Co-Located Haptic Interaction for Virtual USG Exploration*

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Abstract— **Ultrasonography is a widespread diagnostic technique that can take advantage of virtual reality for the purpose of training and rehearsal. The placement, orientation and body interaction of the probe is fundamental for the execution of the exploration. This paper introduces a virtual reality setup that employs visuo-haptic feedback for virtual ultrasonography. The haptic feedback is provided by desktop delta-like haptic interface with a 3D printed ultrasonography probe, and features haptic point-cloud rendering with implicit surface rendering. The visual feedback is provided by a Head Mounted Display that displays the virtual body, the probe and the operator's hand while not in contact with the probe. The system provides a co-located experience by means of precise calibration of the reference system allowing to synchronize the display of the hand and the probe with the location of the corresponding physical entities.**

I. INTRODUCTION

Ultrasonography (USG) is an important diagnostics procedure that allows identifying different types of pathologies or structural alterations. The procedure is based on a hand-held USG probe that is pressed against the body surface of the subject to obtain the correct point of observations of organs and other anatomical structures. In particular, the probe is pressed against the body to highlight views of specific organs, or between ribs for accessing the inner part of the thorax. The USG exploratory process involves the sense of touch of the doctor both for the gentle sliding of the probe over the body surface and for the stronger pressure for specific placements of the probe. The practice of USG could take advantage of the advancements in virtual reality and haptic interaction for supporting the exploration of virtual models of the anatomical structures based on computational model of the organs, or from recorded imagery. In addition these technology can be used for the visuo-haptic rehearsal of previous explorations or for tele-medicine.

This work presents a setup for research in the area of virtual USG that employs visuo-haptic feedback. The haptic feedback is based on a 3DOF Delta-like haptic interface with a 3D printed USG probe, that allows to display forces of interaction with the body surface and interior elements. The use of haptic feedback in medicine is well established (see [1] for a survey) for supporting training, rehearsal or robotic guidance. An important problem of visuo-haptic integration is the co-location, that is the matching of the physical placement of the haptic interface end-effector with its visual representation. Co-location has been typically addressed in the field of Augmented Reality haptics in which the virtual entities are overlaid on the real-world scene, together with the removal of the haptic interface visual appearance. Some solutions are based on screens, or mirrors [2], while others involve projectors [3]. The key challenge in this type of haptic interaction is the calibration between the display and haptic systems [4], with several issues in the resulting quality of interaction.

The visuo-haptic approach taken by this work is based on immersive visualization thanks to Head Mounted Display (HMD). The display of the doctor hands and the co-location of the real USG probe with the corresponding visual element are aimed at increasing the sense of presence and embodiment.

The aim of providing realistic interaction forces requires the use of a grounded haptic interface in favor of wearable interfaces or pseudo-haptic interfaces. The limitations in the workspace for a grounded interface are overcome by an indexing technique that allows to explore a virtual body larger than the workspace, improving over state of the art approach [5].

The paper is organized as follows. First the system design is described discussing the hardware and software setups, with details on the calibration for co-location. Then the interaction is discussed presenting the haptic rendering approach together with testing scenario. The paper is closed by conclusions.

II. SYSTEM DESIGN

A. Hardware Setup

The system is composed of a Virtual Reality (VR) setup and a haptic interface (HI) as shown in Figure 1. The VR setup is based on the Oculus Rift DK2 (960x1080 per eye, 60Hz, $100\,\mathrm{deg}$ FOV) HMD, whose position and orientation are tracked absolutely with respect to a fixed frame (near infrared optical tracking at 60Hz sensor fused with 1kHz IMU). The HMD is also equipped with a Leap Motion sensor for hand tracking (100Hz) mounted on the frontal part. The haptic feedback is provided by a parallel HI that is composed of a custom Delta-like (Delta.3, Force Dimension, Nyon, CH) haptic device in the bottom and of a non-actuated spherical wrist on the top. The bottom part allows for a 3 degrees of freedom (DoFs) translational motion of the end-effector; the workspace is a cylinder whose diameter and height are 0.26m and 0.12m respectively. The force that the device can display is 40 N in each direction within the aforementioned workspace. The top part is a 3DoFs spherical wrist that is only sensed by means of three encoders for measuring the end-effector orientation. For the USG examination simulation, we employed an ABS printed dummy of a real USG probe whose model was obtained by

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3D scanning. A MacBook Pro 2012 with quad-core Intel i7 processor and a GPU NVIDIA GeForce GT 650M runs the software for the VR and collision detection, a Intel PC (Core i7 4770R 3.2 GHz, 8 GB RAM, integrated GPU) running Ubuntu Linux 14.04 runs the high level control and haptic rendering of the HI, whereas the low-level control is provided by a custom board based on an ARM Cortex-M4 32 bits STM32F407VGT6 micro controller unit that manages also both the motors' encoders signals and the input for the motors' drivers.

