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Mobile 3D augmented-reality system for ultrasound applications

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***Abstract*—Ultrasound imaging is a highly valuable diagnostic tool. It is increasingly portable, provides real-time imaging of complex structures, and is considered safe. Yet, because ultrasound is a highly operator dependent modality the uptake of ultrasound within a broader range of medical contexts has been limited and hasn't made major inroads within the offices of General Practitioners, Midwives, and other non-specialists. Learning to effectively use ultrasound can easily take up to 12 months with direct expert supervision.**

To facilitate wider adoption of ultrasound technology we are attempting to determine if using augmented-reality can speed up the process of learning to use ultrasound by providing a patient specific correspondence between the ultrasound data acquired in real-time and a sufficiently detailed augmented 3D scene.

We have established a tablet-based system for visualizing the heart within a patients body using augmented-reality techniques in conjunction with the streaming data provided by a GE Vivid E9 ultrasound machine. This system gives the operator visual feedback as to the location of the heart within the body, the anatomical features the echo plane is intersecting and if the operator is currently tracking the left-ventricle.

I. INTRODUCTION

The difficulty of the ultrasound modality is the requirement that the operator acquire images of specific anatomical structures images oriented correctly and clear enough to be of acceptable diagnostic quality. Anyone without the adequate training is unlikely to acquire for example an apical image of the heart and certainly not an image of high diagnostic value. However, there are a wide range of potential users of ultrasound outside of specialists, technicians and radiologists that could derive great benefit if they could leverage this technology.

Visual guidance during data acquisition, which shows the relationship between the anatomy being imaged and the position of the scan plane, is one way of alleviating the image acquisition and interpretation difficulties. This technique is commonly referred to as augmented-reality and utilizes a variety of computer vision and display techniques to give the diagnostic data real-world points of reference.

Augmented-reality systems have been used for some time in support of clinical research and practice. For example, the support of a complete surgical workflow (pre-, intra- and post-operative) in [1] as part of the larger ARIS*ER project. Also from this project [2] combined pre-operative CT images with live ultrasound data during radio-frequency ablation of liver tumors. The Sonic Flashlight [3] employs a half-silvered mirror to project ultrasound images directly on the patient's body creating a compelling virtual view inside the body. [4] and [5] rely on a head-mounted display (VR goggles) to integrate ultrasound images into a 3D scene. [6] or projector-based setups [7] are typically a pre-requisite for augmentation purposes and this will cause interference with the usual clinical workflow.

The goal of our research, entitled SmartScan, is to provide diagnostic or teaching assistance, extending the past research concepts, while trying not to complicate the clinical workflow by adding a multiplicity of new and potentially expensive equipment.

II. MATERIALS AND METHODS

We use a general purpose tablet devices, based on Apple's iOS or Google's Android, to capture the scene using the built-in forward or rear facing camera and merge it with 3D rendered objects and data streamed from the ultrasound machine.

A. SmartScan - iOS and Android app

The SmartScan app has been written using a combination of platform specific development tools (eg. Xcode, Eclipse) for the front-end and a common C++ and OpenGL backend.

1) Basic framemarker tracking: A single-camera augmented-reality system relies on the calibration of the camera to create the matching 3D coordinate space or projection matrix for the virtual objects on screen. By adopting the Vuforia augmented-reality framework from Qualcomm we avoid the time consuming job of calibrating each camera on each new device. This camera calibration is then used to directly construct an OpenGL

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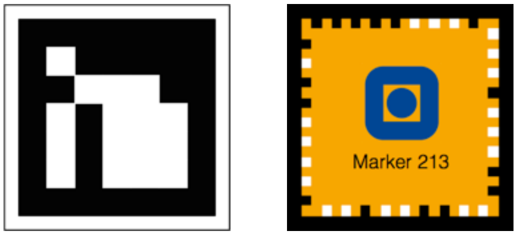
Projection Matrix and apply it to each OpenGL object on screen. The exception to this rule is the background or camera image stream which uses a straight orthographic projection with some aspect ratio correction depending on the similarity of the video and screen aspect ratios.

