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A Qualitative and Quantitative Interaction Technique for Freehand 3D Ultrasound Imaging

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Abstract—**Conventional freehand 3D ultrasound imaging techniques separate the scanning and reconstruction steps from the visualization step. Several approaches that enable real-time volume reconstruction and visualization during acquisition have been described in the literature in recent years. However, these approaches are not fully interactive, since they do not provide sufficient feedbacks on volume reconstruction. In this paper, we present a qualitative and quantitative interaction technique (QAQIT) which can provide accurate feedbacks on volume reconstruction in real time during acquisition. Two threads are designed for data acquisition: one is to acquire B-scan images from the ultrasound scanner sequentially, and the other is to obtain positions and orientations from the position sensor continuously. A matching thread matches the latest acquired image with its relative position and orientation (PAO), and then reconstructs the image into a predefined volume. After the 3D reconstruction of each image, we calculate the reconstructed ratio (RR) and increased ratio (IR) of the reconstruction volume (RV), then update the display of the RR, and drive the volume rendering of the RV according to the IR. A freehand system based on the QAQIT has been developed on a personal computer (PC). We demonstrate our system on an embryo phantom.**

Keywords—**3D ultrasound imaging, reconstruction, interaction**

I. Introduction

THREE-DIMENSIONAL ultrasound imaging is another landmark in the history of medical diagnostic technique, and has been widespread in clinical application. There are mainly two approaches to 3D ultrasound imaging: real-time 3D with 2D arrays, and reconstructed 3D with 1D array [1]. Systems adopting the former technique are expensive, and the main drawback of this promising technique is the limited scan field of existing probes [2]. Consequently, most current 3D ultrasound systems adopt the latter. This technique can be concretely classified into two approaches, as the mechanical scanning and freehand techniques. Attaching the receiver of a position sensor to the probe of a conventional ultrasound scanner, we can use freehand technique to obtain arbitrary volumes. Freehand systems are cheap, and they are also convenient to use. For these reasons, research into freehand technique is very active [3].

Investigations on freehand 3D ultrasound imaging have being carried through for more than a decade. Several commercial systems have become available, like *Invivo ScanNt* developed by *Fraunhofer IGD* [4]. There are also many freehand systems developed for study by research groups, like *Stradx* [5]. Despite identified benefits, however, these systems separate the scanning and reconstruction steps from the visualization step, which makes the acquisition and reconstruction progress invisible. Using these systems, the operator can only scan by experience, and the 3D images obtained do not always satisfy the demands of specific diagnoses. The clinician needs to get hold of as much detailed information as possible about the diagnosed tissue so as to educe a more accurate diagnosis outcome. Therefore, the clinician expects to know which parts of the tissue have been reconstructed and which parts need further reconstruction in real time during scanning process, so that he can scan interactively to obtain a relatively integrated 3D image for accurate diagnosis. This requires the system to provide real-time and interactive (RAI) feedbacks to guide the operator to scan.

Many researchers have been devoted to developing RAI freehand systems to fulfill this requirement, and several approaches that enable real-time volume reconstruction and visualization during acquisition are now available. Edwards et al. [6] developed an interactive 3D ultrasound system, which employed a powerful programmable multimedia processing board to perform volume acquisition, reconstruction and visualization in a single platform. Welch et al. [7] developed a real-time freehand 3D ultrasound system for image-guided surgery. The system allows real-time updates to the scanned volume data as well as the capability to simultaneously view crosses-sections through the volume and a volume-rendered perspective view. Gobbi and Peters [8] described a technique whereby the 3D reconstruction occurred in real time as the data was acquired, and where the operator could view the progress of the reconstruction on three orthogonal slice views through the ultrasound volume. Though providing the qualitative feedback, i.e., views of the RV, nevertheless, current RAI freehand techniques do not pay attention to providing the quantitative feedback on volume reconstruction. Consequently, much effective information is omitted.

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In this paper, our primary focus is to demonstrate how both qualitative and quantitative feedbacks on volume reconstruction can be provided by the QAQIT in real time during acquisition. We also indicate the interactive nature of the QAQIT that allows the operator to scan interactively to obtain a relatively integrated 3D image.

II. MATERIALS AND METHODS

A. Hardware and software

For image acquisition, we use a WEUT-70X ultrasound scanner with a 3.5 MHz curved-array probe. The scanner enables simultaneous video output of the latest acquired image and acquisition of the new image. Videos are captured and digitized into discrete 2D images at 25 frames/s by a video frame grabber (OK_M10A). An electromagnetic position sensor is used to track the PAO of the probe. A 3.0 GHz Pentium IV PC, as the core of the hardware, performs matching, reconstruction, visualization and so on.

