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Automatic ultrasound scanning system based on robotic arm

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Dear editor,

As an indispensable diagnosis-aid technologies, ultrasound (US) examination gains more and more attention in recent years [1]. US could real-time display the 2D images of the region of interest in a way of low cost and no radiation. For handheld scanning, however, it also has some issues, e.g., professional training was needed to achieve good scanning skill and long time scanning aggravates the doctor's physical and mental burden. Moreover, the ultrasound imaging quality as well as corresponding diagnosis is highly operator dependent.

Robotic ultrasound systems (RUS) has combined the US examination with the robotic system in medical interventions [2]. With mechanic device to actuate the probe, the system could precisely record the spatial information of the B-scans, which can enhance the accuracy of the volume reconstruction. Chen et al. [3] used three-dimensional (3D) translating device to actuate the probe to finish the scan. The operator could set the step length and compress depth to ensure stable compression pressure. After the scanning, the system could reconstruct the high quality 3D strain images. Janvier et al. [4] used the F3 Articulated Robot to acquire 2D US images for consequent 3D reconstruction. For each scanned leg, the operator manually moved the robotic arm in teach mode, and then the robotic arm would replay the taught path to acquire 2D images in replay mode. Conti et al. [5] developed a collaborative robotic system for reducing the doctor's fatigue. The operator could control the slave robot in tele-operation mode or semi-automatic mode. A force controller would compensate the pressure to maintain the stable contact between the probe and tissue surface. The system would achieve the 3D reconstruction in nearly real time. Meng et al. [6] proposed a novel robotic US scanning system for scanning the lower limbs. One robot would be manipulated by the operator to inspect one leg. Based on the point cloud acquired by the RGB-D camera, another robot arm would mimic the mirrored motion to scan another leg.

In this study, we propose an automatic 3D imaging system based on 6-degree-of-freedom (6-DOF) robotic arm. In comparison with other RUS, the main merit of our system is to perform automatic scanning and 3D imaging for any part of the human body.

Method. As illustrated in Figure 1(a), the proposed system consists of the following parts: a portable US scanner (Model M5, Mindray, Shenzhen, China) for acquiring the B-scans, a 6-DOF robotic arm (Epson C4-A601S, Seiko Epson Corporation, Japan) for driving the probe, a personal computer (PC) with an Intel Core i5-3317U and 6 GB RAM for linking the robotic arm and receiving the B-scans and corresponding spatial information for subsequent reconstruction, and a depth

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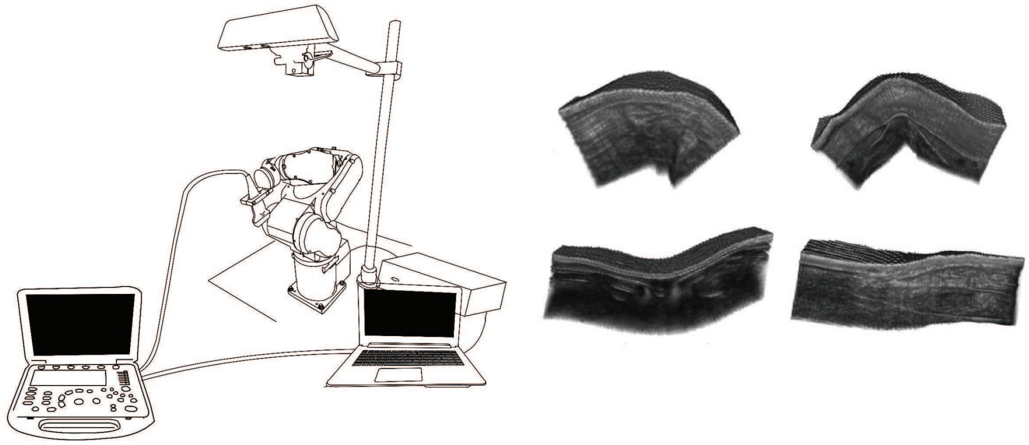

(a) (b)

Figure 1 (a) The system architecture; (b) the experimental results of reconstructed volume.

camera (Kinect, Microsoft Corporation, USA) for obtaining the color image and depth image of the tissue. A custom-designed software was developed for the manipulation of the robotic arm, data acquisition, 3D volume reconstruction, and visualization.

