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Application of single-image camera calibration for ultrasound augmented laparoscopic visualization

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Abstract

Accurate calibration of laparoscopic cameras is essential for enabling many surgical visualization and navigation technologies such as the ultrasound-augmented visualization system that we have developed for laparoscopic surgery. In addition to accuracy and robustness, there is a practical need for a fast and easy camera calibration method that can be performed on demand in the operating room (OR). Conventional camera calibration methods are not suitable for the OR use because they are lengthy and tedious. They require acquisition of multiple images of a target pattern in its entirety to produce satisfactory result. In this work, we evaluated the performance of a single-image camera calibration tool (*rdCalib*; Percieve3D, Coimbra, Portugal) featuring automatic detection of corner points in the image, whether partial or complete, of a custom target pattern. Intrinsic camera parameters of a 5-mm and a 10-mm standard Stryker[®] laparoscopes obtained using *rdCalib* and the well-accepted OpenCV camera calibration method were compared. Target registration error (TRE) as a measure of camera calibration accuracy for our optical tracking-based AR system was also compared between the two calibration methods. Based on our experiments, the single-image camera calibration yields consistent and accurate results (mean TRE = 1.18 ± 0.35 mm for the 5-mm scope and mean TRE = 1.13 ± 0.32 mm for the 10-mm scope), which are comparable to the results obtained using the OpenCV method with 30 images. The new single-image camera calibration method is promising to be applied to our augmented reality visualization system for laparoscopic surgery.

Keywords

camera calibration; intrinsic parameters; augmented reality; optical tracking; laparoscopic surgery

1. INTRODUCTION

Accurate calibration of laparoscopes is essential to enable many surgical visualization and navigation technologies for image-guided procedures.^{1–6} Specifically, it is critical to our recently developed augmented reality (AR) system,^{7,8} which superimposes laparoscopic

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ultrasound images onto real-time laparoscopic video using device location and orientation data from optical tracking. These systems have the potential to help the surgeon better visualize and comprehend locations of critical internal structures, such as the blood vessels, bile ducts, and tumors, beneath the visible organ surfaces. Our own AR system, currently in the clinical evaluation phase, has been tested in 10 patients undergoing laparoscopic cholecystectomy and laparoscopic treatment of median arcuate ligament syndrome at our hospital. Figure 1 shows an AR image we acquired during a laparoscopic cholecystectomy case. Without image fusion, the surgeon needs to perform a mental mapping of the ultrasound image (Fig. 1a) on the live laparoscopic video image (Fig. 1b). This process could be greatly eased and improved by using an AR system such that hidden anatomical structures could be displayed at their precise locations within the surgical field.

A standard laparoscope typically contains two parts—a charge-coupled device (CCD) camera and a long rotatable scope with lens and light source input. At the current stage, the laparoscope we use in our AR system is a single-piece stereoscopic scope (VSII, Visionsense Corp., New York, NY, USA), which has a fixed focal length, integrated light source, and automatic white balance, so that no manual adjustment of the scope is needed (or possible) in the operating room (OR). We calibrate the Visionsense scope in our laboratory prior to sending it for sterilization and OR use. Although intrinsic parameters of the Visionsense scope are fixed, if we want to scale our AR visualization technology to a broader range of clinically used laparoscopes, most of which have adjustable parameters (i.e., the focal length can be changed during a procedure in the OR), our preprocedural calibration strategy will fail. Thus, an accurate and robust laparoscope calibration method that can be performed easily and on-demand in the OR is greatly desirable.

OpenCV has a state-of-the-art camera calibration module based on a generalized camera model,^{9,10} which can be simplified to the well-accepted Zhang's camera calibration method.¹¹ Although this module can automatically detect corner points of a checkerboard pattern used for camera calibration, it requires a minimum of three images of the entire pattern taken from different viewpoints to achieve acceptable calibration result and at least 15 images to achieve good calibration result. The requirement of multiple images makes the OpenCV method as well as other conventional camera calibration methods unsuitable for use in the OR. Recently, single-image calibration based on a division camera model has been proposed, with endoscopic camera calibration as the motivating application.^{12,13} The purpose of our work is to evaluate the performance of this single-image calibration method for determining intrinsic camera parameters and distortion metrics, using the beta-version software *rdCalib* (Perceive3D, SA, Coimbra, Portugal; <http://perceive3d.com>), developed on the previously reported works.^{12,13} We compared intrinsic camera parameters and distortion coefficients obtained using OpenCV and *rdCalib* for a standard laparoscope. In addition, the two calibration methods were compared using target registration error (TRE) as a summary measure of laparoscope calibration accuracy for our AR system.

