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The Fetouch System: Visual-Haptic Rendering of Fetuses

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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. 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 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, which is freely available on the project web page (http://www.fetouch.org), has been tested on twelve cases which have been monitored by doctors at Siena Hospital. New features of the system include the haptic heartbeat feature.

1 Introduction

In the last twenty years ultrasound techniques have grown in popularity among the gynecology and obstetrics communities [2, 19]. 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 solutions, normally referred to as freehand 3D systems, are based on small hand-held probes enhanced with a position sensor[1]. The 3D ultrasound process, consists of three stages:

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[1] Most common position sensors are electromagnetic, acoustic or optical [6]

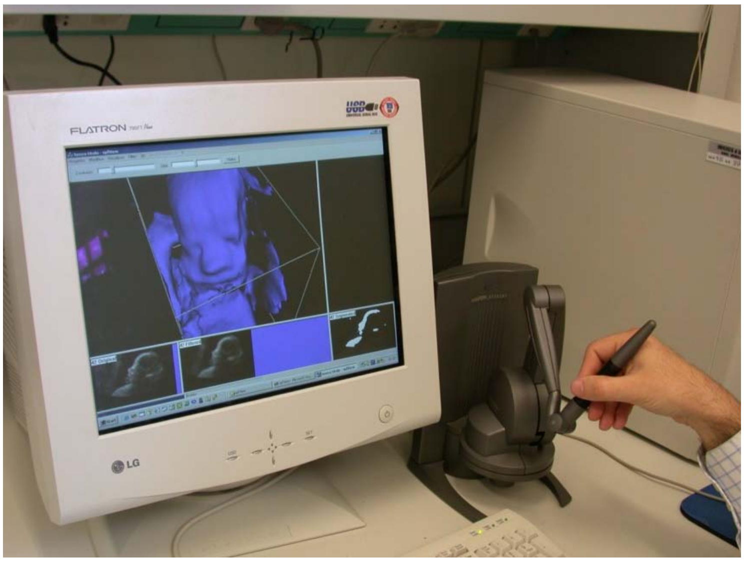


Fig. 1. The Fetouch workstation.

scanning, reconstruction and visualization as described in [15]. More expensive solutions, normally referred to as real-time three-dimensional (4D) ultrasound imaging technologies, are normally characterized by arrays of 2D transducer 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[16, 19]. The latter allow the acquisition of an entire volume at each sample and therefore do not need any interpolation process.

The visualization process is normally based on rendering the 3D volume on a standard 2D PC monitor. While this process has proven quite effective it remains somewhat limited. Depth information is partially lost. Furthermore no physical interaction is allowed. One of the possible ways to enrich the fruition of 3D volumes, one proposed in this paper, 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 [4]. Haptic devices applied to medical imaging is also a growing field of research. In [24], for instance, the authors propose a visio-haptic display of 3D angiograms. In [23] force feedback is used to feel edges of 2D ultrasound images. In [1] the authors propose techniques to add force feedback to the display of volume images. The proposed haptic rendering techniques are however based on voxels and force fields, which have been proven to have problems in various situations [25].

2 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 the case of 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 [12]. The system can thus be used in conjunction with any ultrasound machine. The system has been successfully tested on the fetuses of twelve women at Siena Hospital in 2001/02. The data presented was acquired using a Siemens Sonoline Elegra system[2].

In recent times Novint Technologies has announced the release (at the end of 2002) of a commercial product, the e-Touch Sono, which allows users to interact with 3D fetal models. [13]. While the idea is similar to the one proposed in this paper, differences exist. The Novint product will be based on a dedicated 4D Ultrasound System produced by GE (the Voluson 730 4D Ultrasound). This will certainly ensure a high level of quality but will limit the application to a specific 3D type of ultrasound systems. By using images in the DICOM standard the Fetouch system can be used with data obtained using any ultrasound machinery.