Besides the key custom 3D reconstruction C++ module, our software platform uses a module provided by our Medical Imaging Toolkit (MITK) [9; 10] for volume rendering and a well-designed application framework written in QT [11] for the user interface. Integrating the acquisition, 3D reconstruction and display modules together into the user interface, we can achieve correspondingly full interaction with volume reconstruction in real time.

B. Overall method

Figure 1 illustrates the overall method of the QAQIT. During the scanning process, on the one hand, the video frame grabber captures video outputs of the ultrasound scanner and delivers digitized 2D images to the memory of the PC sequentially; on the other hand, the PC continuously reads positions and orientations from the position sensor into its memory. These two aspects are parallel. The PC matches the latest acquired image with its relative PAO in real time, and then performs 3D reconstruction of this image if the matching is successful. After 3D reconstruction of each 2D image, the PC updates qualitative and quantitative feedbacks, and then returns to matching phase. Thereinafter, we expatiate in detail.

C. 3D reconstruction

As a whole, our reconstruction method can be broken into two stages: coordinate transformation of 2D image pixels and resampling to these pixels in the reconstruction volume space (RVS). The RVS is defined as a cuboid bounding box, which encompasses the region of interest (ROI).

1) Coordinate transformation

The reconstruction process relates to four coordinate systems. P is the coordinate system attached to every B-Scan slice. R and T are the coordinate systems of the receiver and transmitter of the position sensor respectively. C is the coordinate system of the RVS. Following the notation provided by Prager et al. [12], the whole transformation can

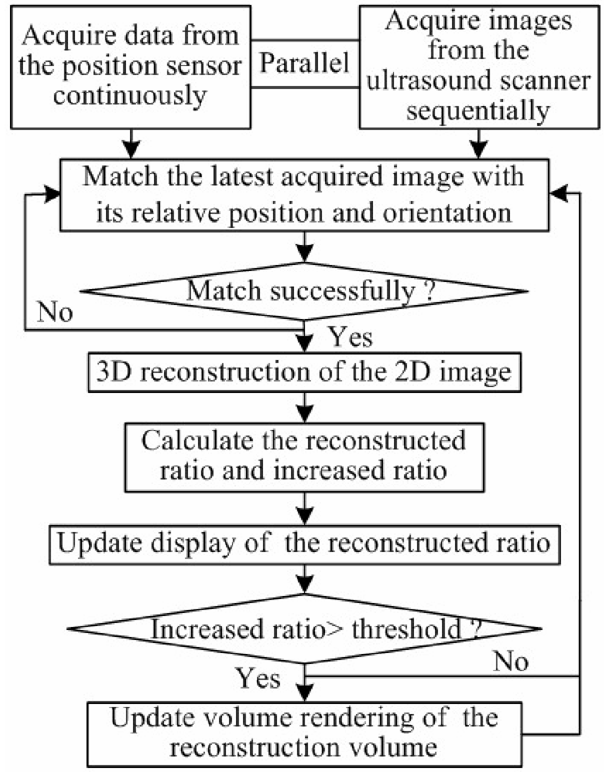

Fig.1. Flow chart of the overall method

be written as:

$$C_X = {}^C T_T \cdot {}^T T_R \cdot {}^R T_P \cdot {}^P X \,. \tag{1}$$

Where ${}^P X$ is the position of each pixel in the coordinate system P. ${}^R T_P$, ${}^T T_R$, and ${}^C T_T$ can be written as a uniform format ${}^J T_I$, which expresses the transformation from coordinate system I to coordinate system J. C_X is the position of each pixel in the coordinate system C.

In (1), ${}^P X$ is known. ${}^R T_P$ can be determined by spatial calibration, and ${}^C T_T$ is chosen as a matter of convenience. Both of them can be predefined before reconstruction, and remain constant throughout the reconstruction process. ${}^T T_R$ can be figured out with the six degree-of-freedom parameters that are read directly from the position sensor. As a result, once obtaining the relative PAO of the latest acquired image, we can perform the coordinate transformation.

2) Matching

For matching, great accuracy can be achieved by interpolating the position between the readings just before and just after each image is acquired [3]. We implement a circular buffer with ten items and employ three recurrent threads to match the latest acquired image with its relative PAO. The ten most recent readings acquired from the position sensor, with their relative time-stamps, are stored into the circular buffer circularly. Three threads are as follows:

Position acquisition thread: To read the PAO information from the position sensor, and store the reading, along with its calibrated time-stamp noted as T_P, into the pre-allocated circular buffer in the PC's memory.

Image acquisition thread: To obtain a 2D image through the video frame grabber, and place the image, along with its calibrated time-stamp noted as T_I, into the memory of the PC.

