A Dual Modeling Method for a Real-Time Palpation Simulator

Sang-Youn Kim*, Sekil Park** and Jinah Park**

Abstract—This paper presents a dual modeling method that simulates the graphic and haptic behavior of a volumetric deformable object and conveys the behavior to a human operator. Although conventional modeling methods (a mass-spring model and a finite element method) are suitable for the real-time computation of an object's deformation, it is not easy to compute the haptic behavior of a volumetric deformable object with the conventional modeling method in real-time (within a 1kHz) due to a computational burden. Previously, we proposed a fast volume haptic rendering method based on the S-chain model that can compute the deformation of a volumetric non-rigid object and its haptic feedback in real-time. When the S-chain model represents the object, the haptic feeling is realistic, whereas the graphical results of the deformed shape look linear. In order to improve the graphic and haptic behavior at the same time, we propose a dual modeling framework in which a volumetric haptic model and a surface graphical model coexist. In order to inspect the graphic and haptic behavior of objects represented by the proposed dual model, experiments are conducted with volumetric objects consisting of about 20,000 nodes at a haptic update rate of 1000Hz and a graphic update rate of 30Hz. We also conduct human factor studies to show that the haptic and graphic behavior from our model is realistic. Our experiments verify that our model provides a realistic haptic and graphic feeling to users in real-time.

Keywords—Haptic Feedback, Dual Model, Palpation, Real-Time Simulation, S-chain Model

1. Introduction

Medical training is advisable before a diagnosis or an operation because an operation or diagnosis on actual patients may result in many medical errors. Even though medical doctors use cadavers or laboratory animals for medical training, it is expensive and raises ethical issues. As an attractive solution for efficient medical training, a lot of medical simulators have been developed. The medical simulators use a large volume of medical data sets that are visualized with surface rendering or volume rendering techniques. The surface rendering shows the external

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shape of a virtual object by using the iso-surfaces extracted from the volume data. Since the surface rendering utilizes only the surface information of a virtual object, it enables us to compute the deformation and the interaction force in real-time. However, it is not easy to understand the internal structure of the object. On the other hand, volume rendering technique let users know the internal state of a target object, whereas it takes too much time to render the target object.

Palpation is an examination method for investigating the state of internal tissues by pressing on the surface of the body. Hence, haptic information becomes the center of interest in palpation simulators and many research activities are under way to implement applications supporting haptic modalities. In order to transfer the stable visual feedback to a human operator, the graphic update rate has to be maintained at over 30Hz. In contrast, the haptic update rate must be maintained at over 1kHz to provide stable force feedback to a human operator. If a virtual object is not computed within the haptic update rate (1kHz), vibration and jerky motion are transferred to the human operator. However, it is not easy to increase the update rate of the virtual object to the haptic update rate with the conventional model due to computational limitation even though the object is represented by surface level.

To overcome the problem, Astley and Hayward [1] introduced the multi-layer mesh method in which a coarse mesh and a finer mesh are applied to the entire body and the interest area of the body, respectively. Cavusoglu and Tendick [2] proposed a multi-rate simulation technique, where a full order model has an update rate of over 10Hz, and a low order local model for representing the interested area of the object has an update rate of 1kHz. Mendoza and Laugier [3] proposed a local topology model that is suitable for both concave and convex objects. In order to simulate the palpation method, it is necessary to use the volumetric data because medical doctors want to obtain the internal state of the human body. However, it is not easy to haptically render not only the interior but also the exterior of a human being's tissues or organs using conventional methods within a haptic update rate (1msec) due to the computational burden. To deal with the volumetric deformable object, researchers have developed many optimization techniques such as precomputation and matrix condensation [4], which can reduce the heavy computational burden. However, it is still difficult to calculate deformation and feedback force from a volumetric deformable object within a haptic update rate using an FEM and a mass-spring model.

Previously, we proposed the Shape-retaining Chain Linked Model (the S-chain model) [5] for the fast haptic rendering of volumetric objects and we developed the palpation simulator prototype [6] with the S-chain model. In the S-chain model, the computation of the deformation and the feedback force are not dynamically coupled with each other and the deformation of the object is computed locally and then propagates outward through its volume. Therefore, the S-chain model guarantees the real-time performance for the haptic rendering of volumetric objects. Furthermore, the haptic sense of the S-chain model is almost the same as that of the conventional methods, whereas the deformed configuration of the object represented by the S-chain model looks too linear to construct a realistic palpation simulator.