Vuforia has many types of built-in object tracking systems, but for this phase of our work we continue using specially encoded square markers commonly referred to as framemarkers [Figure 1]. We previously implemented a custom marker identification [Figure 1a] and tracking system using hamming codes and OpenCV, but we found the Vuforia framemarkers [Figure 1b] to track more consistently in varied lighting conditions. When the app is running and a registered framemarker is visible we stream the pose matrix of the framemarker to the backend and route the matrix to the correct 3D object based upon a simple numeric identifier. This framemarker pose matrix is applied to the Model View of the object and causes the object to move into position relative to that marker in a convincingly realistic fashion.



(a) Hamming-code (b) Vuforia

Fig. 1: Typical Framemarkers

2) Rendering the scene: Vuforia normally handles the rendering of the entire scene or alternatively in conjunction with with a game engine like Unity, but we employ a different framework for scene rendering based upon VES-Kiwi from Kitware. We have removed most of the automated handling of the projection matrix and camera from the framework and rely on the support classes for importing complicated data types. For example, we use the built-in classes to load the Wavefront Object File (.obj) and textures that represents our 3D heart model.

Vuforia controls the camera on both platforms capturing each frame of the video stream and passing it to the VES-Kiwi backend for display as well as the pose of any framemarker within the scene. Once iOS/Android, Vuforia and VES-Kiwi are integrated correctly you can move a framemarker in front of the camera, see the 3D object it represents, and watch it follow the marker's pose in real-time.

B. Cardiac ultrasound

1) GE Vivid E9 scanner plugin: Leveraging our augmented-reality marker tracking and streaming ultrasound data we can visualize the 2D echo plane, render the measured left ventricle volume within the heart model, and deform the heart model in sync with the beating heart. To achieve this we stream data from a GE Vivid E9 ultrasound machine with a 4V-D probe. A custom scanner plugin was implemented, its purpose being to stream the 2D B-Mode ultrasound image for rendering in the scene, the tracking score and anatomical landmarks generated by an extended Kalman filter [8] referred to as Real-time Contour Tracking Library (RCTL). The 4V-D probe is currently required for RCTL to capture the 3D volume.

RCTL fits a deformable reference model to the live ultrasound volumes, e.g. the left ventricle, and computes a tracking score that indicates the confidence of a given fit. A coupled model, depicted in [Figure 2], consisting of three geometric models representing the left ventricle (LV), the LV outflow tract and part of the anterior wall of the right ventricle is fitted to each data frame. A tracking score (i.e. a value in the interval [0 ... 100%]) is also computed as the percent of successful edge detections versus the overall number of edge detection attempts for the given geometric models. A low tracking score is indicative of a poor fit and is typically caused by the absence of valid 3D data (e.g. no contact of the transducer with the subject, wrong acoustic window) or a very poor quality view [9].

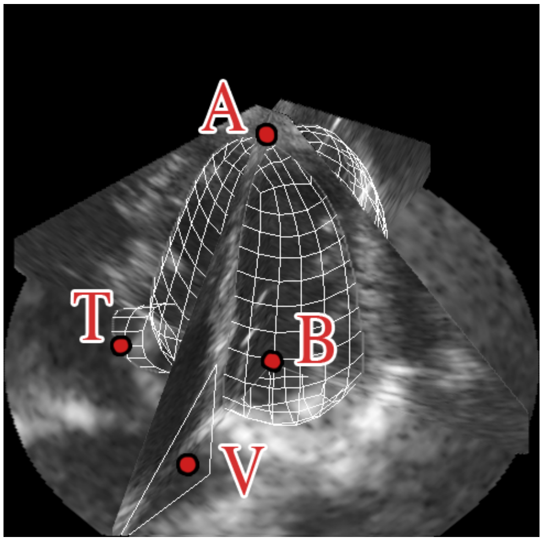


Fig. 2: Wire-frame view of the coupled deformable model of the left ventricle, with the four anatomic landmarks depicted as red spheres.

