Manipulation of dynamically deformable object

Kazuyoshi Tagawa*
Graduate School of Inforation Science and Technology, University of Tokyo

Koichi Hirota†
Graduate School of Frontier Science, University of Tokyo

Michitaka Hirose‡
Graduate School of Inforation Science and Technology, University of Tokyo

ABSTRACT

An approach to realize manipulation of elastic object in virtual environment is discussed. In the approach, the behavior of elastic object during interaction is separately described by two components: rigid-body motion and elastic deformation. The component of motion is simulated by solving equations of motion, while the component of deformation is reproduced from a set of deformation sequences in response to impulse force, or impulse response deformation model. A prototype algorithm and interface environment was built and experiments to evaluate the approach were carried out.

Index Terms: I.6.5 [Simulation and Modeling]: Model Development—Modeling Methodologies; H.5.2 [Information Interfaces and Presentation]: Multimedia Information System—Animations

1 INTRODUCTION

Advancement of communication technology using internet has raised expectation for expanding our communication channels. Transmission of haptic information, in addition to audio and visual information, has been one of challenges toward development of a new communication media. Some general-purpose hapic devices have become commercially available, and these devices have contributed to investigate potentials of haptic interaction. Also, advancement of computers have given us computational power to process more complicated models for haptic interaction than before.

Haptic sensation informs us of various properties of objects through physical interaction with the objects. Softness of object is one of the properties that is hardly conducted through other sensations; the property is intuitively recognized only by the integrated presentation of the relationship between force and deformation that are perceived by tactile and somatic sensations respectively. Softness is also an important property that is essential in various application areas of haptics, such as palpation in medical diagnosis simulation, tactile impression of materials in virtual prototyping.

Softness has usually been dealt as static property of elasticity that is represented by static relationship between force and deformation. However, it is unrealistic to assume quasi-static operation on the object in practical interaction, and according to our preliminary study, dynamic aspect of the relationship is not negligible. For example, static elasticity model immediately returns to the original shape when interaction is over, which is visually unnatural. Also, it can not present resonant vibration of object that often provides us cues to perceive properties such as the density of the material. These drawbacks of static elasticity model are though to become more noticeable as the range of operation is enlarged and degrees of freedom are increased.

*e-mail: tagawa@cyber.t.u-tokyo.ac.jp
†e-mail:k-hirota@k.u-tokyo.ac.jp
‡e-mail:hirose@cyber.rcast.u-tokyo.ac.jp

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We have proposed a model, which is called impulse response deformation model (IRDM), that is capable of representing dynamic deformation using record-and-reproduce, or pre-computing approach. In this paper, an expansion of the model to represent maneuverable object is proposed. A basic idea of the approach is to divide the total behavior of the model into the components of *rigid-body motion* and *elastic deformation*; the component of motion is computed by equation of motion, while the component of deformation is represented by IRDM.

In the next section, previous researches are surveyed and the positioning of our approach is clarified. Details of our approach including formulation of computing process are stated in Section 3, and implementation and experimental results are presented in Section 4. Some problems and future works are discussed in Section 5.

2 RELATED WORKS

2.1 Presentation of force sensation

Presentation of haptic sensation in virtual environment has been a topic of interest from the dawn of virtual reality research, and it has been studied from both hardware and software [6]. Among software for haptics, models and algorithms to compute haptic sensation are core topics of reseach, and they are collectively called haptic rendering [13]. Softness has been a major issue of haptic rendering because it is a fundamental property that defines the relationship between force and displacement.

2.2 Object motion and manipulation

Physical motion of object is simulated by solving equations of motion. A primary issue of the simulation has been the ways to take constraints that are caused by collision into account [10]. Fundamentally, two typical different approaches are known; one method seeks for exact solution by solving equations of constraints simultaneously [5]; another method finds approximate solution by dealing with the constraints by introducing penalty force [3].

An application of computing object motion is manipulation, which is a special case where constraints are imposed mainly by users. Especially in case of manipulation using hands or fingers, the constraints on the object motion becomes complex because of the complicated shapes of hands and fingers, and it is not efficient to introduce constraints as simultaneous equations. Actually, most researches on manipulation have employed the latter approach [22, 11, 18, 4]. Also in case when the manipulated object is deformable, the penalty force approach is considered to be suitable because the equation of constraints becomes more difficult to define, while the penalty force is given by computing the force that is causing the deformation.