2. METHODS

OpenCV and *rdCalib* tools were used to calibrate a standard laparoscopic camera (1188HD camera; Stryker Endoscopy, San Jose, CA, USA) with two forward viewing (0°) scopes (5

mm and 10 mm diameter IDEAL EYES scopes in 30 cm and 33 cm length, respectively). Output image resolution of the Stryker camera is 1280×720 . The focal length of the Stryker camera was adjusted to produce optimal visualization of a typical scene for each scope and maintained throughout the experiments. No other part of the laparoscope was changed during the experiments. OpenCV used a standard checkerboard pattern with 9×6 corner points, whereas rdCalib used its special target pattern with 18×18 corner points. Both methods are capable of detecting the corner points automatically. Figure 2 shows the detected corners points on the target pattern of rdCalib. Different from OpenCV, which requires the entire target pattern to be within the image frame, rdCalib can work with images with only a portion of the target pattern. In our experiments with rdCalib, the average number of detected corner points per image was about 150.

2.1 Comparison of intrinsic parameters and distortion coefficients

We first compare calibration results using a single image for rdCalib and three images for OpenCV to their respective full calibration results. The 3:1 ratio in the number of images used by the two methods ensured that a roughly equal number of detected corner points were input to the two calibration engines. In particular, the following experiments were performed for each scope: (1) a single OpenCV calibration using 30 checkerboard images; (2) ten OpenCV calibrations using three checkerboard images; (3) a single rdCalib calibration using 10 images; and (4) ten rdCalib calibrations using a single image. Intrinsic parameters including the focal length (f_1, f_2), the principal point (c_1, c_2) and the radial distortion coefficient (k_1, k_2 —the first two coefficients in Bouguet's camera model⁹) were obtained and compared. Since the definition of distortion metrics used by rdCalib is different from that in OpenCV's camera model, a Matlab (MathWorks; Natick, MA) program was used to transfer rdCalib's distortion metric to OpenCV's distortion coefficients. We excluded tangential distortion from our study because the tangential distortion coefficients of the images tested are very small (as reported by OpenCV).

2.2 Comparison using TRE

Target registration error (TRE) was obtained with the use of an optical tracking system (*Polaris*; Northern Digital Inc., Waterloo, ON, Canada), and the experimental setup is shown in Figure 3. We designed and 3D printed (on Objet500 Connex; Stratasys, Eden Prairie, MN, USA) a fixture to mount the optical marker (four infrared reflective spheres mounted on a rigid body) on the Stryker camera. The laparoscope was placed standstill when taking pictures.

If we denote the optical tracker as OT, and a point with known 3D coordinates in the optical tracker reference frame as p_{OT}^{true} , the TRE is defined as

$$\varepsilon(p_{OT}^{true}) = d(p_{OT}^{true}, p_{OT}^{est}), \quad (1)$$

where $d(\cdot, \cdot)$ is the Euclidean distance and p_{OT}^{est} is an estimation of p_{OT}^{true} in the optical tracker coordinate system. We set the corner points of a 9×6 checkerboard as p_{OT}^{true} , and their

coordinates in the optical tracker frame are obtained by pointing a tracked pointer (Figure 3) to three divots located near the three corners of the checkerboard plate. Geometric relationships between the divots and the corner points are known beforehand. p_{OT}^{est} was obtained by triangulation of two camera views of p_{OT}^{true} . Specifically, let $\dot{p}_{OT}^{est}$ denote the homogeneous coordinate form of p_{OT}^{est} , we have

$$\dot{p}_{OT}^{est} \sim \tau(p'_1, p'_2, C_1, C_2), \quad (2)$$

where τ is the triangulation method and p'_i is the homogeneous coordinate form of the corresponding point of p_{OT}^{true} in one of the two laparoscope images. In our experiments, we manually identified p'_i in the image. C_i is the camera matrix with respect to a particular pose of the laparoscope, and in our case, it can be expressed as

$$C_i = K \cdot D \cdot P \cdot {}^{Lap}T_{OM} \cdot {}^{OM}T_{OT}^i. \quad (3)$$

In the above expression, K is the matrix of intrinsic parameters, i.e.,

$$K \sim \begin{pmatrix} f_1 & s \cdot f_1 & c_1 \\ 0 & f_2 & c_2 \\ 0 & 0 & 1 \end{pmatrix}, \quad (4)$$

where s is the skew coefficient. D is a nonlinear projective function with distortion coefficients (k_1 and k_2) that account for image distortion, and P is a 3×4 projection matrix. ${}^{Lap}T_{OM}$ is a 4×4 matrix with homogeneous coordinates representing the transformation from the optical marker reference frame (OM) to the laparoscope lens centered coordinate system (Lap). Finally, ${}^{OM}T_{OT}$ represents the transformation from the optical tracker frame to the optical marker reference frame and is obtained from the custom software of the optical tracking system.

