Intraoperative Ultrasonography-based Augmented Reality For Application In Image Guided Robotic Surgery

Jun Shen, Nabil Zemiti, Agnès Viquesnel, Oscar Caravaca Mora, Auguste Courtin, Renaud Garrel, Jean-Louis Dillenseger, Philippe Poignet

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J. Shen[1,2], N. Zemiti[1], A. Viquesnel[1,3], O. Caravaca-Mora[1], A. Courtin[1], R. Garrel[3], J.-L. Dillenseger[2], P. Poignet[1]
[1] LIRMM, University of Montpellier, CNRS, Montpellier, France
[2] INSERM UMR 1099, Rennes, France; University of Rennes 1, LTSI, Rennes, France
[3] ENT Department, Centres Hospitaliers Universitaires Gui de Chauliac, Montpellier, France.

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Purpose

Accurate Tumor delineation in the operating room (OR) is a big challenge for surgical oncologist. For instance, the preoperative images used in the transoral robotic surgery (TORS) for tongue base tumor resection cannot reflect the deformation of the soft tissue during the surgery. Furthermore, due to the camera's small field of view and the loss of cross-modality landmarks in the tongue base, it is difficult to register the preoperative imaging modality to the intraoperative stereo camera with deformable registration. We propose an intraoperative ultrasonography (IOUS)-based augmented reality (AR) framework, which is able to accurately delimit the tumor boundaries and provide them to the surgeon's view during the surgery. Instead of some works requiring manual registration [1], additional fiducial markers attached on the organ [2], or intraoperative imaging modalities which is highly ionizing [2] [3], our solution uses a safe and cheap US imaging modality and does not use additional fiducial markers disturbing the TORS workflow.

Methods

Fig.1 shows the registration pipeline used to achieve AR on stereo camera. A tracking system was defined as the world coordinate system (WCS) *w*. The transformation between the coordinate system (CS) of the camera *c* and the WCS was found by calibrating the camera with the WCS based on the mathematical framework given by ${}^{w}\mathbf{T}_{c} = {}^{w}\mathbf{T}_{s}\,{}^{s}\mathbf{T}_{c}$, where *s* represents the CS of an active marker. The tracking system computed the transformation ${}^{w}\mathbf{T}_{s}$ from the CS of the marker *s* to the WCS, meanwhile, the marker was localized in the 3D camera and its position was used to compute the transformation ${}^{s}\mathbf{T}_{c}$.

After calibrating the stereo camera in the WCS, the preoperative MRI image had to be registered to the WCS, in order to augment the camera view with the information extracted from the MRI. The corresponding mathematical registration framework can be presented as ${}^{w}\mathbf{T}_{m} = {}^{w}\mathbf{T}_{s}\,{}^{s}\mathbf{T}_{i}\,{}^{i}\mathbf{T}_{m}$, where *m*, *i* represent the CS of MRI image and US image. The transformation ${}^{i}\mathbf{T}_{m}$ was achieved in our experiment using Elastix toolbox performing a deformable registration between MRI image and US image. B-spline transformation model and Mutual Information similarity measure were used for the registration. The transformation ${}^{s}\mathbf{T}_{i}$ was obtained by US probe calibration. We developed a fast and automatic calibration method based on a custom-made 3D printed phantom and an untracked marker for 3D US probe calibration. Finally, the tracking system measured the position of the marker mounted on the probe and computed the transformation ${}^{w}\mathbf{T}_{s}$.

The performance of the setup was evaluated with 3 soft tissue phantoms made of soft polyvinyl chloride plastic. There was a triangle-shaped object embedded inside of each phantom. The invisible triangle-shaped objects could be distinguished under palpation and US imaging. Fig.2 shows the experimental setup. The participants were asked to use a calibrated Pointer to localize the boundaries of the invisible targets according to the augmented view projected in a head-mounted display system.

Results

The errors of the US-based AR framework are mainly from MRI/US registration and US probe calibration. The target registration error (TRE) was used to compute the distance, after registration, between corresponding points. MRI and US image registration were performed

on the three phantoms. 6 vertexes of the triangle-shaped targets in the MRI and US images were used as landmarks for computing TRE. The root mean square (RMS) of TRE for the three phantoms were 0.313mm, 0.19mm and 0.41mm, respectively. The US probe calibration was evaluated by point reconstruction tests and obtained the RMS of point reconstruction errors of 1.39mm.
The presented approach was developed for our clinical application in TORS for tongue base tumor resection. Therefore, we compared our AR framework with conventional procedure where preoperative MRI and manual palpation were used to localize the tumor. With these two approaches, 6 participants estimated the boundaries of the invisible targets inside of the 3 phantoms. The localization accuracy was computed by measuring the overlap between the boundaries estimated by the participants and the ground truth using Dice scores. We found the Dice scores from the experiment based on our AR framework remained clearly higher than those from the experiment based on conventional procedures. We achieved all of the Dice ≥ 0.86 and Hausdorff distance ≤ 3.49mm in the experiment based on AR guidance.

Conclusion

We present a US-based AR framework for accurate tumor delineation in soft tissues. The performance was evaluated in an experiment delineating the boundaries of invisible targets in soft tissue phantoms. With our setup, the participants achieved higher accuracy of boundary delineation than with the conventional procedure. This framework was developed for the clinical application in TORS for tongue base tumor.

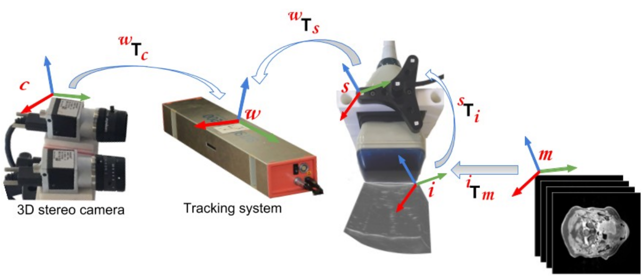

Fig. 1. Registration procedure for augmentation of stereo camera with MRI image

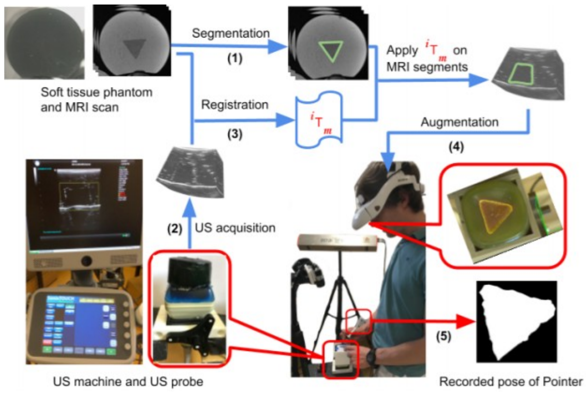

Fig. 2. Implementation of IOUS-based AR framework for the experiment with soft tissue phantoms

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