2.3 Simulation of Deformation

Realistic simulation of deformation has been a topic of research in the field of computer graphics, and various approaches have been proposed. Free Form Deformation (FFD) [21] is a geometric approach based on spatial interpolation using control points. This approach is not a physically-based model, and reactive force is not computed.

In the field of computational dynamics, Finite Element Method (FEM) [19] and Boundary Element Method (BEM) have been commonly used. Although these methods are intended to compute strictly realistic results based on the theory of continuum dynamics, they have drawbacks that the complexity of computation is relatively high. Recently some researches have investigated methods to accelerate the computation process using GPU[7], it is still difficult to perform real-time simulation of practical complexity. Also, it is known that complexity of computation using linear static FEM/BEM model can be reduced [8, 12], however, as stated above, static model has problems of reality in interaction.

There are some other approaches that approximate the mechanism of deformation using spring-mass network [17] and particles [20]. These models are usually solved using explicit formula to reduce computation time. However, it must be noted that the result of this approach becomes inaccurate if the time step of computation is not sufficiently small. Aside from the accuracy, the particle model is thought to have some advantage in representing plastic deformation because it allows changing connection structure of particles dynamically.

For haptic interaction, real-time computation of force is an essential requirement. Mahvash et al proposed a analytical approach for computing tool force-displacement responses of interactions with localized deformation[15]. However, in this approach, dynamic feature of deformation was discarded. Some approaches abandoned physically-based simulation and employed record-and-reproduction approach, or pre-computation approach. One excellent idea is using pre-computed trajectories in state space to describe the temporal change of object shape [9], however, it is thought to have a drawback that increase in the degrees of freedom of interaction causes explosive increase in pre-computed data.

In our previous work, as a way to allow large variety of interaction, impulse response deformation model (IRDM) has been proposed. In the approach, the degrees of freedom of interaction is reduced by assuming linear and time-invariant system, and the behavior of the model is described as temporal sequence of deformation in response to impulse force. A problem of the model was that it is not applicable to objects that are not fixed, or floating, in space.

2.4 Separation solid motion and elastic deformation

It a common practice to implement a floating object by introducing a transformation matrix that defines the relationship between the world and object coordinate systems. The mechanism is integrated in scene graph systems and also in haptic scene graph systems [2]. In case of a solid object, there is no interaction between the object shape and the motion of the object; motion does not change object shape, and parameters of dynamics is kept unchanged. However, in case of deformable object, the object shape and the object motion interact each other. For example, fast spinning of an object causes deformation of the object by centrifugal force, and the deformation changes inertia tensor of the object, which affects the spinning motion of the object. In our study discussed below, the effect of the interaction is ignored, because the merit of reducing computational complexity is thought to exceed the demerit of deteriorating reality of deformation.

In our approach, models of motion and deformation are separately defined. In the pre-computing process, total behavior that is computed by FEM simulation is separated into components of *rigid-body motion* and *elastic deformation*; the component of motion is discarded and the component of deformation is recorded as IRDM. In the presentation process, the motion is computed using equations of motion, while deformation is computed using IRDM, and the total behavior is obtained by adding the components of motion and deformation. By this separation approach, increase in degrees of freedom of the model in accordance with increase in the variety of interaction is avoided.

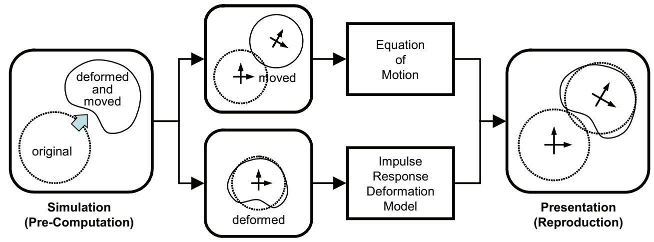

Figure 1: Separation and Integration of motion and deformation

3 SEPARATION AND INTEGRATION OF MOTION AND DEFORMATION

3.1 Overview

A schematic illustration of our approach is shown in Figure 1. In the pre-computation process, as stated above, total behavior of object invoked by impulse force is simulated using FEM program. The object is not fixed, or floating, in space, and consequently it starts moving as well as deforming. From the total behavior of the object, components of *rigid-body motion* and *elastic deformation* are extracted; the component of motion consists of translation of the gravity center of the object and rotation of the object around the gravity center. The rest component is considered as deformation, and the component is recorded using IRDM. The component of motion is discarded because the component can be synthetically reproduced by solving equations of motion. In the presentation process, based on the interaction force, both the dynamics of solid model and deformation by IRDM are computed independently, and these two components are added to obtain the total behavior of the elastic object.