It is important to note that the Fetouch system has not been designed with medical diagnosis in gynecology and obstetrics as a prime focus. The user interacts with the surface of a 3D fetal model (or other model). While such surface is enhanced with various effects, such as compliance, heart beat and skin texture it is important to note that none of these effects are physically based on the data obtained from the ultrasound machinery. While ultrasound data contains information about tissues properties, and such information can be used to simulate different haptic properties for the system at hand (as for instance in [1]), a more precise system that links such data to the parameters characterizing a deformable fetal model would be needed. Such will be matter of future investigation. The Fetouch system is freely available at [22].

3 System software architecture

The functional scheme of the Fetouch system is reported in Fig. 2. The system is divided in two main blocks serving different functions. The first block (US3D) is devoted to creating a 3D visual-haptic model give a set of ultrasound scans. The

[2] 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.

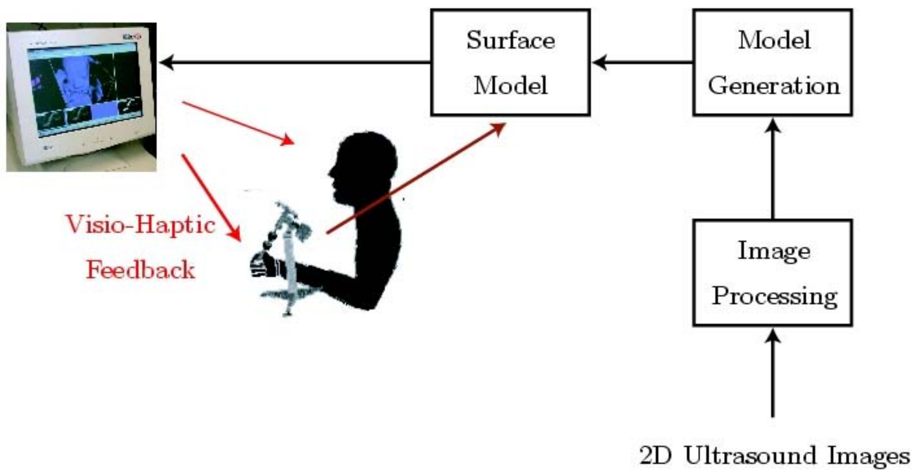


Fig. 2. The functional scheme of Fetouch .

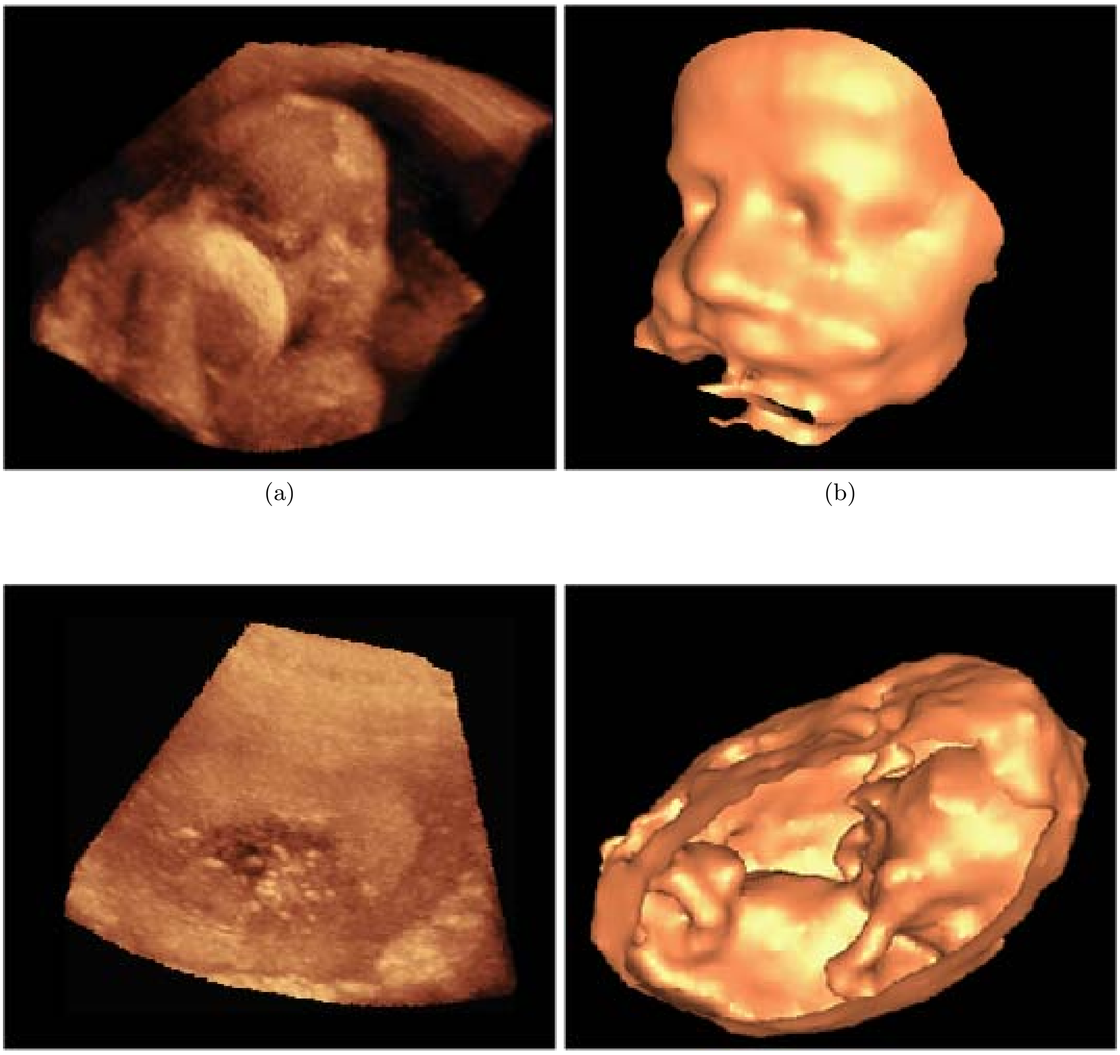
second block (US3Dtouch) allows the user to interact with such system using a haptic device (PHANTOM[21] or Delta[5]) and a 3D image (PC screen alone or enhanced by stereo glasses).

