# Camera Calibration and Real-time Image Distortion Correction in Medical Endoscopy Using Exchangeable Optics

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***Abstract*—Minimally invasive surgery (MIS) is highly beneficial for the patient but it is very difficult to execute by the doctor that have to undergo a long training till acquiring the required skills and hand-eye coordination. Computer-aided surgery (CAS) can play a major role in MIS by enabling more surgeons to practice the technique while decreasing errors of clinical consequence. Such systems will use as input the intra-operative endoscopic video stream, which means that the camera must be calibrated at all times in order to take full advantage of the received data. We argue that, although camera calibration is a mature topic, the problem is far from being solved in the context of surgical applications. We propose a solution that we believe will be important to transfer the existing research in image based CAS from the Labs to the Operating Rooms. In addition we present a system for distortion correction in endoscopic images that handles the high resolution/framerates of current equipment. The correction requires the accurate calibration of the optical system which is handled by our automatic calibration technique from a single image and our adaptive projection model to cope with the lens rotation during operation. Our first clinical trial showed significant improvements in the execution of surgical tasks in knee arthroscopy.**

## I. Background

In minimally invasive surgery (MIS) the doctor executes the procedure guided by the images acquired by an endoscopic camera. Typically the endoscopic camera consists in auto-clavable exchangeable optics that are mounted on a charge-coupled device (CCD) camera head just before the procedure starts. These optics can be forward-viewing, when they look up-front, or oblique-viewing if the tubular lens has a cut of 30°, 70° or 90° to enable a periscope-like view. The viewing direction of the oblique-viewing lenses can be changed without moving the camera head by simply rotating the endoscope around its symmetry axis [1]–[3]. This rotation is typically inferred by observing the position of a triangular mark on the periphery of the circular region. Oblique-viewing endoscopes are specially useful in inspecting narrow cavities, such as the articulations (arthroscopy) or the sinus (rhinoscopy), where the space to maneuver the probe is very limited.

Although being highly beneficial for the patient in terms of recovery time and risk of infection, the stats show that MIS is used only in 25% of the procedures eligible for this technique. The reason for this low penetration is the fact that MIS procedures are much more difficult to execute than the equivalent open surgery counterparts. The access to the organs is very limited and surgeons must use intra-operative video as only guidance. This poses severe problems in terms of hand-eye coordination and some surgeons are simply unable to make the visual-spatial leap needed to master this technique [4].

In this context, the use of systems for computer aided surgery (CAS) can make a significant difference in the adoption and clinical outcomes of MIS. We envision that such systems will receive as input the intra-operative endoscopic video, eventually register the image data with pre-operative models of targeted organs, and use the information for assisting the doctor during the procedures. Such assistance can take multiple forms, ranging from providing a better visualization of the observed cavities to granting that the surgery is executed according to a pre-plan, and passing by helping the doctor to navigate inside the human-body.

## II. Endoscopic camera calibration and real-time correction of radial distortion

Image-based CAS requires the endoscopic camera to be properly calibrated. The camera intrinsic calibration enables to map each image pixel into a light-ray direction, being a necessary condition for inferring 3D information from the video stream. Most of the actual works in image-based CAS focus in higher-level problems, such as segmentation, reconstruction and registration, and disregard the camera calibration which is assumed to be known.

Although camera calibration is a well studied topic [5], the problem of calibrating an endoscopic camera with exchangeable lenses and keeping the parametrization accurate during the entire procedure is far from being trivial. The reasons are threefold: (i) the calibration must be carried in the OR because the lenses are exchangeable, (ii) since the calibration must be carried by a medical non-expert user the procedure must be fast and robust, meaning that standard lab procedures that require acquiring tenth of images of a grid and clicking points are not suitable, and (iii) in the case of oblique-viewing endoscopes the lens rotate with respect to the camera head changing the camera parameters during operation.

We present a method for endoscopic camera calibration that overcomes the above mentioned difficulties of usability and constant updating during the procedure. It is important to refer that providing an effective solution for the camera calibration problem in the context of surgery is fundamental

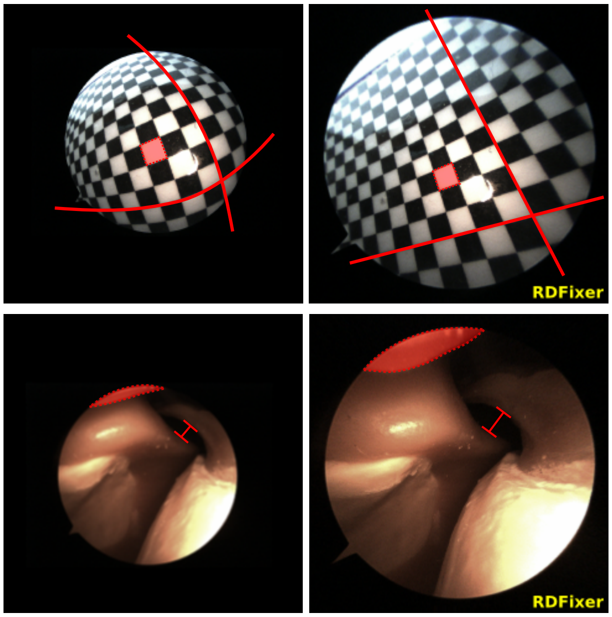



Figure 1. RDFixer distortion correction in a chessboard pattern and a knee model. Left - Original image. Right - Corrected image using RDFixer. It can be noticed, in red, the differences when the distortion is corrected.

