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Developing a Needle Guidance Virtual Environment with Patient Specific Data and Force feedback

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Abstract

We present a simulator for guided needle puncture procedures. Our aim is to provide an effective training tool for students in interventional radiology (IR) using actual patient data and force feedback within an immersive virtual environment (VE). Training of the visual and motor skills required in IR is an apprenticeship which still consists of close supervision using the model i) see one, ii) do one and iii) teach one. Training in patients not only has discomfort associated with it, but provides limited access to training scenarios, and makes it difficult to train in a time efficient manner. Currently, the majority of commercial products implementing a medical VE still focus on laparoscopy where eye-hand coordination and sensation are key issues. IR procedures, however, are far more reliant on the sense of touch. Needle guidance using ultrasound or computed tomography (CT) images are also widely used. These are both areas that have not been fully addressed by other medical VEs. This paper provides details of how we are developing an effective needle guidance simulator. The project is a multi disciplinary collaboration involving practising interventional radiologists and computer scientists.

Keywords: interventional radiology; virtual environments; needle puncture; haptics.

1 Introduction

Guided needle puncture is an essential skill in interventional radiology (IR). Currently, the majority of commercial products implementing a medical virtual environment (VE) still focus on laparoscopy where eye-hand coordination and visual sensation are key issues. Whilst VEs have proven to be highly

effective training tools for laparoscopy [12], IR procedures are far more reliant on the sense of touch. Needle guidance using ultrasound, X-ray or computed tomography (CT) images are core tasks in the radiology training curriculum yet have not been fully addressed by other medical VEs. Training of the visual and motor skills required in IR is an apprenticeship, which still con-

sists of close, expert supervision in patients. Training in this way may, however, subject patients to increased discomfort, greater risk of complication and prolonged procedure times, creating a Clinical Governance dilemma within the modern healthcare environment. At the same time, there is limited access to apprenticeship training in more complex scenarios [8] with inevitable difficulty training in a time efficient manner [2]. Computer-based simulators combining 3D anatomy models and haptic (of or relating to the sense of touch) rendering can provide an alternative. This paper describes our current research activities aimed at providing an effective tool for needle guidance training in IR using actual patient CT data and a force feedback interface within an immersive virtual environment. Related work has been published by Hostettler et al. [5] and their ultrasonography simulator also uses a haptic interface to represent a virtual transducer. Our solution supports stereoscopic viewing, however, and different rendering schemes can be used to represent the real time images displayed to the trainee during the needle puncture procedure. Our use of patient specific data also allows the training simulation to take place on different types of patient and anatomy regions with an accurate representation of the human anatomy.

2 Methods

The Manchester Royal Infirmary has developed a novel environment for training ultrasound guided needle puncture. Their system uses basic equipment, primarily a plastic box filled with foam into which tube like structures have been hollowed out in order to represent blood vessels. The box is filled with water and placed into a microwave oven for

several minutes to remove all of the air bubbles. The foam filled box can then be imaged using a conventional ultrasound scanner (Fig. 1(a)), and produces images similar in appearance to the ultrasound images of real patients that the clinician will see in practice (Fig. 1(b)).

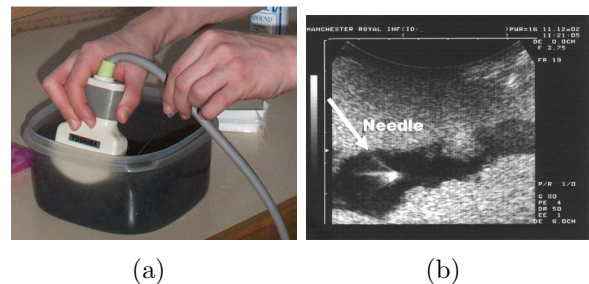


Figure 1: a) Simple environment for training needle guidance with ultrasound; b) Example ultrasound image produced.

Whereas the above solution has proven to be a useful training aid, our goal is to provide the trainee with a more natural and configurable solution using virtual environment technologies. We also want to support several different imaging modalities. The components needed for the implementation of our new solution are described below.

