VR-Based Solution for Medical Ultrasounds Training

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Abstract. In today's advanced era of medical science and techniques, acquiring comprehensive knowledge for conducting medical examinations has become increasingly challenging. While theoretical learning remains essential in the medical field, such as when performing ultrasound scans, the demand for practical learning opportunities prior to working with real patients has grown significantly. By leveraging on VR technology, we propose a solution that provide learners with an immersive and realistic environment where they can undergo training in ultrasound scans. This approach aims to simulate the experience of conducting actual scans, enabling learners to develop their skills effectively. In this paper, we describe our solution focusing on the technique we developed to transform any set of DICOM images into visually realistic ultrasound images to be used inside our real-time VR-based training simulation. The use of VR can overcome the financial obstacles associated with procuring expensive equipment for training purposes, while the flexibility of our approach enhances the learning experience by adapting to various scenarios and accommodating different skill levels. Learners can navigate through a range of simulated cases, reinforcing their knowledge and competence in ultrasound techniques.

Keywords: Ultrasound Simulation · Virtual Reality · Practical Learning

1 Introduction

Medical ultrasound is a diagnostic technique used to perform different types of medical examinations. Even if it is not an invasive procedure, a practical learning phase is required to perform it correctly. Nowadays, training possibilities centers around performing ultrasound examinations on animals, human patients, and mannequins that recreate the feeling of having a real patient. By the way, in addition to acquire confidence with the correct motion of the probe, it is fundamental for the trainee to became capable of identifying possible diseases or illnesses within the patient. This is one of the main challenges addressed by our solution, since, due to the scarcity of incidence of some serious diseases that can be identified using ultrasounds, when training on real patients, learners are exposed to a low variability of case studies. In this paper, we address this challenge through computer simulation, by developing an economically affordable solution that leverages on Virtual Reality to offer the learners an immersive environment where they can practice both with the ultrasound probe motion, both on acquiring confidence in diagnostics by having several different available case studies. Moreover, by using a VR solution, the same simulation can be reused to evaluate different aspects of the ultrasound examination skills developed by the learner. The main contribution of this paper, from a technical perspective, is in presenting a novel technique to transform any set of DICOM images from female abdomen and pelvis CT scans in a three-dimensional texture that, during the VR-based training simulation, is sampled in real-time according to the position of the virtual ultrasound probe operated by the learner. The result of the sampling is a 2D texture image that realistically reproduce the standard output of an ultrasound device. Providing the ultrasound device output as this texture image inside a VR-based training simulation will enhance its realism as a learning environment. We tested the proposed technique in a case study application that, running in the Oculus Quest 2 VR headset, recreate a medical environment where it is possible to perform medical ultrasound scanning on a virtual dummy. This paper is organized as follows: in Section 3, we present the state of the art of computer simulations in medical education, focusing on the practice of medical ultrasound, and its today's developments with the use of Virtual and Mixed reality, followed by Section 2, were we discuss methods used to simulate ultrasound devices. Our training environment, used to test the presented VR-based simulation solution is introduced in Section 4, while the method itself is then detailed in Section **??**. Future research directions conclude this paper in Section 5.

2 Ultrasound Simulations

Medical ultrasound imaging leverages on high frequency sound waves. In diagnostic cases, the reflection of these waves is recorded and used to create an image of a patient's internal body structure, measure certain features, or record audible sounds. This is possible thanks to ultrasound waves generated by piezoelectric crystals in the probe itself. When these are electrically excited, they begin to vibrate, generating waves with frequencies of more than 20 kHz that act on the patient's internal structures. The reflected waves are called back echoes, and by scanning them with a computer it is possible to obtain different images depending on the intended use of the ultrasound system. In achieving educational outcomes, computer-based simulators mimic the ultrasound image produced within a computer. The methods to simulate ultrasound images can be categorized into Interpolative, Generative image-based, or Generative model-based. The interpolative approach uses prerecorded three-dimensional ultrasound volumes and slicing techniques, that can be combined with postprocessing like deformations and artificial shadow insertion in the final image [1] [3]. Generative image-based models rely on Machine Learning and Deep learning techniques, Particularly, almost all the approaches to realistically simulate ultrasound images in this way are based on generative adversarial networks (GANs). The generative approach simulates ultrasound images using geometry from imaging systems like computed tomography (CT) and magnetic resonance (MRI), or it is based on mesh models. Generative model-based ultrasound simulators create an image by extracting a bi-dimensional slice from the model and texturizing it. Although this method is very appealing for generating and depicting cases involving different pathologies, modeling, and confirming the model correctness is challenging. The model creation for this approach is more complex than for the interpolative approach because each model needs some preprocessing [4][5]. Another generative model-based technique is based on ray tracing. Multiple ray emissions from the probe are simulated and the intersection points with the three-dimensional mesh model are calculated. Artifacts like shadowing and refractions can be added with postprocessing.

