Journal of Southeast University (English Edition) Vol.19 No.1 Mar. 2003 ISSN 1003—7985

A robot simulation system with virtual force display and feedback based on master manipulator

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Abstract: This paper describes a virtual environment, which can present dynamic force transformation during the control of objects. A 5-DOF haptic interface with the capability to generate kinesthetic effect is combined. In this system, the operator manipulates an object in a virtual environment by using the 5-DOF master arm. When contacting with the virtual object, the contact force can be calculated and shown in the graphic interface. The contact response and deformation of the virtual object, which are usually called haptic rendering, also can be performed. The study supplies an approach to improve the operator's immersion and can be used in many tele-robot control fields.

Key words: virtual reality; haptic display; contact detection; contact response

Today, advances in computer graphics technology provide us with an excellent visual image of virtual environment. Many interesting studies have been done in the field of virtual reality. However, most of them have focused on the display of the visual images[1]. A realistic simulator should not only construct the virtual environment with physical-based models but also interact with the virtual environment, providing an attractive augmentation to the visual display and enhance the level of immersion in a virtual world. Such simulators can be found in assembling blocks, inserting pegs in holes and microsurgery simulations.

It is essential to manipulate the virtual object, feel the contact force and watch the haptic rendering of it. Manipulation can be achieved via indirect means such as voice, keyboard, or mouse commands. A natural form of manual manipulation is haptic interface with force feedback. Many researchers have provided such devices, for example the Haptic Master developed by Hiroo Iwata at the University of Tsukuba, 3-DOF PHANToM at MIT, and SPICE at Suzuki Motor Corporation[1]. Although a number of haptic devices are becoming available, their applications have been limited. This is specially due to the complexity of detection of collision and accurate calculation of all the contacts' forces and rendering in less than one millisecond.

In this paper, we summarize our work on the development of simulation systems with force feedback. The system in Fig. 1 consists of a master arm, a graphic display interface, and a simulator. The operator manoeuvres the movement of the master arm, and the position of the master arm is measured and sent to the virtual environment in the computer as a command, and then the virtual slave arm can follow it. The geometrical information from the graphic display is renewed through sensing the configuration of the master arm. While the slave arm is interacting with the virtual object, the simulator calculates the interaction depths and estimates the contact forces, and then the master arm with force feedback can generate a contacted signal to the operator. The interactive response, especially the deformation and displacement of the virtual object also can be exerted.

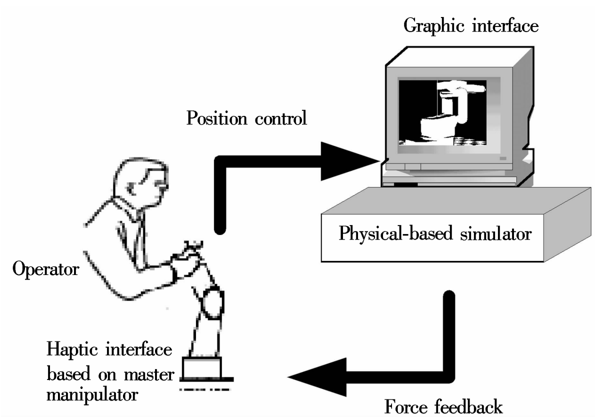

Fig. 1 Simulator system with force display

1 Force Feedback Devices

Force feedback devices are commonly characterized by the capability to sense and manipulate virtual kinesthetic feedback. The hardware is based on our 5-DOF master manipulator system with force/tactile devices for tele-robot. It has 5 active DOF, and the

Received 2002-10-23.

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arm rotates around the axis Z and Y. The fingers have two active freedoms that can cooperate to grasp the object. The world coordinate system is defined on the base of the master arm, which determinates the absolute position and orientation of the arm and fingers. Every joint has a local coordinate system, which is convenient to determine the relative displacement and movement between joints. In order to transform the local coordinate to the world coordinate, the robot transform matrices are recursively multiplied together from the finger end to the arm base. Therefore, the object in the model is manipulated through the master arm. When contact force is calculated, the motor on the arm generates the analog force signal to directly act on the operator. That forms the perfect control loop.

