Automatic Robotic Scanning for Real-time 3D Ultrasound Reconstruction in Spine Surgery

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INTRODUCTION

Ultrasound (US) is a widely used non-radiative medical imaging modality considered for spine surgery. Through 3D reconstruction, US could help surgeons visualize the internal anatomy. Benefiting from intelligent robotic control, US-based robot-assistance could be exploited to perform autonomous scanning without leading to increased discomfort of the patient. Besides, robotic US scans could potentially offer better quality US images by keeping tight surface contact between the US probe and the skin.

During the past years, several robotic US systems have been developed and applied for spine surgery [1], [2]. Victorova *et al.* implemented a robotic US system with hybrid control for spine reconstruction. The proposed system regulated the applied force and enhanced the imaging quality [1]. However, it only focused on flat phantom with continuously surface. The post processing of US images was time-consuming. Zhang *et al.* also implemented an US scanning system with an adaptive approach to visualize spine [2]. The poses of US probe were manipulated while the contact force ranged from 14 to 16 N. Nevertheless, the US images were processed with complex image segmentation and volume rendering procedure. The aforementioned robotic US systems require post processing for 3D reconstruction and visualization. Therefore, it is necessary to develop a real-time reconstruction framework with robust image processing and control strategy for automatic robotic US scanning.

This paper provides a real-time US reconstruction with automatic robotic scanning. With hybrid control, the US probe keeps good surface contact during scanning. Meanwhile, the ultrasound images are simultaneously segmented and accurately reconstructed.

MATERIALS AND METHODS

The employed robotic US system consists of a lightweight robot (KUKA Robot LWR, Augsburg, Germany) and a 7.5 MHz US probe with US device (Sonosite, FUJIFILM, USA). During testing, the US images were recorded as 640×480 pixels by a frame grabber (Epiphan, Palo Alto, USA) at 30 Hz. A 6 DOF F/T sensor (Nano 25, ATI Industrial Automation, USA) was mounted with a custom designed probe housing at the robot end effector. A spine phantom (Model 034, CIRS, USA) was employed for experimental validation. In addition, a PC workstation (Intel i7, CPU @2.6 GHz, 64G RAM) with Nvidia P2000 GPU was used for data acquisition and processing. Fig. 1 illustrates the workflow and the experimental setup.

The developed framework contains an automatic robotic scanning part and a real-time 3D US reconstruction. Before scanning, 15 predefined points were manually selected on the phantom surface with admittance control. The recorded points are used to generate an "S" shape scanning trajectory for automatic scanning. To perform the scanning, the z axis of the US probe was aligned to the normal vector of the surface which was computed from the predefined trajectory. Subsequently, automatic scanning was conducted with hybrid control while the force along probe z axis was kept constant. The target force was regulated on 3 N to which is the maximum force guaranteeing good image quality without leading to tissue displacement. To ensure real-time control, OROCOS (Open Robot Control Middleware) and eTaSL (expressiongraph-based Task Specification Language) were utilized.

The 3D US reconstruction was conducted in real-time during scanning. US spatial calibration was required to assure the reconstruction accuracy. Before scanning, the calibration was implemented with a custom designed sphere phantom [3]. Based on the calibration, the bone contours in the US images could be transformed to robot coordinates with the corresponding end-effector poses. A deep learning network, U-Net, was developed for realizing automatic image segmentation. For training, 500 images in 480×480 pixels were collected and manually labelled. Those images were augmented by mirroring and shifting on vertical and horizontal axes separately. Then, the model was trained with the 2000 augmented images. The trained model was evaluated with 50 images. A precision of 0.82 mm and accuracy of 0.98 mm was found. Subsequently, the model was integrated with the real-time reconstruction. The spine contours in the US images were automatically segmented and generated as point clouds into the robot coordinate. The outliers of the reconstructed point clouds were removed by computing the distance from their neighbors compared to the average with a 0.5 threshold level. Finally, the Visualization Toolkit (VTK) was used to visualize the generated point clouds in real-time by retrieving the data stream.

To evaluate the 3D reconstruction, the automatic scanning was repeated three times with the same scanning trajectory. Then, the three reconstructions were assessed by computing the distance between the three reconstructed point clouds (from source to target point clouds). This error indicates the scanning precision and actual spatial displacement between the reconstructed point clouds.