for image-based CAS to become a reality in the future. Our solution aims at enabling this key step to be performed in the OR, a subject that has been overlooked up until now.

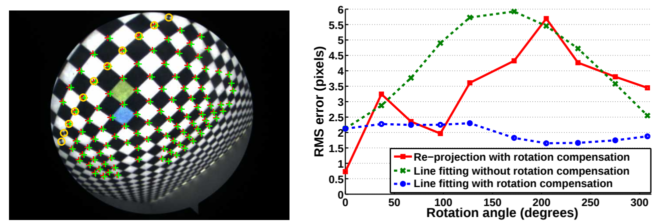
As a first application for the calibration, we present a system for the improvement of the visualization during endoscopy through the correction of image distortion in real-time. In many situations endoscopic video suffers from severe radial distortion (RD), an optical aberration due to limitations in optical construction technology. Optics cannot eliminate this pernicious effect when the lens are small and have a wide field of view (FOV). The problem is that RD severely hinders depth perception. We therefore propose a software-based system that combines calibration information with an hybrid GPU+CPU architecture for removing the distortion in real-time.

## III. System Overview

The system used for distortion correction, dubbed RDFixer, consists in an add-on device that is installed in between the camera control unit and the display, that captures the endoscopic video, updates the projection model according to the lens rotation and corrects the RD in real time. The procedure starts with the acquisition of one calibration image, similar to the one presented in the top row of Fig. 1. The calibration processes is completely automatic and after a few seconds the systems is ready for distortion correction. The bottom row of Fig. 1 shows the distortion correction result in the knee model, with some of the differences in the anatomical structures outlined in red.

The camera calibration is conducted using the single image calibration (SIC) algorithm proposed in [6]. Let $\mathbf{X}$ be the vector of homogeneous coordinates of a 3D point represented in a world reference frame. Point $\mathbf{X}$ is projected into point $\mathbf{x}$ in the endoscopic image such that

$$\mathbf{x} \sim \mathsf{K}_0\, \mathbf{\Gamma}_{\xi}(\mathsf{P}\,\mathbf{X})\,. \tag{1}$$




(a) Test image (1280 × 960) (b) Root Mean Square (RMS) Errors

Figure 2. Experimental validation of the model for updating the camera calibration. The red curve in the graphic of (b) shows the RMS value of the re-projection error for different angular displacements $\alpha$ of the lens probe. The two other curves refer to the error of fitting a line to a set of collinear points (the yellow circles in (a)) after correcting the image distortion and without taking into account the lens rotation.

$\mathsf{P}$ denotes the standard $3\times4$ projection matrix [7], $\mathbf{\Gamma}_{\xi}$ is a nonlinear projective function that accounts for the image radial distortion, and $\mathsf{K}_0$ is the matrix of intrinsic parameters with the following structure

$$\mathsf{K}_0 \sim \begin{pmatrix} a\,f & s\,f & c_x \\ 0 & a^{-1}f & c_y \\ 0 & 0 & 1 \end{pmatrix} \tag{2}$$

where $f$, $a$, and $s$, stand respectively for the focal length, aspect ratio, and skew, and $\mathbf{c} = (c_x,\, c_y)^{\mathsf{T}}$ are the non-homogeneous coordinates of the image principal point. The calibration consists in determining this projection model parameters and this is accomplished using a single image of a checkerboard pattern.

Since the endoscopic lens may rotate relatively to the camera head, assuming unitary aspect ration and zero skew, we decompose the intrinsics matrix into:

$$\mathsf{K}_0 \sim \begin{pmatrix} f & 0 & c_x \\ 0 & f & c_y \\ 0 & 0 & 1 \end{pmatrix}\,, \tag{3}$$

then it can be factorized as

$$\mathsf{K}_0 \sim \mathsf{K}_\mathsf{h}\,\mathsf{K}_\mathsf{c} \sim \begin{pmatrix} f_h & 0 & c_x \\ 0 & f_h & c_y \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} f_c & 0 & 0 \\ 0 & f_c & 0 \\ 0 & 0 & 1 \end{pmatrix}\,, \tag{4}$$

with $f_c$ being the focal length of the endoscopic lens, and $f_h$ being the focal length of the camera head that converts metric units into pixels.