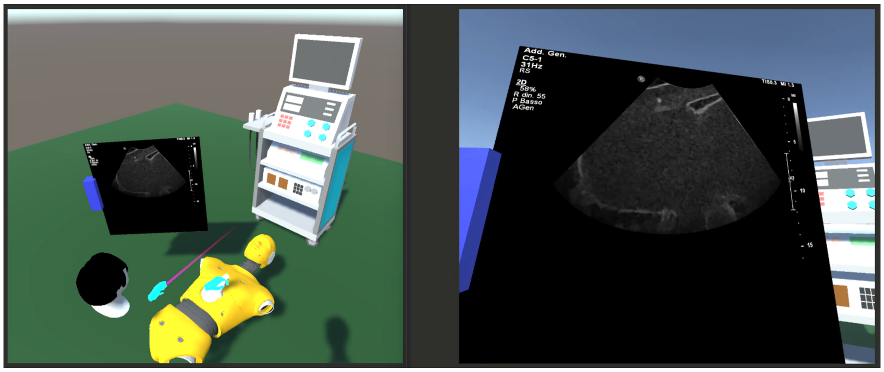
3 Overview of Commercial Solutions for Training

Simulation has the potential to revolutionize skills-based training in healthcare [6]. It enables the systematic development and layering of skills, in contrast to the sporadic training that often happens in clinical settings [9]. An ultrasound simulator is a medical simulation training tool that enables educators and learners to practice diagnostic, therapeutic, and surgical applications as they relate to imaging interventions. With advances in technology and the growing demand for hands-on training opportunities, several commercial solutions have emerged, also for simulated medical ultrasound training [12][13]. In this Section, an overview of the main commercial solutions available on the market is provided, focusing on multi-specialties ultrasound simulators. One of the leading solutions is SonoSim (SonoSim, Inc. USA). It is a portable, light system, consisting of a probe device and an application installed on a personal computer, which emulates the experience of ultrasound scanning without the need for mannequins, as it provides a virtual patient instead [13]. With its extension SonoSim LiveScan, it is possible to transform live volunteers into ultrasound training cases, applying specific tags [11]. UltraSim (MedSim Ltd, Israel) is a large, complete ultrasound simulator for a broad range of specialities, providing an interface that mimics a standard ultrasound system [13]. Another example is represented by VIMEDIX (CAE Healthcare, Canada), a comprehensive ultrasound education mannequin-based platform [13]. Relying also on augmented reality technology, it provides realistic ultrasound images, real-time feedback, and the ability to add variations for more challenging scenarios. Simbionix Ultrasound Mentor (3D Systems, USA) is a similar example of a modular, AR platform used for ultrasound examination and intervention training [8]. CAE Healthcare also offers the Blue Phantom line of ultrasound training models and simulators. These include task trainers for specific procedures and full-body manikins with integrated ultrasound simulation capabilities, providing realistic hands-on training experiences for ultrasound-guided procedures and image interpretation [2]. Unfortunately, there are some disadvantages associated with these simulation systems. One of the main challenges is the very high cost associated with most of these solutions, which often involve expensive hardware and software components, making them a significant investment for healthcare institutions and training programs [2][7]. For this reason, it is not possible to provide one to every student to train. These systems are also generally quite bulky and require a very high computational power, which leads to being forced to use them in places set up for this purpose. Furthermore, some users may find the available scenarios or modules limited or lacking in specific areas of interest or specialization.

4 The Developed Training Environment

In this Section we describe the solution we developed to provide a training environment for medical ultrasound purposes with a focus on the specific methodology we developed to transform DICOM images into 3D textures that can be used to render realistic ultrasound devices output images. A 3D texture is a bitmap image that contains information in three dimensions rather than the standard two. 3D textures are commonly used to simulate volumetric effects such as fog or smoke or to approximate a volumetric 3D mesh. In this work, a 3D texture is made by building a three-dimensional matrix from the DICOM images. 3D texture can be rendered just like normal 2D textures, with the same types of filtering and interpolations to calculate final pixel values. The only difference is, obviously, the presence of one extra dimension for texture coordinates: there will be UVW coordinates, instead of UV only. To develop the proposed solution, the Unity game engine framework is used, along with C# as programming language. Unity is a widely adopted cross-platform game engine that can be used to create two or three-dimensional, Virtual Reality and Augmented Reality simulations and games.

