Haptic Simulation of Breast Cancer Palpation: A Case Study of Haptic Augmented Reality

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Abstract

Haptic augmented reality (AR) allows to modulate the haptic properties of a real object by providing virtual haptic feedback. We previously developed a haptic AR system wherein the stiffness of a real object can be augmented with the aid of a haptic interface. To demonstrate its potential, this paper presents a case study for medical training of breast cancer palpation. A real breast model made of soft silicone is augmented with a virtual tumor rendered inside. Haptic stimuli for the virtual tumor are generated based on a contact dynamics model identified via real measurements, without the need of geometric information on the breast. A subjective evaluation confirmed the realism and fidelity of our palpation system.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O; H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities

1 Introduction

In haptic augmented reality (AR), haptic signals of real environments are modulated or augmented with virtual touch feedback. In recent research we have focused on integrating haptic feedback into visual AR systems [2] as well as on modulating the stiffness of real objects with the aid of a haptic interface [4]; the latter system allows to make the stiffness of a real object virtually harder or softer.

This paper examines the application of this technology in the context of a medical training environment. We introduce AR-based simulation methods for the haptic response of a tumor surrounded by soft tissues, as a case study for breast cancer palpation training. To achieve high-fidelity touch feedback, a real breast model made of soft silicone is augmented with a harder virtual tumor rendered inside. The real silicone model produces natural haptic feedback of the breast tissue deformation, while our AR system is responsible for the tumor simulation. For the recreation of the tumor response, we use a contact dynamics model identified using position and force data measured from a real breast model containing an actual tumor lump. In particular, our framework requires no preprocessing for the geometric model of the breast, preserving a crucial advantage of AR. An initial subjective evaluation confirmed that our system can provide realistic behavior close to the real counterparts.

2 Interaction Model

The goal of the present system is to modulate the stiffness of a real breast model as if a stiffer tumor were placed inside. The behavior of the breast model silicone is highly homogeneous, thus facilitating the model-based estimation of the dynamic response of the tumor.

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Our system is configured as shown in Figure 1(a). The response force from the real breast model at time t, $\mathbf{f}_r(t)$, is what the user perceives if no virtual tumor is rendered. The goal is to alter the force delivered to the user's hand, $\mathbf{f}_h(t)$, from $\mathbf{f}_r(t)$ to

$$\mathbf{f}_h(t) = \mathbf{f}_r(t) + \mathbf{f}_t(t), \tag{1}$$

where $\mathbf{f}_t(t)$ is the force that the haptic interface produces to represent the virtual tumor. The realism of the tumor simulation relies on the recreation accuracy of $\mathbf{f}_t(t)$ according to the user's interaction.

A key idea of our approach is to derive $\mathbf{f}_t(t)$ based on a nonlinear dynamics model identified using data measured from a breast mock-up containing a real tumor. This allows us to minimize the preprocessing for the breast geometric model and the tumor response while preserving plausible simulation realism. We use the Hunt-Crossley model, which can account for the nonlinear viscoelastic contact dynamics of a deformable object such as human tissues [3], to describe the responses of the tumor and silicone models. It has the form of

$$f(t) = K_e\{x(t)\}^m + B_e\{x(t)\}^m \dot{x}(t), \tag{2}$$

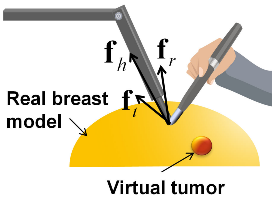
where $x(t)$ and $\dot{x}(t)$ are the displacement and velocity of the haptic device tip, respectively, K_e is object stiffness, and m is a constant exponent (usually between 1 and 2).