2 Algorithm of Interaction

The graphics literature is replete with solid object representations. But it is not particularly easy to synthesize realistic animation through direct application of the geometric representations of solid modeling, and the problems are exacerbated when animate objects can deform. Physical-based animation has begun to overcome some of the difficulties[2]. From the point of physical-based simulation, we deal with two types of problems:

① Contact detection To find the geometrical contracts between the objects.

② Contact response To integrate the resulting reaction and force effects in virtual environment.

In robotic systems, usually the robot is regarded as rigid body. The objects in the environment can be classified into elastic bodies and rigid bodies according to their realistic meaning.

As to the rigid bodies, most of the recent work has focused on using the laws of Newtonian dynamics to simulate the motions of rigid bodies[3]. A realistic simulation of rigid bodies demands that two collision rigid objects are non-penetrating. While virtual objects are determined only by a formal description in the computer's memory, they do not occupy any 'real' volume in space. Nothing can prevent several such objects from occupying the same volume in virtual space. If these objects were to represent solid objects simultaneously existing in a common scene, they would be unrealistically interpenetrating[4].

Dealing with elastic objects whose surface is deformable, the method for controlling the geometric changes on the surface and calculation of the contact force is quite different from that of controlling rigid objects[5].

3 Realization of the Haptic Simulation System

3.1 Contact detection

The goal of contact detection is to automatically report a geometric contact when it is about to occur or has actually occurred. The geometric models may be polygonal objects, spline, or algebraic surfaces. We use Constructive Solid Geometry or CSG to form objects from primitives such as blocks, spheres, cylinders, cones, and tori, by combining them with set theoretical operations such as union, intersection, and set difference. One strength of CSG representation is that it enables an intuitive design process of building shapes by means of cutting (intersection and set difference) and joining (union) simple shapes to form more complex ones. It also makes finding a collision witness easier.

There are many variations of contact detection algorithms, such as bounding volumes, projection methods, subdivision methods and proximity methods[6], which arrange the scene objects according to their geometrical neighborhood and detect collisions between these objects based on the neighborhood structure.

The most common are bounding volumes that are to divide the objects into axis-oriented bounding boxes or bounding spheres[7]. In our system, the bounding spheres described by the center and the radius are used. The main advantage of bounding spheres is that they are not axis-dependent. Thus, they can be transformed by a rigid-body motion along with the transformation of the contained objects and need not to be recomputered. If all agents were spheres, a pair-processing algorithm would be trivial. Few agents are closely approximated by a single sphere, but a set of partially-overlapping spheres can provide a more reasonable approximation. A pair-processing algorithm for agents represented as sets of spheres is also trivial. We use the sphere-tree method. Deeper levels in hierarchy use more spheres to approximate the agent more exactly. The children of a sphere at level i are all spheres at level $i+1$ that it bounds. When the sphere-trees penetrate for two agents, no spheres can penetrate each other unless their parents also penetrate.

3.2 Contact response

To simplify the algorithm, the contact response method used is based on the idea that contact response is a matter of moving specific points on the surface towards specific destination points at a certain rate[8]. The deformations are calculated in time and space proportional to the number of points used to define the surface. We characterize the deformation behavior of surface without using the mass distributions, volume conservation, internal or inherent in the dynamic models of elasticity. We define the deformation as the "the change of a surface caused by the displacement of surface points relative to each other over time".

3.2.1 Calculation of virtual force

When a contact is detected, a very stiff spring is temporarily inserted between the points of closest approach of the two objects. According to the spring law $F = kx$, k is a spring constant controlling the stiffness of the spring. The spring is applied equally and in opposite directions to the colliding objects. The direction of the force is such as to push the two objects apart[9]. This method is easy to understand and program. It can be applied equally well to rigid bodies and to flexible bodies.

