A New Coupling Scheme for Haptic Rendering of Rigid Bodies Interactions based on a Haptic Sub-World using a Contact Graph

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Abstract. Interactions with virtual worlds using the sense of touch, called haptic rendering, have natural applications in many domains such as health or industry. For an accurate and realistic haptic feedback, the haptic device must receive orders at high frequencies, especially to render stiff contacts between rigid bodies. Therefore, it is today still challenging to provide consistent haptic feedback in complex virtual worlds. In this paper, we present a new coupling scheme for haptic display of contacts between rigid bodies, based on the generation of a sub-world around the haptic interaction. This sub-world allows the simulation of physical models at higher frequencies using a reduced quantity of data. We introduce the use of a graph to manage the contacts between the bodies. Our results show that our coupling scheme enables to increase the complexity of the virtual world without having perceptible loss in the haptic display quality.

Key words: Haptic Rendering, Rigid Bodies, Contacts, Coupling Scheme

1 Introduction

Haptic rendering offers the possibility to make a human user interacting with a virtual object as if it was a real one, using the sense of touch. However, in order to haptically render stiff contacts between rigid bodies, a high refreshment frequency must be maintained in order to ensure a stable and accurate interaction [5]. Therefore, it is often considered to create two processes in haptic rendering applications: one for the physical simulation, and another one for the haptic rendering. The simulation process extracts at its rate a so-called intermediate representation [1] from the virtual world. This intermediate representation is a simplified and local model of the world that is exploited by the haptic process to generate orders at frequencies allowing good haptic rendering quality.

There are different models used for intermediate representation in the literature. Some authors proposed to use the Jacobian of forces with respect to a displacement of the tip of the haptic device [4]. An other approach consists in extracting a simplified geometry from the virtual world, around the interaction area. The nature of the geometry can be a single plane [1], a set of planes [7], parametrized surfaces [3], set of nearest triangles [8], or other data for collision detection [6]. Finally, multiresolution approaches have been proposed for deformable bodies, where a part of the body mesh that is close to the tip of the device is extracted, and simulated at different rates, using different levels of details [2]. A linearized version of deformation simulation can also be used in the haptic process [4]. More recent work has been proposed in [9] to deal with haptic display of bodies having complex geometries. The geometry is dynamically simplified in a sensation preserving way around contact points.

Most of the methods have been developed in order to allow haptic interactions with deformable bodies. However, contacts between rigid bodies are simulated using different models, and need higher haptic frequency. Therefore, the methods proposed for deformable bodies can not be applied to rigid bodies. In this paper, we present a multiresolution approach for haptic rendering between rigid bodies. The main idea of our new coupling scheme is to dynamically extract a subset of the global world and to build a second physical world as an intermediate model. We call this second physical world the *haptic sub-world*. As presented in Section 2, the haptic sub-world is built from a limited number of carefully selected bodies, and can therefore be simulated at a higher frequency into the haptic process, as depicted on Fig. 1. The results presented in Section 3 show that our coupling scheme enables to increase the complexity of the global world without any perceptible alteration of the haptic display.

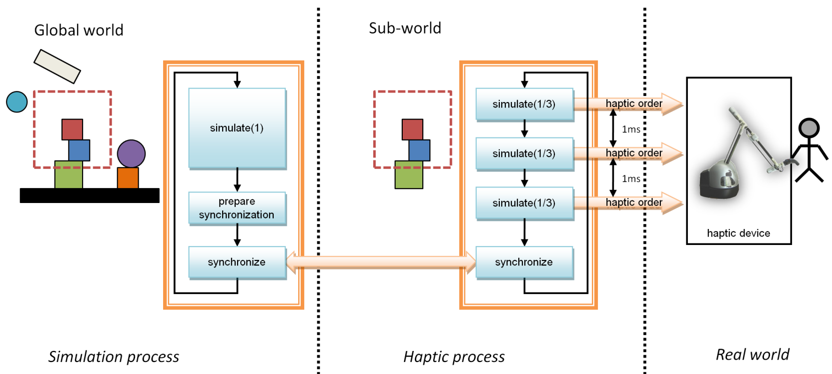

Fig. 1. Haptic-sub world main algorithm. The simulation process simulates the global world once with a time step of dt, while the haptic process simulates for example 3 times its haptic sub-world using a time step of $1/3 \times dt$ (we call the ratio between the time steps the *simulation ratio value*, noted r_{sim}). At the end of the haptic cycle, the two worlds are synchronized, exchanging bodies positions and efforts information.

