical axis of the CCD frame. The relationship between the laser spot and the principal point of the CCD camera can be described based on the following mathematical model:

$$ds + z_i \tan\theta = \frac{z_i}{f} u_i \quad (6)$$

, where θ can be obtained from the calibration procedure and z_i is the distance from a targeted object that we want to measure. f is the focal length of the CCD camera. u_i is the laser spot location in the *x* axis of the CCD frame, The above-mentioned model can be further simplified as follows:

$$z_i = \frac{f \cdot ds}{u_i - f \cdot \tan\theta} \approx \frac{f \cdot ds}{u_i - f \cdot \theta} \qquad (7)$$

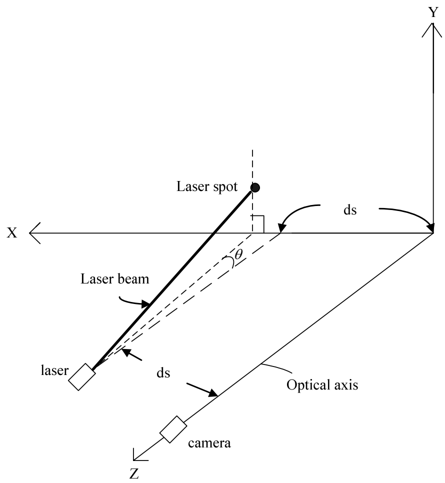

Fig. 7 Un-orthogonal with xy plane of the laser beam.

When the above-mentioned information become available, we can calculate the distance from a targeted object on the basis of a single CCD frame image.

3 Experiments results and discussions

In this paper, experiments are conducted using a Panasonic LX1 camera and a AstroPen's [8] GLM-0505-P 10mw laser pointer. The specifications of the CCD camera are as follows:

CCD camera: PANASONIC Lumix DMC-LX1, with maximum horizontal resolution of 3248 pixels (*x* axis), and maximum vertical resolution of 2160 pixels (*y* axis). As mentioned earlier, the calibration procedure is performed based on Heikkila's method [6]. Fig. 8 shows one of the calibration patterns. After calibration, a set of intrinsic parameters can be obtained:

Focal Length: f_c = [2860], in terms of pixels.

Principal point: cc = [1635, 999]

Radial distortion: k_c = [-0.12108, 0.09684, -0.00339]

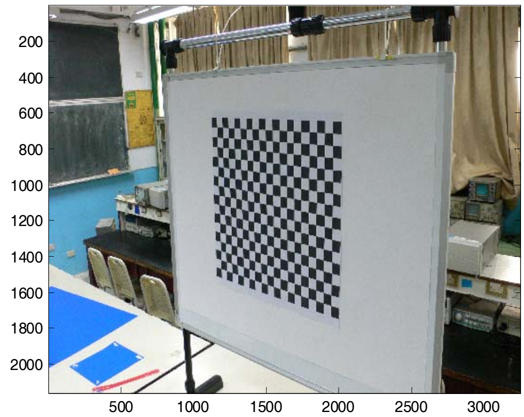

Fig. 8 Diagram showing one of the calibration patterns.

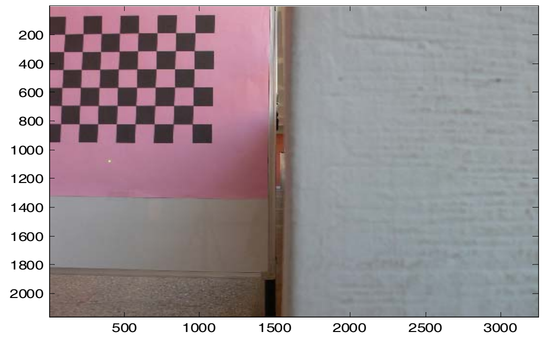

Fig. 9 Measurement of an object at a distance of 106 cm.

Fig. 10 Measurement of an object at a distance of 1406 cm.

Measurement results using the proposed method are shown in Table 1, where real distances, measured distances, and error for distances from 106 cm to 1806 cm are recorded. A mean measured absolute error of 0.502% is obtained. In comparison to previous measuring results where error rates range from 1 to 8% [9]-[10], the effectiveness of the proposed approach has been validated in light of the performance achieved.

Table 1 Experiment results of distance measurement

Real distance(Zi) cm	u_i (pixels)	Measured Distance cm	Percentage Error
106	1338	106.8759	-0.83%
156	916	156.1135	-0.073%
206	696	205.4598	0.262%
256	561	254.9020	0.429%
306	469	304.9041	0.358%
356	405	353.0864	0.818%
406	354	403.9548	0.504%
456	315	453.9683	0.446%
506	284	503.5211	0.490%
556	260	550.0000	1.079%
606	238	600.8403	0.851%
656	220	650.0000	0.915%
706	203	704.4335	0.222%
756	190	752.6316	0.446%
806	178	803.3708	0.326%
856	169	846.1538	1.150%
906	158	905.0633	0.103%
956	149	959.7315	-0.390%
1006	143	1000.0000	0.596%
1056	135	1059.2593	-0.309%
1106	129	1108.5271	-0.228%
1156	124	1153.2258	0.240%
1206	118	1211.8644	-0.486%
1256	113	1265.4867	-0.755%
1306	109	1311.9266	-0.454%
1356	105	1361.9048	-0.435%
1406	101	1415.8416	-0.700%
1456	99	1444.4444	0.793%
1506	94	1521.2766	-1.014%
1556	92	1554.3478	0.106%
1606	89	1606.7416	-0.046%
1656	87	1643.6782	0.744%
1706	84	1702.3810	0.212%
1756	81	1765.4321	-0.537%
1806	79	1810.1266	-0.228%
Mean absolute error			0.502%

4 Conclusion

In this paper, an improved image-based measuring system is proposed to measure distance of a distant object. The proposed method can be used in photogrammetry and robot vision with a lower cost and simpler algorithm for real-time implementation by microcontrollers. Because of the simplicity of the proposed approach, computation-intensive techniques, such as pattern recognition and image analysis methods, are no longer required for obtaining a satisfactory measurement. Furthermore, the problems of diffusion effect caused by laser beams and the identification of the center of the projected spots are also addressed in details in this paper. Though CCD camera calibration is capable of obtaining the non-linear distorted parameters, experimental in this paper are conducted using only linear parameters at present. In the future, we shall consider the non-linear parameters (radial distortion) for improving the accuracy of measurement.

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