ImaGINe-S
Imaging Guided Interventional Needle Simulation

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Abstract

We present an integrated system for training visceral needle puncture procedures. Our aim is to provide a cost effective and validated training tool that uses actual patient data to enable interventional radiology trainees to learn how to carry out image-guided needle puncture. The input data required is a computed tomography scan of the patient that is used to create the patient specific models. Force measurements have been made on real tissue and the resulting data is incorporated into the simulator. Respiration and soft tissue deformations are also carried out to further improve the fidelity of the simulator.

I.3.5 [Computer Graphics]: Physically based modelling, I.3.7 [Computer Graphics]: Virtual reality

1. Introduction

Interventional radiology (IR) uses minimal access techniques to treat a range of conditions, with generally less risk and post-operative pain, and shorter recovery time compared to open surgery. IR procedures use medical imaging to guide needles and other instruments to target specific patient anatomy and pathology. Vascular IR techniques involve blood vessels (arteries, veins), while visceral IR is concerned with organ systems (liver, bile ducts, urinary tract, gut). Fluoroscopic imaging and ultrasound (US) are the most commonly employed imaging modalities. Fluoroscopy is the mainstay for image guidance in some procedures such as percutaneous transhepatic cholangiography (PTC); US is a key imaging modality in biopsy and nephrostomy [MS90].

Basic IR skills such as visceral needle puncture are still acquired during an apprenticeship in patients, though a trainee's inexpert manipulations can increase patients' pain and discomfort, as well as the procedure time and overall risk. A computer-based simulation can offer an attractive alternative, and this has been the motivation for developing ImaGINe-S (**Ima**ging **G**uided **I**nterventional **Ne**edle **S**imulation). ImaGINe-S delivers a cost-effective virtual environment in which a trainee can practice and develop basic skills. It has been designed following a comprehensive task analysis of needle puncture procedures. A stereoscopic projection of the virtual patient is co-located with haptic feedback devices to provide a high fidelity simulation – see Figure 1. Patient-specific data is used and the simulator can be configured for a variety of different scenarios. ImaGINe-S is currently undergoing a series of validation studies at hospitals and training workshops.

To our knowledge, the Haptic Operative Realistic Ultrasonography Simulator (HORUS) is the only other computer-based simulator to address needle puncture [FCV*07] and is particularly aimed at US-guided needle insertion for biopsy and radio frequency thermal ablation. The unique differentiators of ImaGINe-S are that:

- It is based on a detailed task analysis.
- It provides an immersive virtual environment that closely replicates the set up of the real life situation.
- It models organ motion due to respiration together with simulation of fluoroscopy or US images, and can do this interactively by exploiting both the central processor unit (CPU) and the graphics processor unit (GPU) capabilities of a modern PC.
- In vitro studies of the forces obtained from needle insertion into tissues is being used to help create a realistic haptics model.
- Patient specific data is used.
- It is being fully validated as a training tool.

2. Methods and Tools

The main components of ImaGINe-S are described in this section.

2.1 Task analysis

A detailed task analysis of the procedure is essential to identify the individual steps and to document the decision process involved at each point. This information can be obtained by analysing video footage of the procedure being carried out, and through interviews with subject experts. Our psychologist team have carried out this process together with the subject matter experts [JHE*06]. This information then informs the actual design and realisation of the simulator. Pre-procedure steps and general preparation such as cleaning the incision site and injection of local anaesthetic have also been documented in this way. All of this information must be provided within the training curriculum. At this time, however, our simulation begins with the ultrasound image guided needle puncture.

The task analysis also identified the key metrics to be measured in the simulator and used for validation. The metrics are performance indicators and include: any errors made, puncture site location, time taken, path taken by the needle and the final catheter position. Each of these metrics will be further assessed during validation of ImaGINe-S to allow investigation of their utility as performance indicators.

2.2 Patient specific data

With patient consent, selected, routine image data sets (computed tomography, magnetic resonance, ultrasound) of straightforward and complex anatomy and pathology was anonymised and uploaded to a repository. Data sets are then segmented using interactive processes to label target anatomy. This is used to create surface (triangular) meshes and volume (tetrahedral) meshes. Currently, ImaGINe-S uses selected patient case studies. However, the support for patient specific data allows us to extend the use of the simulator to also include pre-operative rehearsal.

2.3 Hardware set up

Commercial off the shelf components have been used. A desktop PC with Intel Xeon 3GHz CPU, 2GB of RAM, and a NVIDIA Quadro FX graphics card provides the computational power required. For the needle puncture step, two PHANToM Omni haptic devices have been connected to the PC using the high speed IEEE 1394 (FireWire) interface – one to act as an ultrasound (US) transducer, and the other to act as the needle. These are housed within the virtual workbench system that can be seen in Figure 1. To provide face validity, and based on the task analysis, the following steps have been taken:

- The Omni's are carefully positioned so that the operator's hands are in the correct position when using the needle and/or probe. A custom made stand holds the Omni's in place.