Matching thread: If T_I is between the smallest T_P and the biggest T_P in the circular buffer, to match the latest acquired image to one of the ten possible intervals in the circular buffer using a binary search, and then calculate the precise PAO by linear interpolation. If T_I exceeds the biggest T_P, to superadd a new reading, and then linearly interpolate the PAO with the new reading and the reading that is corresponding to the biggest T_P. To perform reconstruction of the acquired image if one of these two instances occurs. Otherwise, to discard the current image and wait for the next acquired image. During our experiments, the probability of the first instance was more than 99%, and the last instance never happened.

3) Resampling

Via the matching thread, we obtain the relative PAO of the latest acquired image. Then, by (1), we gain the position of each pixel in the coordinate system *C*. Following, we can perform resampling in the RVS, i.e., to distribute each pixel value of the image onto the appropriate voxel. We utilize the pixel nearest neighbour (PNN) method presented by Rohling et al. [13] to resample each pixel of the image into the RV.

The RV is a discrete modality of the RVS, and in the form of a regular 3D voxel array. The volume size and voxel size are apriori chosen. Two buffers which are the same size as the RV, noted as **A** and **C** respectively, are pre-allocated. Each voxel value of the RV is stored on the corresponding voxel position in **A**. The corresponding voxel position in **C** contains the number of pixels that have contributed to the value of this voxel. The value of each item in **A** and **C** is initialized to zero.

Assume $V(i, j, k)$ is a voxel in the RV, and its counterparts in **A** and **C** are $A(i, j, k)$ and $C(i, j, k)$ respectively. Provided the value of a pixel is $P(u, v)$, and the nearest voxel around this pixel is $V(m, n, l)$. Then this pixel can be resampled into the RV using the following sequence of steps:

1) $$A(m,n,l) \leftarrow \frac{C(m,n,l)\cdot A(m,n,l)+P(u,v)}{C(m,n,l)+1}.$$

2) $$C(m,n,l) \leftarrow C(m,n,l)+1.$$

Simultaneously, the voxel $V(m, n, l)$ is filled or compounded as well. After all pixels of the 2D image are resampled, the 3D reconstruction of this 2D image is accomplished.

D. Qualitative and quantitative interaction

After the 3D reconstruction of the latest acquired image, we calculate the RR and IR of the RV, then update the display of the RR, and drive the volume rendering of the RV according to the IR. The algorithm can be elaborated as follows:

1) Assume the volume's total number of voxels is N_T.
2) Assume the number of the filled voxels, at current time, is N_C. **C** is used to detect whether a voxel is filled, i.e., if the value of the corresponding voxel position in **C** is zero, then the voxel is not filled. The initial value of N_C is zero.
3) Assume the number of the filled voxels, when volume rendering was driven last time, was N_L. The initial value of N_L is zero.
4) Assume the threshold which is used as a gate to re-render the RV is T_H, e.g., 2%.
5) When resampling an acquired image into the RV, once a new voxel is filled, increase N_C by 1.
6) After the resampling to this 2D image, calculate the RR and IR as follows:
   a) $RR = N_C / N_T$.
   b) $IR = (N_C - N_L) / N_T$.
7) Update the display of the RR to provide the quantitative feedback.
8) If $IR > T_H$, let $N_L = N_C$, then update the volume rendering of the RV to provide the qualitative feedback.
9) Return to the matching thread.

These qualitative and quantitative feedbacks allow us to interact fully with volume reconstruction. During the scanning process, we can know where has been reconstructed and where still needs to be reconstructed in approximately real time depending on the qualitative visual feedback, so that we can flexibly alter our scan strategy. Simultaneously, through the display of the RR, we can quantitatively know the rate of progress of the volume reconstruction. This quantitative feedback also provides another alternative for us to determine when to terminate scanning.

III. Results

We designed an experiment to demonstrate the interactive nature of the QAQIT. The experimental materials are shown in figure 2, and the experimental steps are as follows:

1) Use a water bath, i.e., a plastic container with water, to simulate the body surroundings of a fetus.
2) Use a plastic elephant to simulate the fetus.
3) Tie a string at each end of the plastic elephant, and stick the two strings on the plastic container so that the plastic elephant can hang underwater.
4) Utilize our freehand system that has been developed based on the QAQIT to perform 3D ultrasound imaging of the embryo phantom interactively.

The size of the RV was $200 \times 200 \times 200$, and the size of the voxel was 0.5 mm in each dimension. The 2D image acquired for reconstruction was at 552×274 resolution, and the size of the pixel was 0.35 mm $\times$ 0.4 mm. T_H can be chosen interactively. If T_H is zero, volume rendering of the RV is updated after the reconstruction of each image, however it costs much time to finish scanning. If T_H is 1, no volume rendering is driven during reconstruction. We took 5% as a trade-off between real-time feedbacks and scan time.

