Catheter Insertion Simulation with co-registered Direct Volume Rendering and Haptic Feedback

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Abstract: We have developed an experimental catheter insertion simulation system supporting head-tracked stereoscopic viewing of volumetric anatomic reconstructions registered with direct haptic 3D interaction. The system takes as input data acquired with standard medical imaging modalities and regards it as a visual and haptic environment whose parameters are interactively defined using look-up tables. The system's display, positioned like a surgical table, provide a realistic impression of looking down at the patient. Measuring head motion via a six degrees-of-freedom head tracker, good positions to observe the anatomy and identify the catheter insertion point are quickly established with simple head motion. By generating appropriate stereoscopic images and co-registering physical and virtual spaces beforehand, volumes appear at fixed physical positions and it is possible to control catheter insertion via direct interaction with a PHANToM haptic device. During the insertion procedure, the system provides perception of the effort of penetration and deviation inside the traversed tissues. Semi-transparent volumetric rendering augment the sensory feedback with the visual indication of the inserted catheter position inside the body.

1 Introduction

The insertion of a catheter into a vessel (artery or vein) is one of the most common procedures in clinical practice. This procedure has an especially important role during patient care, in order to get a peripheral or a central venous access, or in order to perform endovascular procedures such percutaneous arterial or venous catheterization. Most of the procedures in the endovascular field, angioplasty or stenting, need an arterial catheterization. Catheter insertion can be harmful to the patient, because arterial or venous vessels are often surrounded, e.g. at the thoracic outlet and the femoral triangle, by important anatomical structures (such as nerves, nodes, lungs) that can be easily damaged.

Precise catheter insertion thus requires a perfect knowledge of the three-dimensional development of vessels and a high level of dexterity during vessel puncturing, skills which are only attainable after considerable practice. Computer simulation are expected to be useful in improving training beyond the limitations of in vivo practice and usage of artificial physical models [1].

Fig. 1.

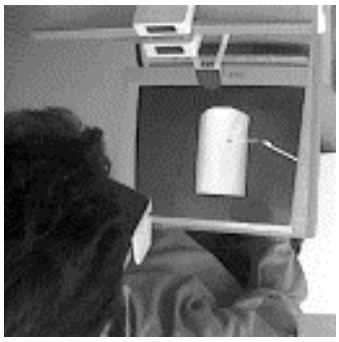

Fig. 2.

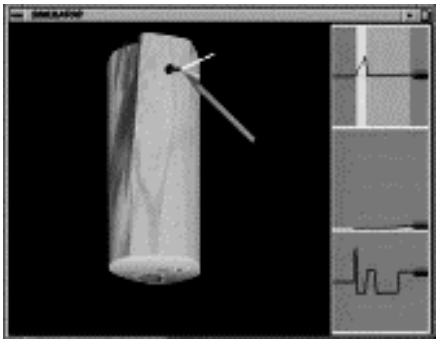

Fig. 3.

The solution we propose in this paper combines the haptic force feedback provided by a PHANToM haptic device with the visual feedback provided by a head-tracked 3D stereoscopic visualization system, both based on a volumetric description of the environment. Simply by directly importing medical imaging data set of patients affected by specific pathological condition, the system is automatically tailored to different training scenario.

Figures 1 and 2 show the system's configuration while fig. 3 shows insertion effort measurement.

2 Data Acquisition, Classification and Visualization

Our system takes as input DICOM encoded dataset acquired with standard medical imaging modalities. The input scalar dataset is used directly, mapping optical properties entirely in real time by means of look-up tables compiled with Drebin classification [2] combined with a pseudo-Gouraud shading algorithm. An optical classification panel is used to recompile the tables in real time. Moving panel sliders and tissues separation bars, the user may change classification parameters (intensity range, colors and opacity) and immediately observe changes in tissues' appearance.

The goal of providing the best perception of the object's shape and position is addressed by two natural vision properties: *Binocular Vision* and *Motion Parallax*. Thus, our system makes use of an ultrasound tracker to take user head position and of 3D shutter glasses synchronized with a stereo display.

To ensure at least minimum performance in terms of frame rate (min 10 fps per eye) and latency (max 300 ms) to provide the sensation of presence, the visualization system uses a technique that takes advantage of high-end graphic workstations hardware: 3D Texture Mapping Direct Rendering [3]. With this technique we render a prefixed number of spherical slices (centered in the viewing position) in back-to-front order inside the volume and let the graphics hardware sample the volume on each slice, map samples by color-opacity look-up tables, project them, with a perspective projection, on the viewing window and blend slice colors with previous accumulated colors.

3 Haptic Classification and Rendering

Like optical classification, haptic classification is computed in real time via look-up tables. The same panel used for optical parameters was extended to assign mechanical parameters to tissues, while threshold values are the same used for colors.

Tissues are modeled with the Brett's incremental viscoelastic model[4] which takes into account the tissue stiffening induced by large deformations.

Needle Control. As the PHANToM is a 3 degrees-of-freedom force-feedback device, no torques can be returned to the user controlling the needle. Thus, we chose to not allow the user to grasp the needle but only touch it at its endpoint, like a tailor using a thimble. We attach the tip of the PHANToM stylus to the endpoint of the needle and reconstruct its movement from the trajectory of that point. Also, global forces exerted by tissues on the needle become a single resultant force exerted by its endpoint on the PHANToM stylus tip.

Needle Kinematics. When the needle tip collides with a tissue surface it don't pierce it until the module of the exerted force is less than a stated tissue-characteristic brake value. The reaction force is always opposite to exerted force and applied to the needle tip.

Once the surface is pierced the system stores the needle insertion position as the equilibrium state. Every subsequent movement of the PHANToM stylus forces the needle to diverge from that orientation (i.e. the needle rotates around its tip) and to slip inside tissues along the new direction. Finally, the system updates equilibrium state proportionally to the amount of the slip.

Reaction Forces. Reaction force is computed by numerical integration by subdividing the needle into a finite number of trunks of constant length and accumulating reaction forces exerted by tissues on the central point of each trunk. At this point the system extracts from the volume a scalar value computed by trilinear interpolation of the eight nearest voxels' value and converts the sample into mechanical parameters via look-up tables. Tissue stress is computed as a function of the distance from the point's equilibrium position and its forced position. Decomposing the distance into an axial component and a rotational component, the system computes the elementary friction force and the elementary torque around the needle tip for that trunk. Finally all torques and forces are integrated to compute a resultant reaction force applied to the needle endpoint.

4 Evaluation

The view of a surgeon who used the simulator was that it is sufficiently representative of a real catheter insertion. He appreciate the usefulness of tracked stereoscopic viewing when locating the catheter insertion point, the excellent agreement between visual and tactile perception of catheter placement and the realistic haptic response of the system during soft tissues (especially vessel) piercing and penetration. He judged as less realistic the needle contact with hard tissues like bone, for the system tendency to generate undesired vibrations when simulating very hard contact with their surface.

We are currently in the process to assessing the system's effectiveness through a controlled statistical study that compares data acquired running the simulator, e.g. total time needed for insertion, catheter angle at the cutaneous level, traversed tissues and forces over time, with different user groups.

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