The triangulation method that we use in Eq. 2 is the *Iterative Linear Least-Squares* method that was described by Hartley and Sturm.¹⁴ To determine ${}^{Lap}T_{OM}$ in Eq. 4 (which we referred to as the extrinsic parameters in our case), we used OpenCV's implementation of solving the Perspective- n -Point (PnP) problem, i.e., an iterative method based on Levenberg-Marquardt optimization. Again, we use one image of the checkerboard pattern to calibrate extrinsic parameters (this image is different from the images used for TRE calculation).

To summarize the procedure of obtaining TRE, we first input intrinsic parameters and distortion coefficients, obtained using rdCalib and OpenCV respectively in Section 2.1, to our software. Then, extrinsic calibration was performed for the two methods, respectively, using the same checkerboard image. Finally, two additional checkerboard images are acquired and used to calculate TRE for the two methods, respectively. Based on this

procedure, the resulting TRE difference between the two calibration methods is dependent only on the difference of intrinsic parameters and distortion coefficients. For each of the 10 single-image calibrations obtained in Section 2.1, we compared TREs associated with them with OpenCV's 30-image calibration and the corresponding OpenCV's 3-image calibration (e.g., the first single-image calibration was compared to the first OpenCV's 3-image calibration, and so on). To acquire TRE of a particular set of intrinsic parameters and distortion coefficients, we performed the procedure (i.e., extrinsic calibration and TRE calculation) thrice and took the average.

3. RESULTS

Assessed visually, rdCalib could accurately detect an average of 150 corner points in every image of its target pattern. There was no noticeable error in all of the detected corner points. Furthermore, all images could be processed using rdCalib's single-image calibration to obtain intrinsic parameters and distortion metrics. The average computer execution time was 4 s on a desktop workstation with Intel® Core™ i7-3820 3.60GHz CPUs and 32GB RAM. On the contrary, OpenCV could not successfully detect all the corner points in about one fourth of its checkerboard images, and extra images with successful corner detection were acquired to replace the faulty ones.

3.1 Comparison of intrinsic parameters and distortion coefficients

Table 1 shows the comparison of intrinsic parameters and distortion coefficients calibrated using rdCalib and OpenCV for the 5-mm and 10-mm Stryker scopes, respectively. The skew coefficient was very close to 0 for both calibration methods, and thus, is not listed. OpenCV calibration using 30 images was considered the reference method and the method against which all other methods were compared.

3.2 Comparison of TRE

Table 2 shows the TREs obtained using rdCalib's single-image calibration in comparison with OpenCV's 30-image calibration and OpenCV's 3-image calibration. The mean and standard deviation of 10 calibrations for each method are given. The TREs obtained using rdCalib's single-image calibration are only slightly greater than those using OpenCV's 30-image calibration and much less than those using OpenCV's 3-image calibration.

4. DISCUSSION AND CONCLUSION

As shown in Table 1, rdCalib's single-image calibration produces intrinsic camera parameters and distortion metrics that are similar in value (i.e., similar means and small variance) to the full 10-image calibration results. Moreover, rdCalib's single-image calibration produces intrinsic camera parameters and distortion metrics that are also similar to the reference result obtained using OpenCV with 30 images. The only exception is the 4th order radial distortion coefficient k_2 , which is less significant than the 2nd order radial distortion coefficient k_1 . In contrast to rdCalib, if the number of images is reduced to three, OpenCV's calibration suffers in accuracy and the calibration result is highly depended on which three images are used. This suggests that rdCalib is an accurate and consistent camera

calibration method that is less affected by the number of images used, compared with OpenCV's method. In addition, rdCalib has demonstrated its robustness in corner point detection as well as its efficiency in computation. It is also capable of working with a partial image of the target pattern and is virtually insensitive to the camera perspective. All of these properties are highly desirable for the OR use.