Based on the model fit, the positions of four anatomic landmarks can be computed automatically for each 3D frame [8]. The anatomic landmarks generated represent the apex of the left ventricle $A(x, y, z)$, the base of the left ventricle $B(x, y, z)$ assumed as the center of the mitral ring, the middle of the aortic outflow tract $T(x, y, z)$ and $V(x, y, z)$ a point situated on the inferior right ventricle wall [Figure 2].

For each 3D ultrasound volume acquired by the scanner the image plane corresponding to the 0° elevation is also extracted from the 3D data and resampled to a Cartesian grid. Finally, a structure containing the image plane together with the landmarks and the tracking score is sent to the tablet device, over WiFi.

2) Dynamically deforming the heart model: By combining the SmartScan app with the data acquired from the ultrasound machine we can now render the scene shown in [Figure 3].

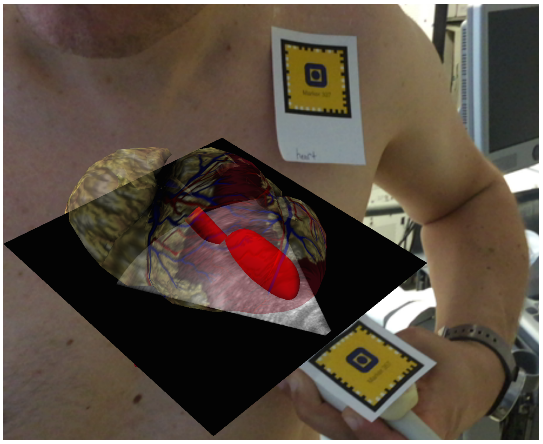


Fig. 3: Typical SmartScan scene where the echo plane, LV volume and semi-transparent heart are visible.

The final touch is to deform the 3D heart model in real-time, in sync with the beating heart. In [10] we established a kinematic heart model [Figure 4] that simulates the movement of the AV plane. The movement is realized in the OpenGL vertex shader by holding the H_{apex} and H_{base} position constant and translating the vertices indicated by M and LV_{base} in [Figure 4].

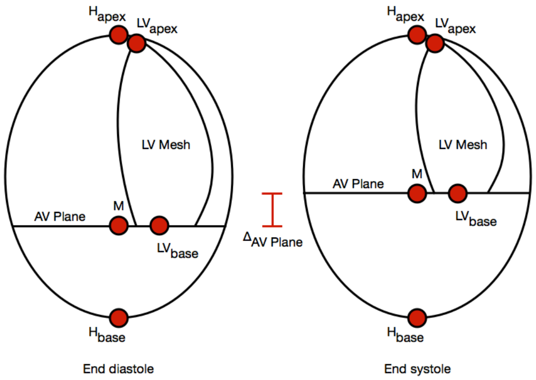


Fig. 4: Cross-sectional four chamber view, the simplified kinematic model for the whole heart and left ventricle. In the given view, LV_{apex} and LV_{base} are tracked automatically, while H_{apex}, M, and H_{base} were manually identified on the model.

3) Fetal ultrasound: A fetal version of SmartScan has been prototyped using the same basic principle, namely tracking a framemarker attached to a curvilinear probe and one on the patient. The prototype of the tracking and the rendering of the 3D fetal model can be seen in [Figure 5].

III. Experiments and Results

We measured the performance of the framemarker tracking using both our tracking software and Vuforia. In the 15 to 100 cm range, the typical range of our application, using ambient room lighting. Both the depth and rotational accuracy of the system were evaluated by placing the frame marker at 15, 20, 30, 60, and 100 cm and at three different axis angles (0 and ±30°). The experimental setup used for evaluation can be seen in [Figure 6]. For our framemarker tracking code the computed mean angle error and standard deviation for a camera distance 15-30 cm are -1.60 ±2.85° while overall +0.32 ±4.60° which is reasonable when compared to the 2° elevation resolution of the cardiac probe. Distance tracking accuracy for 15-30 cm is 0.62 ±0.56 cm and overall +0.65 ±2.31cm. The Vuforia tracking accuracy is consistently good over the entire range of depth values with the error mean and standard deviation of -0.31 cm ±0.38 cm. The mean angle error and standard deviation are $-0.05° \pm 1.77°$, $2.91° \pm 0.29°$ and $-3.39° \pm 0.15°$ for an Y-axis angle of $0°$, $-30°$ and $30°$ respectively. The tracking evaluation was performed in realtime on an iPhone 5S.

