A Framework for Visuo-Haptic Simulation of Puncture Interventions

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Abstract: A framework for virtual reality based training of puncture interventions is presented. The system uses a haptic device with six degrees of freedom (6DOF) to enable realistic force sensations during needle insertions into virtual patients. A manifold of different visualization techniques gives new insights into the anatomy of the punctured region. The 3D effect is enhanced by stereoscopic visualization. An evaluation component rates the quality of virtual punctures to give the user feedback and improvement suggestions. Currently the system supports the training of three different puncture tasks. Two of them have been evaluated in a pilot user study with 55 participants. The questionnaire based study indicates a high user acceptance.

1 Introduction

Puncture interventions are performed by inserting a needle into the human body. This needle is then used to either inject drugs for therapeutic purposes or to extract fluids or tissue material for diagnosis and/or therapy. During the insertion different forces can be felt while the needle pierces different structures like skin, fat, muscles, ligaments or bones. These forces can give information about the current position of the needle. In some cases the intervention is also guided by imaging technologies like ultrasound, x-ray or computer-tomography in other cases the needle is inserted ”blindly”. Experience in placing a needle correctly is usually gained with the apprenticeship method where an experienced supervisor guides the trainee in directly practicing on the patient. This method has some drawbacks for patient and trainee. While the patient is forced to take every possible failure of the trainee which can result in unnecessary pain, tissue damage or injury, the apprentice is heavily stressed by the possibility of incorrectly performing the puncture. These drawbacks make it hard to maintain an untroubled learning atmosphere. Furthermore this method is dependent on voluntary patients in need of puncture so that trainees sometimes have to wait a long time until they can attempt to improve their skills. An alternative for the apprenticeship method would therefore be desirable.
Recently the relevance of virtual reality (VR) based simulators is increasing in the field

of medical education because with the use of simulators experience can be gained without risking the patient's health, different training scenarios can be taught (e.g. numerous virtual patients), the users performance can be evaluated during the training and insights into the human anatomy can be given.
In this work our lumbar puncture simulator prototype presented in [FHH07, FHD+08] has been extended by a multiproxy haptic rendering technique, new visualization techniques and the use of an immersive workstation with a high force haptic device. Furthermore the simulation framework has been adapted to enable VR-based training of several puncture interventions (see section 3:lumbar, ascites, PTCD). Our work therefore distinguishes from approaches presented in [DGS06] and from other approaches working on puncture or anesthetic simulation [GKW+00, DKG06, DAS01]. Other work in the field of needle insertion simulation has been done by DiMaio et al. for needle insertion planning [DS05]. A good overview for needle insertion into soft tissue is given in [APM07].

2 Methods

The system presented uses an immersive workstation that consists of a haptic device and a shutter glass enhanced CRT-monitor to enable stereoscopic visualizations. The mirror-inverted monitor is mounted above the haptic device. The user watches the scene through a mirror (fig. 1). In the following the different components of the simulation system are described in more detail.

2.1 Haptic

Haptic device A haptic device with six degrees of freedom (6DOF) is used for the haptic I/O. The "Sensable Phantom Premium 1.5 6DOF High Force" device enables force feedback in three directions in space and for three rotation axes of the pen-like end-effector. The nominal position resolution of this device is 860 dpi (dots per inch) for translation sensing, 0.0023 degrees for yaw and pitch rotation and 0.008 degrees for roll rotation. The translational force output is limited to 37.5 N (Newton) maximum (peak force) and 6.2 N continuous force output. The maximum exertable torque is 515 mNm for yaw and pitch and 170 mNm for roll. The continuous exertable torques are 188 mNm and 48 mNm, respectively.