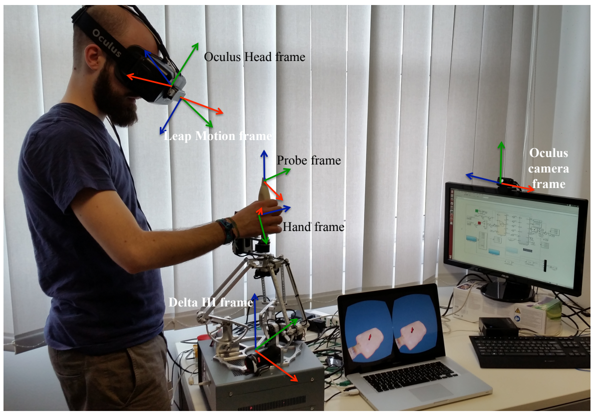

Fig. 1. System setup annotated with the reference systems. On the left side the operator with the haptic interface, on the right side the stereoscopic image displayed on the Oculus HMD.

B. Software Setup

The overall software setup of the system is based on three main blocks running in three different machines: two computers and one embedded platform. These three blocks correspond to three levels of abstraction: high-level graphic and interaction, medium haptic rendering computation and low level haptic control, as shown in Figure II-B. The high-level part is managed by the parallel Compact Components (CoCo) framework ([6], [7]) that has been designed to process and integrate 3D graphics, sensors and interactive devices taking into account multicore systems and real-time timings. The high-level part comprises a 3D visualization module that displays the mannequin, the probe mesh and the user's hand. At the same time CoCo deals with the sensor information from the Oculus HMD, Leap Motion and Haptic Interface managing the reference system transformations, as discussed in the following section. Collision detection and proxy computation of the haptic rendering are processed at this level. The graphics loop runs at 60Hz while the collision detection and haptic rendering at 1kHz.

The medium level, based on Simulink, deals with the computation of the force, the medium level loop with the haptic interface, comprising indexing and safety measures. The low level control algorithm is implemented in Matlab Simulink ® and it is compiled and downloaded into the embedded controller to run at 1kHz frequency. The algorithm manages also the gravity compensation, whereas, since the measured friction is rather small and the speed of the device during USG examination is small, we decided to not implement neither friction nor dynamics compensation.

C. Co-location Calibration

An important aspect of the proposed setup is the co-location of the 3D visual display in the HMD with the physical interaction with the haptic interface. The co-location means that when the user moves the hand and finds the probe in the real world it is perceived at the same location as displayed in the HMD. When the user moves his hand it is displayed as an animated virtual hand, whose pose and fingers are obtained from the Leap Motion sensor.

The co-location is obtained by means of the absolute positioning provided by the HMD and a calibration procedure that is discussed in the following. The process involves the following 7 reference systems:

- Haptic Interface base and USG end-effector
- Virtual geometry: comprising mannequin mesh and implicit surfaces
- HMD tracking camera origin and head pose
- Leap-Motion base (attached to the HMD) and hand pose

The above reference systems are related by a set of transformations, some of which are dynamic and measured, others fixed and known, and others that needs to be computed by the calibration process. The origin of the virtual world has been arbitrarily placed in the Haptic Interface base, and the virtual geometry has been positioned in a way to be reachable by the HI end-effector. For the visual part the hand pose can be easily referred to HMD tracking origin by means of the fixed transformation of the Leap Motion to the HMD local reference system.

The key action for achieving co-location is the calibration of the HMD reference system with respect to the HI base. Currently, the calibration is obtained as follows:

1) The USG probe is positioned in $(0, 0, z_0)$ and null rotation in the HI base frame.
2) The user places his hand horizontally on top of the probe rotated so that it is aligned with the probe. In this way the transformation between the hand frame and the probe frame is fixed and known.
3) When the above steps are done a key is pressed on the keyboard and the system reads the poses of the hand and of the probe in their respective frames and computes the calibration matrix that allows to related the HI base frame with the HMD camera origin.

An alternative approach is based on the recognition of markers placed on the HMD tracking camera and the HI base.

III. INTERACTION

The objective of the interaction is the simulation of USG examination combining surface body representation with a virtual model of the interior. The approach used for the haptic rendering is based on the superposition of the force feedback from two different volumes: a soft outer volume associated to the skin, and harder interior volumes.