3.2 Separation of Motion and Deformation

As stated in Section 3.1, the component of motion consists of translation and rotation. The translation part is theoretically represented by the translation of gravity center, which is derived from the conservation of total momentum of the model as shown in A.1 and 2. The rotation part is estimated by a kind of model matching approach; evaluation function was defined as sum total of the squared distance between corresponding nodes in deformed model and non-deformed rotated model, and rotation that minimize the evaluation function was sought by a repetition algorithm.

The component of deformation is computed by subtracting the component of motion (i.e. both translation and rotation parts) from the total behavior and transforming the result in global coordinate system into values in local coordinate systems of the object. Impulse response matrix is determined by using the component of deformation.

3.3 Computation of motion

In the presentation process, component of motion is retrieved by solving initial-value problem of equations of motion:

$$M\frac{dV}{dt} = \sum F_{ext} \tag{1}$$

$$\omega \times (I\omega) + I\frac{d\omega}{dt} = \sum \tau_{ext}, \tag{2}$$

where, M is total mass of the elastic object, I is inertia tensor, V and ω are velocity and angular velocity of the solid model respectively, and F_{ext} and τ_{ext} are external force and torque that are applied by the user. In the implementation that will be discussed in the next section, Euler's method was used to numerically compute the solution. As stated above, the effect of deformation on the dynamics of rotation, including the change of inertia tensor, was ignored.

3.4 Computation of deformation and force

As stated in Section 3.1, the component of deformation is computed using IRDM. The process of this computation is almost identical with that process that is discussed in [14].

In case of using position-input force-output device, such as PHANToM, interface points of the device applies forced displacement on the model, and the reaction force on these points become unknown. The reaction force is computed from the values of current and forced displacements using the initial component of impulse response (i.e. R[0]) (see [14] for details).

3.5 Complexity of computation

The computation algorithm inherits both advantage and drawback of IRDM. The complexity of computation is independent of the complexity of the model, and in case where forced displacement is applied only on small number of nodes at a time, then it is possible to compute interaction force in real time at haptic update-rate. Also, the computation time of deformation for visual feedback is proportional to the complexity of the model.

As stated in Section 2.4, a basic idea of our approach is reduction of the degrees of freedom by assuming linearity of the model. This assumption has significant effect on decreasing spatial complexity of the algorithm; any sequence of interaction with the model is described by a combination of interaction with each degree of freedom, and change in the number of interaction points and difference in timing of interaction do not require any additional pre-computation data.

On the other hand, the ability of the model to express realistic deformation has not been made clear; although approximation by linear model is an established approach to simplified description of target system in engineering field, it is not clear whether the approximation is appropriate for the presentation of elasticity. In our study, as described in the next section, a preliminary experiment to evaluate the reality by comparing the result of our approach with the result from off-line FEM simulation.

4 EXPERIMENT

4.1 Pre-computation

Simulation of deformation in response to impulse force in the pre-computation process was performed using a FEM software . In the software, the model was defined as a set of tetrahedral elements. An impulsive force, instead of theoretically impulse force, is applied to each degree of freedom of surface node, and the resulting temporal sequence of displacements on all degrees of freedom were recorded. Then, the component of *rigid-body motion* was estimated and removed from the record to obtain the component of *elastic deformation*; the deformation data corresponds to a column of a impulse response matrix R. By repeating the process of applying impulse force for all degrees of freedom, the entire matrix is obtained.

In the experiment, a cubic model ($12 \times 12 \times 12cm$) was used (Figure 2). The complexity of the model is shown in Table 1. Physical parameters of the model were set as follows: Young's modulus $E = 2000$ N/m^2, Poisson's ratio $\nu = 0.49$, and density $\rho = 110$ kg/m^3. The sequence of deformation was recorded at an interval of 2 ms for 1s of duration (i.e. impulse response for 500 steps).

Time step of FEM simulation changed according to the speed of deformation; in the initial stage of deformation just after impulse force is applied, the time step was set to 0.1 ms by subdividing each interval of recording deformation. Computation time that was required for the pre-computation process using a PC (Dual-Core Xeon, 3.0GHz) is summarized in Table 1.

Figure 3 shows an example of impulse response of the cube model where a rightward impulse force was applied on a node on the left side of surface. Propagation of surface elastic wave is observed. The velocity of the wave is approximately $6-8$ m/s, which coincides in its order with theoretical value obtained from the physical parameter of the model. Also, it is observed that the entire model starts moving after the impulse force is applied. Figure 4 shows the component of *rigid-body motion* extracted from the simulation resultby red wireframe, and Figure 5 shows the component of *elastic deformation*.