In the palpation procedure, medical doctors watch the surface shape of a human body and haptically sense the internal abnormal portions beneath the object. Therefore, with this in mind, this paper suggests a dual modeling method that employs two different sub-models for haptic rendering and graphic rendering. That is, in our method, graphic rendering is performed at a surface level, whereas haptic rendering is done with a volumetric model that has the whole internal structure of the object. In this research, we applied the S-chain model to compute the haptic behavior of a target object and use a mass-spring model to calculate the graphic behavior of the object. To describe the performance of the proposed dual model, we first explain the virtual liver object, which is employed for the system. Secondly, we illustrate both a graphic model to deform the surface of the virtual liver and a haptic model to calculate the feedback force. Finally, experiments are performed to show that the proposed model computes realistic haptic and graphic behavior of a volumetric deformable object in real-time. Throughout these experiments, we verify that the proposed dual model is suitable for real-time palpation simulators.

2. RELATED WORKS

Medical doctors palpate a patient's body to examine the location and the size of abnormal portions beneath the body with their hands or surgical instruments. Although palpation is an important technique for discriminating abnormal portions from healthy tissues during medical operation or diagnosis, the research on palpation simulators are less common. Dinsmore *et al.* [7] developed a virtual palpation simulator to detect subsurface tumors. The simulator used Rutgers Master II as a haptic device in order to search for hard regions beneath the surface of a body. Kaufman and Bell [8] conceptually designed a palpation training system using a PHANToM™ haptic device and addressed teaching and assessing skills. Burdea *et al.* [9, 10] developed a palpation simulator for diagnosing prostate cancer with a PHANToM™ haptic interface. Williams *et al.* [11] introduced a virtual haptic back system (VHB) where a human operator interacts with a virtual back with two PHANToM™ haptic devices operated by two fingers (the left and right fingers) Crossan *et al.* [12] developed a horse ovary palpation simulator (HOPS) and tried to investigate the performance of human operators. Baillie *et al.* [13] developed a bovine rectal palpation simulator and evaluated that the simulator is suitable for palpation training. M. Takaiwa and T. Noritsugu [14] developed a breast cancer palpation simulator using pneumatic parallel manipulator. D.H. Kim and J. A. Reyer [15] constructed a palpation simulator system with magneto-rheological fluids in order to investigate the state of the human body.

However, these systems still used a layered surface model or a simplified volumetric model for stable visual and haptic feedback. In order to transfer the stable visual feedback to a human operator, a graphic update rate has to be maintained at over 30Hz. In contrast, a haptic update rate must be maintained at over 1kHz to provide stable feedback force to a human operator. If the feedback force is not computed within the haptic update rate, vibration and jerky motion are transferred to a human operator. To haptically render volumetric deformable objects, the S-chain model [5, 6, 16] was developed. Although we can obtain the realistic haptic behavior of the high resolution volumetric objects in real-time with the S-chain model, graphic behavior requires further improvement when there is a large deformation. Therefore, this paper proposes a dual model that can satisfy the graphic and haptic behavior of an object in real-time.

3. METHOD

For constructing palpation simulators, it is necessary to consider high resolution volumetric objects. The S-chain model is suitable for the haptic rendering of a volumetric deformable object in real-time. However, the deformed shape of the object represented by the S-chain model looks linear. On the other hand, the deformed shape of the object represented by conventional models

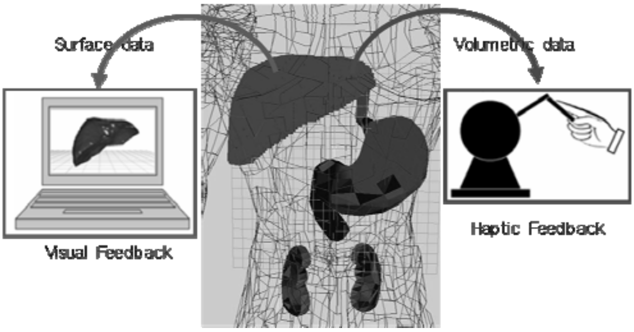

Fig. 1. Dual model for visual and haptic feedback

(mass-spring, FEM, and etc) is realistic. When the volumetric object is presented by the conventional method, the time complexity of building the stiffness matrix (F = KX) is $O(n^2)$ and that of solving the system matrix ($X = K^{-1}F$) is $O(n^3)$. Therefore, it is not easy to handle a high-resolution volumetric object within the haptic update rate (1kHz) due to the computational limitation.