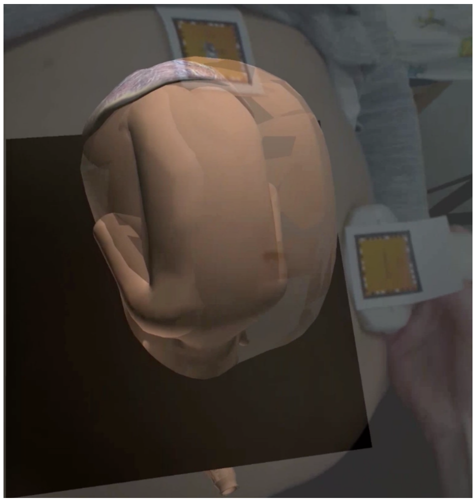


Fig. 5: Fetal model and echo plane rendered with respect to their markers.

When using the system the patient lies on the examination table either flat on their back or on their side facing away from the examiner. The examiner sits to the patients right on a stool or edge of the table. The tablet and stand are on the patient's left-side angled so the front-facing camera can acquire the marker attached to the patient representing the heart and still capturing the area of interest while still affording the examiner with a view of the augmented scene. Optionally, you can send the scene to a larger display for group viewing using an Apple TV or Chromecast. The tablet stand is a König & Meyer boom microphone stand, gooseneck and generic tablet holder. This is the most examination table friendly stand found to date. The ultrasound machine is placed in the usual location on the same side as the examiner, opposite the tablet. This arrangement is in support of our requirement not to introduce any unnecessary modifications to existing examination practice. During the examination they can toggle on-off the display of the heart, echo plane, left-

Fig. 6: Depth and rotational accuracy experimental setup.

ventricle volume and change the opacity of the heart model with a slider. The 4V-D probe has a marker attached about 8 cm down the handle so that it isn't in the way of the examiner's hand. This marker and the measured distance to the top of the transducer is used to display the echo plane in the scene as if it is radiating out from the transducer's tip. Initially, the heart is only roughly located in the vicinity of its real location. After RCTL has locked onto the left-ventricle the heart is translated, rotated and scaled into the correct anatomical position.

The fetal model experiments aren't as far along since we lack RCTL model fitting for the fetus, but we have demonstrated the proof-of-concept and feel that we're on the right track.

IV. Discussion and Conclusions

Throughout the development process of the cardiac version of SmartScan we solicited feedback from our cardiologist to refine the basics of the app. Some of the improvements that came out of the process include more granular control over how the scene is rendered and the acquisition of a more accurate 3D model of the heart. We also tried a couple of different ways of mounting the tablet so that it can both view the patient with the built-in cameras and give the operator a good view of the augmented scene.

The SmartScan project is about to enter broader testing as a teaching aid for medical students, but even without clinical validation we have progressed considerably since the HeartPad experiments. Combining marker tracking with the RCTL LV volume tracking has allowed us to place the heart in the correct anatomical position within the patient's body and show how the echo plane is situated with respect to the 3D heart model without the need for a manual patient registration process. This gives the student quick insight into which anatomical structures they are viewing even if their ability to interpret diagnostic images is not yet fully formed. The LV volume also changes from red to blue when they obtain or lose a good lock on the LV volume which can help the student more quickly acquire the correct transducer position. We believe the SmartScan app has great promise as a teaching aid for both cardiac and fetal ultrasound applications.

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