ORIGINAL ARTICLE

The FeTouch Project: an application of haptic technologies to obstetrics and gynaecology

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Abstract
Ultrasound technologies have been widely used in gynecology and obstetrics. Modern ultrasound systems allow the reconstruction of a 3D model of the subject being scanned, but even though visual interfaces have reached very high standards, the problem of representing a 3D image on a 2D computer screen still exists. Moreover no physical interaction is possible with such a model. The FeTouch system, developed at Siena University in the last two years, partially solves such issues by using stereo visual feedback and haptic devices. While the system can be used with any 3D model obtained from ultrasound scans, its current prime use is to allow mothers to interact with a model of the fetus they are carrying. The system is freely available on the project web page.

Keywords: gynaecology, obstetrics, fetus, robotics, haptic rendering, medical imaging

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INTRODUCTION
In the last twenty years ultrasound techniques have grown in popularity within the gynecology and obstetrics communities [1, 2]. Ultrasound technologies have become a standard in detecting several morphologic and functional alterations involving both fetus and internal female genitalia. The success of ultra-sonography is mainly due to its non invasive nature, low cost and ease of use.

Medical ultrasound imaging is inherently tomographic, i.e. it provides all the information necessary for the 3D reconstruction.

Ultrasound machines are based on the same basic principle: ultrasound pulses are sent to the part of the body being scanned and echoes are received. The time delay of the echoes and their intensity allow to create a 2D image of a cross section of the body commonly referred to as the 2D B-scan of the scan plane. However, various types of ultrasound machines exist. Low-cost devices, normally referred to as freehand 3D systems, are based on small hand-held probes enhanced with a position sensor (Most common position sensors are electromagnetic, acoustic or optical [3])

The 3D ultrasound process, consists of three stages: scanning, reconstruction and visualization as described in [4]. More expensive solutions, normally referred to as real-time three-dimensional (4D) ultrasound imaging technologies, are normally characterized by arrays of 2D transducers which allow them to directly acquire the volume of the part under investigation.

The former systems are often less accurate. Acquisition errors are typically due to errors in tracking the probe's exact location. In order to limit such errors the reconstruction process, i.e. retrieving 3D data volumes from a series of 2D B-scans, becomes critical [5, 2]. The latter allow the acquisition of an entire volume at each sample and therefore do not need any interpolation process.

Once a 3D image is available, its visualization process is normally based on standard 2D PC monitor rendering.

While this process has proven quite effective, it remains somewhat limited. Depth information is partially lost. Furthermore no physical interaction is possible. One conceivable way to enhance 3D volumes is based on the use of haptic devices. Haptic devices are small robotic structures that allow users to touch virtual objects. This is accomplished by measuring the user position, translate such position to a virtual environment, compute collisions and interaction forces between user and virtual objects and then return such forces to the user through the device.

Haptic devices are now widely used in the field of medical simulation for training purposes [6, 7]. Haptic devices applied to medical imaging is also a growing field of research. For instance, the authors have previously proposed a visio-haptic display of 3D angiograms [8, 9]. Wang [10] used force feedback to feel the edges of 2D ultrasound images. Avila *et al* have proposed techniques to add force feedback to the display of volumetric images [11]. The proposed haptic rendering techniques are however based on voxels and force fields, which have been proven to have problems in various situations [12].

System description

The system proposed in this paper allows users to reconstruct 3D visual-haptic models from sets of 2D slices obtained using ultrasound machines. Such models can then be touched using any haptic device. While the system has been mainly developed for interaction with fetal models, the scope of the project is wider. In order to make the proposed system as general purpose as possible, the FeTouch workstation has been designed to process data from standard 2D ultrasound scans in DICOM format [13]. The system can thus be used in conjunction with any ultrasound machine. Fetal 3D images were acquired using a Siemens Sonoline Elegra system (Because of a lack of a probe tracking system the scans have been performed following linear trajectories at a constant speed. A scan speed indicator is used to assure such conditions).

In recent times Novint Technologies has announced the release of a commercial product, the e-Touch Sono, which allows users to interact with 3D fetal models [14]. While the idea is similar to the one proposed in this paper, the solutions adopted and their scope are different. The e-Touch Sono system is based on a dedicated 4D ultrasound system. While this certainly ensures high quality levels it also limits the applicability of the system. By using images in the DICOM standard, the FeTouch system can be used with data obtained using any ultrasound machine. Moreover the FeTouch system is not commercial in nature and can be downloaded freely from the project's web site [15].

