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Breast Cancer Palpation Training System Using Five-Fingered Haptic Interface Robot and GPGPU

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Abstract: As the number of breast cancer patients grows, teaching more medical students is highly demanded than ever. However, seeking for real patients and actually having a training session with them are very difficult due to the nature of the training involving touching their body. Our approach to this problem is to develop a virtual breast cancer palpation training system that can completely eliminate the need for real human patients for the training. Our training system uses HandHIRO, a five-fingered haptic interface robot to create haptic sensations of the deformations of a virtual breast including tumors. The deformations of the virtual breast are entirely computed on a GPU using an FEM and the computational results are rendered both haptically using a HandHIRO and graphically using a 3D display system with a half mirror. In this paper, the design and implementation of our training system and preliminary experimental results are presented.

Keywords: breast cancer palpation, haptic interface robot, 3D display, deformable body simulation, FEM, GPGPU

1 INTRODUCTION

Training environments for breast cancer palpation that are easily accessible by medical users have been greatly in demand reflecting the increasing number of breast cancer patients. Creating a virtual human breast model utilizing VR technologies such as haptic interfaces and 3D displays can completely eliminate the need for real human patients. Based on this idea, we have been developing a virtual training system for breast cancer palpation.

Takaiwa et al. [1] created a breast cancer palpation simulator based on a real off-the-shelf breast training model and a pneumatic parallel manipulator to create force feedback. Jeon et al. [2] created an augmented reality system based on a real silicone breast model and a PHANToM haptic device. Although these systems create realistic haptic sensations utilizing real breast models, they are required to replace the breast model when simulating breasts of different geometry. Moreover, they do not simulate multi-fingered touch sensations. The basic idea of our training system is to create a complete virtual model of a breast as a deformable body and simulate its deformation in realtime. The haptics are rendered for each finger individually by a five-fingered haptic interface robot called HandHIRO (Endo et al. [3]) and the graphics are rendered by a 3D display system with a half mirror. The simulator is based on an FEM (Finite Element Method) with a corotational formulation. Our system allows the user to specify the stiffness for each finite element to place tumors with arbitrary shapes and position, up to the mesh resolution. Introducing GPGPU (General Purpose computing on Graphics Processing Units) technologies, the simulator runs entirely on a GPU. The use of GPUs allows us to simulate large-scale models in realtime that are intractable to conventional CPU implementations. These features enable the user to quickly change the virtual models without lengthy offline precomputations. This means that the users can train using a wide variety of virtual patients with different medical conditions.

This paper presents the design and implementation of our training system featuring the HandHIRO, 3D display system, and a GPU-based FEM simulator. Preliminary experimental results are also presented.

2 SYSTEM OVERVIEW

Fig. 1. shows the overview of our training system. It is comprised of a HandHIRO installed at the bottom, and a 3D display based on a LCD (Liquid Crystal Display) attached at the top, and a half mirror in between. As shown in **Fig. 2.,** a user wearing a pair of 3D shutter glasses sits down in front of the half mirror and sees the 3D images of a female chest including breasts which are projected on the half mirror as a stereoscopic image. At the same time, all the five fingers of the user are connected to the HandHIRO that is placed behind the half mirror so that he/she can receive haptic sensations for each finger individually, while seeing his/her own hand through the half mirror. The 3D images of the deformed virtual breast generated by a PC with GPUs

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are overlaid on top of their own hand, thereby a mixed reality effect is created. This effect is expected to enhance the user's training experience.

2.1 HandHIRO: five-fingered haptic interface robot

Fig. 3. shows the appearance of HandHIRO. HandHIRO is a five-fingered haptic interface robot that features the ability to present high-precision three-directional forces to each of the user's five fingertips individually. HandHIRO has many DOFs: 15 DOFs for the haptic hand and 6 DOFs for the interface arm. Thanks to this arm, HandHIRO can be used in a large workspace. A user connects his/her five fingertips to HandHIRO through passive spherical permanent magnet joints. These joints will automatically come off when excessive amount of forces are exerted, thereby HandHIRO allows to touch a virtual object with five fingers in a safe manner. **Fig. 4.** shows an example of graphics rendering of a virtual breast. The white spheres represent the user's five fingertips. As the user pushes the breast, dents are made and reaction forces are given to the user through HandHIRO. The breast deforms in realtime in response to the movements of the user's fingertips.