The system used a stainless steel clip on the gripper to fix the probe. Having determined the configurations of the robotic arm, the probe could be driven to the desired point. Among these configurations, the pose of the robotic arm, i.e., the coordinate value of the gripper with respect to the robot base coordinate system R was

$$^{\text{gripper}}P_R = X, Y, Z, U, V, W, \tag{1}$$

where $^{\text{gripper}}P_R$ has six DOF: three translations (X, Y, Z) and three rotations (U, V, W). The order of rotations would be: first about x axis of R by angle W, then about y axis of R by angle V, and finally about z axis of R by angle U.

Calibration is a necessary procedure to ensure the accuracy of proposed system. We have two spatial calibrations. One is conducted to determine the transformation relationship between the B-scan coordinate system B and the gripper coordinate system G because our system needs it to execute subsequent volume reconstruction. As the scanning is based on the point cloud acquired by the Kinect, the other spatial calibration is to estimate the transformation relationship between R and the Kinect coordinate system K.

The Kinect was attached to the end of a customized steel bracket, which was 30 cm higher than the robotic arm. The Kinect could acquire the color image and depth image of the scanned tissue. After the calibration experiments, the system could transform the scan points from K to R. Therefore the robotic arm would know the coordinate value of the scan point in R. By using an empirical rule (i.e., the area which satisfied Red>Green>Blue would be extracted firstly), the system could determine the scan range of the color image acquired by the Kinect. Then the operator could arbitrarily choose two points to determine a line as the scan path.

To achieve the 2D US images with good quality, the pose of the probe should be carefully determined during the scanning. The motion planning of the robotic arm is important [7]. In our system, it is obvious that different poses of the robotic arm can make the center point of the probe's emission plane coincide with the same point. We should obtain the optimal pose of the robotic arm during the scanning. With respect to the routine freehand scanning in a clinical examination, the operator often holds the probe perpendicular to the skin surface as far as possible. Thus, we designed a normal vector based method [8] to obtain the optimal pose of the robotic arm. The system located three points around every scan point to construct a triangle that represented a 2D plane on which the scan point lay. By calculating the normal vector of this triangle, the system could determine normal vector corresponding to the scan point, and therefore manipulate the pose of the robotic arm corresponding to the scan point to make the axial direction of the probe consistent with the normal vector. This method was based on two hypotheses: (1) The surface of the scanned tissue was smooth. (2) The scan points of the scan path were dense enough. Actually, these hypotheses would be satisfied. The workflow of the entire system could be summarized as follows:

(1) Boot and reset the robot arm in low power mode. Start the research mode of the ultrasound machine for acquiring the B-scan.

(2) Connect the IPC, PC, and the ultrasound machine through the local area network.

(3) The Kinect would capture the color image and depth image of the scanned tissue. Then the system would extract the scan range and determine the scan path.

(4) For each scan point, the system would calculate the optimal pose of the robotic arm.

(5) The robotic arm would drive the probe to scan the tissue. When arriving one scan point, the PC would inform the ultrasound machine to send the B-scan of current scan point to the IPC. Meanwhile, the PC would send the current pose of the robotic arm to the IPC.

(6) After the scanning, the system would realize the 3D volume reconstruction [9] and display the result in the interface.

Experimental results. We used the system to scan a breast ultrasound training phantom (Model 073, CIRS, Inc., USA), a thyroid training phantom(Model 074, CIRS, Inc., USA), and a lumbar training phantom (Model 034, CIRS, Inc., USA) and a real human forearm of a 24 years old male. The experimental results show the performance of the proposed system in different body parts. Figure 1(b) shows the reconstructed volume images of the breast phantom, the thyroid phantom, the lumbar phantom and the human forearm, respectively. There was not much difference between the time spent by automatic scanning and that spent by doctors scanning. From the volumes, we could clearly observe the shape of the phantoms and the scanning trajectory of the forearm, indicating its good performance for scanning irregular body parts and in reconstruction of 3D US images with high quality.

Discussion and conclusion. In this study, we proposed an automatic 3D imaging system based on a 6-DOF robotic arm. The Kinect was adopted to capture the point cloud of the scanned tissue. The system could extract the scan range and determine the scan path. According to the scan path, the system found the optimal pose of the robotic arm corresponding to each scan point based on the normal vector of the region around the scan point. After the scanning, the system could complete the 3D volume reconstruction. Experimental results have validated the feasibility of the proposed system. A more complete feedback control scheme would be the major research direction in our future work.

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