Variables necessary to derive $\mathbf{f}_t(t)$ are defined in Figure 1(c). In our current model we assume that the tumor has a spherical shape. $\mathbf{p}_t$ is the position of the tumor sphere, and $\mathbf{p}_{ts}$ is the closest point on the original non-deformed breast surface from $\mathbf{p}_t$. Both values are known at the start, and our algorithm assumes that they are constant over time. The effect of tumor movements on $\mathbf{f}_t(t)$ is, however, still captured in the response model obtained in the preprocessing step and is thus included in $\mathbf{f}_t(t)$. Let the line segment $\overline{\mathbf{p}_{ts}\mathbf{p}_t}$ be l_0. We first identify the Hunt-Crossley model that describes the force response of the tumor along l_0 in the preprocessing (see Section 3). This is the only information that our algorithm needs in advance. Then, using this identified information we approximate $\mathbf{f}_t(t)$ at positions not on l_0 and render the virtual tumor based on this approximation (see Section 4).

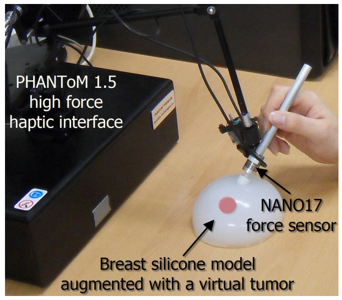
3 Preprocessing Tumor Response

To identify the Hunt-Crossley model describing the tumor's response along l_0, we use data collected from two real breast models; one with a real tumor model of higher stiffness included and one without. The two breast models were made by casting a mixture of Ecoflex 0030 (SmoothOn Inc.) and silicone thinner into a breast-shaped mold (half sphere of 55 mm radius). The *no-tumor* model had uniform elasticity, and its linear stiffness measured at 10 mm displacement was 0.13 N/mm. The *tumor-embedded* model had the same stiffness except for a 12.5 mm-radius, harder tumor (stiffness of 0.54 N/mm) at 25 mm below the surface.

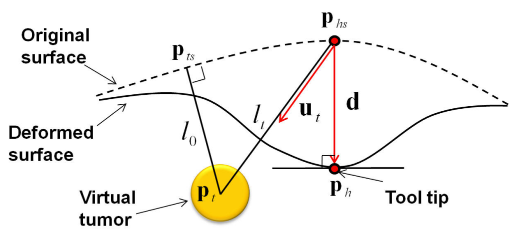
The hardware configuration is shown in Figure 1(b). We use a PHANToM 1.5 high force model (Sensable Technology) for the haptic interface, which is capable of 3DOF force feedback and 6DOF pose sensing. A 6D NANO17 force sensor (ATI Automation) is attached at the end of the interaction tool to measure the reaction force from a real object.



(a) System configuration



(b) Hardware



(c) Definitions of variables

Figure 1: System configuration and variables definition.

Using this setup, we palpated the two models and collected a set of data triples (reaction force, deformation displacement, and velocity) for each model. We denote the data triple for the *no-tumor* model as $(f_1, x_1, \dot{x}_1)$ and that for the *tumor-embedded* model as $(f_2, x_2, \dot{x}_2)$. When palpating the *tumor-embedded* model, special care was taken to press along l_0 by carefully selecting the contact point and the pressing direction. Then, we estimated the Hunt-Crossley model parameters for the *no-tumor* model using $(f_1, x_1, \dot{x}_1)$, which is denoted by $H_1(x, \dot{x})$. This represents the magnitude of $\mathbf{f}_r(t)$ in (1). Since f_2 values measured from the *tumor-embedded* model include both $\mathbf{f}_r(t)$ and $\mathbf{f}_t(t)$, the magnitude of $\mathbf{f}_t(t)$ can be extracted by subtracting f_1 from f_2. To this end, we passed all data pairs of $(x_2, \dot{x}_2)$ to $H_1(x, \dot{x})$ and computed the differences by

$$f_t(x_2, \dot{x}_2) = f_2 - H_1(x_2, \dot{x}_2). \tag{3}$$

By identifying the Hunt-Crossley model again using the data of $(f_t, x_2, \dot{x}_2)$, the response of only the tumor along l_0 was derived. This model is denoted by $H_t(x, \dot{x})$. The parameters of the Hunt-Crossley model were identified using the recursive least-square estimation proposed in [1].