2 The Graph-based Haptic Sub-world Coupling Scheme

We define the haptic sub-world as a subset of the bodies of the world that is simulated at a frequency allowing a good haptic rendering. We noticed that during the interactions, only the bodies that are directly or indirectly in contact with the proxy (the body linked to the haptic device) can influence it. Therefore, we define the haptic sub-world based on the graph of contacts between the bodies. Let us define β, the set of bodies of the global world and $p \in \beta$ represents the proxy. If we suppose that we have a function called $contact : \beta \times \beta \rightarrow \mathbb{R}$ that provides the number of contacts occurring between a pair of bodies, then we can define the graph $\mathcal{G} = (\beta, \mathcal{V})$, where an edge $v = (b_1, b_2)$ from the edges set $\mathcal{V} \subset \beta \times \beta$ exists only if there is a direct contact between b_1 and b_2, i.e.:

$$\forall\, b_1, b_2 \in \beta,\ contact(b_1, b_2) \geq 1 \Rightarrow (b_1, b_2) \in \mathcal{V} \tag{1}$$

From the graph $\mathcal{G}$, we define $\mathcal{H} = (\beta_h, \mathcal{V}_h), \beta_h \subset \beta, \mathcal{V}_h \subset \mathcal{V}$ as the connected subgraph of G that contains p (the proxy). Fig. 2 shows an example of how the graph $\mathcal{H}$ is obtained.

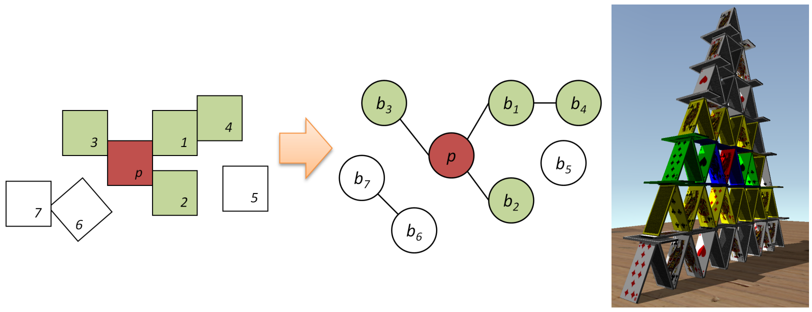

Fig. 2. The graph $\mathcal{G}$ (middle, containing all nodes) defines the contact configuration of the bodies of the global world. The colored connected components of the graph containing the proxy (in red) form the graph $\mathcal{H}$ (containing only colored nodes) of the bodies that compose the haptic sub-world. The card house (right) illustrates the haptic sub-world composed of colored cards extracted from the proxy (red card).

In practice, we only need the graph $\mathcal{H}$ (the connectivity information of the other bodies in $\mathcal{G}$ is useless for our purpose). Therefore, we designed an algorithm that progressively builds the graph $\mathcal{H}$ over the simulations, starting from the proxy and the bodies that are directly in contact with it.

From this definition, a body can belong to the haptic sub-world only if it has a (direct or not) contact with the proxy. However, a haptic cycle is needed before a body is added to the sub-world. Therfore, we anticipate all potential contacts by bringing bodies close to the proxy even if there is no contact with it (Paragraph 2.1). Also, we must limit the complexity of the haptic sub-world to preserve the haptic frequency (see Fig. 2, card house). However, if the graph is limited, it may exist contacts between the two worlds, and we must manage the exchange of energies to avoid loss of physical plausibility (Paragraph 2.2).

2.1 Building the Haptic Sub-world

A body close to the proxy is a body that can be reached by the proxy in less than two haptic cycles. Indeed, the linear velocity of the proxy has a limit v_{max} defined by the mechanical constraints of the haptic device. For a given fixed haptic frequency rendering f, and a chosen simulation ratio value r_{sim}, the maximum displacement p_{max} of the proxy during two haptic cycles is $p_{max} = \frac{r_{sim}}{f} \times v_{max}$. Assuming that the size of the proxy bounding cube side is c_{size}, then we define a boundary cube with a side size of $c_{size} + 2 \times p_{max}$ centered around the proxy that represents the limit of close bodies. All the bodies intersecting the boundary box are added into the sub-world to avoid the loss of physical information.

2.2 Building the Graph and the Interface

As previously mentioned, using a haptic sub-world with a small number of bodies enables to perform a parallel simulation at high rates for the haptic rendering concerns. However, it is possible that the haptic graph $\mathcal{H}$ has too many nodes (we may have $\mathcal{H} = \mathcal{G}$, the global graph), and in that case, the sub-world looses its sense. To ensure a fixed haptic frequency, we limit the propagation of the graph to a maximum number of bodies. We define an interface that manages the energy exchanges between the global world and the haptic sub-world when the graph is limited. Different exchanges are controlled:

Efforts Coming from the Global World We define border bodies as bodies of the haptic sub-world having a contact with a body of the global world (*e.g.* the yellow cards on Fig. 2). During the simulation of the global world, we store non-penetration impulses applied at these contacts and apply them on border bodies at each simulation step of the haptic cycle.

