Catheter Insertion Simulation with Combined Visual and Haptic Feedback

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Abstract. We have developed an experimental catheter insertion system supporting head-tracked stereoscopic viewing of volumetric reconstruction registered with direct haptic 3D interaction. The system takes as input patient data acquired with standard medical imaging modalities and regards it as a visual and haptic environment whose parameters are defined using look-up tables. By means of a mirror, the screen seems to be positioned like a surgical table providing the impression of looking down at the patient in a natural way. Co-registering physical and virtual spaces beforehand means that the patient appears at a fixed physical positionj on the surgical table and inside the workspace of the PHANToM device which controls catheter insertion. During the insertion procedure the system provides perception of the force of penetration and positional deviation of the inserted catheter.

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 percutaneous cardiac catheterization and in order to get a central venous access. Precise catheter insertion requires a perfect knowledge of the three-dimensional development of vessels and a high level of dexterity during vessel puncture, which is only attainable after considerable practice. Computer simulation will be useful in improving training beyond the limitations of in vivo practice and usage of artificial physical models [1].

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. The system enhances touch perception with visual perception by reflecting the displaied image and registering it's reference frame with the PHANToM reference frame (e.g. physical position perceived by hand is confirmed by stereoscopic catheter viewing). Figure 1 shows the system's configuration.

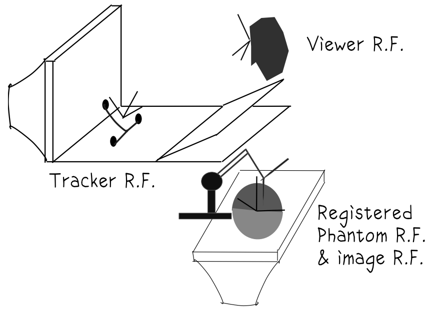

Fig. 1. Haptic Workbench.

2 Dataset Acquisition, Classification and Visualization

2.1 Acquisition

Our system takes as input data acquired with standard medical imaging modalities. To make it possible to have it connected directly to standard medical acquisition devices, the system employs the DICOM standard for input dataset coding. Thus, new acquisition is made available for simulation in a few minutes.

2.2 Tissues Classification

Because the simulation system uses directly the input scalar dataset, no segmentation process is required before starting session. Optical properties mapping is done 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.

2.3 Texture Mapping Direct Visualization

The main goal of the visualization system is to provide the best perception of the object's shape and position (in this case the surgeon needs to exactly establish the catheter insertion point). More than Gouraud shading, this task 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 must use 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

3.1 Tissue Classification and Modeling

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.

Initially we tried to model tissues with a simple spring-damper model. What we observed, manipulating some medical datasets, was a good response applying small forces but an excessive deformation with high ones. So, to take into account tissue stiffening induced by large deformations, we chose to implement the incremental viscoelastic model used by Brett [4].

3.2 Rendering

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 we impose that it stays attached to the collision point (we consider the collision point to be a micro-hole in tissue surface) until the dot product of the exerted force and the surface normal is negative. Tissue surface reaction force is always opposite to exerted force and applied to the needle tip. As we assign at each tissue a surface break force, we can decide when surface is pierced and the needle entered inside tissue.

Once this happens, the system stores the needle insertion position and orientation 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. If it equals the final needle depth (i.e. before movement needle was just touching tissue) the new equilibrium orientation equals forced orientation, while no update of equilibrium direction is required if no slip occurred.

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. For single reaction evaluation, the system traverses the volume on the central line of the needle equilibrium position, samples the volume in the central point of each trunk (i.e. extracts from volume a scalar value computed by trilinear interpolation of the eight nearest voxels) and converts the sample into mechanical parameters via look-up tables.

At each trunk's central point, tissue stress is computed as a function of the distance from its equilibrium position and its forced position. Distance is decomposed into a rotational component (deviation from initial direction) and an axial component.

Rotational reaction components are used to compute elementary torques about the axis through the needle tip and integrated to find a global reaction torque, which equals the torque due to a single force applied to the needle endpoint: the rotational component of reaction force sent to the haptic device.

Axial distances are used to compute elementary friction forces and are integrated to give a global axial reaction force returned to the haptic device together with the rotational component. In computing friction forces, the system verifies if the static friction threshold is exceeded, in which case it computes the amount of the slip used later in needle equilibrium state update.

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 visive 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.

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