DISTANCE ERROR ESTIMATION FOR RANGE IMAGING SENSORS

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ABSTRACT:

The recent development of range imaging technology has enabled 3D data capture with a high resolution and the ability to measure the distance to the corresponding object point in each pixel. Besides some promising advantages, there are a number of drawbacks with the major being the distance measurement precision and accuracy which are still limited due to large systematic and random errors of the range imaging sensors. In order to reduce the effect of the systematic errors, a system calibration is essential which includes the calibration of the sensor as a camera device and the calibration of the range camera as a metric machine. This paper deals with the latter and aims to present a distance calibration approach. The methodology involves the capture of the calibration plane by the range camera and two video cameras. The calibration procedure is applied on the Swissrange SR-3000 sensor.

1. INTRODUCTION

The requirement to quickly obtain 3D measurements is common to a variety of tasks in different fields of applications. Especially laser scanners have become state-of-the-art regarding speed and accuracy with respect to their ability to acquire points from objects in distances up to several tens of meters. A main drawback of laser scanners and even geodetic total stations is the sequential mode of operation which results in the measurement point by point. Recently, a new technology, the so-called range imaging, has been developed that enables the 3D data capturing with a high resolution. Range imaging is based on digital imaging technology and includes the ability to measure the distance to the corresponding object point in each pixel. The distance measurement is either based on the direct or indirect time-of-flight principle. Briefly, a bundle of distances is determined simultaneously at every pixel of a two-dimensional sensor array of a range camera. These ranges are deduced from the time it takes an emitted signal to return to the device. Instead of implementing the approach to register the time-of-flight directly using light pulses, the range imaging sensors employ continuously modulated signals. By sampling the return at every quarter of the modulation period, the phase shift and hence the object distance are deduced (Schwarte, 1999). Contrary to other relevant technologies, range imaging sensors do not require multiple observation rays to determine a point's position which results in minimising the number of device setups necessary to capture complex objects.

Also, due to its parallel acquisition with up to video frame rate, range imaging sensors are even able to capture moving objects. The real-time capability provided by this type of sensors offers further advancements to a number of mapping and surveying applications if environment dynamics are considered. To date, 3D range imaging sensors with a resolution of about 20 thousand pixels and a frame rate with up to 30 frames per second are available. Besides the notable advantages of high data rate, low weight and small size, the range imaging sensor is very fragile to changing lighting conditions which leads not only to imprecise data but also to completely wrong measurement data. These errors are influenced by the physical properties of the sensor as well as by environmental conditions (Rapp, 2007).

As explained, the range camera uses distance measurements within the process of a conventional CCD camera, enabling each pixel to measure the distance towards the corresponding object point. The measured distances in connection with the geometrical camera relationships are then used to compute the 3D coordinates of the acquired object in space. As a camera disposes of a standard optical lens to capture the rejected light, it needs to be calibrated just like a standard video camera in order to model errors due to distortions and misalignments of the optical axis of the lens and the sensor. Since the measured distances are strongly affected by large systematic and random errors, a distance calibration should be also employed. The distance calibration is usually accomplished by comparing distances measured by the range camera with corresponding distances estimated with a higher level of accuracy. Clearly, the straightforward approach to detect and quantify error characteristics is to set up laboratory experiments for the sensor calibration. The camera calibration has been investigated resulting in different approaches (e.g. Kahlmann & Ingensand, 2005a). This paper addresses the distance calibration problem and presents a calibration procedure using the Swissrange SR-3000 sensor.

The 3D SwissRanger camera has a size of (14.5 × 4× 3) cm and can be connected to any PC equipped with a standard USB interface. The camera comprises the illumination unit and the control board with the sensor. The illumination unit emits a sinusoidal wave with a wavelength of 870nm. The light is modulated with a frequency of 20 MHz, resulting in a non-ambiguity range of 7.5 m and the returning signal is reconstructed and two images are generated: an intensity (gray scale) image derived from the amplitude of the signal and a

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range image (depth measurement per pixel) derived from the phase offset of the signal (Oggier et al., 2005). The accuracy of the depth measurements is subject to error due to many factors. These can be attributed to internal effects such as noise of the sensor, diodes as well as the camera calibration by the manufacturer. Also the scene that is to be captured affects the camera with its complexity and reflective properties by causing multiple reflections.

The paper comprises four sections. Section 2 describes the distance calibration methodology of the SR-3000 range camera and provides the mathematical formulae to compute the actual distance for every pixel of the range camera which is then compared with corresponding range distance. Section 3 of the paper presents the implemented calibration approach and describes the set-up which uses two high resolution CCD video cameras and a SR-3000 range camera all placed on a stable aluminium bar, in such a way that all three sensors capture almost the same optical scene. A calibration plate in the form of equally spaced circular targets was used for the experiments. The two video cameras are used as a 3D measurement coordinate machine, allowing the measurement of any point in the optical scene with high accuracy. The conclusions and suggestions for further work are given in section 4.