Border Friction To include friction at border, we create a "friction point" constraint at each border contact where an impulse is applied. This constraint imposes the body point to stay along the contact normal line. If a big enough tangential effort is applied, the constraint is freed. The threshold is determined using Coulomb friction model. Namely, knowing the normal impulse magnitude i applied at border contact and the coefficient of friction μ at that point, the intensity threshold used for the perpendicular effort is $\mu \times i$. Sliding friction is not applied, but approximated by the fact that the friction point constraint is updated at each synchronization.

Efforts Coming from the Haptic Sub-world In order to propagate the normal actions coming from the haptic sub-world to the global world, we simply impose the positions of the bodies of the haptic sub-world to their equivalent body in the global world. For tangential efforts, we store at each friction constraint the sum of impulses applied to maintain the constraint, and apply them on each body of the global world that has a contact with border bodies.

3 Results and Evaluation

Our tests and experiments have been performed on PC running on Windows XP, equipped with 2 processors Intel Pentium D (3.4 GHz) and 2 Go RAM. The haptic device used is a 6 DOFs Virtuose 6D35-45 (Haption company, France). The graphic card for display is a NVidia Quadro FX 3450. We used Havok physics software (`http://www.havok.com`) for collision detection and rigid body simulation (the solver complexity is $\mathcal{O}(n)$, n being the number of constraints). We used a third process to manage visual rendering in order to increase computation time performances.

3.1 Same Haptic Frequency for more Complex Scenes

The simulation process has r_{sim} haptic periods of time to simulate its world and prepare the synchronization (see Fig. 1). Namely, the number of bodies allowed into the global world is approximatively equal to the number of bodies allowed into the haptic sub-world multiplied by r_{sim}. For example, on our configuration, using a value of 10 for r_{sim} enabled us to perform satisfying haptic rendering in virtual worlds containing more than 500 cubes at a frequency of 1kHz. Without our method, this frequency can be maintained only for scene containing less than 50 cubes.

3.2 Accuracy Measurements

We performed accuracy measurements based on the velocity of the bodies on scenes containing up to 250 bodies, and about 2000 contacts. We measured that the sub-world method generates a loss of energy of 6% in the worst case (compared to the simulation without sub-world), using a simulation ratio value of 8. This loss of energy is due to the approximations and filters applied during the haptic cycle in order to avoid energy gain, that could lead to instability. Even if these approximations increase with r_{sim}, we experienced that the haptic feedback remains the same for the user, even with high r_{sim} values (> 10).

3.3 Comparison with Other Coupling Methods

We implemented and compared the haptic feedback obtained with our method to other coupling schemes between the physical simulation and haptic rendering: the direct coupling, the interpolation of position and a static sub-world coupling. With a direct coupling, a stable and accurate haptic rendering is obtained, but the complexity of the virtual world is limited. With the interpolation method, the efforts returned by the haptic device are stored during the haptic cycle, and are then applied all at a time during synchronization. This behavior produces artifacts and decreases the stability of the haptic feedback, even for small values of r_{sim} (under 4). Using a static sub-world, we no longer simulate the haptic sub-world: it is freezed and all objects are fixed. The position of the proxy is imposed into the simulation process at each synchronization. This produces a stable simulation, but the late integration of the action of the proxy produces annoying vibrations artifacts. Using our sub-world method, we can increase the complexity of the virtual world while avoiding the artifacts produced using the interpolation or the static sub-world methods.

4 Conclusion

In this paper, we presented a new coupling scheme based on a haptic sub-world principle with the use of a graph to manage the contacts between rigid bodies. The scheme allows to couple the physical simulation of rigid bodies and haptic rendering, and enables to increase the complexity of the virtual world without having perceptible loss in haptic rendering quality. We also presented an interface that manages the exchanges of energy between the sub-world and the global world when contacts remains between the two worlds. With our coupling scheme, we have been able to perform 1kHz and satisfying haptic rendering in scenes containing more than 700 cubes with many contacts.

Future work will be focused on the use of our method as a tool for haptic rendering applications. We also project to validate it on user-based scenarized scenes. Also, we think it is possible to use our coupling scheme to perform several haptic displays together from the same global world without loss of computation time performance.

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