To satisfy the haptic and graphic behavior of a volumetric deformable object, we consider the differences between the sense of vision and the sense of touch. While a human operator understands the overall surface shape of a target object with visual feedback, he/she grasps the internal structure of the object with haptic feedback. In this section, we introduce a new dual model that computes the internal haptic behavior of a volumetric deformable object and that can calculate the deformed surface shape of the object. The proposed dual model consists of two sub-models (a haptic model and a graphic model). The graphic model is used for computing the surface deformation of a target object, and the haptic model is used to haptically render the internal structure of the target object (Fig. 1). In order to compute the graphic and haptic behavior of the object, we combined these two sub-models. We applied a mass-spring model to the surface data of a target object and the S-chain model to the volume data of the target object.

3.1 Dual Model

Unlike traditional methods, the proposed model is composed of two different sub-models (a model for computing the graphic behavior of an object and a model for calculating the haptic behavior of the object). When a haptic interface point (a HIP) collides with a virtual object, a graphic sub-model computes an object's surface deformation at 30Hz and a haptic sub-model calculates the haptic behavior of the object according to the amount of the operator's interaction and the material property of the object.

As for the choice of the individual graphic or haptic model, it is solely up to a developer to employ any modeling method (e.g., an FEM, a mass-spring model, the S-chain model, or etc.) according to applications. For our experiment, we used a mass-spring model for handling surface data and the S-chain model for dealing with volume data.

3.1.1 Graphic Sub-model

Generally, a human operator understands the surface shape of an object through his/her visual information if the object is not transparent. Therefore, we accepted the surface data of the liver

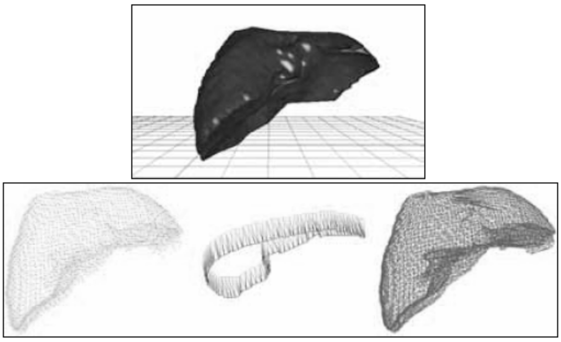

Fig. 2. The generation of the liver's mesh

extracted from the Visible Korean Human (VKH) [17] dataset and the surface of the liver is represented with a mass-spring model for graphic deformation of the surface. The generated liver's mesh is composed of 3,253 vertices and 6,473 surfaces as shown in Fig. 2. For mass-spring formulation, we regarded vertices as point masses and the line linkages as springs. After formulating mass-spring model, we calculated the force on an arbitrary node ($node_m$) using equation (1) and computed the displacement of the node ($node_m$) in the virtual liver.

$$F_m = -\left[k_{m,n}(|P_m - P_n| - R_{m,n}) + c_{m,n}\left\{ (V_m - V_n)\frac{P_m - P_n}{|P_m - P_n|} \right\} \right] \frac{P_m - P_n}{|P_m - P_n|} \tag{1}$$

where,

$k_{m,n}$: a spring constant between $node_m$ and $node_n$,
P_m : a position of $node_m$,
$R_{m,n}$: the rest length of the spring between $node_m$ and $node_n$,
$c_{m,n}$:a damping constant between $node_m$ and $node_n$,
V_m : a velocity of $node_m$.

3.1.2 Haptic Sub-model

In the case where a human operator wants to find the internal feature of a soft object, he/she normally obtains the haptic sense by pushing the object. Therefore, for generating haptic sensation, we decided to use a volumetric liver model extracted from the VKH dataset. The generated volumetric virtual liver consists of 16,338 voxels. It is not easy to generate haptic response within 1kHz by using traditional methods such as an FEM or a mass-spring model. Hence, for satisfying the haptic update rate (1kHz), we employed the S-chain model, which can handle high-resolution volumetric objects in real time, as the haptic sub-model. Our previous research works show that the S-chain model provides a realistic haptic feeling to human operators in real-time even if its deformed shape is a little awkward [5, 6, 16].

