A unified haptic representation for fluid and deformable objects

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Abstract: This paper presents a unified haptic modeling method for physical systems irrespective of their types. Previously, we have proposed an energy-based approach which haptically renders rigid and deformable objects without reference to their material. However, it is not easy to represent the haptic behavior of a fluid or fluid-deformable object with the previously proposed method because there is no method for handling fluid objects and no additional interface between a fluid object and the other objects. Therefore, this paper proposes a modeling framework in which rigid, deformable, and fluid objects are represented by one modeling method.

Keywords: haptic model, unified modeling, energy-based representation, bond graph

Classification: Science and engineering for electronics

References

1 Introduction

Nowadays, with a growth of haptic technology, a demand for non-rigid haptic models [1, 2, 3, 4] is rapidly increasing. Most haptic models have still focused on haptically displaying the shape and the deformation of a virtual object. These models are mainly based on a mass-spring method [1, 2] and a finite element method [3]. The finite element method provides realistic behaviors with high accuracy based on an assumption of energy minimization. Its major drawback, however, is high-computational cost because a large number of differential equations must be computed to obtain the deformation and the feedback force of a deformable object. On the other hand, for the fast haptic rendering of deformable objects, researchers have focused on mass-spring models. The mass-spring model consists of point masses (nodes) and springs. The springs exert forces on nodes when the nodes are displaced from their rest positions. The mass-spring model is relatively easy to construct. However, it may generate unstable interaction according to the distribution of nodes.

Although a lot of research works for deformable object have been conducted, there have been few approaches for fluid objects. Monaghan et al. suggested particle-based fluid models using smoothed particle hydrodynamics (SPH) [5]. W. Baxter and M. C. Lin suggested a haptic interaction method for fluid objects based on the equations of fluid motion [6]. Mora et al. suggested a real-time 3D fluid haptic interaction system where the physical forces are generated by the real-time fluid animation (stirring movements and fluid changes) [7]. Even though these modeling method are useful to represent the behavior of virtual objects, it is not easy to compute the behavior of a rigid, deformable, and fluid object with a same modeling method.

The energy-based approach using bond graphs, first introduced by Paynter [8] and further developed by Karnopp [9], is well known in system engineering technology for computing the behavior of a wide range of materials with a same modeling concept. Previously, we have proposed an energy-based haptic model [10] for obtaining the graphic and haptic behavior of a
virtual object. One of the key differences between the previously proposed model and traditional methods is that an object is rendered without any reference to its material property. However, the previous works [10] only focused on haptic rendering for deformable bodies. Therefore, this paper presents a truly unified haptic model which can handle not only rigid and deformable objects but also fluid objects. We select a target object as a deformable body with fluid inclusions (we call it a fluid-deformable object) and represent it in the energy domain. Furthermore, the properties of the fluid-deformable object in the unified haptic model are redefined and reconfigured modularly.

2 Deformable Model with Energy-based Approach

Physical phenomena can be described and interpreted by several mechanisms in different domains: electrical, mechanical, pneumatic, hydraulic domain, and thermal domains. However, they can be seamlessly described by energy-based approach in the same way because their physical concepts are based on energy and energy exchange. The mechanism of energy exchange can be described as power flow [9, 10].

Consider a mass-spring model (Fig. 1(a)) consisting of N-particles and...
the power connections between particles (Fig. 1 (b)). The power connection consists of a pair of input/output signals where the input is velocity (flow) and the output is force (effort) or vice versa. We already defined 2D power behaviors of one particle and its power connection in the previously work (see Fig. 3 in [10]). In this section, we extended the 2D particle model and its power connections to 3D. The 3D particle model and its interface can be shown as depicted in Fig. 1 (c) and Fig. 1 (d). When the mass $M_{i,j,k}$ is moved with the power $P_{x,y,z}$, this power is distributed to each of masses ($M_{i,j+1,k}$, $M_{i,j,k+1}$, $M_{i,j,k-1}$, $M_{i+1,j,k}$, $M_{i+1,j,k+1}$, $M_{i+1,j,k+1}$, and $M_{i+1,j+1,k}$) via springs and dampers as depicted in Fig. 1 (d). Thus, the power $P_{x,y,z}$ is computed by the sum of each power ($P_1$, $P_2$, $P_3$, $P_4$, $P_5$, and $P_6$). The angular constraints can be calculated by Eqs. (1), (2), and (3), and the power connections in 3D particle models are defined as Eqs. (4), (5), and (6).

$$\theta_x = \tan^{-1}\left(\frac{\Delta z^2 + (S-\Delta y)^2}{\Delta x}\right)$$  \hspace{1cm} (1)
$$\theta_y = \tan^{-1}\left(\frac{\Delta y^2 + (S-\Delta z)^2}{S - \Delta y}\right)$$  \hspace{1cm} (2)
$$\theta_z = \tan^{-1}\left(\frac{\Delta x^2 + (S-\Delta y)^2}{\Delta z}\right)$$  \hspace{1cm} (3)

$$P_x(i,j,k) = P_{1x}(i,j-1,k) + P_{2x}(i,j-1,k-1) + P_{3x}(i,j,k-1) + P_{4x}(i,j-1,k-1) + P_{5x}(i,j,k) + P_{6x}(i-1,j-1,k)$$  \hspace{1cm} (4)

$$P_y(i,j,k) = P_{1y}(i,j-1,k) + P_{2y}(i,j-1,k-1) + P_{3y}(i,j,k-1) + P_{4y}(i-1,j-1,k) + P_{5y}(i,j,k) + P_{6y}(i-1,j-1,k)$$  \hspace{1cm} (5)

$$P_z(i,j,k) = P_{1z}(i,j-1,k) + P_{2z}(i,j-1,k-1) + P_{3z}(i,j,k-1) + P_{4z}(i-1,j-1,k) + P_{5z}(i-1,j,k) + P_{6z}(i-1,j-1,k)$$  \hspace{1cm} (6)

