Stable Haptic Interaction with Non-homogenous Object

Sang-Youn Kim, and Jee-Hwan Ryu

Abstract— The challenge comes from the fact that soft objects are highly non-homogeneous in which the material property is not uniform. When we control a haptic display during interaction with the area where the stiffness is extremely high or with the area where the stiffness changes drastically, we often get unexpected haptic feedback. A sudden change of stiffness in a target object can cause unstable interaction with the object. This paper proposes a stable haptic interaction framework to solve this problem. To achieve stable haptic framework, we adopt an adjustable passive element and a passivity observer to the haptic interaction method.

Keywords— Haptic modeling, Haptic interaction, Soft objects, and Stable interaction

I. Introduction

GENERALLY, users understand the overall shape of a target object with their visual information, whereas they normally grasp its roughness or its hardness with their touch information. From among these, touch information can be one of the most important instrumentation for manipulating and delicately investigating a target object. To create the touch sensation, haptics, which is technology for providing touch information, has broken out and has been studied. For creating haptic information and conveying it to user, many electro-mechanical displays have been developed [1].

In order to transfer stable visual feedback to a human operator through graphic instrumentations, graphic update rate has to be maintained at over 30Hz. In contrast, to provide stable haptic feedback to users through haptic instrumentations, haptic update rate must be maintained at over 1kHz. If feedback force cannot be computed within a haptic update rate, vibration and jerky motion can be transferred to a human operator. This haptic update rate varies according to the stiffness of a target virtual object [2]. However, it is not easy to increase the update rate of a virtual object to the haptic update rate with the conventional model due to computational limitation even though the virtual object is represented by surface level.

To satisfy the haptic update rate, many research works have been proposed based on a multi-layer mesh structure [3] or multi-rate simulation technique [4]. Although, it would be greatly valuable for human operators to use a volumetric model as a simulation target to explore internal information of a target object, there have been only few attempts [5,6] to haptically render the interior and the exterior of a volumetric deformable object with a haptic instrumentation. Even though many methods provide a wide range of benefits for haptic instrumentations, unstable haptic feedback can be conveyed to a human operator. In order to make stable haptic interaction with a stiff virtual object, it is necessary to minimize sampling time and to increase the inherent damping of a haptic instrumentation [2]. However, since we can hardly increase the inherent damping of the haptic instrumentation to an unlimited extent, unstable interaction force can be generated in the case where there is considerable alteration in interaction force. To put it concretely, the unstable force can be generated in the case where the material property of an element in the object is very much different from that of its neighbors or in the case where a user collides with an extremely hard portion. If there is even a piece of such a portion in a target object, a human operator feels jerky motion or unstable force during interaction. To provide stable haptic feedback to a human operator, this paper proposes a stable haptic interaction framework. In our framework, adjustable damping component is used to make the haptic behavior of the deformable objects stable.

II. Stable Haptic Interaction

Due to the development of stable haptic devices, haptic rendering technology that enables a human operator to touch and to manipulate soft objects has been an important research area. For the haptic rendering of soft objects, we first need to define a representation or a model, which unifies a portion of data as an entity. Although many haptic models are used to haptically render a deformable object, these modeling methods can hardly be applicable to the case where the variation in feedback force at a given moment is considerably large. Colgate et al. addressed that a haptic system is stable if the following equation is satisfied [13].

Consider the case where a haptic interface point is collides with a stiff virtual object. To have stable haptic interaction with the stiff virtual object, we need to design a haptic display whose inherent damping is maximized and need to increase the sampling frequency. However, since it is difficult to increase the sampling frequency to an unlimited extent and it can hardly increase inherent damping of the haptic display without end, unstable haptic interaction force can be created.

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Even though there have been many approaches for achieving stable haptic interaction, it is not easy to haptically render the highy non-homogenous deformable object with the approach. Especially if fixed damping, such as virtual coupling [7], is used, transparency will be dramatically reduced because the intermediate virtual spring and damper will smooth out the intended force change. Therefore, we need to measure the energy which is stored in the haptic system and then adjust the virtual damper. In this paper, we propose a new haptic rendering method for achieving stable interaction with non-homogenous soft objects.