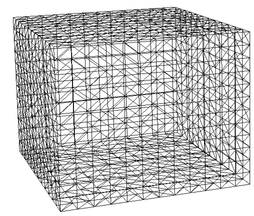

Figure 2: Experimental model

Table 1: Complexity of model

free nodes (n)	866
triangle patches	1728
entire nodes	1360
tetrahedral elements	5309
pre-computation time per d.o.f. (s)	1462
data size per d.o.f. (MB)	9.9

4.2 Presentation and interaction

The environment for presentation consists of two PCs and two PHANToM devices [16] (Figure 6). All computation that is related to the model was performed by PC1 (CPU: Itanium2 1.4GHz×4, memory: 16GB, OS: Linux); processes of computing force and deformation are asynchronously executed respectively by using thread mechanism. In the process of force computation, first, the position of interface point (or, the tip of stylus) is obtained from PC2 (CPU: Pentium3 500MHz×2, OS: Windows) through Ethernet, next, collision detection with the model is performed. If the interface point is colliding with the object, then reaction force is computed. Finally, the history of interaction force is updated, and the information of reaction force is sent back to PC2 to feedback the sensation of force. The process is repeatedly executed at an interval of 2 ms. Collision detection was performed using an algorithm that is similar to God-Object Method [23]. In the process of deformation computation, total behavior of the model is computed using the history of interaction force.

Program for PC1 was developed using Intel Compiler and Performance Libraries [1]. The process of computing current deformation using the history of passed forces was parallelized using OpenMP Compiler and 3 CPUs were allotted for the process. Also, other part of deformation computation was implemented using Math Kernel Library.

PC2 is dedicated to controlling two PHANToM devices. Force update process running in the PC performs simple conversion from GHOST API [2] to TCP/IP connection interface. The main loop of GHOST runs at a rate of 1kHz, and it passes the latest value of output force to the device and updates the information of current position of interface point that is cached by the PC.

4.3 Result

Figure 7 shows an example of interaction; a sequence of images during the interaction is presented. Since it was not possible to cap-