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)[20]. In the following we will focus our attention on the two main blocks that make up the system.

3.1 Automatic model extraction algorithm

This section describes the software for automatic model extraction referred to as 3DUS. 3DUS 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)

A direct visualization of the ultrasound volume is available in US3D. The Maximum Intensity Projection (MIP) approach is used to render the image in Fig. 3-(a,c). 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[9, 10]. 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.



(a) (b)

(c) (d)

Fig. 3. Examples of 3D model reconstruction: (a,c) Ultrasound volume visualization by maximum intensity projection. (b,d) 3D surface rendering.

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, see Fig. 4.

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 [11, 18] to extract surface information from 3D field 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 isosurface generated by US3D is given in Fig. 5. Such surface

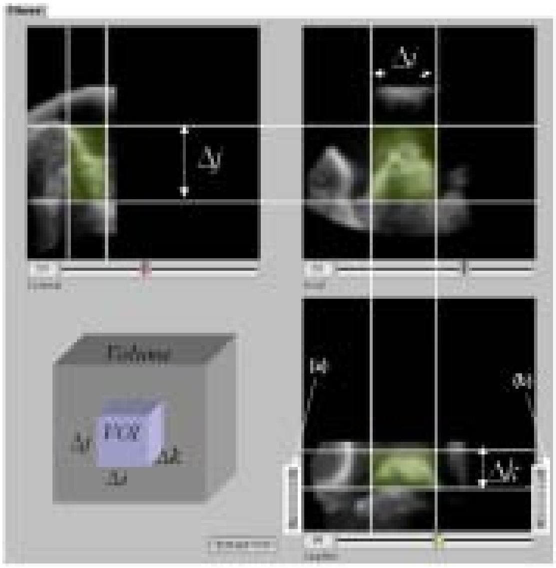


Fig. 4. Selecting the volume of interest (VOI).

can be saved using various formats (currently VTK binary and VRML files are supported).

4 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 [17, 25] 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 (> 1KHz) collision detection algorithms. In order to limit such problem two different approaches have been followed:

- the number of triangles making up the system can be considerably reduced (see Fig. 4). In order to avoid cusps or other unwanted shapes due to the decimation process a smoothing procedure is used [3, 14].
- fast collision detection algorithms are used. More specifically OBB-tree [7, 8] are used to make the process faster (see Fig. 6). 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 Fig. 1) but Delta devices [5] can be easily supported.