2. METHODOLOGY

The SR-3000 range camera introduces the distance measurement within the process of a conventional CCD camera, enabling each pixel to measure the distance towards the corresponding object point. The measured distances in connection with the geometrical camera relationships are then used to compute the 3D coordinates of the acquired object in space (Rapp, 2007). Because the SR-3000 camera uses standard optical lens to capture the reflected light, this results to the need to implement appropriate calibration procedures to estimate the distortions and misalignments of the optical axis of the lens and the sensor. Also, as mentioned above, the measured distances are strongly affected by large systematic and random errors, and thus a distance calibration is performed by comparing distances measured by the range camera with corresponding distances estimated with a higher level of accuracy.

The distance of each camera pixel from the acquired scene can be estimated with high accuracy by employing photogrammetric methods. This can be accomplished if the interior and exterior orientation of the range camera is known and the optical scene has a simple and known geometry in a common coordinate system. The simplest geometry that can be used is a planar object placed at a known distance and orientation in front of the camera. In this case the distance of each camera pixel from the acquired object can be estimated by a simple ray-plan intersection. While this is certainly not representative for all measurement situations, it has the advantage that such a calibration field can be precisely known and only depends on the distance and orientation from the sensor.

The equation of a plane in front of the range camera can be estimated if the coordinates of at least three points of the plane are known in a reference coordinate system. The reference coordinate system can be any arbitrary coordinate system in which the exterior orientation of the range camera is known. To identify the required points two high resolution CCD video cameras are used in conjunction with the range camera. The two video cameras are forming a stereo ring allowing the measurement of 3D coordinates at discrete plane points. The three sensors are oriented to the same coordinate system. Thus, the equation of the plane is estimated in a reference coordinate system in which the exterior orientation of the range camera is known.

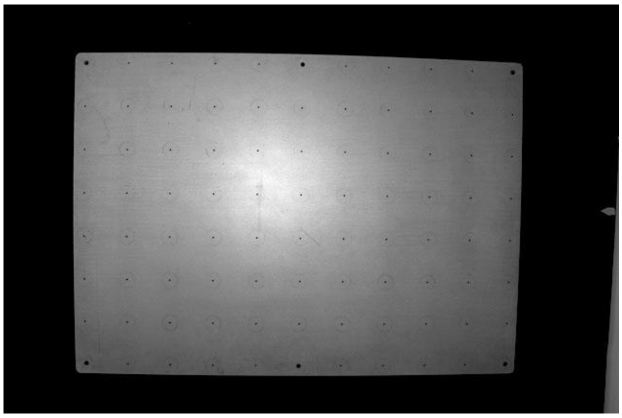

Figure 1. Calibration plate

Photogrammetry provides a variety of methods for determining the interior and exterior orientation parameters of a camera, relating image measurements to scene coordinates of an appropriate calibration field (Fraser, 1997). Due to the low resolution of the SR-3000 camera and the high accuracy demands for the distance calibration, the use of an accurate calibration field is crucial. Such a calibration field should satisfy two basic requirements: automatic target recognition using well known image processing techniques and absolute accuracy better than 1 mm.

In our implementation a calibration plate of a form of equal spaced circular dots is used, as shown in figure 1. The calibration method adopted has been proposed by Zhang and is described in detail in Zhang (1999). Several photographs of the calibration plate are acquired at different orientations and rotation angles. The circular targets are automatically extracted from the images by means of a least squares template matching operation (Gruen, 1985) and used as input measures for the calibration procedure. As a result the extrinsic and intrinsic parameters of the camera calibration are estimated. The same calibration method is used for the two CCD video cameras, as well as for the range camera.

In order to compute the equation of a reference plane in front of the range camera the coordinates of three points lying on this plane are calculated by photogrammetric space triangulation. These points should satisfy the following equation:

$$AX + BY + CZ + D = 0 \tag{1}$$

where, A, B, and C provide the components of the normal of the plane. In practice, four or more points are used and the unknown parameters are estimated by least squares adjustment. Since the accuracy achieved with photogrammetric measurements is by far improved compared to the accuracy of the range camera, the computed reference plane can be used as a ground truth for range distance calibration.

The distance of the range camera from the reference plane is calculated by employing a ray-plane intersection that can be implemented for every pixel of a range image. For a given pixel in the range image (x_i, y_i) a view ray V is defined by its origin (i.e. the camera focal point) $V_o = [X_o\ Y_o\ Z_o]^T$ and its normalized direction vector $V_d = [X_d\ Y_d\ Z_d]^T$:

$$V(t) = \begin{pmatrix} X(t) \\ Y(t) \\ Z(t) \end{pmatrix} = V_0 + t \cdot V_d = \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix} + t \cdot \begin{pmatrix} X_d \\ Y_d \\ Z_d \end{pmatrix} \qquad (2)$$

where, t is the distance between a point V(t) on the ray and the origin V_o.

