New Concepts for Intraoperative Navigation: Calibration of a 3-D Laparoscope [1]

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Abstract. Our work presents a new concept to assist with laparoscopic surgical procedures. Rather than the simple visualization of the images from a 3D laparoscope on a stereoscopic visualization display, our goal is to register intraoperative stereoscopic images with preoperative patient's diagnostic data (CT), without measuring fiducial markers. A graphical overlay on the visualization would allow the surgeon to see through the organs, beyond their surface. The success of this system highly depends on an accurate 3D-laparoscope camera calibration. The major problems arise because of the small distance between the cameras, the high lens distortion and the illumination conditions. We have performed several calibration procedures based on the pin-hole camera model. Comparative results are reported and discussed.

Keywords: Computer Assisted Surgery, Registration, Computer Tomography,

1 Introduction

Laparoscopy is one of the most familiar of the therapeutic approaches referred to minimally invasive surgery. It offers advantages over open surgery including less postoperative discomfort, shorter hospitalization and reduced convalescence. The importance of broadening the spectrum of minimally invasive techniques is evident in the proven advantages for the patient.

Although this technique is a powerful visualization and intervention tool, the observation of the internal anatomy with a monocular laparoscope lacks depth information of the operative field. Together with the application of 3D visualisation techniques, a 3D-Laparoscope allows the surgeon to perceive a 3D impression, which might improve hand-eye coordination in delicate surgical procedures.

Up to now, this stereoscopic visualitzation has been the main application of the 3D laparoscopes. However, they can provide a great amount of useful information to be used in an Augmented Reality system.

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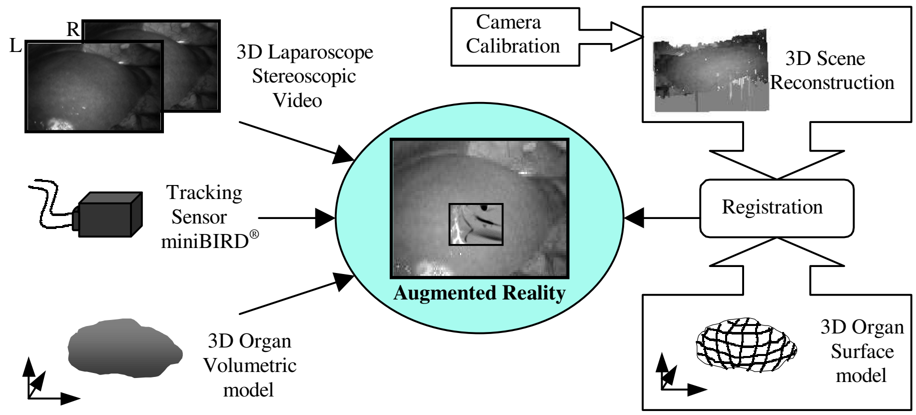

Figure 1. Concept overview

We present a new concept to assist with laparoscopic surgical procedures. Rather than the simple visualization of the 3D laparoscope images on a stereoscopic visualizaton display, we propose to register intraoperative stereoscopic images with preoperative patient's diagnostic data (CT), without the use of fiducial markers. Once the registration is accomplished, computer generated graphical models and live stereoscopic video can be merged allowing the surgeon to see beyond the organ surface. This Augmented Reality system would provide help for the intraoperative navigation, even for the experienced surgeon.

To make this system feasible, it is very important to attain a very accurate 3D laparoscope calibration. Fig.1 shows an overview of the concept. We have applied several calibration algorithms and the results with real images are reported in the last section. Parts of the experimental environment that this work presents have been built up in the Surgical Research Unit OP2000 (OP in German for operating room).

2 Description of the system

In order to relate preoperative data with the actual reality of the patient on the operating table, fiducial markers are normally used ([2,3]). They enable to deal with different coordinate systems (preoperative 3D medical images, patient and 3D laparoscope) and to determine the correspondence between each coordinate system.

We postulate that the surface of an organ exposed intraoperatively can be used as an anatomic reference structure for a subsequent registration, avoiding the use of material landmarks. Thus, this registration involves two different 3D models: a 3D organ volumetric model (generated from CT images) and a 3D reconstruction of the intraoperative field, viewed from the laparoscope tip.

The key element of this computer assisted surgery concept is the intraoperative shape acquisition, i.e. to derive the depth map associated with the images from the laparoscopic cameras. Although an active vision system would overcome many of the problems of a passive stereo laparoscopic system (mainly the correspondence

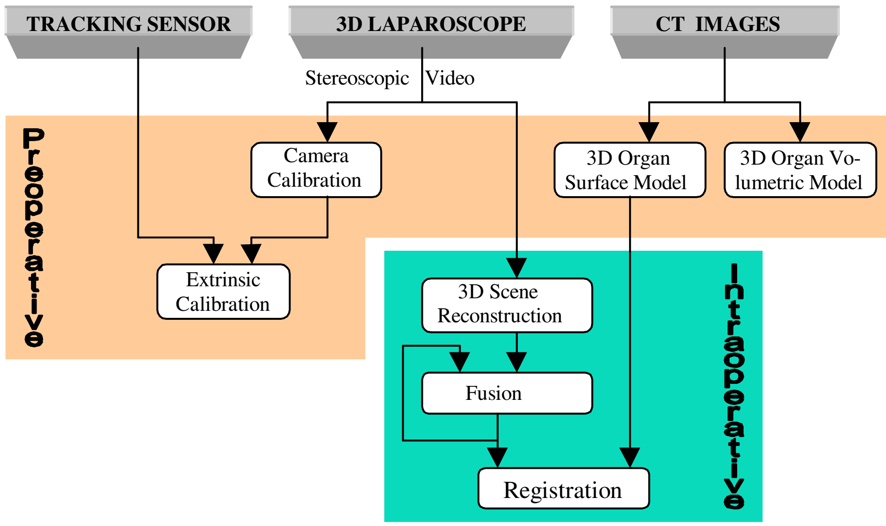

Figure 2. Preoperative and Intraoperative data to be calculated

problem), the later is a less invasive technique and it also allows the surgeon to see 3D visual information with the aid of glasses.

