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Intraoperative Ultrasound-based Augmented Reality Guidance

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This paper presents an ultrasound-based augmented reality framework for minimally invasive surgery. We achieved high accuracy in each calibration step. The framework was evaluated by localizing a hidden target in a soft tissue phantom.

1 Introduction

Minimally invasive surgery (MIS) such as laparoscopic surgery is done through small incisions. It brings many benefits to patients for instance small incisions, low risk of infection and quick recovery time. Meanwhile, it increases the difficulty for surgeons by reducing surgeons ability of differentiating the lesions and healthy tissues. Augmented reality (AR) system facilitates the surgical procedure by augmenting the endoscopic view with structures that are not visible directly from cameras but are visible in medical imaging data. This allows surgeons to localize tumors and vessels without palpating and tactile feedback.

Some of the MIS are performed under US guidance. The intraoperative US is able to localize and track in real time the target (e.g. a tumor) even in high soft tissues deformation conditions. In 3D conditions, the US images can be used to generate a 3D virtual model of the tumor for AR systems [1][2].

In this paper, we propose an intraoperative US-based AR framework for hidden structures visualization and surgical gesture guidance.

2 Framework Overview

Fig.1 shows the process of implementing an US-based AR framework. A 2D US probe is used and motorized to obtain a 3D US image. The objective of implementing this framework is to extract useful information (e.g.

tumor area) from the 3D US image and superimpose it on the 3D endoscopic view, as shown in the visualization flowchart in blue in Fig.1. A mixture of the real and virtual information is presented to the user through a head mounted display (HMD). The key point of the visualization workflow is the registration $^{c}T_{us}$ between the 3D US image and the endoscopic camera. To solve it, we propose the following registration flowchart (in red in Fig.1): A tracking system is used as world coordinate system (CS) w and tracks a marker $m1$ (with CS $m1$) fixed on the endoscope and the marker $m2$ (with CS $m2$) fixed on the US probe. The transformation $^{m1}T_{c}$ between the endoscopic camera (with CS c) and the marker m1 is obtained by hand-eye calibration method [3]. The transformation $^{m2}T_{us}$ from 3D US image (with CS us) to the marker $m2$ is obtained by US calibration [4]. Finally, the transformation $^{c}T_{us}$ is computed by:

$$^{c}T_{us} = (^{m1}T_{c})^{-1} * (^{w}T_{m1})^{-1} *^{w} T_{m2} *^{m2} T_{us} \quad (1)$$

where $^{b}T_{a}$ represents the transformation from CS of a to CS of b.

3 Ultrasound Calibration

The goal of US calibration is to find the rigid transformation $^{m2}T_{us}$ between the acquired 3D US image and a marker fixed on the probe. In a previous study, we proposed a fast US calibration procedure [4] which greatly simplified the calibration procedure compared to some classical methods [5][6]. The main idea was to use a custom-designed calibration phantom attached to the marker and visible by the US device. In order to adapt this method to our US probe, we designed a calibration phantom as a tube in which the US probe can be inserted. On this tube, we hollow out some circles and squares that are features for US imaging (Fig.2). Marker $m3$ is fixed on the phantom and the
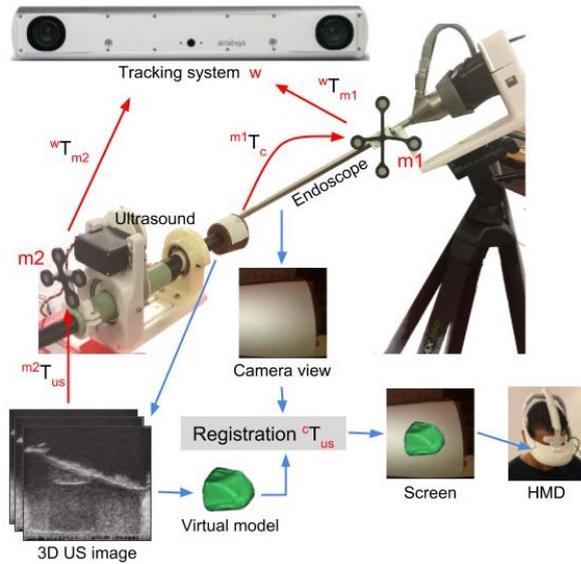
Figure 1: *Framework overview of the augmented reality setup based on a calibrated ultrasound.*