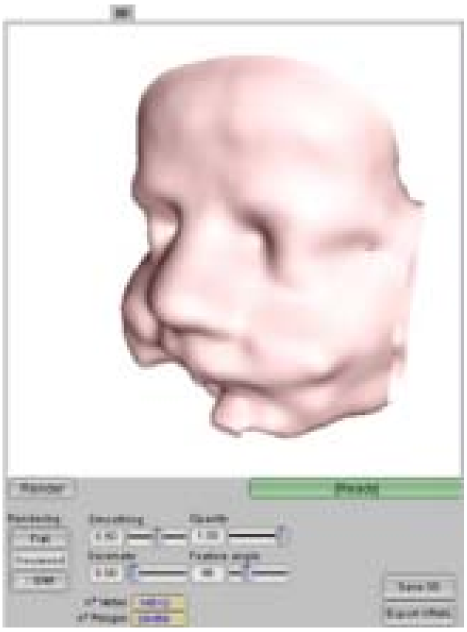


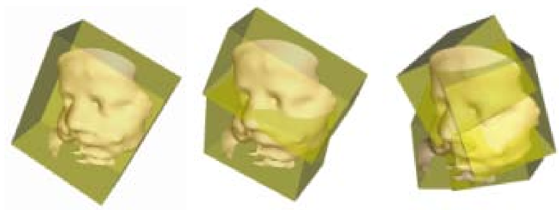
Fig. 5. Isosurface extracted

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.
- The contact stiffness varies throughout the fetal model. This allows us to create realistic effects, such as making the fetus head feel stiffer than the rest of the body.

– A heart–rate effect is haptically simulated. More specifically the mother's heart–rate is measured and decomposed in various sine waves. The heartbeat signal is directly acquired from the fetus. A pre-processing phase adapts the heartbeat signal to the haptic rendering system. In particular, the signal is filtered and the Fourier analysis is used to extract the low frequency components. The heartbeat signal is rendered by simply adding the pre-processed signal to the normal force of the surface haptic rendering procedure. The amplitude of the heartbeat signal is scaled according to the distance from the hearth area of the virtual fetus. The hearth area is defined by the user in the initialization phased of a Fetouch system session.
– 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.

It is important to note that while the effects described above usually accomplish the purpose of making the simulation more realistic, not all of such effects have, at the current stage of the project, a scientific 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 been used as a diagnostic tool.

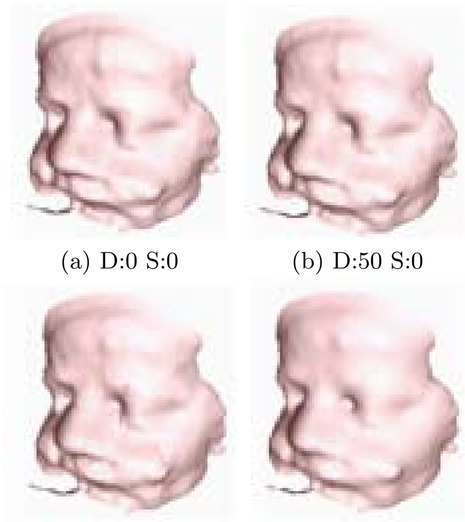


(a) (b) (c)

Fig. 6. The Oriented Bounding Box tree. (a) Level zero. (b) Level one. (c) Level two.

5 Current limitations and future work

As previously mentioned the current system has been created as a tool for mothers to better interact with 3D models 3-(b,d) of their fetus and not as a diagnostic tool. While this is an incredibly fascinating prospect, it is far from being a reality. Various challenges must be met in order to solve such problem. 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 modeled (be it a fetus or a generic human organ). Such issues will be subject of future investigation.



(a) D:0 S:0 (b) D:50 S:0 (c) D:70 S:0 (d) D:70 S:50

Fig. 7. D : factor of decimation. S : factor of smoothing . The number of triangles are : (a) 34167 (b) 23629 (c) 16702 (d) 3192

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