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Data analysis on virtual stiffness in 6DoFs haptic rendering system

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ABSTRACT

We present an optimization analysis method for virtual stiffness in 6-DoFs haptic rendering system. The method is based on the locally optimized generalized penetration computation algorithm which computes the minimum translational and rotational motion to separate two overlapping objects. The essence of penalty-based haptic rendering method is computing an amount of penetration depth, and the output force magnitude is following the Hooke's law. We use the virtual coupling method to calculate the output force and analysis the damping and stiffness coefficient in order to get a rendering force which optimizes the haptic feedback value in haptic rendering system. We mapped the virtual contact results to the feedback force and torque, and successfully integrated the algorithm into the off-the-shelf 6Dof haptic device. Our rendering algorithm can handle highly complexity polygon models and make no assumption about the underlying geometry topology. The experiment result shows the optimization analysis method can generate stable and realistic haptic feedback.

1. Introduction

Recently, many graph-based models are applied in multimedia and computer vision [10–37]. They can be used as geometric image descriptors [24] to enhance image categorization [38–41]. For instance, these methods be used as image high-order potential descriptors of superpixels [25–27,30]. The graph-based descriptors can be used as a general image aesthetic descriptors to improve image aesthetics ranking, photo retargeting and cropping [28,29,31,32]. In another hand, people want to get the tactile feelings about the virtual models. In the field of digital entertainment [1,2], medical training [3], physical simulation and etc., people think highly of that haptic rendering technology is an important research direction in haptics. Haptic rendering is the technique that can generate a realistic force feedback to the user when virtual objects interacting with each other. User can touch the 3D object in virtual environment and get a realistic tactile sensation, this would be propitious to experience better interaction with the virtual reality. Ordinarily, we hope to get a real physical feedback and manipulate the virtual object neatly to achieve complicate tasks [4,5]. Three-degrees-of-freedom (3-DoFs) haptic rendering method which is a foundation technique has got broad and deep study. Nevertheless, virtual torque is more necessary to get a realistic haptic feedback, 6-DoFs haptic rendering method include both force and torque feedback is extremely challenging [6,20,7], most of all, in high complexity objects interaction [8,9].

In highly complexity geometry objects' haptic simulation, virtual stiffness can be a huge influence on the stability of haptic rendering system. The feedback force in Penalty-based haptic rendering method simulates as a damper-spring system. Thus, the selected virtual stiffness is very crucial. The essence of the penalty-based haptic rendering algorithm due to how to calculate a measure of penetration depth (PD) between the movable haptic probe and fixed interacting objects, mainly including two methods: translational penetration depth and generalized penetration depth [11,12]. According to the limit of some applications, the translational penetration depth cannot get the exactly penetration depth results, even cannot separate the two overlapping objects reasonably. Equivalent to the translational penetration depth, generalized penetration depth could get more realistic results and more stable haptic feedback. However, existing PD calculation methods are either too slow for complicated objects [14], applicable to a certain type of objects [13], not properly defined in a mathematical sense [2], or require too much computational resources such as memory [22].

Generalized penetration depth is a computation method which can use both translation and rotation to separate two overlapping objects with a rigid motion. For computing generalized penetration depth [13], presents an effective and fast method which is based on contact-space sampling technique. However, these computation methods for penetration depth cannot content to the requirement of

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complicate models and haptic rendering [14]. Lately [15], Min and etc. shows an interactive algorithm to compute penetration depth, not only can resolve some more complexity objects interaction, but also can satisfied with the ideal haptic update rate 1000 Hz [9]. Yi gives a comparison of translational penetration depth and generalized penetration depth computation method in his paper, and analysis the differences in haptic rendering by using two methods, the conclusion shows that the haptic rendering method based on generalized penetration depth has more advantages and more realistic haptic result than using translational penetration depth, moreover, the generalized penetration depth based method can produce more stable haptic feedback [9]. This paper based on Yi's paper, gives an optimization method on their prior work, which shows a more effective haptic rendering methods and get an approving results on both stability and accuracy.

In the sequel, Section 2 point out the prior work for haptic rendering and penetration depth computation method; Section 3 specifies the definition of generalized penetration depth and the haptic rendering method based on generalized penetration depth; Section 4 describe the virtual stiffness analysis method to increase the stability of the haptic rendering results; Section 5 presents our experiment results; Finally, Section 6 gives the conclusion about our optimization method and the deficiency of our algorithm, then mentions our future work to make the rendering method more sufficiently.

2. Previous work

In this section, we briefly review the work relevant to penetration depth based 6DoFs haptic rendering method.

2.1. Penetration depth computation algorithms

Penetration depth defined as the minimum distance to separate two interacting objects in physical simulation. Generally, in penetration depth computation, we need to think about the collision detection between the colliding objects. Usually, we define two colliding objects, one is the movable object and the other is fixed. Due to the differences of the object in the contact space, the penetration depth computation can be classified into two methods: translation penetration depth and generalized penetration depth.