4 Rendering

The palpation begins with touching the breast model using the haptic tool. The time instance when the tool collides with the breast surface is detected by our algorithm in [4]. After the contact, the haptic interface exerts forces for virtual tumor rendering.

Suppose that a user makes a deformation of $\mathbf{d}(t)$ at time t in Figure 1(c). $\mathbf{d}(t)$ is directed from $\mathbf{p}_{hs}(t)$ to $\mathbf{p}_h(t)$, where $\mathbf{p}_h(t)$ is the haptic tool position, and $\mathbf{p}_{hs}(t)$ is the closest point from $\mathbf{p}_h(t)$ on the non-deformed breast surface. To determine $\mathbf{p}_{hs}(t)$, we use an estimation method that uses dynamics models based on reaction force measurements [4], instead of a geometric model of the breast.

Then, the tumor response force $\mathbf{f}_t(t)$ is determined by

$$\mathbf{f}_t(t) = f_t(t)\frac{\mathbf{p}_h(t) - \mathbf{p}_t}{|\mathbf{p}_h(t) - \mathbf{p}_t|}. \tag{4}$$

$\mathbf{f}_t(t)$ is directed from $\mathbf{p}_t$ (tumor position) to $\mathbf{p}_h(t)$ (tool tip position) with magnitude $f_t(t)$.

To estimate $f_t(t)$, we use the following algorithm. Let $l_t(t)$ be a line segment $\overline{\mathbf{p}_{hs}(t)\mathbf{p}_t}$. Then, we can project the tool position $\mathbf{p}_h(t)$ to $l_t(t)$ as

$$x_{lt}(t) = \mathbf{d}(t) \cdot \mathbf{u}_t(t), \tag{5}$$

where $\mathbf{u}_t(t)$ is a unit vector from $\mathbf{p}_{hs}(t)$ to $\mathbf{p}_t$. $x_{lt}(t)$ represents the deformation caused by the virtual tumor reflected in $\mathbf{d}(t)$.

From $x_{lt}(t)$, we determine $f_t(t)$ using the Hunt-Crossley model of the tumor obtained by the preprocessing, $H_t(x, \dot{x})$. $H_t(x, \dot{x})$ represents the exact response dynamics of the tumor when a user presses along l_0. Under the homogeneity assumption, the tumor response along $l_t(t)$ can be described by $H_t(x, \dot{x})$ if the length of l_0 is identical to the length of $l_t(t)$. But in general, $|l_0| \leq |l_t(t)|$, thus we use the following approximation:

$$x(t) = x_{lt}(t)\frac{|l_0|}{|l_t(t)|}, \tag{6}$$

where $x(t)$ is a linearly-normalized deformation magnitude in relation to the reference deformation along l_0. Then, the force magnitude due to the virtual tumor is estimated as

$$f_t(t) = H_t(x(t), \dot{x}(t)). \tag{7}$$

This algorithm is a plausible approximation to the real physical responses, designed for real-time rendering while avoiding the need of geometric models of real objects. We confirmed in an initial subjective evaluation reported in Section 5 that virtual tumors rendered using this algorithm are perceptually similar to real cases. We note that the algorithm may not be applicable to the cases where body parts surrounding a tumor are highly inhomogeneous.

5 Subjective Assessment

The performance of our haptic AR algorithm was verified through a user experiment. Twelve subjects were asked to freely explore two breast models—one with a real tumor and the other with an augmented tumor—placed side by side, and to rate the perceptual similarity of tumor palpation in a 7-point Likert scale. Point 1 represented that the two breasts were completely different, and point 7 that the two breasts were exactly the same. The mean and standard deviation of the similarity scores were 6.1 and 0.79, respectively. This initial result indicates that the haptic feedback of the augmented tumor is comparable to the real tumor mock-up. However, more detailed studies will be carried out in the future.

6 Conclusions

We developed a promising AR-based training system for breast tumor palpation. The system achieves excellent realism without the need of a real object geometry model, which is an advantage of our system for practical applications. We hope that this work would prompt more attention to the field of haptic AR and its application.

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