- A wrist rest can be placed into the workspace at the appropriate height to allow the operator to rest his hand during the procedure. In the actual task, some radiologists will rest their hand against the patient's body.

- The simulated ultrasound or fluoroscopy image is output to a second monitor, not superimposed in a window within the 3D virtual environment. This represents the real situation where the radiologist looks away from the patient to focus on the image being displayed on the scanner.

- The stylus of the Omni can be replaced with a mock-up of a transducer.

Figure 1: *ImaGINe-S Platform: A virtual workbench with two PHANToM Omni haptic devices (one for the needle and one for the ultrasound transducer)*

2.4 Algorithms and software

ImaGINe-S has been coded in C++ and makes use of OpenGL, GLSL (the OpenGL Shading Language), the H3D haptics library from Sensegraphics, and a wxPython interface to allow patient parameters to be changed interactively.

Our first prototype platform used static CT volume data [VJH*08]. In reality, however, the image data being viewed will alter dynamically in response to respiration and deformation forces introduced by the needle insertion. We have developed a methodology for deriving such dynamic volume rendering from patient imaging data. The deformation module has been implemented on the CPU. After studying the physiology involved, we chose to control the respiration by the rib cage and the diaphragm. Mesh models of the relevant anatomy are obtained through standard segmentation techniques [VJG*09]. Ribs are modeled as rigid bodies with kinematic laws, while diaphragm motion is simulated by the up and down motion of the central tendon coupled with its rib attachments [VBB08]. Soft-tissue deformation is handled by an extended Chain Mail algorithm allowing fast multi-organ

interaction [LB03]. Parameters to simulate the deformation behaviour control compression, stretching and shearing. Figure 2 illustrates the effect of the diaphragm moving during exhalation. Deformations due to the needle insertion require the detection of collisions between the needle and the organ concerned. This is performed using the H3D API and allows us to know the area of the collision and the magnitude of the touching force. The deformation is then computed in real-time using the mass-spring method. Full details of our algorithm can be found in [VJG*09].
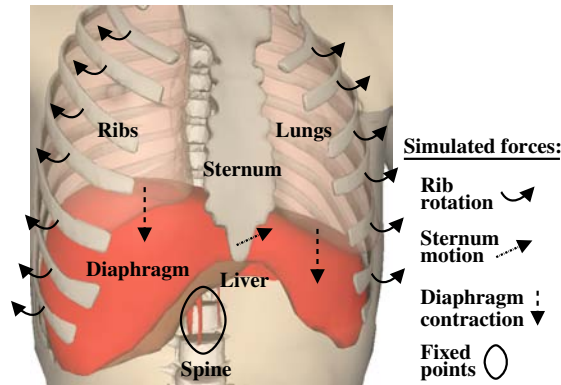

Figure 2: *Respiration - diaphragm motion is simulated by the up and down motion of the central tendon coupled with its rib attachments*

The X-ray simulation has been implemented on the GPU. It is a three pass algorithm using an OpenGL pipeline. For each X-ray pixel, the first pass computes tissue penetration, the second computes an intermediary result required in the final pass to compute the cumulative attenuation using the Beer-Lambert law. An example of the images produced can be seen in Figure 3.
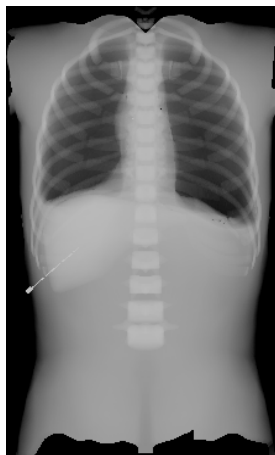

Figure 3: *X-Ray image calculated on the GPU*

The ultrasound simulation is also implemented on the GPU. Currently, a 2D multi-planar reconstruction (MPR) image is extracted from the CT voxel data set based on the position and orientation of the transducer. This can be efficiently achieved using the OpenGL frame buffer object architecture (FBO). All voxels that have been penetrated by

the needle are assigned a high value corresponding to the metallic material of the needle shaft, which reflects US. Acoustic shadowing effects are simulated by post-processing the MPR image to compute a shadow mask, and high frequency noise is also added. Bright reflections may occur in US images at interfaces such as with bone, gas, and fat/tissue. This effect can be produced in the final image by detecting and enhancing horizontal edges in the MPR image using a Sobel filter. Finally, the MPR image, the shadow mask and the noise data are blended using multi-texturing. Images from both linear and curvilinear US probes can be generated; an example can be seen in Figure 4.
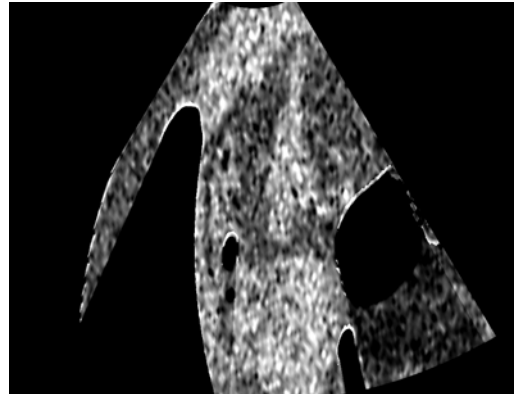