coordinates of the features (circles and squares) in the CS of the marker $m3$ are obtained by computer-aided design (CAD). The calibration process started with mounting the phantom on the US probe and placing the acoustic matching layer of the probe and the phantom into water for US imaging. The transformation $^{m2}\hat{T}_{us}$ is estimated by

$$^{m2}\hat{T}_{us} = (^{w}T_{m2})^{-1} \, ^{w}T_{m3} \, ^{m3}T_{us} \qquad (2)$$

where us, $m2$, $m3$ and w respectively represent the CS of the 3D US image, marker $m2$, marker $m3$ and the tracking system. $^{m3}T_{us}$ is obtained by rigid registration between the US image and the phantom's CAD model, as explained in method [4].

The accuracy of the US calibration was evaluated by point reconstruction tests, as presented in [4]. we acquired the data of the stylus tip at 5 different positions and the root mean square (RMS) error was 0.92 mm.
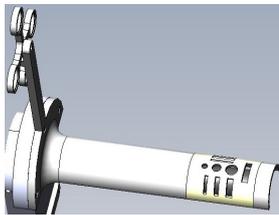

Figure 2: *CAD model of calibration phantom for our US probe.*

4   Endoscope Tracking

Before using the 3D endoscopic camera, it has to be calibrated to find the camera projection matrix. The calibration is achieved by a chessboard-based stereo camera calibration method proposed in [7] which is implemented in OpenCV library [8].

Hand-eye calibration method proposed in [3] is implemented to obtain the transformation $^{m1}T_c$. Fig3 (a) illustrates the data acquisition for applying hand-eye calibration method proposed in [3]. The transformation $^{w}T_{m1}$, $^{w}T_{m4}$ and $^{c}T_{ch}$ in 17 different positions are saved. The data is used in method [3] to estimate the transformation $^{m1}T_c$ and $^{m4}T_{ch}$. The obtained $^{m1}\hat{T}_c$ was evaluated as shown in Fig3 (b): the green circle is the coordinates of a fiducial's contour projected on the endoscopic view by $^{m1}\hat{T}_c$. The distance between the green circle and the fiducial's contour in the endoscopic view was computed. The RMS of distances along 72 radial directions was 0.32 mm for the left camera and 0.44 mm for the right camera.
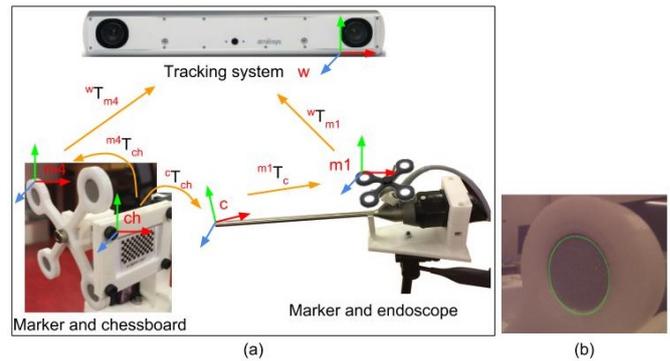

Figure 3: *(a) Hand-eye calibration for 3D endoscopic camera; (b) using obtained $^{m1}\hat{T}_c$ to project the coordinates of a fiducial's contour on the endoscopic view in green color.*

5   Result and Conclusion

The proposed framework was evaluated by localizing a hidden target set inside a soft tissue phantom (Fig.4 (a)). An US imaging was performed on the hollowed silicon phantom and the hidden target was manually segmented on this data to generate the virtual model. Our AR framework presented the virtual information to the user (Fig.4 (b)), then the user cut the phantom according to the augmented view (Fig.4 (c)). We found that the hidden target was well resected from the soft tissue phantom.

In conclusion, we presented an US-based AR guidance system with high accuracy in the design and each calibration step. The framework successfully localized a hidden target from a soft tissue phantom.
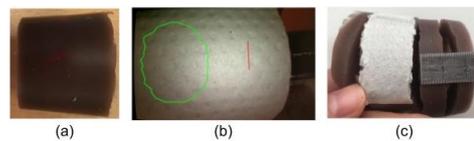

Figure 4: *(a) soft tissue phantom, (b) AR view showing the hidden target (green) and resection margin (red) , (c) scalpel cut following the augmented view.*

Acknowledgement

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