When a human operator interacts with a soft virtual object with a haptic device, the target object is deformed. According to the amount of the deformation and material property of the object, feedback force is computed. Consider a haptic system including a virtual object and a haptic device. Depending on operating conditions and the specifics of the element's dynamics, the system may or may not be unstable. If we can compute the energy which is stored in the haptic system, we are able to design a time varying damping element to dissipate only the required amount of energy. The time-varying damping element takes the form of a dissipative element in a series or parallel configuration depending on the input causality. Stable interaction force can be generated by the adaptive virtual coupling element to make the haptic system stable.

III. Material Setting Method Using Elastography

To detect the mechanical property of a target object non-invasively, some researchers have focused on Elastography. Kruse *et al*., used Magnetic Resonance Elastography for detecting abnormal portions in a human body [16]. In their research, they acquired the material properties of a target object as shear moduli and they grasped the relationship between the frequencies of shear wave and shear modulus. In their research, the shear modulus and the propagation speed of shear waves were computed by (1) and (2), respectively. Generally, the relationship between Young's modulus and Shear modulus can be expressed by (3). In FEM, the material property of a target object is mainly represented by Young's modulus. In a mass-spring model, however, the material property is expressed by the stiffness value. Therefore, Young's modulus has to be converted to the stiffness value by (4).

$$\mu = \mathrm{v}^2 \rho \quad (1)$$

$$\mathrm{v} = f\,\lambda \quad (2)$$

$$E = (1+\nu)\,2\mu \quad (3)$$

$$\text{stiffness (k)} = \frac{A_c E}{l_c} = \frac{2A_c(1+\nu)\mu}{l_c} \quad (4)$$

Where,

v : the speed of shear wave,
ρ : the density of target object,
f : the frequency of externally applied excitation,
λ : wave length,
E : Young's modulus,
μ : Shear modulus,
ν : Poisson's ratio,
A_c : the cross-sectional area of a volume element,
l_c : the length of a volume element.

IV. Result and Evaluation

To evaluate the performance of the proposed method, we experimented with a virtual object under the conventional method (CM) and under the proposed method (PM). During this experiment, we saved each result as a separate file in order to plot the haptic behavior of the target object. The haptic simulations were carried out by a program written in VC++ with openGL. We used a desktop computer with a 2.4GHz Pentium IV processor and a PHANToM™ device for providing haptic feedback to a human operator. For the haptic rendering for the deformable object, mass-spring models[8,9,10,11] and models based on finite element method [12,13,14,15] are widely used. Unfortunately, in practice, the physically motivated deformable models are very much limited to surface modeling mainly due to overwhelming computational requirements. As an alternative, Shape-retaining Chain Linked Model (the S-chain model) was proposed for the fast haptic rendering of volumetric objects [5]. The S-chain model resembles the voxel representation of an object and computes local deformation for computing haptic feedback of a volumetric soft object in real time. Due to its advantage, we use S-chain model, as well as a mass-spring model, for our experiments.

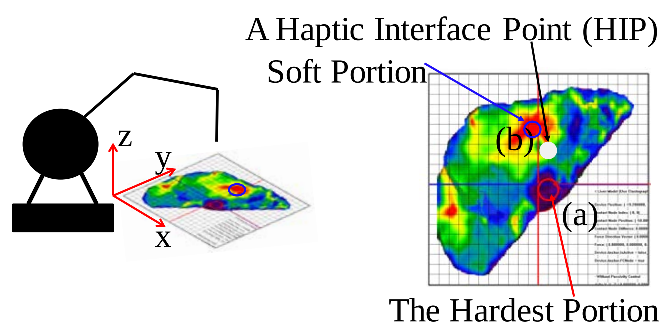

Fig. 1. Experimental environment and a target object whose stiffness value is graphically displayed. As the gimbal of the haptic device is released, it falls from the initial position along the negative z-direction

Fig. 1 shows the experimental environment and a target virtual liver whose stiffness value is graphically displayed. In Fig 1, color is related to the frequency of input wave for Elastography (refer to Appendix). That is, the hardest portion is depicted in purple (marked in (a) in Fig. 1), whereas the softest portion is colored in red (marked in (b) in Fig. 1). In order to compare the haptic behavior of the proposed method with that of the conventional method, impulse input was applied to the simulation system. For the impulse response of the system, the gimbal of the haptic display was positioned above the target area of the liver model, and then the gimbal was fallen free to hit the target area. In this experiment, we ignored the movement of x and y direction, and only considered the movement of the down direction (z direction). We dropped the gimbal in two areas of the target liver – one in a soft area and the other in the hardest area. Since the liver overall is soft, the soft area represents the more-or-less homogenous portion, where the hardest area represents the portion of rather big changes in stiffness.