Figure 4: *Example of US-like images generated in real time from original CT data*

As the trainee moves the Omni that is used as the US transducer over the skin of the virtual patient, an US-like image corresponding to the position and orientation of the image plane is computed and displayed in real-time (see Figure 5). The force of the probe against the skin can be felt by the operator. Similarly, the sensation of puncturing into the viscera with the virtual needle can be felt through the feedback provided by the second Omni. The force feedback delivered in virtual environment simulators is generally an approximation to a real procedure, as assessed by experts. Haptics based on actual procedural forces should allow a more realistic simulation of the subtle cues [GMO04]. In evaluating needle puncture procedures *in vitro* studies are essential for detailed understanding of the physical components and effects of overall summated forces, and we are collecting such experimental data [VHJ*08]. The observed behaviour can then be modelled analytically using a radial-basis function (RBF) network, where each RBF corresponds to a Gaussian function. Thus we obtain essential information on tissue properties and we use this to help create a haptics look up table (LUT). The position of the tip of the virtual needle is tracked as it penetrates the virtual patient. The voxel in which the needle tip currently resides can therefore be mapped to the original CT data set. The CT Hounsfield value of that voxel is used as the index to the LUT, and it returns an appropriate force co-efficient depending on the tissue type. A force calculation (using Hooke's Law) is then applied to the haptics device. Full details of how the haptic forces are calculated can be found in [VJH*08].
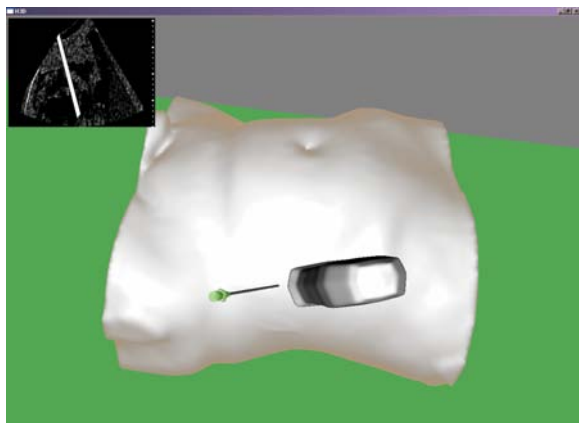
Figure 5: *The virtual patient with ultrasound probe and needle. The needle is clearly visible in the current ultrasound image. Note that the ultrasound image is normally displayed on a separate monitor.*

3. Results

The most important question in any project to build a medical virtual environment is: does it actually improve the trainees skill at carrying out the procedure without negative training artefacts? Extensive validation is therefore an ongoing process run in parallel to the development phase. Following the attainment of ethical approval, experienced and trainee subjects have been recruited within the partner hospitals. Construct and content validation studies are currently being carried out and with ethical approval, we have collected data from pilot studies at the Cardiovascular and Interventional Radiological Society of Europe (CIRSE 2008, Copenhagen) and the British Society of Interventional Radiology (BSIR 2008, Manchester). 53 subjects (49 male, 4 female: 30 trainees and 23 subject matter experts) underwent baseline testing on a simulated percutaneous nephrostomy. Face and content validation were assessed using a 5-point Likert scale. Outcomes showed that 41/53 (78%) participants thought that the design of ImaGINe-S was moderately realistic with content validity being rated averagely for all critical task steps. 44/53 (83%) participants thought that ImaGINe-S is a useful model for training skills for nephrostomy.

Our preliminary results indicate the usefulness of ImaGINe-S for training skills for nephrostomy. With further development, it will allow trainees to also train the basic skills of percutaneous renal collecting system access. Improvements are being made as a result of these pilot studies and further assessment of face and content validity is underway.

4. Conclusions

Anonymised patient datasets form an essential basis for construction of 'virtual reality' training models such as that offered by ImaGINe-S. Training scenarios can be developed and validated in the academic environment, combining the skills of a multi-disciplinary team of experts in computer science, psychology, and medicine. Initial results augur well for the fidelity of our simulator. Further construct and concurrent validation, and skills transfer studies, form a key part of future, proposed work. This will be conducted within IR curricula to evaluate the clinical effectiveness of the simulator to train visceral needle puncture procedures. Other functionality, such as the inclusion of palpation support, is also planned.

ImaGINe-S is now set to move into a commercialisation stage. Medic Vision Ltd. (Melbourne, Australia) have been involved in the project to develop this simulator and are currently drawing up productisation plans to package and sell the simulator to hospitals.

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