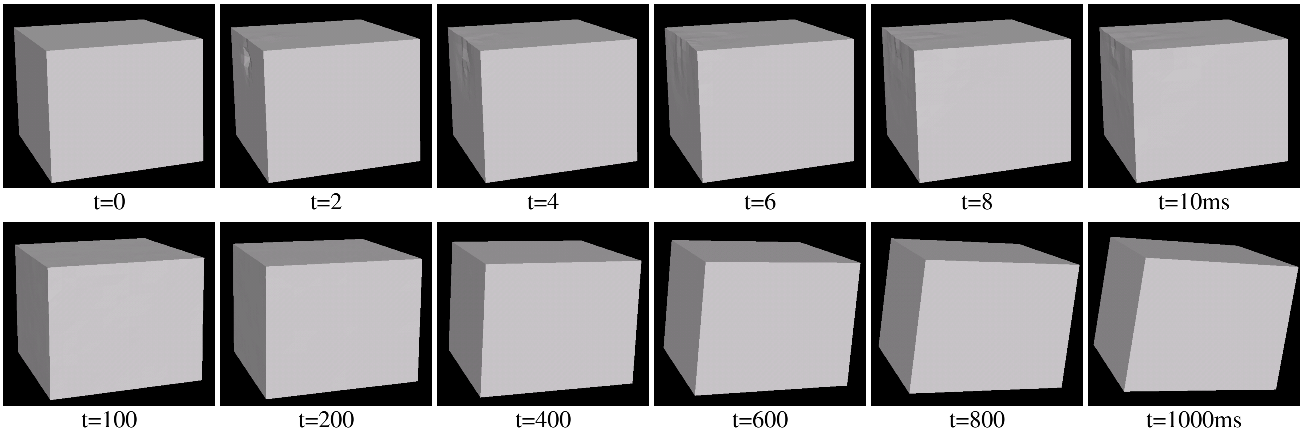

Figure 3: Example of impulse response

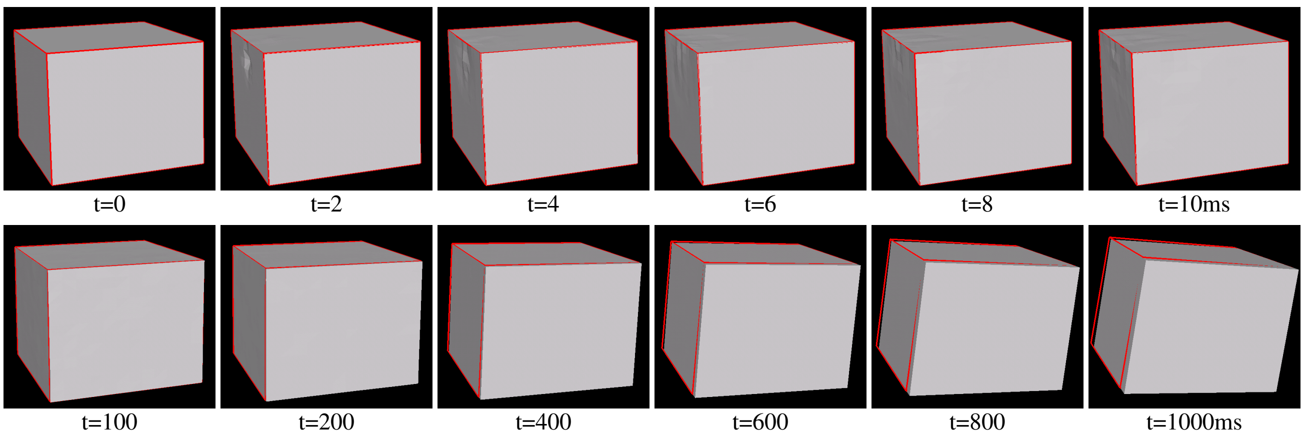

Figure 4: Example of component of rigid-body motion

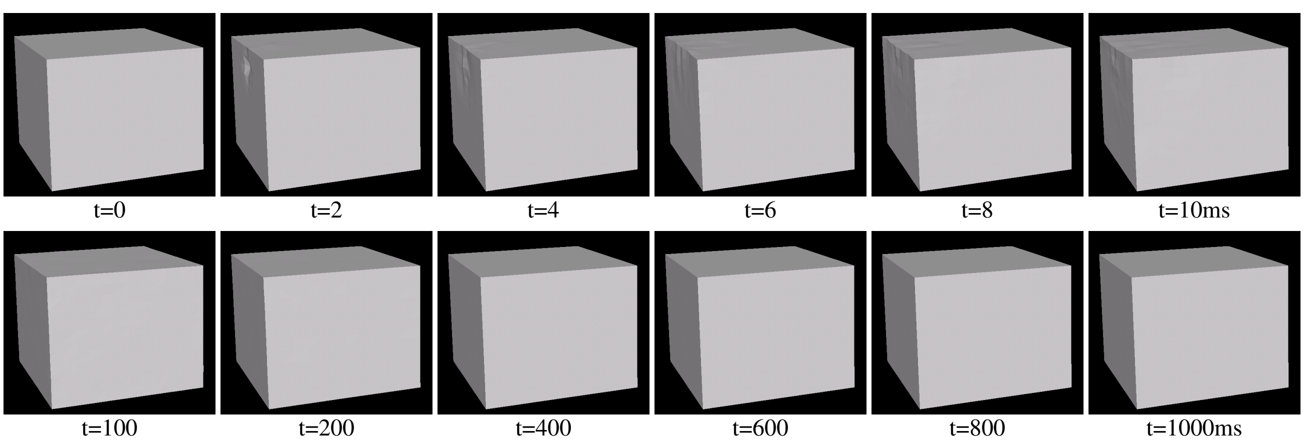

Figure 5: Example of component of elastic deformation

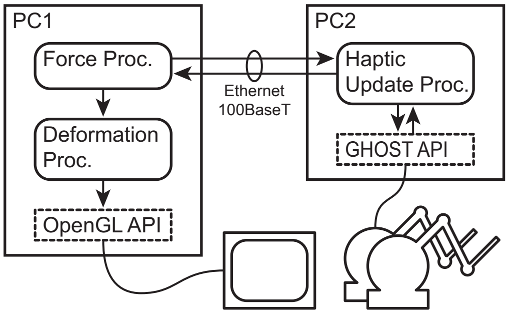

Figure 6: Experimental system

ture and store screen images in real time, these images were generated off-line based on the record of the history of interaction force. Figure 7(a) shows cases where the user is swinging cube model by pinching a node on the top surface of the models; resonant vibration that is determined by the form factor of the model observed. Figure 8 shows the time change of force during the swinging interaction. Figure 7(b) show the response of two models after they are tapped on a node respectively. The motion of entire body of the object, as well as the deformation on the surface of object, is invoked. Also, a relatively quick response of the model just after tapping is represented.