To calculate the direction vector V_d the inverse of the collinearity equation is used:

$$\begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix} = \frac{1}{\lambda} R^{-1} \begin{pmatrix} x_i \\ y_i \\ -c \end{pmatrix} \qquad (3)$$

where, R is the rotation matrix of the range camera relative to the calibration field, and c is the calibrated focal length of the camera.

From equations (2) and (3) the direction vector V_d of the ray can be calculated from the image coordinates x_i, y_i :

$$\begin{pmatrix} X_d \\ Y_d \\ Z_d \end{pmatrix} = \frac{1}{t} \cdot \begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix} = \frac{1}{(\lambda \cdot t)} \cdot R^{-1} \cdot \begin{pmatrix} x_i \\ y_i \\ -c \end{pmatrix} = \frac{1}{(\lambda \cdot t)} \cdot \begin{pmatrix} R_{11}x_i + R_{21}y_i - R_{31}c \\ R_{12}x_i + R_{22}y_i - R_{32}c \\ R_{13}x_i + R_{23}y_i - R_{33}c \end{pmatrix} \qquad (4)$$

The distance S between the camera focal point ($X_o\ Y_o\ Z_o$) and the reference plane along the view ray with direction vector (X_d Y_d Z_d) is given by:

$$S = -\frac{AX_O + BY_O + CZ_O + D}{AX_d + BY_d + CZ_d} \qquad (5)$$

The distance S is calculated for every pixel of the range camera. By knowing the actual distance and comparing it with the distance provided by the range camera an offset value is calculated for each pixel and for each acquired scene. The reference plane is captured from several distances and particular correction tables are created for each distance of acquisition. Assuming linearity between consecutive acquisitions intermediate correction values can be estimated by interpolation.

3. IMPLEMENTATION

In order to implement the calibration procedure presented in section 2, two high resolution CCD video cameras and a SR-3000 range camera were placed on a stable aluminium bar (Fig. 2). The video cameras used are available from Prosilica Inc. under the brand name GC1600. They offer a 1620×1220 pixel resolution at a frame rate of 15 frames per second and can be connected to any PC equipped with a gigabit Ethernet network card. Since the GC1600 cameras offered without lenses, two Fujinon HF9HA-1B (1:1.4/9mm) lenses were attached to the camera devices. The two cameras were placed at a base distance of 0.70 m and the SR-3000 was positioned in the middle. A small 8” thatch screen device was also placed in the middle of the bar, allowing the control of the three sensors without the need of additional input devices.

The intrinsic and extrinsic parameters of the two CCD cameras were estimated by using the calibration plate shown in figure1. The calibration plate is made from aluminum, with 88 circular dots located at 10 cm equal distances with a tolerance of the order of 1/5 mm. The calibration plate was attached on a planar wall, at a distance of about 1.5 meters from the two cameras. Several photographs of the calibration plate were acquired at different distances and rotation angles. The circular targets were automatically extracted from the images. The computation of the calibration parameters was performed using the OpenCV computer vision library, available from Intel Inc. The accuracy of the calibration was estimated by the residuals of the image coordinates, which were in the order of 0.30 pixels.

Figure 2. Camera setup

In order to calibrate the SR-3000 range camera using the same calibration plate, 70 additional targets made from retro-reflective material were attached on the calibration plate. This was necessary since the existing circular targets were too small to be detected on the low resolution images acquired from the range camera. The coordinates of the additional targets were calculated by photogrammetric triangulation, using the two CCD cameras stereo ring. The accuracy of the estimated target coordinates was better than 0.5 mm, which is satisfactory for the calibration of the range camera. The calibration results for all cameras used are presented in table 1.

Interior Orientation			
i.o. parameter	**CCD 1**	**CCD 2**	**SR-3000**
focal length c	2098.2	2101.2	201.9
principal point x	795.7	774.7	90.3
principal point y	591.1	630.5	72.8
radial distortion k_1	-2.609e-001	-2.768e-001	-1.343e-001
radial distortion k_2	1.997e-001	2.488e-001	3.092e-001
decentering distortion p_1	3.538e-004	7.866e-004	-1.021e-003
decentering distortion p_2	-7.403e-005	1.076e-003	-3.424e-003

Table 1. Interior Orientation

The external orientation of all cameras used was computed in the calibration plate coordinate system using a single view of the calibration plate to solve for the unknown extrinsic parameters.