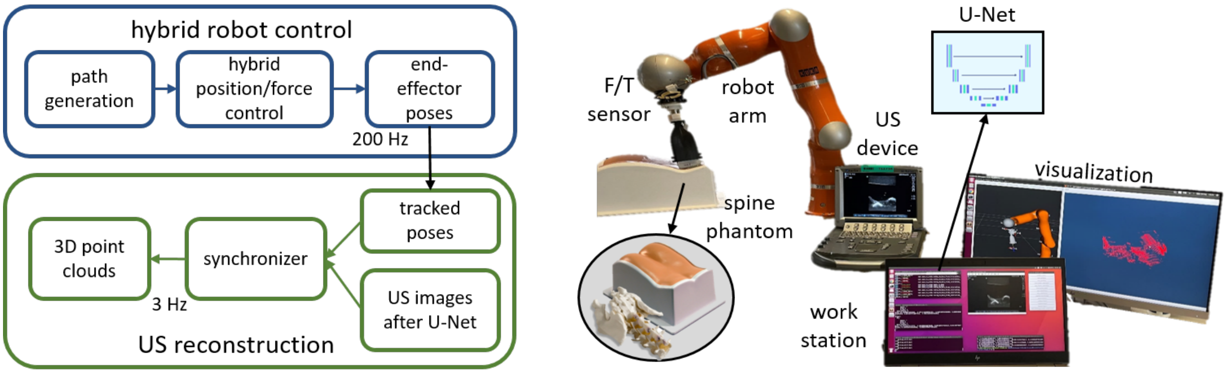

Fig. 1: (Left) Workflow of automatic robotic 3D US reconstruction. (Right) Overview of experimental setups.

RESULTS

The obtained force measurements are shown in Fig. 2 A). The force along the z axis is kept constant at 3 N during scanning. The mean value of measurements is 2.95 N while the standard deviation is 0.21. The mean force measurements along x and y axis are 0.05 N and 0.09 N respectively. The average scanning time is 273 seconds for the three repeated experiments.

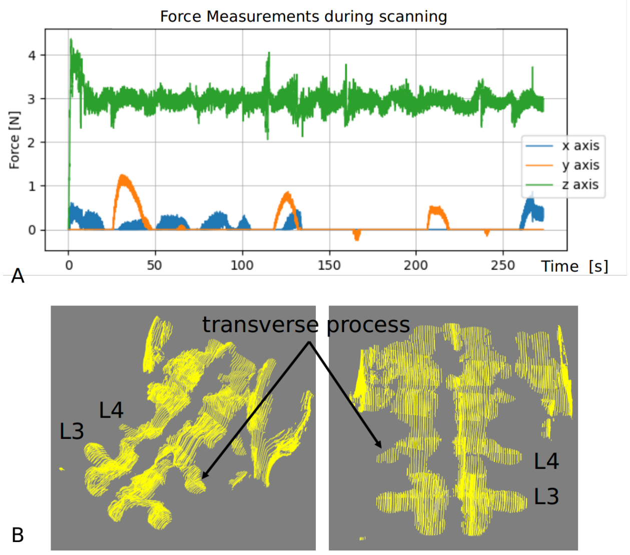

Fig. 2: A) An example of force measurements. B) An example of automatic reconstructed 3D point clouds.

The US images were segmented and processed in real-time during scanning. With the U-Net, the point clouds were generated and visualized at 3 Hz. The reconstructed 3D point clouds were displayed in Fig. 2 B). This result shows the geometric structures and features of the spine. The shape of the transverse process and the pedicle are visibly reconstructed. Table I shows the repeatability of the three 3D reconstructions. The mean errors of the reconstructed point clouds ranged from 0.53 to 2.14 mm.

CONCLUSIONS AND DISCUSSION

This paper implements a real-time robotic US reconstruction approach for spine surgery. With hybrid control, the proposed method constantly keeps the scanning force within a safe range to ensure good surface contact with patient's skin. The proposed scanning framework is not affected by the curvature of phantom while following the predefined scanning trajectory. For future research, it is interesting to focus on trajectory optimization to reduce the scanning time while keeping good reconstruction accuracy.

TABLE I: Results of the repeatability assessment

source - target	RMSE [mm]	Mean [mm]	Std. Dev.
1-2	0.73	0.53	0.94
1-3	0.91	0.83	1.82
2-1	0.66	0.43	0.91
2-3	1.45	2.11	2.89
3-1	1.46	2.14	2.70
3-2	1.41	1.99	2.64

Besides, the real-time DL-based image segmentation improves the reconstruction efficiency and accuracy. The image reconstruction is implemented with scanning simultaneously. Thus, the post reconstruction in previous research [4], up to 8 seconds, is not required anymore. Furthermore, the 3D reconstructions are also accurately repeated with an RMSE lower than 1.46 mm. The reconstructed point clouds illustrate the geometric features of anatomy and spatial relation between each vertebra.

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