Proxy-based haptic volume rendering The use of proxy techniques for haptic rendering has recently become very common among haptically enabled virtual environments. The proxy technique introduces a virtual proxy $\vec{x}_p$ into the virtual scene that is coupled to the instrument tip $\vec{x}_t$ by a spring. This proxy interacts with the virtual objects.

$$\vec{f} = -k\vec{d} \tag{1}$$

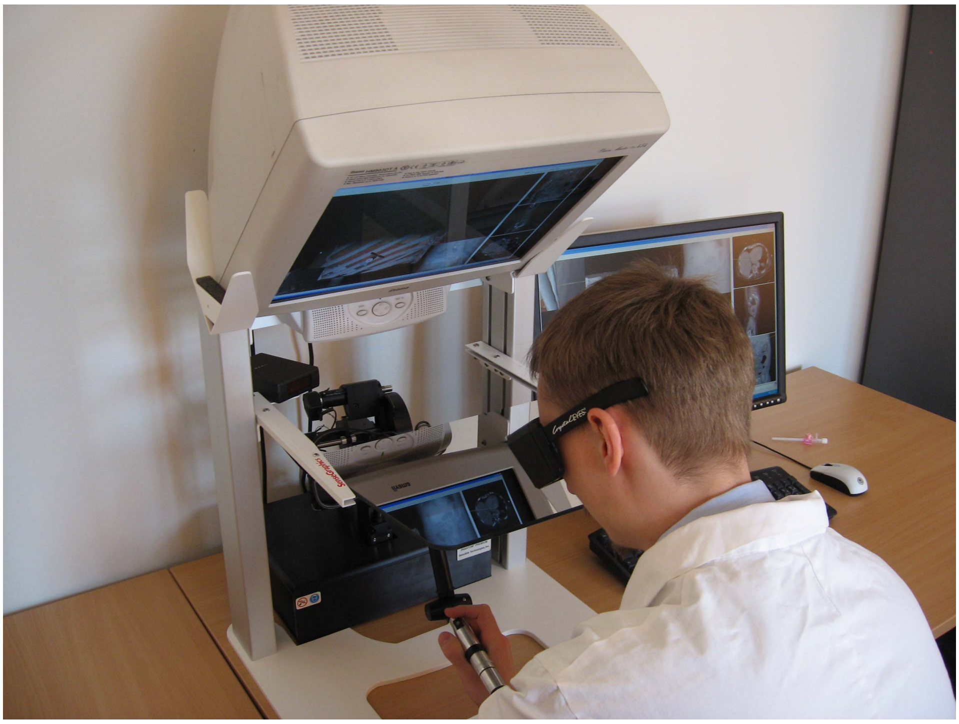

Figure 1: Immersive hardware setup of the training system. The user watches the scene through a mirror and shutter glasses are used to enable stereo view.

is used to calculate the forces acting between proxy and tip depending on the stiffness of the spring k. $\vec{d}$ is the distance between proxy position $\vec{x}_p$ and instrument position $\vec{x}_t$. The computation of the new proxy position given the new position of the haptic device should be done at least 1000 times per second to enable smooth realistic forces during a simulation.

In proxy-based surface rendering the movement of the proxy is constrained by virtual surfaces. As an alternative that allows for force generation directly from volumetric image data Lundin et al. [LYG02] proposed a proxy-based volume haptic approach that uses the image gradient $\vec{\nabla}V(\vec{x}_p)$ to represent virtual surfaces in the image data (fig. 2). Therefore, this method enables haptic feedback directly from volumetric density data (e.g. CT data). In detail, the force vector $\vec{f}$ from the spring simulation is split up in two orthogonal portions $\vec{f}_N = \vec{f} \cdot \hat{N}$ and $\vec{f}_T = \vec{f} \cdot \hat{T}$ where

$$\hat{N} = \frac{\vec{\nabla}V(\vec{x}_p)}{\left|\vec{\nabla}V(\vec{x}_p)\right|} \quad \text{and} \quad \hat{T} = \frac{\vec{d} - \hat{N}\left(\vec{d} \cdot \hat{N}\right)}{\left|\vec{d} - \hat{N}\left(\vec{d} \cdot \hat{N}\right)\right|} \quad . \tag{2}$$

