Affordable Ultrasound Training Simulator

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ABSTRACT

Ultrasound diagnostic skills for medical students and professionals are becoming increasingly important as ultrasound technology has become more portable and effective, but the training to develop these skills is also very expensive due to cost of equipment and the requirement of a human subject. Our goal is to create an inexpensive computer-based augmented reality training simulator to supplement existing hands-on training, in order to allow institutions to more efficiently utilize fewer ultrasound machines for training purposes. Several ultrasound training simulators already exist, but they often require very expensive equipment. To make our training system more accessible and affordable, it is designed to require only a PC with modest video hardware and a motion game controller. Using the Unity3D game engine, we have developed a volumetric raycasting method to render 2D ultrasound images in real-time from 3D mesh models of organ systems. We also investigated various motion game controllers currently available on the market and evaluated pros and cons of each, and found that the PlayStation Move is the most suitable of the controllers we tested.

Categories and Subject Descriptors

I.6.8 **[Simulation]**: Types of Simulation – *visual.*

J.3 [**Computer Applications]**: Life and Medical Sciences – *Health*.

General Terms

Documentation, Design

Keywords

Ultrasound, imaging, training, game controller, game engine

1. INTRODUCTION

As portable ultrasound technology has improved and decreased in cost, the opportunity for use of these devices has increased in several fields of medicine. Most notably, portable ultrasound devices can be used for field diagnosis in many emergency medical situations, including disaster relief, military conflict, and general first-response [1]. It has therefore become very beneficial for any individual who is training for a medical career, including as an EMT or nurse, to become familiar with diagnostic medical ultrasound procedures, as well as the use and function of ultrasound devices in general.

Although the cost of portable ultrasound devices has significantly decreased over the past few decades, units can still cost tens of thousands of dollars. For example, even the very basic Sonosite Titan is priced at $16,999, while a more complex system like the GE Logiq E is priced at $29,999 [2]. It can still be quite cost-prohibitive for organizations to purchase multiple units solely for educational purposes, and also difficult to find human subjects to use for instruction. The general trend in medical education has been to supplement hands-on training with computer-based simulation to provide more comprehensive training and to improve patient safety [3]. For these reasons, we are developing an augmented reality ultrasound training simulation that requires only a motion-sensor video game controller (<$100) and a PC with modest video hardware. Such a simulation can supplement other training and enable students to establish a familiarity with ultrasound diagnosis procedures before they get hands-on training with a real device and a real human subject. Ideally, this supplementary training would allow educational organizations to more efficiently utilize a smaller number of devices and subjects, thereby cutting costs while still providing effective training.

The benefits from ultrasound training also go beyond direct applications in ultrasound diagnosis. A 2007 study showed that ultrasound training for first year medical students was effective in giving the students an overall better understanding of anatomy and examination techniques, even in procedures not involving ultrasound [4]. A training simulator may provide similar benefits as a broad educational tool, but at a drastically lower cost than a real ultrasound machine.

This project also has potential implications about medical simulations in general. Many virtual/augmented reality training systems exist and are highly effective for professional training, but most of these systems rely on costly input controllers and sometimes other proprietary devices. Consequently, these systems are rather expensive and are virtually completely inaccessible to the general public. By demonstrating that an effective training tool can be developed to utilize a widely-available and highly-affordable game controller, we hope that future developers of similar training simulations will also consider using a game controller to make their projects more accessible and economical to the end user.

For the simulator to be most effective, it is important that a suitable motion controller is selected to use with the simulator. The goal of any training simulator is immersion-based learning, similar to the sort of immersion for which game designers strive. Research has shown that gaming immersion can be greatly augmented with a natural, realistic controller [5]. It is for this reason that a one-to-one motion controller is preferred, with 3D movement and rotation being directly linked to physical movement by the user. In addition, it is critical that the controller be precise enough that the user can perform natural movements without being inhibited by poor motion precision or noise in the controller's motion detection.

It is important to note that the purpose of this project is not to develop a highly-realistic ultrasound imaging engine, but rather to develop a flexible, tangible, and accessible training simulator to help users develop the spatial cognition skills and hand-eye coordination required to effectively use and interpret ultrasound devices. While high-realism ultrasound image generation software is very useful for reference, we have chosen to forgo high-realism and have used much simpler models and methods so that the simulator can run in real-time on a personal computer at a reasonable frame rate.