Fig. 3 illustrates the virtual liver represented by the S-chain model. The current version of our S-chain model library can handle the object whose shape is rectangular parallelepiped. To represent the volumetric liver with the S-chain model, we set the stiffness values of the outer part of the virtual liver to zero and only the inner part contribute to the feedback force of the virtual

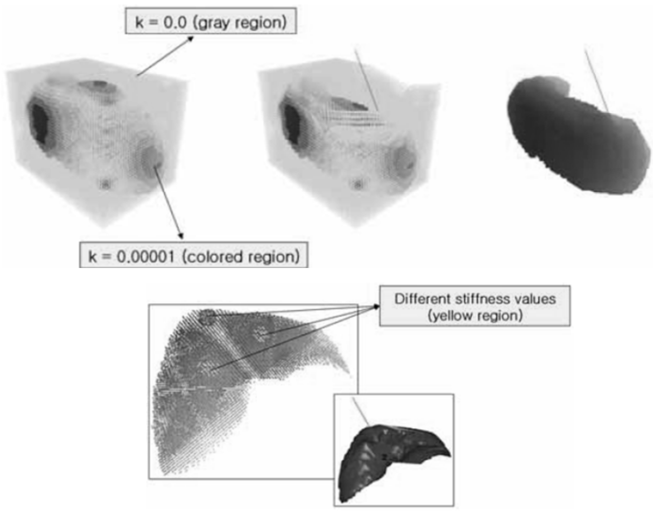

Fig. 3. Human liver represented by the S-chain model

liver like the image that is furthest to the right, as shown in Fig. 3. In Fig 3, the color of the model is used for helping the users recognize the shape of the liver easily. In our work, a human operator can set the stiffness value of each voxel and he or she can decide the location and the size of a target object.

3.2 Representation of the Dual Model

We adopted two sub-models (a mass-spring model and the S-chain model) in our work. The mass-spring model takes charge of the global deformation and the S-chain model computes the feedback force, which is provided to a human operator. When a human operator interacts with a virtual liver represented by the proposed dual model, we firstly have to find a contact point between the virtual liver and a haptic interface point (HIP). Since there is no haptic interaction with a target object before collision, we used the graphic sub-model for detecting the collision. Secondly, we found a CCP (a corresponding contact point) in a haptic sub-model using contact information in the graphic sub-model in order to compute the haptic behavior of a target object with the haptic sub-model. Fig. 4 shows a contact point (origin of axis) in the graphic sub-model

Fig. 4. A contact point (origin of axis), (b): corresponding contact point

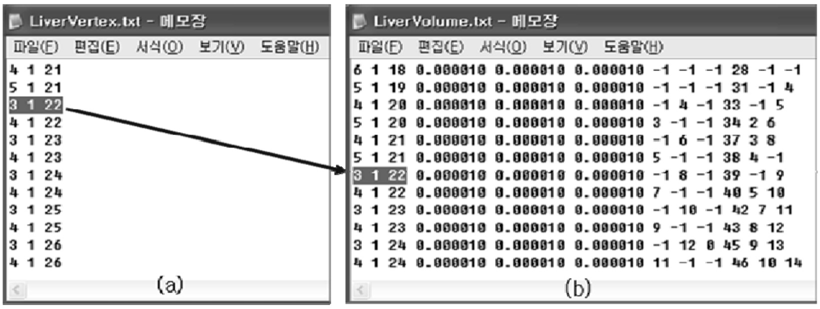

Fig. 5. Lookup table

and a corresponding contact point in the haptic sub-model.

To speed up finding the CCP, we employed a lookup table method that allows us to connect a surface data index with a corresponding volume data index as shown in Fig 5. The lookup table was pre-computed when the system was starting. Fig. 5(a) shows the x,y, and z coordinate values of vertices on a virtual liver and Fig. 5(b) shows the x,y, and z coordinate values of voxels on a virtual volumetric model. In Fig. 5, a contact point is (3, 1, and 22) in the graphic sub-model. The lookup table allows us to seek the coordinate values of a voxel (CCP) corresponding to the contact point (3,1, and 22). If the same CCP is not found in the lookup table, we may find the nearest corresponding point.