In Figure 1, we show a couple of screenshot of the simulation environment devised as a proof-of-concept (Figure 1a), to show the potential of our solution in term of ultrasound image realism (Figure 1b). The 3D models used are created using Blender or acquired with creative common licences. Since virtual environment realism is mandatory for immersivity, we are currently developing different scenes, each corresponding to a different medical testing situation by including more background elements, as well as a realistic patient model. The simulation allows the trainee wearing the head-mounted display to move in the scene around the patient and maneuver the ultrasound probe handling the device's controller. If the output image is perceived as too small, it is possible to grab the ultrasound machine and bring it closer to the point where the inspection is being carried out. The possibility to perform ultrasound scans of different parts of the patient's body and of several different pathologies is one of the features of our solution. Indeed, a dedicated system to easily add new ultrasound scans to the training



a. b.

Fig. 1. The training environment. a) Aerial view and b) detail of the virtual ultrasound output, moved closer to the user for better vision.

environment is developed, allowing the user to test with different clinical cases. Starting from the CT scans of a given patient, usually provided in the form of DICOM image, a 3D texture is generated. A DICOM is a container for several information, the most prominent of which are a set of medical images that allow to reproduce sectional and three-dimensional images of patient's anatomy. The generated 3D texture then represents, in a format quickly accessible in real time, the same patient's anatomy that can be then virtually explored during training by the user operating the virtual ultrasound probe.

The process of visualizing only some portions of this 3D texture, according to the position of the virtual ultrasound probe, is obtained thanks to a sequence of operations that together compose the *3D texture shader* described in this Section. The method extends and adapt to a different domain what we presented in [10]. The scene contains seven reference points to define the position of the scanned volume and of the probe, as shown in Figure 2. Point V_o is set in the position in world space where the origin of the scanned volume is placed. Points V_x, V_y and V_z will define respectively the positions of where the scanned volume will terminate along the x, y, and z axes in world space. These four points should be parented with the body of the subject being scanned. Point S_o is instead the origin of the plane the scanner will be showing. Points S_u and S_v determine where the plane of the scanner ends horizontally and vertically, corresponding to the points where the u and v coordinates associated to the generated texture assumes respectively values $u = 1$ and $v = 1$. These points are parented with the sensor. Three vectors, which define the directions where the scanned box is oriented, are then computed according to the following equations:

$$\mathbf{d}_x = V_x - V_O \qquad \mathbf{d}_y = V_y - V_O \qquad \mathbf{d}_z = V_z - V_O$$

These vectors are then used to compose an adaptation matrix $\mathbf{M}_T$ defined as follows:

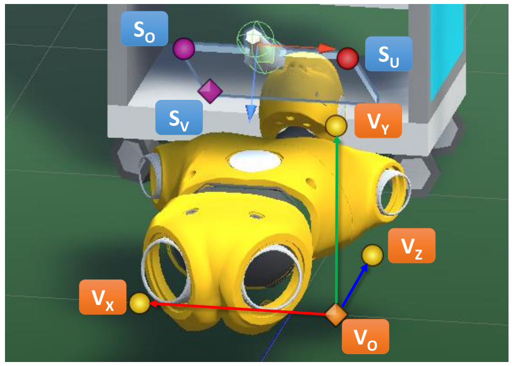


Fig. 2. The reference points of the 3D texture mapping.

$$\mathbf{M}_T = \begin{vmatrix} \frac{\mathbf{d}_x.x}{|\mathbf{d}_x|^2} & \frac{\mathbf{d}_y.x}{|\mathbf{d}_y|^2} & \frac{\mathbf{d}_z.x}{|\mathbf{d}_z|^2} \\ \frac{\mathbf{d}_x.y}{|\mathbf{d}_x|^2} & \frac{\mathbf{d}_y.y}{|\mathbf{d}_y|^2} & \frac{\mathbf{d}_z.y}{|\mathbf{d}_z|^2} \\ \frac{\mathbf{d}_x.z}{|\mathbf{d}_x|^2} & \frac{\mathbf{d}_y.z}{|\mathbf{d}_y|^2} & \frac{\mathbf{d}_z.z}{|\mathbf{d}_z|^2} \end{vmatrix} \tag{1}$$