3 DEFORMABLE BODY SIMULATION FOR VIRTUAL BREAST CANCER PALPATION

Many parts of a human body, including organs and/or tissues are modeled as a deformable body. We focus on simulating the breast part only as a deformable body. Deformable body simulation is generally a difficult task since deformable bodies have infinite DOFs. Therefore, usually we have to discretize the deformable body using numerical methods such as FEM. Our past breast palpation simulator (Daniulaitis et al. [4]) is also based on an FEM. It realized realtime simulation of a deformable body based on precomputation of the body's displacement and reaction forces: the deformations of the entire body and the reaction forces are precomputed for unit displacements for each vertex of the FE model. At runtime, the deformation of the entire body and the reaction forces for each finger are computed as a linear combination of these precomputed displacements, given a set of contact points. The drawback of this method is the need for the lengthy precomputation and lack of dynamics. Our method simulates the dynamics of a deformable body in realtime using GPGPU and at the same time interacts with HandHIRO for haptic rendering so that more realistic results can be obtained on the fly.

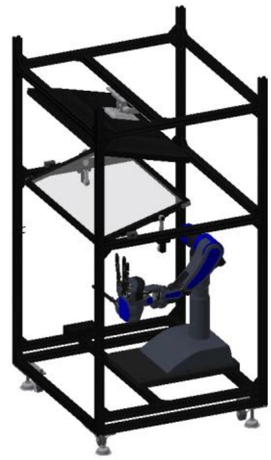

Fig. 1. Proposed breast cancer palpation training system

Fig. 2. Actual use of our training system

Fig. 3. HandHIRO, five-fingered haptic interface robot

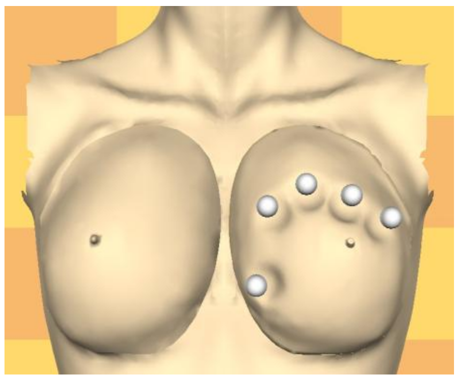

Fig. 4. Deformations of breast by multiple fingertips

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3.1 Simulation algorithm overview

Our simulation algorithm is comprised of (1) collision detection and response and (2) FEM computation. The first step for the algorithm is to receive the current position of fingertips from HandHIRO and perform collision detection between the fingertip spheres and the deformable body surface. If a collision is detected, its contact forces are computed and used as boundary conditions for the FEM. At the same time, the contact forces will be sent to HandHIRO for haptic rendering. Finally, the time step in the simulator is proceeded and the next time step's physical states are calculated.

3.2 Corotational FEM

In our simulator, the deformation of breast is simulated using an FEM based on a corotational formulation on the GPU (Allart et al. [5], Parker and O'Brien [6], Nesme [7]). The corotational formulation accounts for geometric nonlinearities of the deformations. It can avoid so-called "inflation" artifacts when subject to large deformations. The idea of corotational FEM is to rotate the stiffness matrix by a rotational matrix that brings it to the original coordinate space before deformation. This eliminates the bad influence of the rotational component of the deformation to the linear strain that leads to an inflation effect. The system of ordinary differential equations is solved by implicit time integration based on backward Euler scheme for stability. The backward Euler scheme updates the velocity using the acceleration at the end of the time step. This requires to solve a system of linear equations at every time step. This is done by a conjugate gradient solver.

3.3 Modeling fingertip contact

HandHIRO has 5 fingers and each fingertip is modeled as a rigid sphere. The spheres and the deformable body need to avoid interpenetration. We employ a penalty method for simplicity. Proximity is checked for each sphere center against all the vertices within the deformable mesh. If the distance is less than the sphere radius r, then the vertex is considered in contact and proceeds to penalty force computation. This process is efficiently done on the GPU in parallel. The penalty force is given by

$$F = -k_s d - k_e v \tag{1}$$

where d is the penetration depth and v is the rate of change of the penetration distance, k_s and k_e are a spring constant and a damping constant, respectively. For each sphere, all the penalty forces exerted on the sphere are applied to the deformable body as external forces at each contact point. The penalty forces for each sphere are summed and converted into one 3D force vector for haptic rendering. Note that in some cases we observed some noticeable vibrations due to the penalty force when a sphere and the deformable body collide. To suppress these vibrations, we apply a low-pass filter for the computed forces.

3.4 GPGPU: General Purpose computing on GPUs

The entire FEM and collision detection and response are implemented based on GPGPU by CUDA technology (NVIDIA [8]). In the GPU kernels, shared memory is extensively utilized to maximize memory bandwidth utilization. Most of vectors in the algorithms are mapped to a vertex buffer object and made interoperable with OpenGL. This allows direct graphics rendering of the computational results by GPU without copying the results back to the CPU memory.