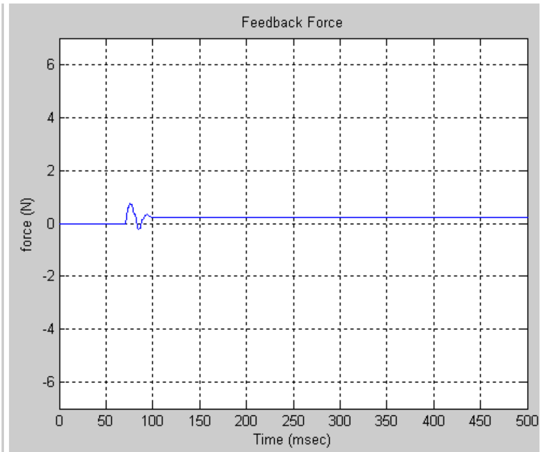

Fig. 2. Results of the case where a stiffness value of the hardest portion in the target object is small (without the proposed haptic rendering method) : the haptic behavior of the haptic device

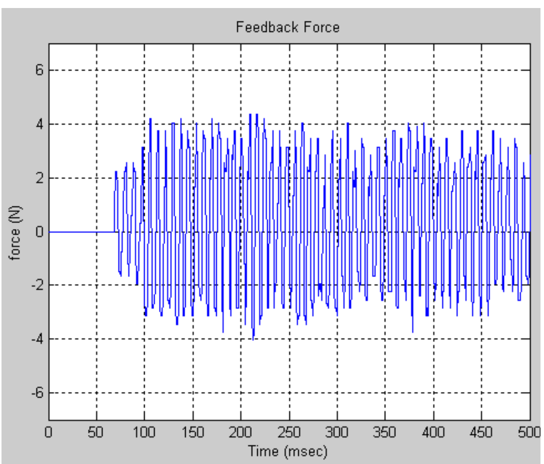

Fig. 3. Results of the object behavior without the proposed haptic rendering method.

Fig. 2 shows the displacement of the gimbal of the haptic device when the gimbal collides with the soft portion. We did not observe much of unstable results. On the other hand, when the HIP collides with the hardest portion, unstable force (Fig. 3) was clearly observed under the CM. We then execute the same experiment of applying impulse input to the hardest area, this time, under the PM. Fig. 4 shows the position and haptic results of the target object when the PM was applied to the system. We could verify that the amount of instability was remarkably reduced in comparison with the result of Fig. 3.

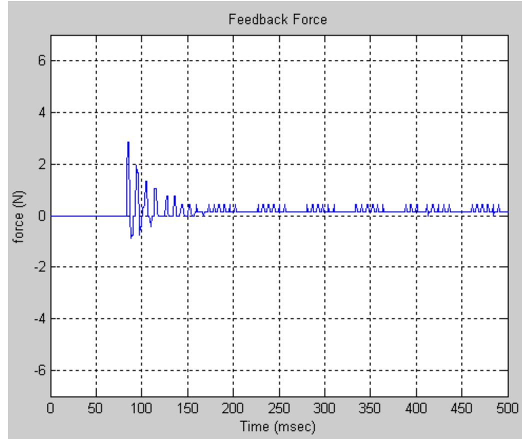

Fig. 4. Results of the object behavior with the proposed haptic rendering method.

V. CONCLUSION

While we speak of real-time haptic rendering for deformable objects, we need to consider the stability of the system. This paper presents a stable haptic rendering method based on the passivity controller. Since time-varying dampling element in the proposed method takes energy, the proposed method guarantees stable haptic interaction with deformable objects. We have experimented with non-homogenous virtual objects, and we have been able to verify realistic haptic interaction with a PHANToM^{TM} haptic device.

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