2. BACKGROUND

2.1 Medical Ultrasound Techniques

An ultrasound probe functions by transmitting and detecting ultrasound pulses using an array of piezoelectric transducers. Tissues inside the body reflect or absorb the sound pulses, and an image is generated based on the amplitude of these detected reflections as a function of the depth (time delay) of the echo. In the case of a two-dimensional scan, an array of transducers is used so that the sound can be transmitted on individual angles along an arc, where the data collected from each angle is referred to as a scanline [6].

The interaction between tissue and the ultrasound pulses is a highly complex three-dimensional physical process, and it is difficult (both in terms of mathematical complexity and computational cost) to attempt to simulate the reflection and scattering behavior within any heterogeneous medium [7]. Currently, even highly-optimized algorithms require expensive processing hardware to run in a reasonable amount of time, and would still not feasibly be able to run in real-time [8] [9] [10].

For our purposes, it makes more sense to focus on directly generating the end result (a 2D cross-section) rather than to devote resources toward modeling a complex physical process. Volumetric raycasting is a graphical method to directly generate a 2D projection of a 3D object, and it can be easily implemented with Unity3D's built-in raycasting library to create a cross section. This simple approach, however, creates an image that is "too good", lacking many of the imperfections that characterize an actual ultrasound image, such as speckle, acoustic shadowing, and other acoustic artifacts.

Speckle refers to noise that appears in the ultrasound image, caused by very small scattering elements. In a real ultrasound setting, it is not usually possible to identify the source of these artifacts. Therefore, it is not important that speckle be realistically simulated; instead, the characteristic appearance of speckle in an ultrasound image may be sufficiently imitated by adding visual noise to the final image. Acoustic shadowing is caused by high absorption or reflection levels of a structure (such as a bone or a lung), preventing sound from reaching other objects behind the obscuring structure; consequently, objects behind the obscuring structure do not produce any echoes. This is an important limitation in ultrasound diagnosis, as it prevents certain orientations from being viable examination points (e.g. through the ribcage). Acoustic shadowing can also be important for diagnosing certain abnormalities, such as kidney stones. It is therefore important to include an acoustic shadowing component in our ultrasound simulator. There are a number of other types of artifacts (such as artifacts triggered by reverberation, overpenetration, and sound velocity differences) that may be useful to simulate for specific scenarios, but are not crucial to basic simulation [6].

2.2 Overview of Related Work

There are some existing commercially- and academically-developed ultrasound simulation systems using a variety of image-generation techniques. Many of these systems have been already been demonstrated to be effective in improving professional and student performance [4] [11] [14].

One very similar system to ours is one in development at the LUMS School of Science and Engineering, where the goal was to create an inexpensive and flexible training simulation [12]. Their system does not dynamically generate any images, but instead relies on having a library of actual ultrasound imagery for each scenario. This means that they must record a single image corresponding to every possible position and orientation of the ultrasound probe. To prevent the image library from being too large, only a limited number of positions around the target area are available for each scenario, whereas real-time image generation can dynamically generate any position or orientation desired without storage constraints. Their system also has the disadvantage of having to devote a significant amount of time recording ultrasound data for every desired scenario, whereas mesh models are more readily modifiable.

Another comparable simulation of interest is one developed at University of Leeds, specifically for ultrasound-guided needle insertion [13] [14]. While it is different from our system in that it is designed to simulate a specific set of procedures and in that it simulates two virtual objects (both a needle and ultrasound probe), the imaging process is relevant. It does generate images in real-time by rastering a voxel model generated from a CT dataset, and using 3D volumetric texture mapping to shade the generated image. A ray-casting method is also used as an acoustic shadowing component. Their image generation process also makes use of an alpha-blending radial blur effect to make a more realistic image. However, it utilizes a highly expensive motion sensing system and so would be cost-prohibitive for general use.

3. METHODS

Our simulator is built using the Unity3D game engine, and the development process has focused on three areas: image simulation, modeling and textures, and user input.