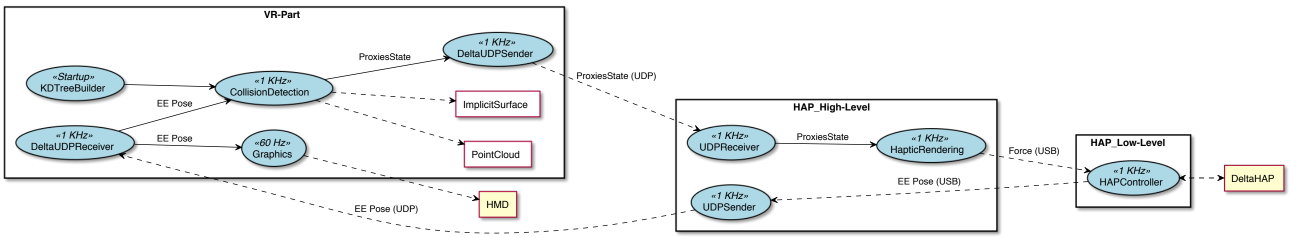

Fig. 2. Architectural diagram

The virtual model of the patient has been obtained by scanning a mannequin using the Kinfu algorithm. Two versions of the resulting models have been employed. A medium triangulated version has been used for the graphics display (3k tris), while a higher resolution version, based on surface Poisson disk resampling has been generated for the haptic interaction (16k vertices). Differently from real-time acquired point clouds the normals are correctly estimated from the scanned model.

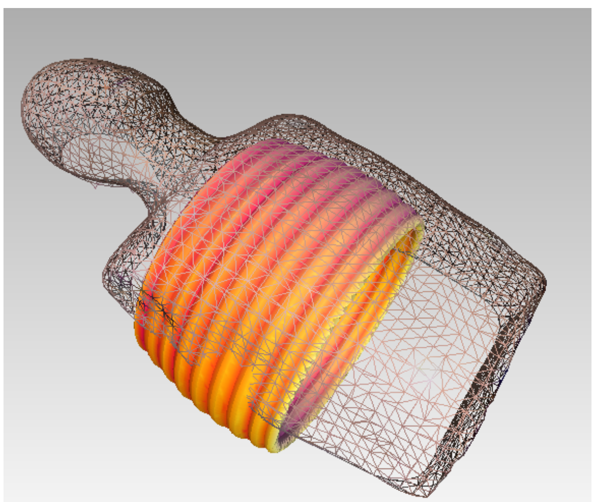

Fig. 3. Model used for the haptic rendering showing the external surface model and the inner implicit model for the ribs

A. Haptic Rendering

The haptic rendering is based on the implicit surface technique [8] that, using an implicit surface $f(x, y, z) = 0$ paired with a local gradient $\Delta(x, y, z)$, manages a 3DOF proxy on the surface, making the proxy slide over the surface using a planar constraint. This approach is employed in this work for both the layers, using two proxies whose effects are summed.

The outer layer is obtained from the rendering of an implicit volume defined by a set of local potentials generated by the point-cloud surface point augmented by the normals [9]. At time step a KD-Tree is queried for the points and normals around the end-effector. These points are then combined to obtain an implicit surface.

The inner layer displays virtual ribs that have been modeled as implicit surfaces. These surfaces have been obtained by combining multiple tori functions by means of constructive solid geometry semantics. The resulting virtual model used for the haptic interaction is shown in figure 3.

In particular a custom developed C++ library allows us to describe a generic implicit surface as a tree structure whose leaves are primitive implicit surfaces, such as torus, sphere, planes and capsules, and whose internal nodes are operators that transform these surfaces such as union, intersection, blending, coordinate system transformation and clipping. Each node of this tree exposes the implicit function evaluation $f(x, y, z) = 0$, the gradient $\Delta(x, y, z)$ and the bounding box for fast collision detection. The resulting tree can be efficiently evaluated at haptic rates, and it can be transformed into a mesh by means of marching cubes. The following is an example of the syntax, based on a direct polish notation where tr is the translation, tx is rotation and translation and torusx is a torus aligned along the x axis specified with inner and outer radius. The plus operator is the union of two surfaces:

```
tr 0.5 0.35 0.015
tx -0.6 -0.3 -0.06 -30 0 0 1
+ tr -0.03 0.0 0.0 torusx 0.182 0.009
+ tr -0.01 0.0 0.0 torusx 0.184 0.01
...
```

B. Indexing

The thorax and the abdomen of a person are larger than the workspace of the haptic device. Therefore, workspace indexing was implemented in this way: if the end-effector of the haptic device is within a circular cylinder that is centered in the device radial symmetry axis, the user interacts with the patient body. When the end-effector is beyond the cylinder boundary, the interaction with the patient is disabled and the user perceives a force that recalls the end-effector towards the axis of the cylinder that is proportional to the distance of the end-effector form the cylinder surface. At the same time, the center of the explorable workspace of the patient body is shifted in the horizontal plane in the opposite direction of the recalling force, the displacement speed is proportional to the recalling force magnitude.