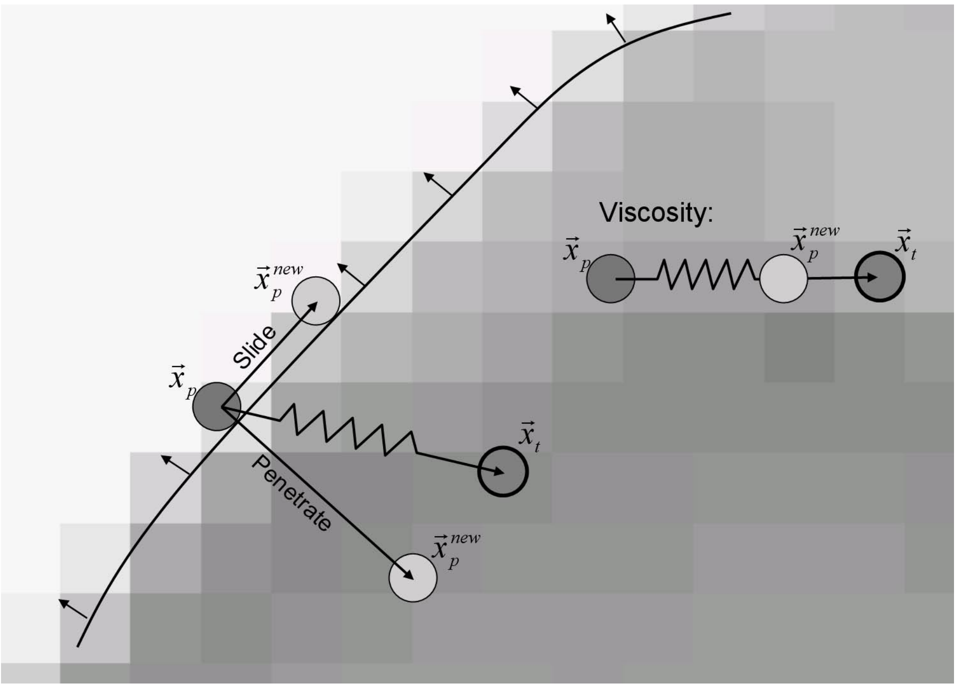

Figure 2: Proxy-based haptic volume rendering. The proxy-movement is constrained by the image gradient to simulate penetration and friction forces. In absence of a strong image gradient viscosity is simulated by delaying the proxy movement.

The movement of the proxy depends on its current position in the image data which results in the simulation of either penetrability (eq. 3), friction (eq. 4) or viscosity (eq. 5).

$$\vec{x}_p^{new} = \begin{cases} \vec{x}_p + \hat{N}(\vec{d} \cdot \hat{N} - T_N/k) & \text{if } T_N < k(\vec{d} \cdot \hat{N}) \\ \vec{x}_p & \text{otherwise} \end{cases} \tag{3}$$

$$\vec{x}_p^{new} = \begin{cases} \vec{x}_p + \hat{T}(\vec{d} \cdot \hat{T} - T_T/k) & \text{if } T_T < k(\vec{d} \cdot \hat{T}) \\ \vec{x}_p & \text{otherwise} \end{cases} \tag{4}$$

$$\vec{x}_p^{new} = \begin{cases} \vec{x}_p + \frac{R(\vec{d})}{k|\vec{d}|} & \text{if } R/k < |\vec{d}| \\ \vec{x}_p & \text{otherwise} \end{cases} \tag{5}$$

$\vec{x}_p$ is the original position of the proxy at the beginning of the time step. T_T and T_N are thresholds that define how the proxy sticks to its current position and R and k are the constants for viscosity and spring elasticity. These thresholds and constants can be used to define material properties like friction, stiffness, viscosity and penetrability by using them as transfer functions (e.g. $k = K_{tf}(V(\vec{x}_p))$).