The modules that are involved in this new concept of Augmented Reality are shown in Fig. 2. First of all, a calibration of the 3D laparoscope must be performed. Beside this, 3D image models are computed from the CT images: the surface model of the target organ and its corresponding volumetric model. The former is used in the registration module, whereas the later is only used for visualization purposes, to overlay on the video the internal organ structures. This division between preoperative models allows to speed up the registration task.

Due to the fact that the 3D laparoscope provides a sequence of stereoscopic images, the fusion of different views of the same operating field would improve the accuracy of the 3D reconstruction, making the registration more reliable.

The computational cost of such global registration would not allow a real-time tracking of the laparoscope's movements. Therefore, a 3D digitizer must be attached to the laparoscope. An initial registration is performed, and meanwhile the following global registration is computed, the laparoscope is tracked with this digitizer. This solution would make feasible a real-time Augmented Reality system, displaying the superimposed graphical model accordingly to the tracked position and orientation, and updating the data each time that a global registration is carried out.

Although optical 3D digitizers offer the greatest accuracy, they cannot localize objects through the skin and body wall. This is a desirable feature if one seeks to compensate breath movements. If we use two magnetic sensors, one attached to the 3D laparoscope and a second one stitched on the surface of the target anatomic structure, the registration could be accomplished regardless of patient movement. The position and orientation of the sensors coordinate system relative to the focal point of one 3D laparoscope camera has to be determined by an extrinsic calibration.

3 3D Laparoscope Calibration: Experimental Results

In this system, the 3D reconstruction plays a crucial role because it substitutes the information supplied by the fiducial markers. Any 3D reconstruction is strongly influenced by the geometrical and physical parameters that characterize the 3D laparoscope cameras. Therefore, these parameters must be known with very high accuracy if we want to extract valuable 3D information from the scene views and to succeed in the subsequent registration.

The process that determines such parameters is called camera calibration. Besides the calibration of the laparoscope's left and right camera, we must also calculate the relative position and orientation between their focal points [5].

The whole process is based on the analysis of the views of a calibration pattern. Fig.3 shows the pattern that we have used in our experiments. The image features that we have used for calibrating are the corners of the pattern's black squares. It can be seen that the light source of the 3D laparoscope concentrates the light on the image central area, leaving some parts of the image almost in the darkness. To overcome this problem, we have developed an algorithm that it is capable to extract the image coordinates of all the corners with subpixel accuracy, even when the luminance contrast is very small. The foundation of the algorithm is the intersection of the lines that aproximates the four sides of each square. This estimation is carried out in a robust way [10], neglecting the outliers. The algorithm requires a little user interaction in order to match the world coordinates and the image coordinates accordingly.

An accurate calibration of a 3D laparoscope is difficult due to the very small distance between the cameras, the high lens distortion and the inhomogeneous illumination. We have applied three different calibration methods, well-known by the computer vision community [7,8,9], to the same data. The best results were obtained using the Heikkilä's calibration method [9], as it was expected. This method [9] makes use of two radial and two tangential distortion coefficients, whereas the Tsai [8] and the Toscani's [7] algorithm employ one radial distortion coefficient and none respectively.

However, the parameters were not good enough to perform a 3D reconstruction of a test object (a plane) located at 12 cm in front of the laparoscope. Errors up to 3 cm are detected when the original surface and the reconstructed one are compared.

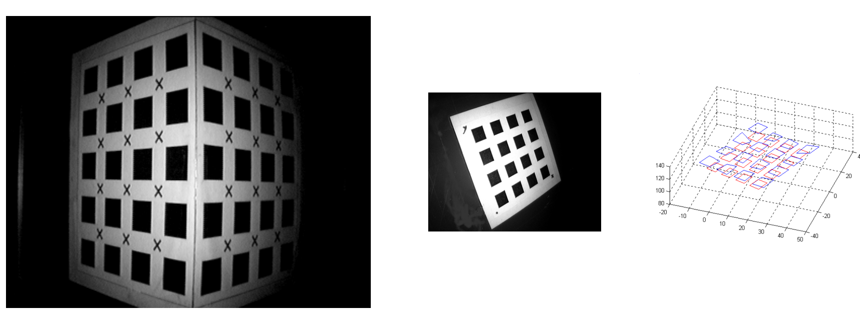

Figure 3. Calibration Pattern and test object reconstruction

These errors can be understood if we observe the difference of magnitude between the left to right focal point distance (base line = 1.4 mm) and the object distance (120 mm). A small error in the estimation of the base line distance can cause a large error when the 3D reconstruction is computed, since the backprojection of stereo images is an ill-conditioned problem. The accuracy could be increased building a calibration pattern of higher accuracy (e.g. 20 µm.) and adding more lens distortion coefficients to the camera model.

4 Conclusion

Registration of preoperative and intraoperative data provides the crucial step required to relate the "virtual patient" of surgical planning with the actual patient on the operating table. This paper has presented a new concept for intraoperative navigation, based on the registration of preoperative 3D medical images and 3D reconstructions of the operating field, without the use of fiducial markers. The feasibility of this system highly depends on the accuracy of this scene reconstruction, which it is closely related to the camera calibration process. We have observed that the more lens distorsions coefficients are taken into account in the 3D laparoscope calibration process, the better results are attained. Further research has to be done to improve the accuracy of the calibration process and to integrate the different modules.

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