IV. RESULTS

The system has been tested by two doctors and two non-specialized users, that volunteered and signed content form. Thanks to the good calibration of the system the users were

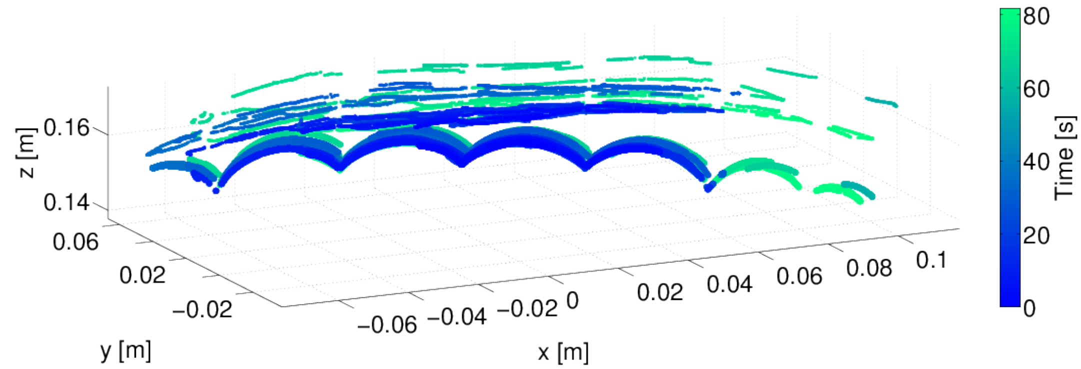

Fig. 4. Representation of the interaction over the two layers. The proxies from the two layers are displayed with color corresponding to time in seconds. The top part is the soft layer of the skin, while the lower one is the implicit surface.

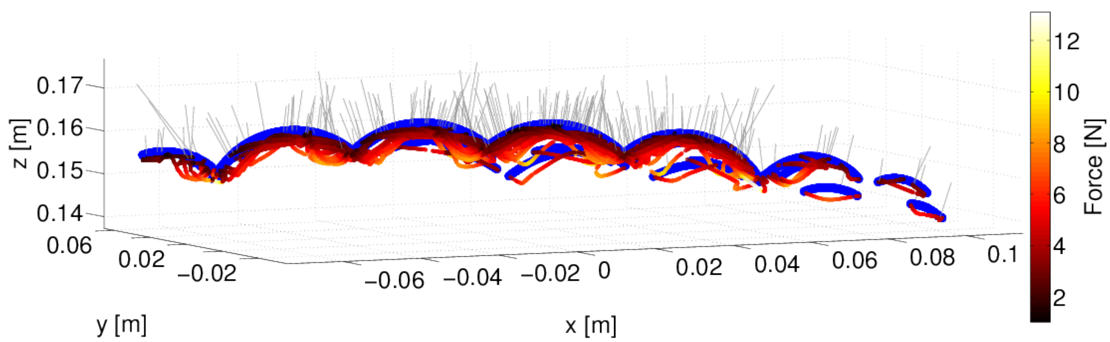

Fig. 5. Blue lines represent the position of the proxy on the ribs. Red shaded lines represent the position of the end-effector colored according to the intensity of the force feedback. Arrows represent the force versor.

able to easily find the probe wearing the HMD even when the virtual hand was not visible. The doctors where satisfied with the fidelity of both the graphic and haptic feedback and had just few comments on how to slightly improve the shape of the virtual ribs. Furthermore they proposed to add more implicit volumes under the belly to simulate the different organs.

Figure 4 shows the two proxies during the example examination. This figure is matched by the one with the display of computed forces, i.e. Figure 5. The blue lines represent the position of the proxy on the ribs, and they show the undulating shape of ribs. The red lines proof that the more we indent in the surface the more the haptic feedback increases capping few millimeters below the surface due to the high stiffness of the bones.

V. CONCLUSIONS

The paper has presented a VR setup that has been designed for the virtual exploration and training in USG. This setup will be assessed for evaluating the effectiveness of the haptic rendering, in particular for the purpose of placement of the probe in given positions, like between the ribs. Additional improvements will be performed for supporting multiple layers of materials with different stiffness values. In parallel to this aspects the generation of simulated USG image will be investigated.

This paper acknowledges the EU Project REMEDI, grant number 610902.

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