4. RESULTS

To build a palpation simulator, we used the volumetric liver object obtained from real anatomy image dataset (Visible Korean Human (VKH) [17]), which is serially sectioned (interval: 0.2 mm, slice: 8,500) with the cadaver's dataset of a Korean person. The volumetric liver is represented by the S-chain model to provide the feedback force to a user as shown in Fig. 6. We extracted surface data from the segmented VKH image for constructing the surface shape of the object and applied a mass-spring model to the surface in order to compute the surface deformation of the object. The generated virtual liver's mesh is composed of the 3,253 vertices and

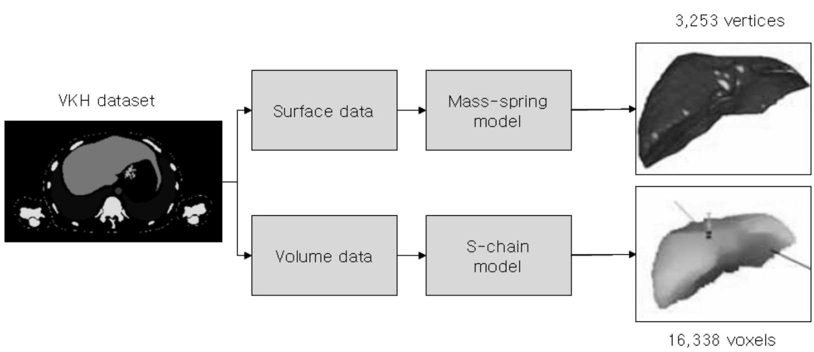

Fig. 6. Virtual liver data obtained from the VKH dataset

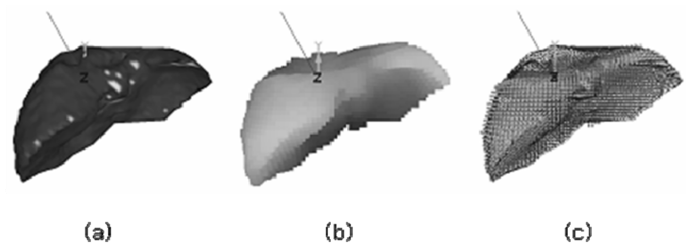

Fig. 7. The virtual object's behavior (a) : the result with graphic sub-model (surface data), (b) the result with haptic sub-model (volumetric data), (c) both model

the 6,473 surfaces, and the virtual liver's volume data has 16,338 voxels. The experiment was carried out by a program written in VC++ with openGL. The experiment was conducted with a PHANToM™ Omni device. We simulated the virtual liver object at a haptic update rate of 1 kHz and the graphic update rate of 30Hz. To apply a mass-spring model to the liver, we regarded the vertex elements as point masses (nodes) and the line linkages as springs. We computed the force feedback (interaction force) with the S-chain model according to the amount of user's input and the mechanical property of the object.

The graphical and haptic results are shown in Fig. 7. The mass-spring model (the graphic sub-model) computes the deformation of the object's surface shape (Fig. 7(a)) when an HIP (haptic interface point) collides with the object. The S-chain model (the haptic sub-model) takes charge of calculating the feedback force (Fig. 7(b)). A human operator can understand not only the deformed surface shape of the target object with visual information but also the internal structure of the object with haptic information due to the graphic and haptic sub-models.

In our dual model, users can determine the stiffness value of each voxel and can set the size of the abnormal portion in the object. Fig. 8(a) and 8(b) show the results when a user interacts with normal and the abnormal portions, respectively. Fig. 8(c) is the wire-frame view of the overlapped with the stiff area in the volume model.

We performed a simple experiment in order to verify the feasibility of the proposed dual deformable model. Six subjects (average age of 27.8 and 1 female) participated in this experiment, and four questions were presented to each participant. The fourth question presents the degree of

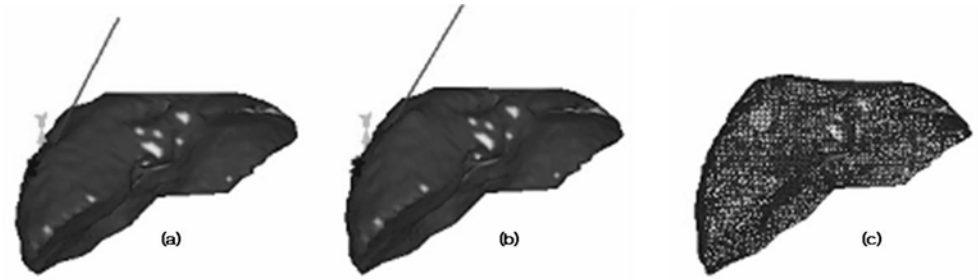

Fig. 8. The behavior of a non-homogeneous object (a): when a user interacted with a normal portion of the object, (b): when a user interacted with an abnormal portion of the object, (c): wire-frame view of the model