It is important to note that the FeTouch system has not been designed with medical diagnosis in gynecology and obstetrics as a prime focus. In fact while using ultrasound it is possible to capture the exact 3D geometry of an internal organ it is normally impossible, to obtain its physical features. The overall level of realism can be improved by introducing various effects, such as compliance, heart beat and skin texture, and such is the case for the FeTouch system. However, it is important to note that none of these effects are physically based on the data obtained from the ultrasound machinery and thus their usage in diagnosis would be unreasonable.

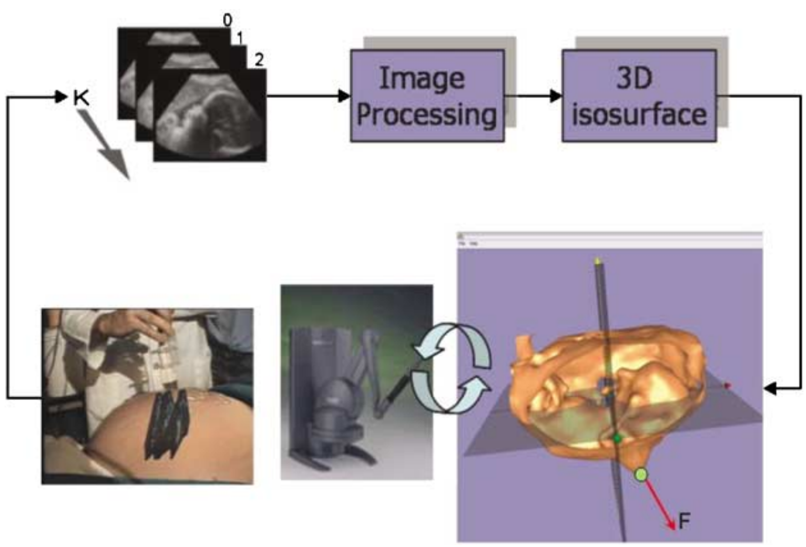

Figure 1 The Fetouch workstation.

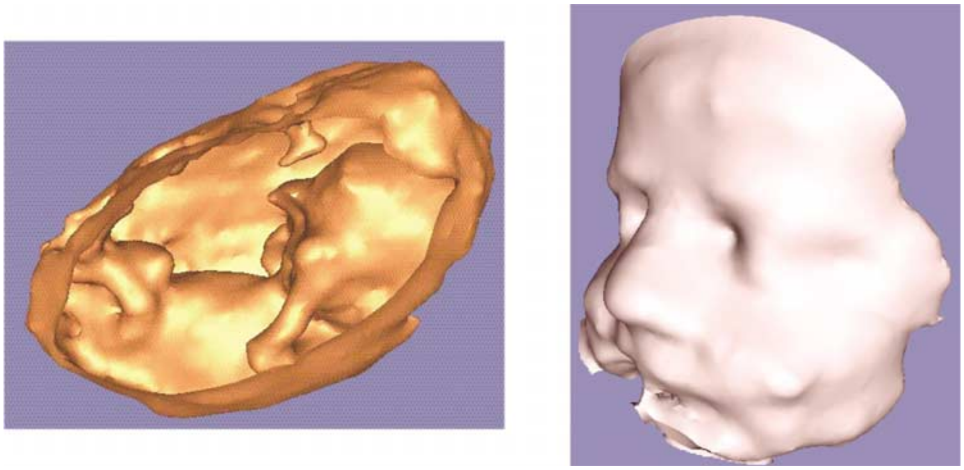

Figure 2 The visio-haptic rendering of a 12-weeks fetus.

System software architecture

The functional scheme of the FeTouch system is outlined in Figure 1. The system is divided in two main blocks serving different functions. The first block (US3D) is devoted to creating a 3D visual-haptic model given a set of ultrasound scans. The second block (US3Dtouch) allows the user to interact with such system using a haptic device (PHANTOM [16] or Delta [17]) and a 3D image (PC screen alone or enhanced by stereo glasses).