The three points defining the probed area, are then transposed into texture space, according to the following equations:

$$T_O = (S_O - V_O) \cdot \mathbf{M}_T; \quad T_U = (S_U - V_O) \cdot \mathbf{M}_T; \quad T_V = (S_V - V_O) \cdot \mathbf{M}_T$$

If points S_O, S_U and S_V are all contained in the probed area, then vectors T_O, T_U and T_V have all the three x, y and z components in the $0 \ldots 1$ range. The Shading Network shown in Figure 3 use the considered coordinates to sample the 3D texture and generate the image on the display. The display has UV coordinates mapped in the $0 \ldots 1$ range. They are used to sample two 2D texture: the *Background*, which includes the layout of the screen of the scanner, reproducing its GUI and controls, and a *Mask*. The latter has white pixels in the area where the display shows the reading of the scanner, and black for the points displaying the GUI. The most important part of the shading network is the sampling of the 3D texture containing the CT scan of the body. The network receives the three points T_O, T_U and T_V previously computed. The UV coordinates are used to interpolate T_O with the corresponding point T_U and T_V. To find the proper coordinate on the 3D textures, the two interpolated points are added, and corrected by removing T_O, which otherwise will be considered twice. The point read from the 3D texture is then masked and added to the GUI by a couple of product and a sum node.

5 Conclusions and Future Works

The goal of this paper is to propose a valid alternative solution to the expensive training systems currently on the market for the learning and practicing with

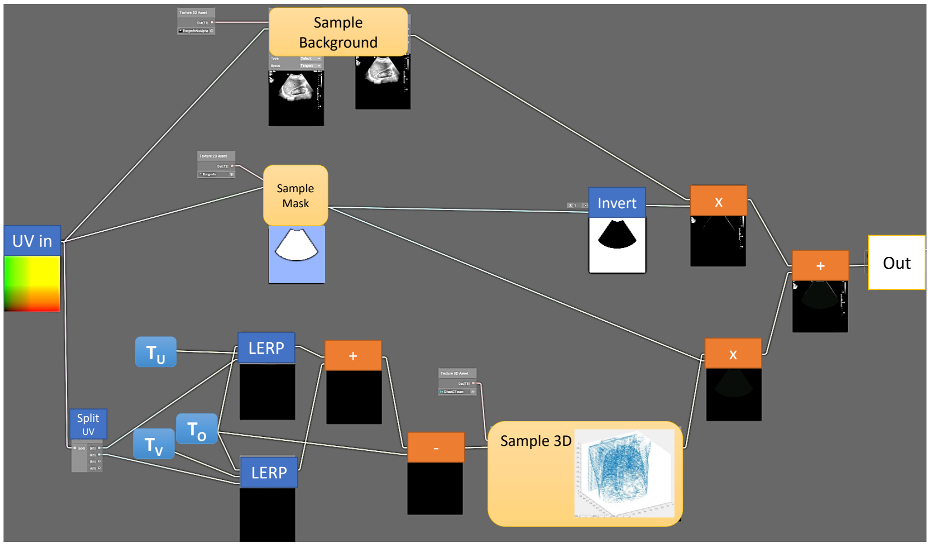


Fig. 3. The shading network used to reproduce the display of the scanner.

ultrasounds devices,in a safe environment, with several potential clinical cases to access from. To this end, we presented a novel technique to transform any set of DICOM images to visually realistic ultrasound images to be used inside a real-time VR-based training simulation. This ability to quickly add new CT scans in the training environment as new case studies, adds value to the solution, allowing it to expand at no additional cost. Future works are aimed to improve the features offered by our training simulator. We want that users can train with an extended choice of ultrasound probes, which will require to modify the 3D texture shader to reproduce different types of output images. We will also add other types of patients, classified according to different bio-metrical data, to increase the training efficacy and the realism of the simulation. In an ultrasound simulation, the interaction between the probe and the patient is a core aspect. In our solution, the patient body does not react to the pressure of the virtual probe on the skin. This impacts on the realism of the training, so a future extension of this work will include an interaction process by means of a soft body simulation. Also haptic feedback on the controller used to maneuver the virtual probe will be considered. As a final remark, it is worth mentioning that we are currently working on a graphically improved and complete training simulator which is currently under testing by a selected group of medical students. At the present state of development, no data of this testing phase are currently available for publication. They will be included in a future dedicated work.

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