Needle forces The forces a user feels during needle insertions can be split up into forces that act on the needle's tip (surface resistance, surface friction and viscosity) and forces that act on the needle's body only (needle friction and transversal motion constraints). Theses forces are simulated using a multiproxy-technique that couples n proxies equidistantly to the needle's body and one special proxy to the tip of the needle.
The needle tip forces are calculated by restricting the **needle tip proxy** using the volume rendering method described above. To also feedback forces from structures that can not be seen in the CT data (e.g. ligaments) this method has been extended to integrate information from a label data volume $V_L(\vec{x})$ in which the segmentation results of the virtual patients are stored. If the needle is about to enter a region that has been segmented predefined forces have to be exceeded to pierce that structure.
To restrict transversal motion and rotation of the needle inside the body the **needle body proxies** are forced to only move on a straight line (needle insertion vector) that is defined at the moment the needle pierces the skin. The torque values that control the rotational axes of the 6DOF haptic device are calculated by integrating the lever action of each proxy on the needles grip.

$$\vec{M} = \sum_{i=1}^{n} \vec{l_i} \times \vec{f_i} \tag{6}$$

where $\vec{l_i}$ is the lever arm and $\vec{f_i}$ the force of proxy i. Furthermore, a friction force that resists the needles body from sliding through the tissue is computed based on the friction force of each needle body proxy. This approach can also be used to deform the needle model and simulate needle bending (see [FDBH09]) for details).

2.2 Graphics

A manifold of different visualization techniques can be used to give the user insight into the virtual patient (fig. 3). 3D visualizations with optional stereoscopic view show the relevant anatomical structures at freely adjustable opacities and from different perspectives. The 3D organ models are extracted from the segmented patient data by the marching cubes algorithm and different needle models have been designed with 3D-Studio-Max to allow for the simulation of different puncturing tasks. The original patient CT-data is visualized using three slice viewers that show orthogonal slices of the image data depending on the position of the needle tip. Furthermore the image data can be visualized directly at the needle's position in the 3D main window using multiplanar reconstructions that align with the current needle orientation.

2.3 User performance quantification

An evaluation component can be used to rate the user's performance during the puncturing task and to give the user a feedback. For this purpose the needle path during the virtual

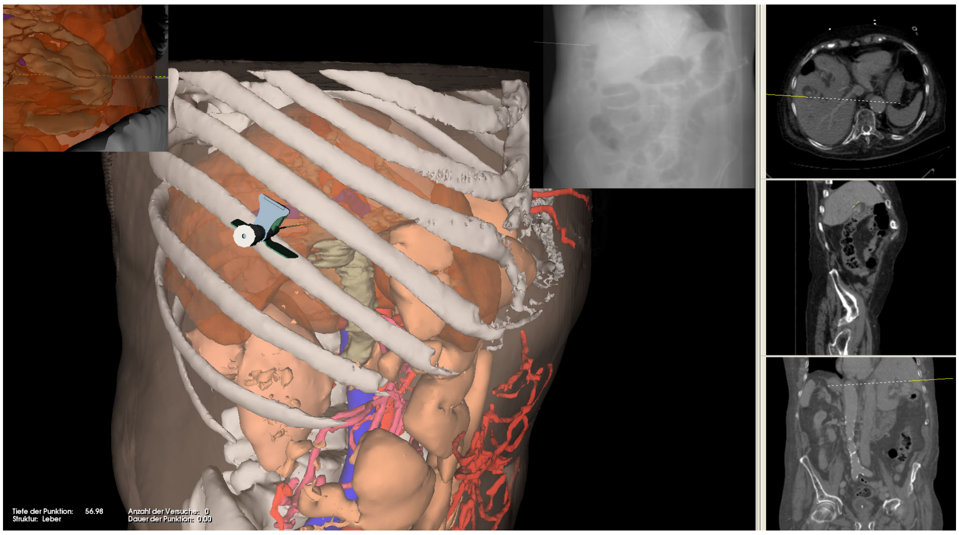

Figure 3: Graphical user interface for PTCD: The 3D view shows the different anatomical structures and the virtual needle. The side view (upper left corner) shows the structures near the current needle position. Slice viewers (right border) show the original CT data at the needle's position. In an x-ray simulation the needle is indicated by a white line.

intervention is recorded. The user path can then be compared to previously defined expert needle paths. Furthermore the structures that have been pierced during the training are recorded to analyze if the target region has been reached and if structures at risk have been hurt by the trainee. After each puncture attempt the evaluation results are presented to the user as a total score, and if appropriate hints to improve the puncture are shown (e.g. "The insertion point was to far left, move the needle to the right before inserting it").