Software has been designed in C++ in an object oriented setting and is portable on various platforms (e.g. Windows and Linux). The Visualization Toolkit (VTK) has been used [18] to create a visual feedback to the user as well as for performing collision detection between the user and the 3D fetal model. The Graphical User Interface has been developed with the fast light toolkit (fltk) [19]. In the following we will focus our attention on the two main blocks that make up the system.

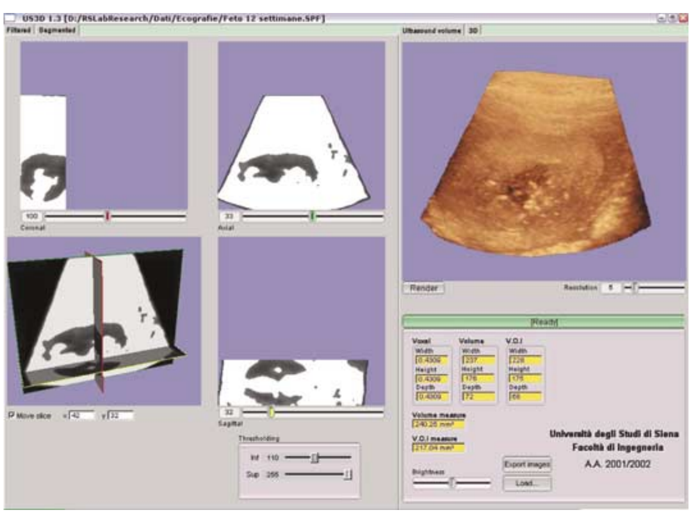

Figure 3 Volume visualization by maximum intensity projection and segmentation process.

Automatic model extraction algorithm

This section describes the software for automatic model extraction referred to as US3D. US3D allows ultrasound 2D-scans, in DICOM format, to be gathered and displayed as a volume. In order to better visualize the ultrasound volume, data is re-sliced along three directions (axial, sagittal and coronal) as shown in Figure 4.

A direct visualization of the ultrasound volume is available in US3D. The Maximum Intensity Projection (MIP) approach is used to render the image in Figure 3. This technique of direct volume rendering, also known as ray-casting, is based on drawing parallel rays from each pixel of the projection screen and then considering the maximum intensity value encountered along the projection ray for each pixel [20]. This method does not need any pre-processing phase and is fast but it is not truly a 3D visualization technique since any information on depth is lost.

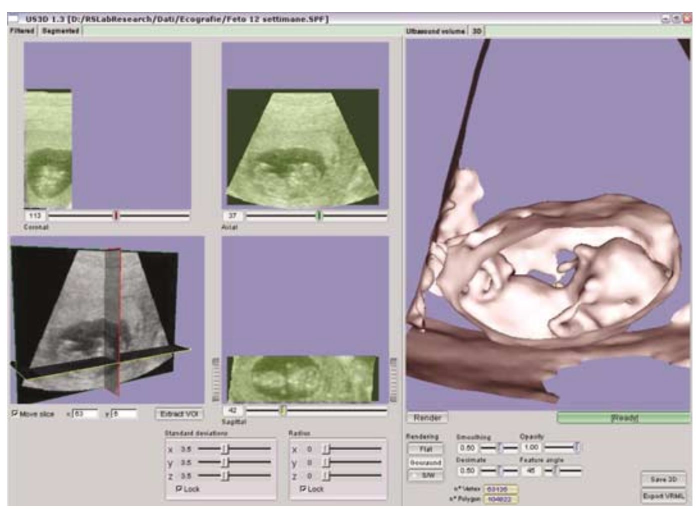

Figure 4 The axial, sagittal, coronal and 3D surface visualization of the fetus.

(a) (b) (c)

Figure 5 The Oriented Bounding Box tree. (a) Level zero. (b) Level one. (c) Level two.

The noise affecting raw data can be filtered by a 3D Gaussian smoothing kernel. The volume of interest (VOI) can be selected using the GUI of the US3D software.

The VOI is first segmented from the background to obtain, by means of a threshold filter, a binary volumetric data set. The surface fitting algorithm known as *marching cubes*, designed by Lorensen and Cline [21, 18] to extract surface information from 3D fields of values is then used to render the model isosurfaces. The surface is constructed according to the following basic principle: if a point inside the desired volume has a neighboring point outside the volume, the isosurface lies between these points. This analysis is performed at the voxel level. An example of 12-weeks fetus is shown in Figure 2. Such surfaces can be saved using various formats (currently VTK binary and VRML files are supported).