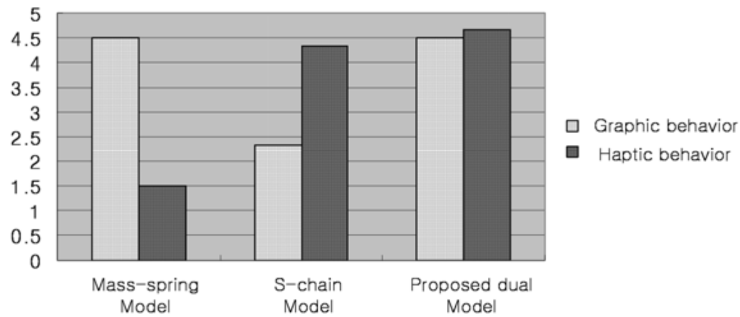

Fig. 9. The degree of the participants' satisfaction

the participants' satisfaction. Five-point Likert scales represent the degree of each participant's satisfaction: five indicates the total satisfaction of a participant, while zero represents a participant's complete dissatisfaction.

1. Did the object deform according to the movement of your haptic device in real-time?
2. Did you feel a stable force as you moved the position of the haptic device in real-time?
3. Were there any discords caused from the two internal sub-models? (We explained the dual deformable model before the question.)
4. How would you rate the proposed dual model in its ability to provide a realistic visual and haptic feeling to the participants compared to the mass-spring model, and the S-chain model? (We described and showed three models before the question.)

In each question except the last question, the answers of participants were confined to "Yes (Y)," "I do not know (I)," and "No (N)." All participants answered "Yes" for questions 1 and 2. This means that they felt stable haptic and visual sensation as they interacted with the virtual object. Furthermore, they sensed continuous force as the penetration depth was increased. For the question 3, they answered "No" (they did not find any discords in the two sub-models).

Since two internal sub-models represent one virtual liver object, we need to investigate how well our proposed dual model provides a realistic feeling to users through question 4. Fig. 9 shows that the degree of the participants' satisfaction. In the case of the mass-spring model, the participants felt the jerky motion or vibration (the average score for haptic feedback is about 2.3) because the update rate is too slow to provide stable haptic sensation (about 180Hz). In the case of the S-chain model, the participants were dissatisfied with the graphic behavior (the average score for haptic feedback is about 1.7) because the deformed shape is linear. However, in the case of the proposed dual model, the average score was 4.5 for the graphic behavior and 4.7 for the haptic behavior. Since the graphic and haptic update rates are about 50Hz and over 1kHz, respectively, a user could watch the continuous scene and could feel the stable haptic sensation without a jerky motion or vibration. From the results, although two internal sub-models represented one object, users did not feel a discord between the two sub-models. Therefore, the proposed model is suitable for the real-time graphic and haptic simulation of volumetric deformable objects.

5. Conclusion

To construct an efficient medical simulator with graphic and haptic feedback, we suggested a dual model consisting of two different sub-models. In our method, graphic behavior was computed by the mass-spring model at a surface level and the haptic behavior was calculated by the S-chain model at a volume level which has the internal structure of the object. Through the proposed dual modeling method, we obtained the realistic deformed surface shape of an object and the realistic feedback force related to the deformation, user's interaction, and the material property of the object. From experiments, we verified that the dual model has the ability to handle the volumetric deformable object in real-time and to provide stable feedback force to a human operator. As such, the proposed dual modeling method would be useful for a real-time palpation simulator. We are planning to develop a dual processing system where one processor takes charge of visualization and the other processor plays a role in haptic rendering in order to maximally increase the quality of the proposed dual modeling method. Multi-layer or multi-rate techniques will be also incorporated into the proposed dual model for improving interaction between a graphic model and a haptic model. Based on these techniques, we will implement a palpation simulator as a real application.

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