3 Applications

The simulation environment can be used to simulate different puncturing tasks.
The lumbar puncture is done by inserting the needle above or below the fourth lumbar vertebra into the spinal canal to extract cerebrospinal fluid for diagnostic purposes. The insertion position is identified by palpating the dorsal processes of the lumbar vertebrae and the iliac crests. Since the simulator does not yet provide palpation simulation the relevant points are visualized using markers during the virtual puncture. Five virtual patients have been generated from the Visible Human and the Visible Korean Human datasets and three patient CT-scans.
Ascites punctures are done when free abdominal water is caused cirrhosis of the liver, abdominal tumors or inflammation. The ascites is punctured for diagnostic purposes and to relieve the patient. Since there are many possible paths to reach the ascites no expert path can be defined. Nevertheless it is crucial for the intervention to not hurt epigastric vessels

or the intestine. Currently the virtual ascites puncture can be performed on five virtual patients that have been generated from patient CT-data.
Percutaneous transhepatic cholangio drainage (PTCD) is a procedure to extract bile from the bile duct system in the liver. It is mainly performed on pancreas or liver cancer patients that suffer from tumor blocked bile ducts. This x-ray guided procedure is done under local anesthesia by radiologists. During the intervention, a thin needle is inserted through skin and liver into a bile duct. Injection of contrast agent indicates that the needle has reached the target zone. Since the bile duct system is very complex and crosses the arterial and venous system of the liver it is hard to successfully complete this procedure. Therefore we prepared a virtual patient for this procedure and integrated an x-ray simulation into the VR-system (fig. 3) as a prototype for VR-based PTCD training.

4 Results

The virtual lumbar puncture and the virtual ascites puncture have been evaluated by 55 medical students. After two training sessions of approx. 25 minutes the users were asked to fill out a web-based questionnaire by agreeing or disagreeing to statements about the simulator (six point likert scale with $1 =$ "strongly agree" and $6 =$ "strongly disagree"). The users stated that they find a training with such a simulator useful ($\bar{m} = 1.5$), they consider the visualization of the anatomical structures and the haptic feedback as realistic ($\bar{m}_{visual} = 1.9$, $\bar{m}_{haptic} = 2.4$), and they believe that after the training they feel more confident about doing their first puncture ($\bar{m} = 2.0$). Using an additional free text comment many users stated positive comments for the simulator. A few users suggested to improve or adjust the haptic feedback for bones and the ligamentum flavum. Many users pointed out that the visualization from different perspectives were very impressive and gave new insights into the human anatomy. An extensive evaluation focusing on the training effect of the lumbar puncture simulator has been presented in [FHGH09].

5 Conclusions and future work

The system presented enables integrated visuo-haptic simulation of puncture interventions. We introduced methods for needle force simulation based on proxy-based haptic volume rendering. Synchronized stereoscopic visualizations together with the visualization of the underlying three-dimensional image data help the user to imagine the anatomy of the punctured region. The evaluation component analyzes the users performance and gives the user a feedback. The questionnaire based user study shows a high user acceptance of the system. Nevertheless, some aspects of a real lumbar puncture like communication with the patient or palpation can not be simulated. Therefore, the use of a virtual training system can not replace the direct training on the patient. It should rather be considered as enhancement of the usual training methods that supports the users in preparing their first real punctures.

Our future work will concentrate on the generation of more virtual patients and the integration of other puncturing tasks. To fully enable the simulation of image guided puncture interventions some improvement of the already existing x-ray simulation (contrast agent spread out) has to be done and the simulation of ultrasound images has to be implemented.

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