3.1 Image Simulation

The ultrasound display simulation is the most important component of the simulator. The software simulates a 2D brightness-modulation (B-mode 2D) ultrasound scanning system. A b-mode 2D scan effectively generates a 2D cross-section or "slice" of a 3D model. In our system, that 2D slice will ultimately be drawn onto a 2D texture to represent a display. To generate the slice, a volumetric raycasting procedure is used. Rays are cast iteratively over a range of angles in a 2D projection plane from the virtual ultrasound probe. Since we are working with mesh-based models rather than voxel-based models, the raycasting detects only the edges of the objects and generates a line between collinear enter and exit points on the surface of the model. When these lines are drawn to a display texture, a composite image of the cross-section is generated (see Fig. 1 & 2).

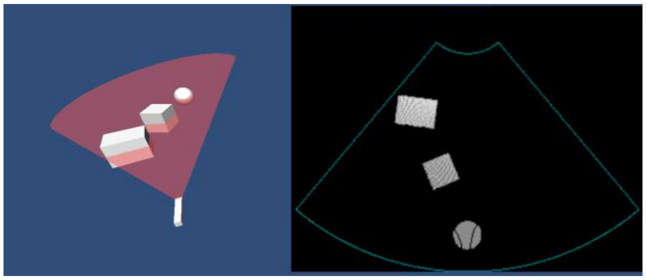

Fig. 1 - (Left) An example scene with a few simple objects in 3D space, with an approximate projection arc drawn in with an image editor. (Right) A screenshot of a cross section generated from a volumetric raycast of the objects to the left.

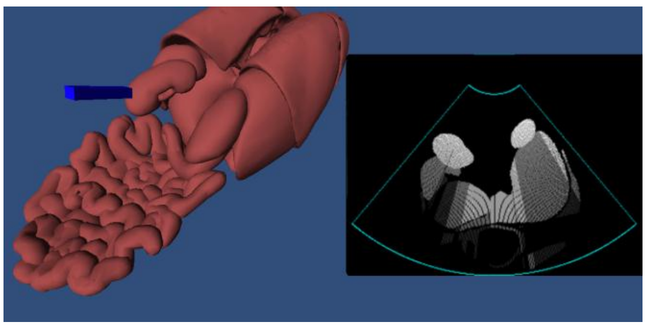

Fig. 2 - An example scene with the probe and a few organs from the BodyParts3D library [15]. The generated cross section (with placeholder acoustic shadowing, but without any texturing or post-processing applied) is rendered in real-time on a display texture on the right.

The raycasting also uses a simple Reflection/Absorption model to shade the image. Every model has corresponding Reflection (R) and Absorption (A) values, which are based on behavior of the organ or structure the model actually represents. For each individual scanline, a raycast strength variable (S) simulates the decay of amplitude of an ultrasound pulse. S is initially 1.00 when starting on a scanline, but is diminished by each collision with an object. This effect is modeled by the following equation 1, where S0 is the raycast strength prior to the collision, and S1 is the new strength for the next collision along this scanline.

$$S_1 = S_0 - (R + A) \quad \text{(Eq. 1)}$$

The raycast, on collision with an object, also records an alpha modifier (α) based on S0 as well as the absorption and reflection values of the object collided with. The alpha modifier will affect the transparency of the line when it is drawn to the display texture (i.e. a lower alpha modifier will cause part of the final image to appear darker). Specifically, for each collision:

$$\alpha = S_0 + R - A \quad \text{(Eq. 2)}$$

For example, an abnormal object like a kidney stone may have a high reflection value (R = 0.80) and a moderate absorption value (A = 0.15). The stone will then be colored brightly in the image (from Eq.2, $\alpha = S_0 + 0.80 - 0.15$), but almost completely mask any objects behind it (from Eq.1, $S_1 = S_0 - (0.80 + 0.15)$), creating an acoustic shadowing effect. Another example would be a bone structure, which may have a lower reflection value (0.05) and a high absorption value (0.75). The bone would then appear dark in the image and also mask objects behind it.

After the display texture has been generated from the volumetric raycasting, other post-processing visual effects can be added. For example, low-level image noise can simulate speckle effects, and a radial motion blur can also create a more realistic image [13].