4 EXPERIMENTAL RESULTS

A preliminary evaluation was conducted using a PC with Intel Xeon E5606 2.13GHz, 48GB main memory, and NVIDIA Tesla C2075 for running GPGPU, and NVIDIA Quadro 2000 for stereoscopic 3D graphics rendering with NVIDIA 3D vision technology. The frequency of the haptic control loop is kept to 1 [kHz] and the graphics frame rate is set to 30 [Hz].

4.1 Constructing a virtual breast model

A virtual breast model was constructed as follows: A real silicone palpation training model was first scanned. Then after the data is cleaned up, it is processed with mesh generation software to generate a triangular surface mesh and a tetrahedral volumetric mesh. **Fig. 5.** shows the breast model represented with a surface mesh (6004 triangles). A volumetric mesh (44208 tetrahedra, 9097 nodes) is constructed from the surface mesh. According to Krouskop [9], the Young's modulus of the entire breast except the tumor part is set to E=19000 [Pa] and the tumor is set to 107000 [Pa], so that the tumor part can be felt stiffer than other parts of the breast. **Fig. 5.** also shows the size and location of the tumor used in this experiment. The tumor's radius is set to 1.5 [cm] and is located on the x axis at x = 0.125 [m]. Only one of the breasts (the one on the right hand side in the **Fig. 4.**) is modeled by an FEM and simulated. Other body parts are static and not included in the simulation. The base part of the breast is given Dirichlet boundary conditions to fix the breast part on top of the chest part.

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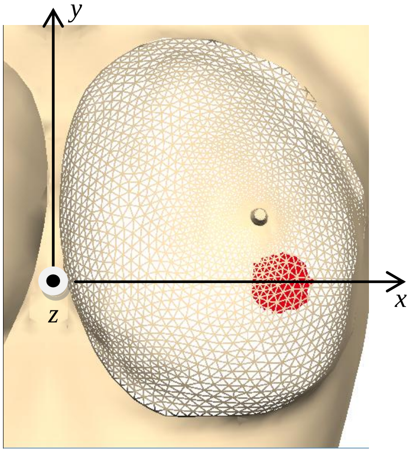

Fig. 5. Tetrahedral mesh and tumor (red part: *E*=107000 [Pa]). *E*=19000 [Pa] for the rest of the mesh.

4.2 Results from virtual breast palpation

A virtual palpation session was conducted using the constructed model. Although the user can generally use up to 5 fingers simultaneously, here we show only the results of 1 finger case for simplicity. The palpation is done using his/her index finger by periodically repeating a push/pull motion along *z* direction (in **Fig. 5.**, +*z* points towards the reader) translating his/her hand along the *x* axis from the left to the right, and then from the right to the left (repeat this 2 times). **Fig. 6.** shows the changes in the index finger's *x* position (dotted line) and the corresponding *z* component of the target reaction forces (solid line) that are computed by the computational module. These target forces are sent to the HandHIRO and rendered to the user's fingertip. As shown in the figure, the reaction force becomes noticeably high at positions around x = 0.12 [m]. This means that, around this location, the user should be receiving significant reaction forces in +*z* direction and feeling the existence of the tumor. The position x = 0.12 [m] approximately corresponds to the *x* position of the tumor that is predefined as shown in **Fig. 5.** This verifies that the location of the tumor is reasonably well represented, thus showing the effectiveness of our system.

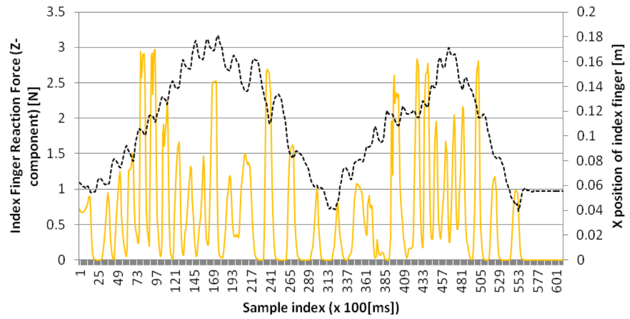

Fig. 6. X-component of index fingertip position vs. Z-component of reaction force of index fingertip measured in a virtual palpation session

5 CONCLUSION

We have discussed the implementation of our virtual breast cancer palpation training system based on a five-fingered haptic interface robot HandHIRO, a 3D display, and GPGPU. The deformation of breast is modeled using a corotational FEM and is computed on a GPU. This enables large-scale realtime simulation of the deformations of a virtual breast. The preliminary experimental results show that our system can simulate the physical behavior of a breast and is effective for breast cancer palpation training.

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