2.1 The Virtual Environment Platform

An immersive virtual environment has been developed using the Reachin Display hardware [7], which enables the co-location of 3D graphical models with a haptic joystick. This hardware platform includes a Phantom Desktop force feedback interface from SensAble Technologies [10], and a display monitor placed at a 45 degree angle that projects its image onto a semi-transparent mirror located above the force feedback de-

vice. The CrystalEyes liquid crystal shutter glasses and infrared emitter by StereoGraphics Corporation [11] are used to visualize 3D stereoscopic images. The effect for the user is that the 3D anatomy models appear to float in the volume of space below the mirror, and he/she can touch and interact with the models via the haptic interface (see Fig. 2). A 3D Space mouse can also be used



Figure 2: The VE platform.

to rotate the anatomical models.

2.2 Software and Algorithms

The patient’s CT data (in the standard DICOM format) is pre-processed in order to extract an intermediate model that approximates the skin surface of that specific patient. The Visualization Toolkit (VTK) [9] has been used to extract the surface by applying the well known marching cubes algorithm [6]. This creates triangular meshes that can be exported into the Virtual Reality Modelling Language (VRML) file format. VRML 97 is the established ISO standard used on the Web to describe three dimensional data, however, it only contains visual properties. In addition, the segmentation and exportation into VRML models of the skeleton structure and key organs from

the patient data are considered. Indeed, transparency can be used when rendering the anatomy surfaces, which is useful in the early learning stages for the student and in review for understanding the relationship of needle, patient and beam. However, during the needle puncture procedure, the skin surface will be fully opaque. To add haptic properties to 3D surfaces, i.e. to enable force feedback, Reachin Technologies AB has extended the original VRML specification within its Reachin API (application programming interface) software, which can be used to manage the graphics and haptic rendering in the simulation. During the simulation, the haptic interface can act like a virtual ultrasound (US) transducer (Fig. 3(a)). As you move the probe over the

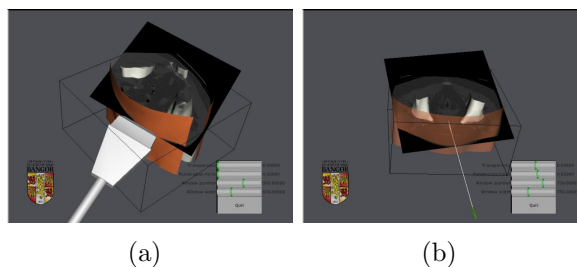
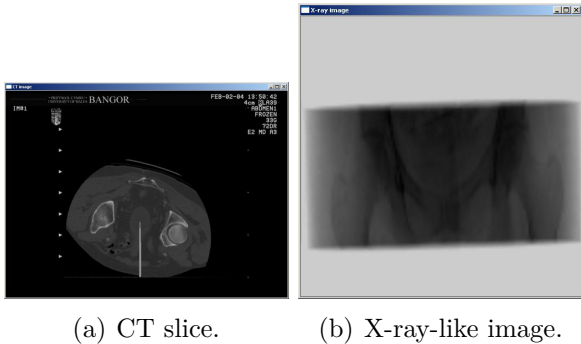


Figure 3: Simulation using the haptic interface as a) a probe; b) a needle.

surface of the body you can feel the surface in order to maintain contact with the skin. An image corresponding to the position and orientation of the transducer is then computed and displayed in real-time on a second monitor. We currently provide two formats for representing these images (Fig. 4): as a re-sampled CT image; and as a simulated X-ray-like image, such as you would get from fluoroscopy. Such fluoroscopic images are produced using a ray casting algorithm called additive reprojection. At each pixel of the image on the projection plane, a



(a) CT slice. (b) X-ray-like image.

Figure 4: Simulated images.

ray is sent through the volume, orthogonal to the viewing direction. The pixel intensity is the average of the voxel values along the ray [3]. Work is also ongoing to produce a simulated ultrasound image.

The haptic interface can also be used to simulate the insertion of a needle into the anatomy (see Fig. 3(b) and bright line in Fig. 4(a)). In this case, the user can feel the resistance of the virtual needle as it passes through the skin and tissue layers. If the needle intersects the cutting plane, the user will see the needle on the reconstructed slice. The needle insertion parameters are calculated before simulating the CT or X-ray images. A straightforward algorithm using trigonometric identities detects whether a given voxel V in the original CT data set is penetrated by the needle (Fig. 5). Indeed, if the vector dot product between NV and D is negative (i.e. the voxel V is behind the tip of the needle) and if the distance $|VV'|$ is less than or equal to the needle radius (i.e. V is into the infinite cylinder defined by P , D and the needle radius) then the original Hounsfield value of the voxel is replaced by a high value (e.g. 3000).