3.2 Models and Textures

Any number of individual mesh-based models is used to generate a single scenario in the simulator. Currently, we are utilizing the BodyParts3D database of anatomically-accurate mesh models [15] for building a stock scenario. However, these organ models only represent a single perfectly healthy human body, so it will be useful in the future to modify these models or create new ones to simulate specific abnormalities and ailments. Further work will also need to be done to develop realistic-looking organ-specific textures, as the Reflection/Absorption model only simulates relative brightness of organs, but otherwise creates unrealistic flat-colored shapes.

Each scenario is represented as a single Scene in Unity3D, where the models are imported and centered in the world coordinates, and an ultrasound probe game-object is added to the scene and linked to the motion controller that is actually held by the user.

3.3 Controller Selection

We tested several different commercial game motion-controllers to see how appropriate they would be for our simulator: the Wii MotionPlus Remote, the XBox 360 Kinect, and the PlayStation Move.

The Wii MotionPlus has all the right components to function for our simulator, but was rejected because of fidelity issues. The motion-reading was not nearly precise enough for fine adjustments. The controller also had too much noise - even if held perfectly still, the input still wobbled significantly. Simply put, the Wii MotionPlus was too imprecise for the level of controller immersion that is needed.

Although the Kinect is designed for full-body motion sensing, it can be utilized to track the motion of a single body part (in our case, the hand and wrist) as well. Unfortunately, the Kinect is limited in that it cannot directly track rotation information from the hand and wrist, which would be essential to be able to effectively manipulate the virtual probe. In addition, even if rotation information were to be available, the Kinect can only directly track body parts, not a held object, so a user would not be holding a tangible object that actually controls the virtual ultrasound probe. Therefore the Kinect was not well suited to our project.

The PlayStation Move is a very promising choice, as it supports both rotational and positional tracking. The rotation can be determined via gyroscope readings, and the Move lends itself well to one-to-one motion tracking by using computer vision algorithms. Sony's move.me server application allows a PC to use a Move controller as an input device with both position and rotation tracking. However, move.me requires a full PlayStation 3 system as well as purchase of the move.me service ($100) to perform motion control, and so would probably be cost-prohibitive for many users [16]. Instead, we are considering open-source alternatives. Unimove, a Unity plug-in to interface with the PlayStation Move controllers via Bluetooth, can track the rotation of the controller and detect what buttons are pressed on the controller. However, Unimove lacks any capability to detect position other than by reading accelerometer values, which is too imprecise for one-to-one motion [17]. We are investigating using OpenCV as a framework to track the position of the Move Controller via a webcam. An OpenCV implementation that could accurately track 3D position, in conjunction with Unimove for detecting rotational data, could provide accurate one-to-one motion control.

There are two additional controllers that we have not had the opportunity to test, but are promising and may be useful in further research: the Razer Hydra and the Leap Motion. The Razer Hydra has very high precision, but has an optimal sensitivity at around 2-3 feet from the base station, which may inhibit the effective range of motion to simulate an ultrasound exam [18]. The Leap Motion, while unreleased as of August 2012 (estimated release is Dec. 2012), is also promising as it allows high precision tracking of a user's hands and fingers as well as objects held in the hand [19].

4. ONGOING WORK

While we have developed a good proof-of-concept, a great deal of further development can be done to improve the system:

- Investigate an OpenCV or other computer vision implementation for tracking 3D position of the PlayStation Move controller.
- Implement organ-specific textures to generate a more realistic image and to enable users to more easily identify organs.
- In order to improve the realism of the generated ultrasound image, simulate other acoustic artifacts that appear in ultrasound images [6], either by modifying the volumetric raycasting procedure or by implementing additional post-processing image effects.
- Build a variety of scenarios of normal and abnormal organ systems for use with the simulator.
- Develop further input options to simulate controls and tools in actual ultrasounds - e.g. time-gain compensation, transducer frequency adjustment, calipers, image capture, etc. [6].
- Further optimize the program to allow it to run more readily on more hardware, bringing us closer to our goal of making a simulator that is accessible and affordable to almost anyone.
- Test other game controllers, such as the Razer Hydra, the Leap Motion, and any other new controllers that enter the market.

In addition, since the system will be used for medical training, it will be important that it is properly validated. Validation should involve comparison of simulated images with actual ultrasound images to determine the degree of realism. It will also be necessary to conduct trials to gauge the effectiveness of the simulator as training software.

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