Fig.2. Experimental materials: water bath (left) and embryo phantom (right)

Figure 3 shows the qualitative and quantitative feedbacks on the volume reconstruction when the RR was 32%, 68%, 84% and 95% respectively. The RR can reach 100% in theory. Nevertheless, we found the increase rate of the RR became small when the RR exceeded 95%. That's because the rest of the voxels were very difficult to intersect by B-scan slice. However, the reconstructed 3D image was comparatively sufficient for vision at that time. Therefore, we terminated scanning when the RR reached 97% and obtained a relatively integrated 3D image. Interpolation may not be necessary in this circumstance because voxels were almost filled. We archived the 3D image as a standard medicine image file and managed it by our 3D Medical Image Processing and Analyzing Platform (3DMed) [14]. Figure 4 and 5 show portion processing results on 3DMed.

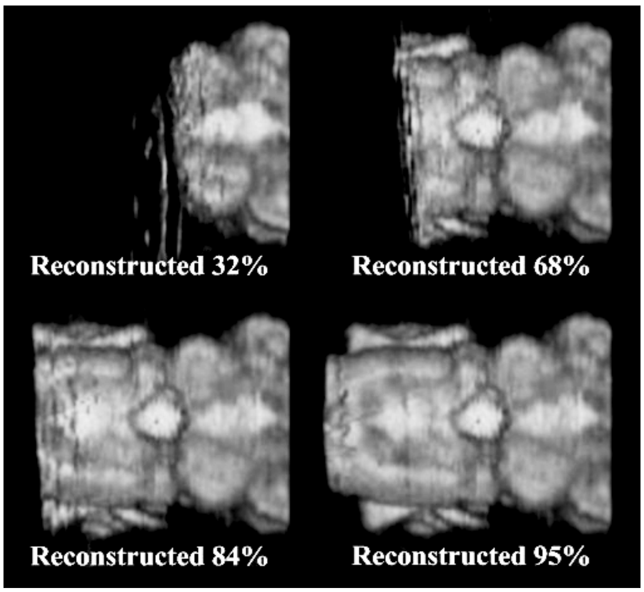

Fig.3. Dynamic feedbacks on the volume reconstruction

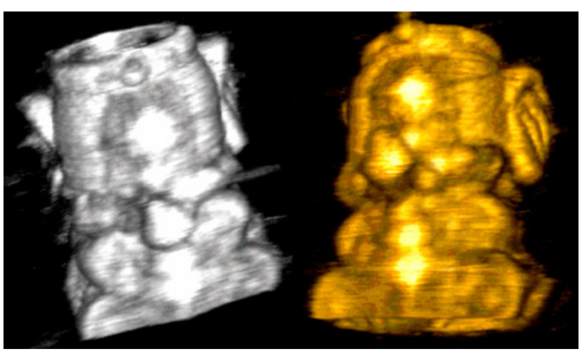

Fig.4. Volume rendering results

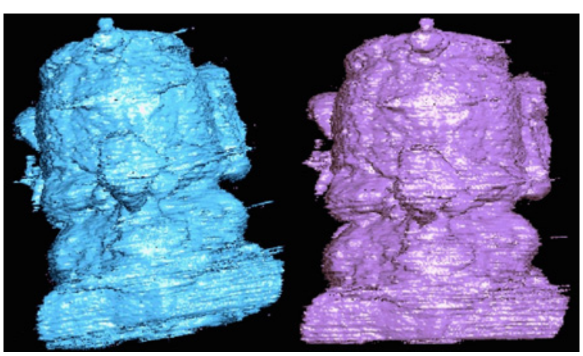

Fig.5. Surface rendering results

Quantitative performances of the system were worked out through ten repeated trials. Each 2D image was reconstructed at about 43 ms/frame (23 frames/s). It basically depends on the size of the 2D image. The RV was incrementally reconstructed at 80 ms/frame (12.5 frames/s) on average. It depends on the volume rendering rate and T_H. It cost 70 s on average when the RR reached 95%. The alteration mainly relies on the scan strategy.

IV. Conclusion and Future Work

We have introduced a quantum idea into RAI freehand 3D ultrasound imaging, and demonstrated a QAQIT which can provide both qualitative and quantitative feedbacks on volume reconstruction in real time during acquisition. Through the dynamically displayed volume rendering image of the RV and the sequentially displayed RR, both provided by the QAQIT, the operator can scan interactively to obtain a relatively integrated 3D image. A novel approach has been used to update the volume rendering of the RV. This approach is possible to achieve an optimal trade-off between scan time and real-time feedbacks. Our future work is to make more inherent characteristics of RAI freehand 3D ultrasound imaging by the QAQIT.

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