US3DTouch

The US3DTouch software has been developed to allow users to physically interact with any fetal model extracted using the US3D software. The standard proxy and god-object algorithms [22, 12] have been implemented and tested on various fetal models. Particular care has been placed on creating a stable haptic interaction. This is made difficult by the number of polygons that typically make up a fetal model, which is on the order of several tens of thousand, and by the consequent problems in creating fast (>1 KHz) collision detection algorithms. In order to limit such problems two different approaches have been followed:

- The number of triangles making up the system can be considerably reduced (see Figure 6). In order to avoid cusps or other unwanted shapes due to the decimation process, a smoothing procedure is used [23, 24].
- Fast collision detection algorithms are used. More specifically OBB-tree [9, 25] are used to make the process faster (see Figure 5). Note that this is made simpler by the fact that, even though the fetal model feels compliant to the user, interaction forces are computed using a static shell representing the fetus.

The system is PHANTOM based (see Figure 1) but Delta devices [17] can be easily supported.

Various visual and haptic effects are added to the fetal model in order to make the overall simulation more realistic:

- As previously mentioned, the surface of the model is smoothed in order to eliminate bumps due to noise.
- A heart-rate effect is haptically simulated. More specifically the heart-rate of the fetus is directly measured and pre-processed in order to decompose the signal into its principal components through standard FFT techniques. Such signals are then haptically added to the standard force feedback due to contact with the fetus. While the frequency of the heart-beat signal does not change throughout the

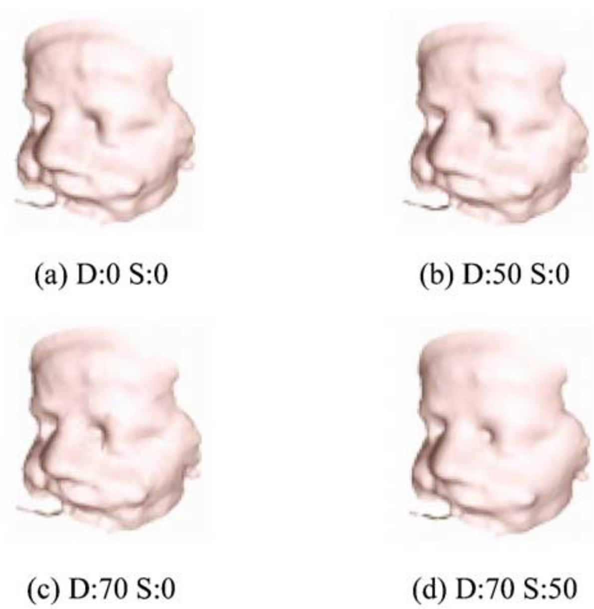

Figure 6 The number of triangles are: (a) 34167 (b) 23629 (c) 16702 (d) 3192. D is the decimation factor and S the smoothing factor.

body, its amplitude is inversely proportional to the distance between fetus heart location and current contact point with the 3D model.

- The visual feedback is greatly improved by using graphical textures obtained by pictures of new born babies. Similarly, haptic textures are added to the fetal model in order to make its surface feel like human skin.
- The 3D fetal model is rendered to be locally compliant by using a spring-mass technology. However, compliance parameters are not tuned on the basis of any real physical parameters of the actual fetus. An example of model deformation is shown in Figure 1.

It is important to note, once again, that while the effects described above usually accomplish the purpose of making the simulation more realistic, at the current stage of the project, not all of such effects have a realistic base, i.e. properties such as varying stiffness and skin texture are not tuned according to real parameters of the fetus. For this reason the FeTouch system is not currently being used as a diagnostic tool.

CURRENT LIMITATIONS AND FUTURE WORK

The current system has been created as a tool for mothers to better interact with 3D models of their fetus and not as a diagnostic tool. While the diagnostic purpose is a fascinating prospect it is far from being a reality. Various challenges must be met in order to solve a number of problems. More reliable techniques to simulate deformable objects must be developed along with procedures for in-vivo identification of stiffness parameters for the specific subject being modelled (be it a fetus or a generic human organ). Such issues will be the subject of future investigation.

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