### 3 Deformable and Fluid Flow Model

#### 3.1 Concept of the proposed model

Generally, deformable bodies have been represented by an FEM or a mass-spring model. In the case of a deformable body with fluid inclusions, however, an additional model to interface between two different dynamics is necessary. Consider one-dimensional incompressible flows (the bulk modulus is zero) in an object with fluid dynamic interaction through the influence of fluid inertia and friction loss as shown in Fig. 2 (a). If we do not consider the gravity term, this model can be mathematically described by Bernoulli’s equation (7). In Eq. (7), $Q$ is the volume flow rate, $p$ is the pressure, $A$ is the cross-section area, $\rho$ is the mass density of the fluid, $l$ is the length, and $R$ is the friction loss of the fluid.

$$\rho \int_0^l \frac{ds}{A(s)} \frac{dQ}{dt} + \rho Q^2 \frac{1}{2} \left(\frac{1}{A_1^2} - \frac{1}{A_2^2}\right) = p_1 - p_2$$  \hspace{1cm} (7)

This method can be extended to an object consisting of deformable elements and incompressible fluid. Fig. 2 (b) shows the concept of the power connections for fluid-deformable objects. Generally fluid dynamics systems
can be plausibly represented as lumped models of quasi-flows [9]. Fig. 2 (c) shows the concept of the micro-lumps in which incompressible fluid flows interact with deformable line elements. In this case, Eq. (7) becomes a non-linear equation because the area A is varied with the deformation of the line elements. The micro-lumped model can be graphically described using the bond graph representation as shown in Fig. 2 (d). Therefore, the coupling between fluid and deformable objects can be achieved by merging this bond graph model of a micro-lump with previously proposed model (Fig 1(d) in [10]), namely that the power port (p2 \times Q_c) is connected with the input power port (P_{1(i,j1,z)}) of the deformable model as shown in Fig. 2 (d).

3.2 Implementation and Simulation Results

We previously conducted an experiment with a 2D deformable model of the size of 20 \times 20 to show that the proposed modeling method can haptically render the 2D deformable object without any unstable force (see Fig. 3 in [10]). For a demonstration of the proposed model, let us consider a human arm in which incompressible flow is enclosed by a deformable body as shown in Fig. 2 (e) and Fig. 2 (f). We represented the human arm by the unified model (Fig. 2 (g)) consisting of micro-lumped elements (fluid model) and deformable particle elements. In Fig. 2 (g), A_1 \sim A_7 are the vertical
deformations of the deformable line elements and $P_1 \sim P_7$ are power connections between micro-lumps in the fluid model and the deformable particle models. They ($A_1 \sim A_7$ and $P_1 \sim P_7$) are transmitted from the deformable model to the fluid model to calculate the inertia and friction changed by the deformation of the line element (see Fig. 2 (d)).

We simulated the model depicted in Fig. 2 (g). In this simulation, we used the previously developed haptic device [Fig. 2 in [10]] which has a 3DOF position input and an 1DOF force output. We computed the position of the haptic device with stereo IR cameras (WiiMote [11]) and an inertia measurement unit (IMU). For the haptic device, we applied a small linear actuator whose maximum stroke is about 20 mm within frequency region below 340 Hz in order to create reflected force. A pulse as a source of pressure is provided into the fluid-deformable model. Fig. 3 (b) shows the simulation result of the haptic behavior of the model depicted in Fig. 2 (g). Without the input source, the behavior of the fluid-deformable model is zero. When starting the input source of pressure, the fluid energy flows along the deformable line element. At this time, the deformable particles are vertically moved by the pressure of the fluid and then the reflected force is generated. In Fig. 3 (b), we plotted the reflected forces at three contact nodes ($M_1$, $M_2$, and $M_3$) to compare the reflected forces at the nodes. The feedback force becomes maximized at the very position where fluid flows and is smaller as the distance from the position where fluid flows becomes more distant. Furthermore, from the haptic result, we have verified that the proposed method can haptically render the fluid-deformable object without any vibration and unstable force.

![Image](image.png)

**Fig. 3.** Experimental Result of a fluid-deformable object.

### 4 Conclusion

There are growing demands for haptic models of various physical dynamics. How to merge deformable and fluid models into one haptic model which has high plausibility and physical correctness is one of the most important issues in haptic rendering. In this paper, a unified haptic model for fluid-deformable objects using the energy based approach is presented. We developed 3D deformable models in which the property of deformation was redefined and reconfigured modularly. We also presented a fluid-deformable model consist-
ing of micro-lumped models of quasi-flows and proposed the coupling method between deformable and fluid models. As a demonstration of the coupling between fluid and deformable objects, a unified model of 1D incompressible fluid flow in the 2D deformable line element was implemented and simulated. From the simulation results of the unified model, we proved that the fluid model can be seamlessly connected with the deformable model in the energy domain, without any additional models to interface between two different dynamics. We are currently developing a palpation simulator for diagnosing a human body with the proposed method.

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