The TRE in this study is a measure of the accuracy with which a laparoscope was calibrated, and it directly relates to the overall accuracy of our AR visualization system. The 1.18 ± 0.35 mm and 1.13 ± 0.32 mm mean TREs obtained using rdCalib's single-image calibration are comparable to those previously reported by our group for a stereoscopic laparoscope (VSII, Visionsense Corp., New York, NY, USA), which yielded a mean TRE of 0.93 ± 0.18 mm and was obtained using 40-image OpenCV's calibration.⁸ The TRE is a combination of errors associated with intrinsic camera parameters and distortion metrics, as well as errors associated with extrinsic parameters, i.e., the transformation from the optical marker reference frame (Figure 3) to the laparoscope lens frame. In this study, the extrinsic parameters were calibrated using one checkerboard image containing 54 corner points. In the future, rdCalib's target pattern could be used for this process so that more corner points will be included for extrinsic calibration. To achieve this, an optical marker needs to be fixed on the target pattern with known geometric relationships between it and the corner points. The TRE could be further improved if we replace the optical tracking system with an electromagnetic (EM) tracking system, e.g., the tabletop system we previously evaluated for our AR system.¹⁵ Unlike optical marker which can only be attached to the handle of the laparoscope due to its line-of-sight requirement, a small EM sensor could be placed close to the laparoscope lens, which will greatly improve extrinsic calibration.

One may notice in Table 1 that f_1 and f_2 calculated by rdCalib are very close to each other, that is, the estimated aspect ratio is very close to 1. Although this works fine for most regular laparoscopes which have close-to-unity aspect ratio, such as the scopes we tested in this study, the current version of rdCalib may not be ready to handle special laparoscopes with large deviations from a unitary aspect ratio. Nevertheless, it is anticipated that rdCalib could be adapted to meet this need in the future.

In conclusion, we have evaluated rdCalib's single-image calibration for a standard laparoscope camera with two different scopes. The results suggest that the method is accurate and robust. With its flexibility to automatically detect corner points using just a portion of the target pattern, rdCalib is promising for fast and accurate laparoscope calibration in the OR.

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Figure 1.

AR images acquired during a laparoscopic cholecystectomy case. Our AR system overlays ultrasound image (a) on laparoscopic video (b) in real time, providing more direct visualization of hidden structures (c). For better illustration, we labeled critical anatomical structures made visible by ultrasound in (c).

Figure 2.
Detected corner points (in red) using rdCalib for the 5-mm scope (left) and the 10-mm scope (right), respectively.

Figure 3.

TRE calculation. Left: experimental setup. Right: custom-designed 3D-printed fixture to attach the optical tracking reference frame on the coupler of the Stryker camera.

Values of intrinsic parameters and distortion coefficients calibrated using rdCalib and OpenCV for the 5-mm and 10-mm Stryker laparoscopes (the units of f_1 , f_2 , c_1 and c_2 are pixel).

Table 1

Scope	Method	Description	f_1	f_2	c_1	c_2	k_1	k_2
Stryker 5 mm	OpenCV	30 images (reference)	1168.5	1175.5	634.8	373.7	-0.395	0.054
		10 sets of 3 images	1309.9±122.4	1471.3±311.5	642.0±30.8	330.5±42.6	-0.491±0.352	-2.19±18.1
	rdCalib	1 set of 10 images	1182.2	1182.4	628.9	341.0	-0.513	0.422
		10 sets of single images	1181.9±3.3	1182.1±3.4	628.6±3.0	340.7±2.2	-0.512±0.008	0.421±0.01
Stryker 10 mm	OpenCV	30 images (reference)	1358.5	1351.6	631.7	369.7	-0.405	0.374
		10 sets of 3 images	1373.4±90.7	1445.0±259.6	633.4±43.2	395.8±44.7	-0.427±0.225	-0.057±4.5
	rdCalib	1 set of 10 images	1345.2	1345.8	614.7	371.6	-0.411	0.307
		10 sets of single images	1346.1±4.6	1346.1±4.6	615.8±11.6	370.2±3.5	-0.409±0.004	0.305±0.01

Table 2

Mean TRE (mm) for 10 calibrations performed using three different methods.

Scope	OpenCv 30-image	OpenCV 3-image	rdCalib single-image
Stryker 5 mm	1.06 ± 0.30	8.82 ± 0.55	1.18 ± 0.35
Stryker 10 mm	1.05 ± 0.35	2.35 ± 0.47	1.13 ± 0.32