The intrinsic matrix of the compound optical system formed by the camera head and the rotated endoscope becomes

$$\mathsf{K} \sim \mathsf{K}_h\,\mathsf{R}_{\alpha,\mathbf{q}'}\,\mathsf{K}_c\,, \tag{5}$$

with $\mathsf{R}_{\alpha,\mathbf{q}'}$ being a plane rotation by $\alpha$ and around the point $\mathbf{q}'$, where the optical axis intersects the image plane.

During operation, this rotation is tracked in the endoscopic image by searching for the triangular mark as it moves and the projection model is updated accordingly. Fig. 2(a) shows the change in the re-projection error while rotating the lens as well as the result of fitting a line to a set of points after distortion correction using the adaptive projection model presented [8].

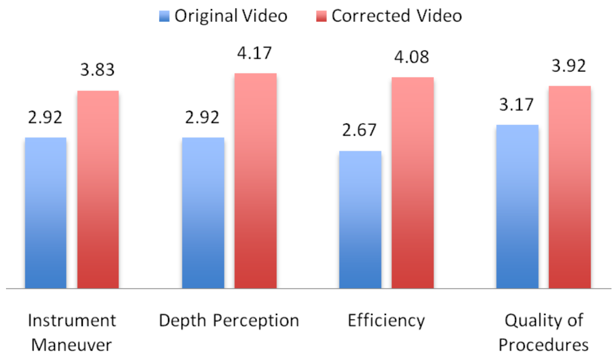



Figure 3. Performance evaluation by the supervisor using the Global Rating Score [10]. The performance is evaluated in a scale from 1 to 5, with 5 representing the greatest performance for each indicator. The values are the mean score for all subjects in each visualization.

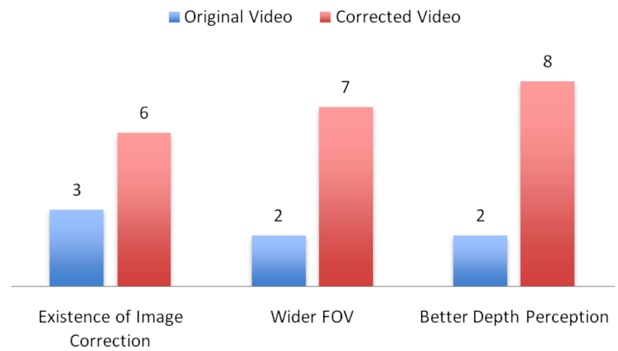



Figure 4. Subject survey results. The count above each column represents the number of "Yes" answers among all subjects when prompted about the subjective impressions depicted.

Given the initial calibration, we track the triangular mark, update the projection model and correct the distortion using the approach proposed in [9]. The heterogeneous system presented in [9] uses both CPU and GPU to process the 1080p@60Hz video stream in real tme. This requires efficient memory access patterns on the GPU to cope with such high data throughput without delaying the stream.

## IV. First clinical trial in the impact of RD correction in surgical performance

We evaluated the performance impact of correcting the RD in a common surgical procedure - the loose bodies removal during the arthroscopy of the knee. Loose bodies are another name for free floating pieces of debris in the knee joint. They are tissues that have torn away from their original location and move around the joint causing pain, swelling, and locking. The procedure consists in removing the loose bodies using a 3.4mm soft tissue grasper, which requires a considerable skill in hand-eye manipulation.

The trial involved a group of 12 training interns, which were supervised by an experienced orthopaedic surgeon, and aimed to validate the improvements in visualization and depth perception. Each subject was individually called to a separate room and asked to remove the same free body using the original and corrected visualization. The visualization mode sequencing was properly balanced across subjects to maintain the statistical reliability of the results. The procedure was conducted without the trainee knowing the purpose of the test, or the type of visualization used for each trial. After each successful removal the supervisor scored the clinical performance of the subject according to an adaptation of the Global Rating Scale presented in [10], and the trainee also filled a subjective questionnaire about the visualization experience. Figures 3 and 4 show the results of the trial, where an improvement of over 30% can be observed in the procedure quality (Fig. 3).

The results of this trial supported our assumption that removing the RD provides a better visualization experience that is clearly noticed by the clinician, and that influences the surgical performance.

## V. Conclusions

This paper describes an effective solution for camera calibration in the OR, which is crucial to enable future image-guided CAS applications. We use the calibration in a first CAS application where the camera model is used to correct the lens distortion via software. Our first trial shows that this visualization application has a significant impact in the surgical outcome.

## Acknowledgments

The authors gratefully acknowledge the Portuguese Science Foundation (FCT) that generously funded this work through project PTDC/EIA-CCO/109120/2008.

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