Figure 7(c) is the result of off-line simulation of the identical interaction with Figure 7(b) using FEM. These two results are approximately same each other; the difference in the orientation of object is gradually increasing over time, which is thought to be caused by the difference of computation algorithms in pre-computation and presentation processes; although, theoretically, the object is expected to rotate around a fixed axis of the cube, rotation axis in FEM simulation is changing its orientation, probably because of subtle computation errors that derives from asymmetric mesh structure of the object.

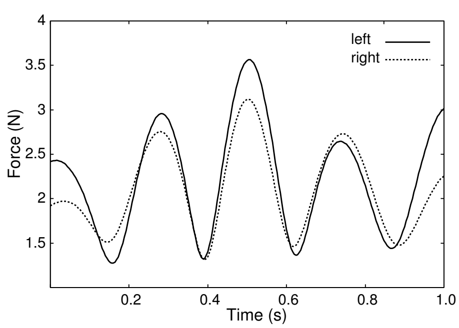

Figure 8: Interaction force

5 DISCUSSION

5.1 Separation of Motion and Deformation

In our approach, the behavior of elastic object was separated into components of *rigid-body motion* and *elastic deformation*, and they are modeled and simulated independently, although, as stated in Section 3.1, these components affects each other theoretically. The effect of the assumption of independence on the resulting shape was perceptible in some cases in the experiment. For example, the result of FEM simulation in Figure 7(c) is causing larger deformation compared with the corresponding result of our approach in Figure 7(b). Range of allowable difference, or error, in deformation thought to depend on application; in our impression through experimental interaction, the error was not noticeable so far as relatively small object is manipulated in a usual and moderate manner; on the other hand, our approach will not be suitable for applications where swinging long object is a primary task.

5.2 Futureworks

An important topic of research of our future work is compression of impulse response data. Size of the data in our current implementation is too large for practical use in usual PC hardware. One approach under investigation is retrieving the whole data set from a reduced representative data subset by interpolation. This approach is based on the idea that sequences deformation on neighboring nodes in most cases are similar each other. According to a preliminary experiment, compression ratio of one-tenth or less, depending on allowable error, is expected to be attained.

Another topic is evaluation of reality. Comparison with the result from FEM model, as reported above, certainly provides an index of evaluation. A problem of the index is that it is not taking the characteristic of human perception of hapic sensation into account; for example, relatively small vibration of object, that is visually not important, may have haptically significant impact. An evaluation method or experiment to clarify the advantage and drawback of our approach must be developed.

6 CONCLUSION

In this paper, an expansion of impulse response deformation model for floating and movable object is discussed. By this expansion, manipulation of dynamically deformable object became possible. Softness is a essential information that is obtained only through haptic sensation, and in our daily life, the softness is perceived while holding and manipulating the object. The result of our research is expected to contribute to present haptic sensation in natural interaction with virtual objects.

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A APPENDIX

A.1 Conservation of momentum

Spatial distribution of mass in FEM model is approximately described by a set of nodes on which the mass of connected elements is appropriately assigned. Equation of motion of node i in the model is:

$$m_i \frac{d}{dt} V_i = F_i + \sum_{k \neq i} F_{ki}, \tag{3}$$

where m_i and V_i are mass and velocity of node i respectively, and F_i and F_{ki} are external and internal forces on the node respectively. By summing up the equations for all nodes:

$$\frac{d}{dt} \sum_i (m_i V_i) = \sum_i F_i + \sum_i \sum_{k \neq i} F_{ki} = \sum_i F_i, \tag{4}$$

where action-reaction law: $F_{ik} + F_{ki} = 0$ was applied. Incase where no external force is affecting, the right-hand side of the equation equals zero, and consequently:

$$\sum_i (m_i V_i) \quad = \quad (const). \tag{5}$$

The equation implies that the total momentum of a model is conserved as far as internal forces in the model are balanced out.