2.1.1. Translational penetration depth

The contact space of the translational motion is in 3D space, so there have 3-DoF x, y, z [16]. The translational penetration depth which can be shortly described as PD_t is computed as a minimum distance to separate two overlapping objects by translational motion in 3DoF space. The computation complexity of PD_t needs $\mathbf{O}(n^2)$ and $\mathbf{O}(n^6)$ times for polygon soups consisting of n polygons respectively. Most of the known algorithm for PD_t computation relies on Minkowski sum [17]. Since the high computational complexity, the existing algorithms to compute PD_t are using an optimization method to get the exact penetration depth results [18]. uses a hierarchical structure to compute the directional penetration depth by the given direction [19]. C. Je shows a method called PolyDepth is a good solution, since its fast computational capability and can deal with high geometry complexities with no assumption of underlying geometry topology [20,21]. proposed the methods to compute the upper and lower bounds of PD_t by using CPU and GPU respectively. The PD_t based haptic rendering method can generate stable haptic feedback by using contact clustering method for multi-contacts. And the result of the force and torque magnitudes are more accurate.

2.1.2. Generalized penetration depth

The contact space of the translational and rotational motion are in 6D space, so there have 6-DoF [22,23]. The generalized penetration depth (PD_g) is defined as the measure of a minimal rigid motion to separate two overlapping object by translational and rotational motion in 6DoF space [19] proposed an contact-projection based technique and combined with local optimization interactive algorithm for rigid and articulated models [9]. gives a comparation by using both PD_t and PD_g for 6DoF haptic rendering. In haptic rendering, PD_g based method can generate more stable haptic feedback than PD_t, and the torque feedback in PD_g are more realistic. And since PD_g estimates the amount of interpenetration more accurately than PD_t, so PD_g suffers less pop-through problem in penalty-based system. So we select PD_g for our rendering algorithm.

2.2. Virtual coupling

Virtual Coupling technique is important in 6DoFs haptic rendering. In virtual coupling method, the position and direction of haptic probe will be sent to the bidding object in the end of the simulation and use a virtual stiffness method to calculate the rendering force. If the virtual force beyond the limit range of haptic device, the system will cause instability problem.

3. Generalized penetration depth computation

3.1. Definition

As mentioned above, the main difference between translational penetration depth (PD_t) and generalized penetration depth (PD_g) is that the PD_g can using both translational and rotational motions at the same time to separate two overlapping interaction objects. We suppose that there have two polygon models $\boldsymbol{A}$ and $\boldsymbol{B}$ which are overlapping with each other, $\boldsymbol{A}$ is a movable object and $\boldsymbol{B}$ is fixed, the local frame of object $\boldsymbol{A}$ is initially the same as the world frame $\mathbf{o}$. The object $\boldsymbol{A}$ can be separated from object $\boldsymbol{B}$ by using a rigid motion. Therefore, we have the definition of generalized penetration depth (PD_g) in six-degree-of-freedom (6DoF) configuration space to compute the minimum distance to separate object $\boldsymbol{A}$ from object $\boldsymbol{B}$ with some distance metric as [18]:

$$PD_g^{\sigma}(A,B)=\left\{\min\left\{\sigma_A(q,o)\right\}\middle|\,\mathrm{interior}(A(q))\cap B=\varnothing, q\in F\right\} \tag{1}$$

where $\mathbf{q}$ is the configuration of $\boldsymbol{A}$ and $\boldsymbol{F}$ is respected the free contact configuration space.$\boldsymbol{\sigma}$ is a distance metric defined between two configurations of $\boldsymbol{A}$ in 6DoF space. Thus, the computation of PD_g with a minimal rigid motion to separate $\boldsymbol{A}$ from $\boldsymbol{B}$ is under a distance metric $\boldsymbol{\sigma}$. Generally, we can choose any distance metric to define $\boldsymbol{\sigma}$, but in our case here we are using object norm as underlying distance metric because of the simple computation. The object norm at two different configurations $\mathbf{q}_0$ and $\mathbf{q}_1$ on the object $\boldsymbol{A}$ can be defined as follows [18]:

$$\begin{aligned}\sigma_A(q_0,q_1)&=\frac{1}{V}\int_{x\in A}(x(q_0)-x(q_1))^2\\&=\frac{4}{V}(I_{xx}{q_1}^2+I_{yy}{q_2}^2+I_{zz}{q_3}^2)+{q_4}^2+{q_5}^2+{q_6}^2\end{aligned} \tag{2}$$

where x($\mathbf{q}$) represented a point in $\boldsymbol{A}$ at configuration $\mathbf{q}$. [$\mathbf{q}_1$,$\mathbf{q}_2$,$\mathbf{q}_3$] means the vector part of the quaternion to represent the relative orientation difference between $\mathbf{q}_0$ and $\mathbf{q}_1$;[$\mathbf{q}_4$,$\mathbf{q}_5$,$\mathbf{q}_6$] means the relative position difference between $\mathbf{q}_0$ and $\mathbf{q}_1$, $\boldsymbol{V}$ is the volume of $\boldsymbol{A}$ and $\boldsymbol{I}$ means the diagonal entries of inertia tensor of $\boldsymbol{A}$.