To evaluate the distance accuracy of the range camera, a test environment using a planar wall located at a fixed distance to the optical axis of the sensor was used. It is also taken into account that the major parameter to estimate is the distance offset that varies with range. The range dependence of the offset is almost linear, but varies for each pixel as the signal strength decreases for the image peripheral area. Range calibration can be performed only approximately, since it also depends on other parameters such as the integration time. For this reason, a series of images of the reference planar wall was captured at fixed distances between 80 and 200 cm, at three different integration times 20 ms, 40 ms and 60 ms. In each measurement series the integration time was kept constant for all images, making them comparable in this way. The calibration scene was captured simultaneously by the range camera and the two CCD video cameras in order to ensure that objects within the field of view (FOV) held similar reflection properties. Moreover, to reduce the noise a 3×3 median filter was applied to the range data.

The equation of the reference plane was computed by measuring four signalized points, lying on the planar wall. The coordinates of these points were estimated in the range camera coordinate system by photogrammetric triangulation. Equation (5) was then applied for each pixel of the range image to calculate the actual distance to the calibration plane. By comparing the actual distance to the distance provided by the range camera a calibration table with correction offsets was created for each distance of acquisition. The calculated offsets at distance 80cm from the calibration plate at integration time of 40ms are presented in figure 3 as an example. The minimum and maximum offset values are -6.91 cm and 2.3 cm respectively, the mean value is -4.8 cm and the standard deviation is 0.8. The deterioration in precision towards the image borders and the decrease of the distance offset are apparent.

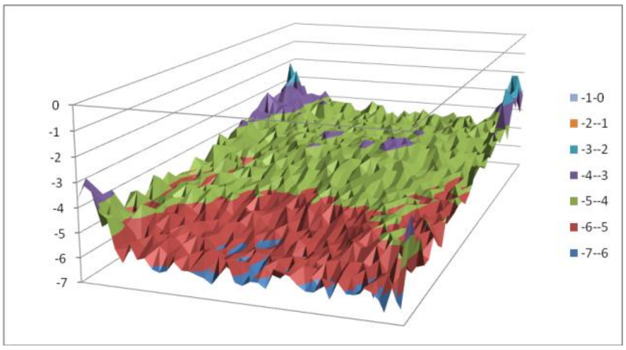

Figure 3. Per pixels offsets at 80cm calibration distance

These results corroborate with similar calibration experiments that create Look Up Table (LUT) correction values for the distance data (e.g. Kahlmann et al., 2006). Experiments with modeling of the offset data with linear and cosine functions have not provided better results and therefore, a calibration value table is satisfactory.

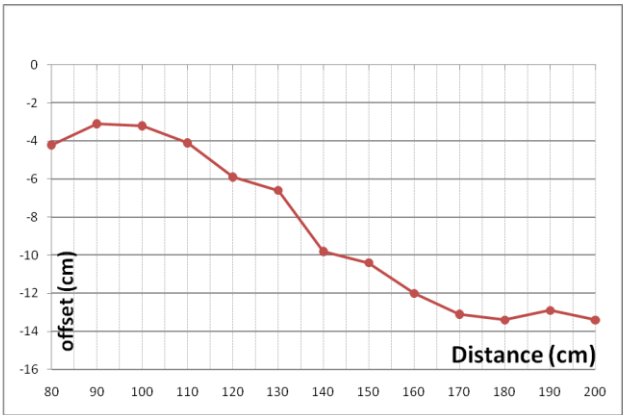

Figure 4. Offsets at the principal point (80-200cm distances)

The computed offsets near to the principal point of the range camera (90, 73) are presented in figure 4. Their values vary between -4.3 cm and -13.4 cm at distances between 80 cm and 200 cm, at integration time of 40 ms. The experimental offsets are considered higher than offsets reported by other researchers but this can be attributed to the fact that different experimental conditions from our implementation have been used which also take into account the impact of the internal (self-induced heating) and external temperature influences of the sensor (Kahlmann & Ingensand, 2005b; Steitz & Pannekamp, 2005).

4. CONCLUDING REMARKS

In this work a distance calibration procedure to improve the accuracy of range imaging sensors has been presented. The procedure was implemented in the Swissranger SR-3000 sensor. The method requires no additional equipment other than a pair of high resolution CCD cameras. The two CCD cameras are forming a stereo ring which is used to create calibration planes in any desired distance from the range camera.

The distance calibration was accomplished by comparing distances measured by the range camera with corresponding distances estimated with a higher level of accuracy (i.e. photogrammetric triangulation). The distance offsets were estimated for the whole sensor array as opposed to other distance calibration procedures which provide values for only the central point of the range sensor.

Whilst the results indicate deterioration in precision near the image borders, the distance offsets are higher than the measurement uncertainty for the observed distances. Clearly, the environmental effects on the range sensor as well as internal sensor parameters need to be further investigated in order to estimate reliably the distance calibration parameters. Finally, additional study is required to enable exploitation of results to applications beyond tracking that require higher accuracy levels.

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