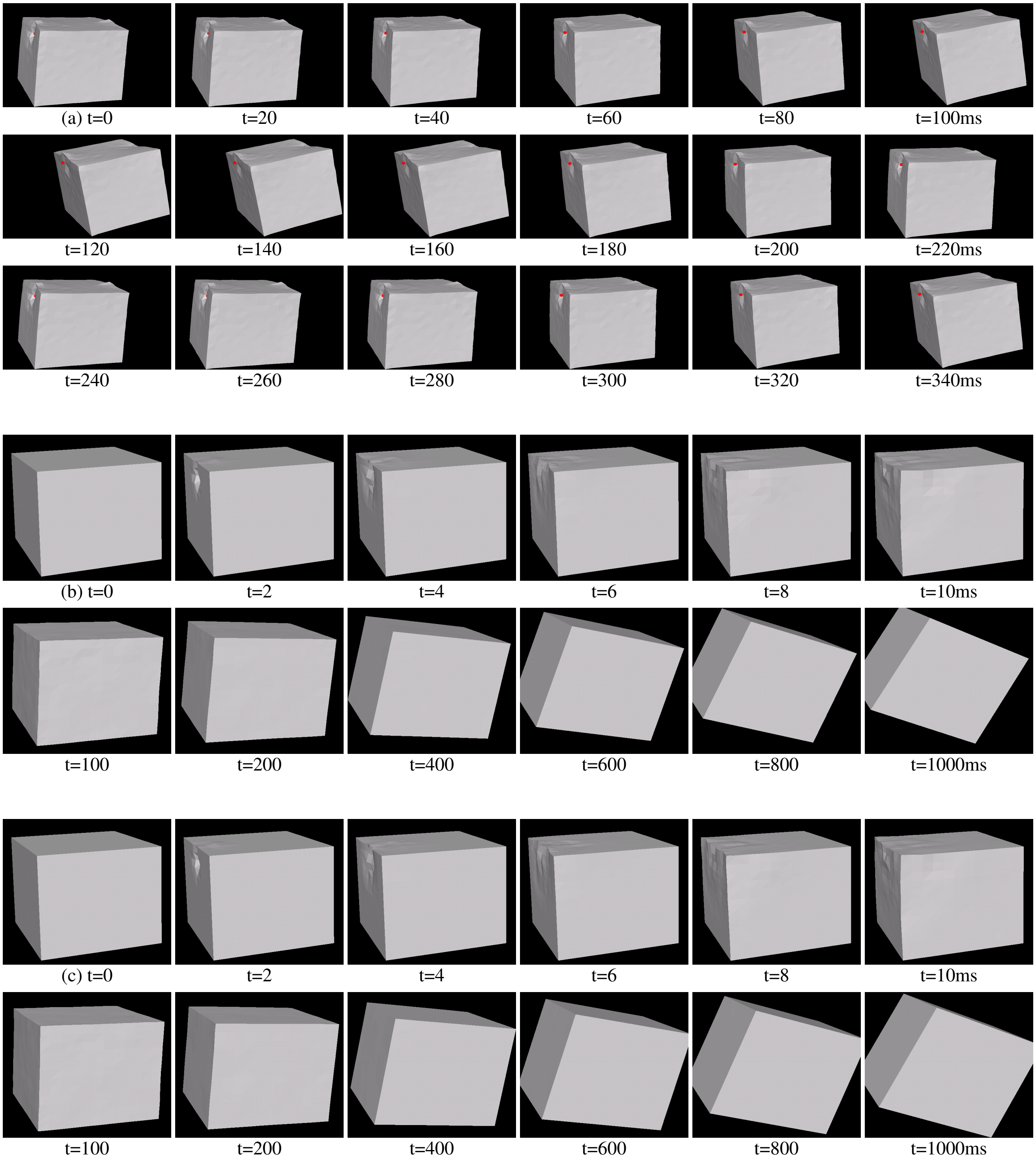

Figure 7: Example of interaction

A.2 Motion of gravity center

Position of gravity center of a model that consist of mass points r_G and total mass M are defined by:

$$r_G = \frac{\sum m_i r_i}{M}, M = \sum m_i, \tag{6}$$

where m_i and r_i are mass and position of node i. From these equations, the relationship is derived:

$$M\ddot{r}_G = \sum m_i \ddot{r}_i = \frac{d}{dt}\sum(m_i V_i) = \sum_i F_i. \tag{7}$$

This equation implies that the motion of the gravity center of the model is identical with the motion of a point mass of M.

A.3 Impulse response deformation model

Suppose a one dimensional model whose temporal change of displacement after impulsive force is given by $r(t)$. The response of the system to a given sequence of force $f(t)$ is computed by a convolution as:

$$u(t) = \int_0^\infty r(s) f(t-s) ds. \tag{8}$$

A time-discretized expression of the equation for processing by computer systems is given by:

$$u^{[t]} = \sum_{s=0}^{T-1} r^{[s]} f^{[t-s]}, \tag{9}$$

where, s and t in square brackets are indices of discrete time, rather than time itself. Also, the duration of impulse response is limited to T steps.