Different haptic models are being developed and implemented in the simulation. A relatively simple model has currently been

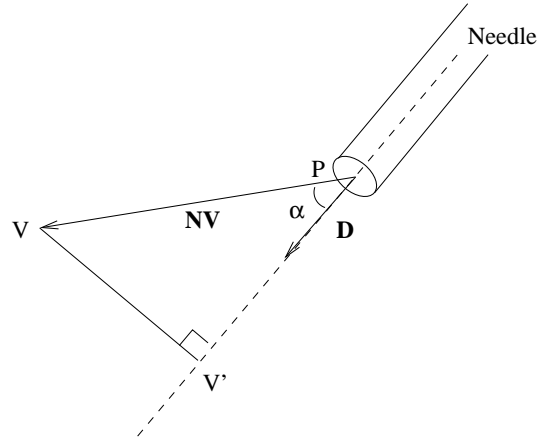


Figure 5: Needle/voxel intersection, (with P the needle position, D the needle direction and V the voxel position).

implemented, which only allows the penetration of the skin surface. The next step is to improve the force feedback sensation felt by the end-user as the needle progresses through the different tissues. For example, work is ongoing to apply a more complex algorithm originally developed for the case of cricothyrotomy [1]. It is also planned to apply a haptic model constructed from experimental force measurement data acquired during procedures on patients in the IR operating theatre [4]. The current environment implements a single haptic interface. The user can select the probe or the needle using a programmed button on the Space mouse or the keyboard. Nevertheless, a second haptic interface will be added as it is absolutely necessary that the trainee holds both the probe and the needle to allow constant changes and redirection of the probe while targeting with the needle. The inexpensive Phantom Omni will be ideal to use as the second haptic interface.

3 Results

To date, eight DICOM datasets containing regions of interest, including the kidney, liver and neck, have been selected and “converted” into VRML anatomical models, augmented with a description of the appropriate haptic properties of those tissues using the methods described above. During the simulation, a single haptic device is first used to navigate through the CT dataset in order to find a suitable cross section image in which to guide a needle for the biopsy (Fig. 3(a)). The same haptic joystick is then used to simulate the virtual needle (Fig 3b). The image computed during the simulation is currently presented to the operator as a 2D multiplanar reconstruction (MPR) image, i.e. a re-sampled CT slice, or fluoroscopy image (Fig. 4). The needle insertion is simulated using a simple haptic model and the location of the ‘needle’ within the simulated image is represented as a bright (CT) or dark (fluoroscopy) attenuation, the extent and shape of which conforms to the computed needle location and angle through the baseline CT image data (Fig. 4(a)). In the ultrasound simulation, the needle will be similarly represented as a bright reflection. Feedback from experienced clinicians on the value of our virtual environment for training image guided needle puncture has been positive. We are now planning a face validity study, and a concurrent validity study to compare results with the existing training system (as depicted in Fig. 1).

4 Conclusions and Future Work

Early medical simulators aimed for total realism, but they were largely unsuccessful.

Indeed, graphics hardware was too expensive, which prevented wide-spread use, or was too slow, which did not make real-time simulations possible. Nowadays, simulating realism is becoming possible although many research challenges still remain, such as realistic physical behaviour and haptic modelling. This research project is attempting to translate the progress made in computer graphics and in haptic technologies to interventional radiology training. The early results from this approach justify more development, currently underway, which includes ultrasound guided puncture simulation, use of two haptic devices at a time, improved haptic models, physical and clinical validation. The needle guidance simulation will also be integrated into a more comprehensive system for visceral interventional needle puncture procedures. This new system is being developed by the CRaIVE (Collaboration in Radiological Interventional Virtual Environments) consortium, a multidisciplinary group of clinicians, physicists, computer scientists, clinical engineers and psychologists who are working together to implement and validate sophisticated virtual environments for IR training [13].

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