In case of n degree-of-freedom model, the relationship is expanded as follows:

$$u^{[t]} = \sum_{s=0}^{T-1} r^{[s]} f^{[t-s]}, \tag{10}$$

where, f an u are $(n \times 1)$ arrays of forces and displacements respectively on all degrees of freedom, and R is a $(n \times n)$ matrix.

REFERENCES

[1] Intel software development products. pages http://www.intel.com/cd/software/products/asmo–na/eng/index.htm.

[2] *GHOSTR SDK Programmer's Guide*. SensAble Technologies, Inc., 2002.

[3] B.Mirtich and J.Canny. Impulse-based simulation of rigid bodies. *Proc. Symp. Interactive 3D Graphics*, pages 181–188, 1995.

[4] C. Borst and A. Indugula. Realistic virtual grasping. *Proc. IEEE VR 2005*, pages 91–98, 2005.

[5] D.Baraff. Dynamic simulation of non-penetrating rigid bodies. *Computer Graphics*, 23(3):223–232, 1989.

[6] G.Burdea. *Force and Touch Feedback for Virtual Reality*. A Wiley-Inter-Science Publication, New York, 1996.

[7] D. Goeddeke, R. Strzodka, and S. Turek. Ergebnisberichte des instituts fur angewandte mathematik. *Nummer 292, FB Mathematik, Universitat Dortmund*, 2005.

[8] D. James and D. Pai. Artdefo, accurate real time deformable objects. *Proc. ACM SIGGRAPH 99*, pages 65–72, 1999.

[9] D. L. James and K. Fatahalian. Precomputing interactive dynamic deformable scenes. *Proc. ACM SIGGRAPH 2003*, pages 879–887, 2003.

[10] J.E.Colgate, M.C.Stanley, and J.M.Brown. Issues in the haptic display of tool use. *Proc. IROS95*, pages 140–145, 1995.

[11] K.Hirota and M.Hirose. Dexterous object manipulation based on collision response. *Proc. IEEE VR 2003*, pages 232–239, 2003.

[12] K.Hirota and T.Kaneko. Haptic representation of elastic object, 2001.

[13] K.Salisbury, D.Brock, T.Massie, N.Swarup, and C.Zilles. Haptic rendering: Programing touch interaction with virtual objects. *Proc. Symp. Interactive 3D Graphics*, pages 123–130, 1995.

[14] K.Tagawa, K.Hirota, and M.Hirose. Impulse response deformation model: an approach to haptic interaction with dynamically deformable object. *Proc. IEEE Haptic 2006*, pages 209–215, 2006.

[15] M. Mahvash, V. Hayward, and J. Lloyd. Haptic rendering of tool contact. *Proc. Eurohaptics 2002*, pages 110–115, 2002.

[16] T. H. Massie. *Initial Haptic Explorations with the Phantom: Virtual Touch Through Point Interaction*. Master Thiese at M.I.T., 1996.

[17] A. Norton, G. Turk, B. Bacon, J. Gerth, and P. Sweeney. Animation of fracture by physical modeling. *Visual Computer*, 7:210–219, 1991.

[18] S.Hasegawa and M.Sato. Real-time rigid body simulation for haptic interactions based on contact volume of polygonal objects. *Computer Graphics Forum*, 23(3):529–538, 2004.

[19] D. Terzopoulos, J. Platt, A. Barr, and K. Fleischer. Elastically deformable models. *Computer Graphics*, 21(4):205–214, 1987.

[20] T.Ezumi, N.Suzuki, A.Takatsu, T.Kumano, A.Ikemoto, Y.Adachi, and A.Uchiyama. An elastic organ model for force feedback manipulation and reali-time surgical simulation. *Proc. ICAT'97*, pages 115–121, 1997.

[21] T.W.Sederberg and S.R.Parry. Free-form deformation of solid geometric models. *Computer Graphics*, 20(4):151–161, 1986.

[22] T.Yoshikawa, Y.Yokokohji, and T. nad X.Z.Zheng. Display of feel for the manipulation of dynamic virtual objects. *Trans. ASME J. DSMC*, 117(4):554–558, 1995.

[23] C. Zilles and K. Salisbury. A constraint-based god object method for haptic display. *Proc. IROS '95*, pages 145–151, 1995.