3.2.2 The rendering and force display

In our system, referring to K. Hirota and M. Hirose's idea in Ref. [10], we present a virtual sheet the height of which is defined on each of the 16×16 girds. After finding the exact contact point (u, v), its edge-adjacent neighbors horizontally $(u \pm 1, v)$, vertically $(u, v \pm 1)$, and its diagonally adjacent neighbors $(u \pm 1, v \pm 1)$ can be defined. We calculate the displacement of each surface gird according to the following expression[10]:

$$f(d, F) = \frac{F}{F_0}\left\{\exp\left[-\left(\frac{d}{k}\right)^2\right] - \exp\left[-\left(\frac{d_0}{k}\right)^2\right]\right\}$$

where d is the plane distance from the rods in mm; F is the intensity of force exerted on the rod in N. The constants are defined as $d_0 = 44$ mm is the maximum distance influenced by force; $k = 40.1$ mm is a constant determining the acuteness of transformation; $F_0 = 3.0$ N/mm is the constant to determine the sensitivity against force.

The function applied in this implementation is based on the Gauss function

$$f(x) = \exp\left[-\left(\frac{x}{k}\right)^2\right]$$

By applying the parameter that satisfies this relation, we are able to interpolate the surface peaks, thereby achieving a smoother surface between the tips of the rods. To change the transformation characteristics of the virtual sheet, we simply replace the function just described with another function. We calculate the transformation as a sum total of the displacement for all the rods in every calculation cycle. Also, because interaction with the object is not always done by hand, we try to transcribe the shape of a sphere onto the virtual sheet to reflect interaction done by other objects. In this manner, we hope to simulate how users will handle the presented surface of a real object located in the same place. Fig.2 shows the transcription of the shape of a real object onto a virtual object. In Fig.2, the shape of the object is a sphere. Fig.3 is the model of the Gauss function, which shows the relation between deformation and offset from the contact point.

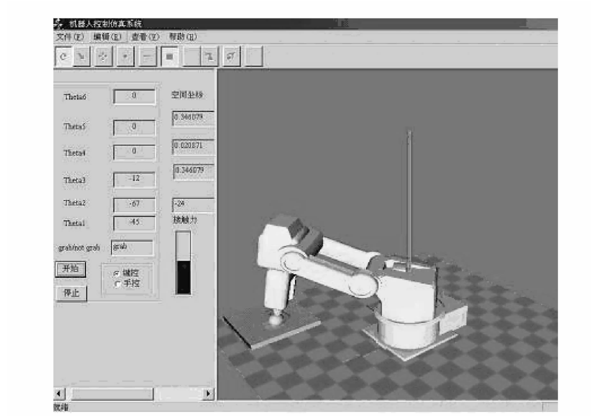

Fig.2 Display of deformation and force in contract

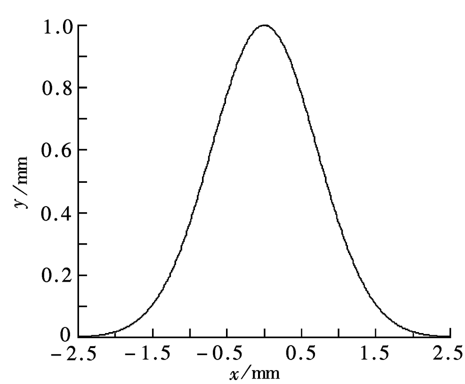

Fig.3 Gauss deformation model

4 Experimental Result

The virtual environment consists of a virtual slave Motoman manipulator, a virtual rigid ball, and a virtual sheet. The operator's task is to explore the ball, manoenvre the virtual slave manipulator to grasp the rigid ball and move to the virtual deformable sheet, and then put it on the sheet through direct interaction with the master manipulator. According to the function of each area, the graphic interface can be divided into three parts. You can choose the display mode in the menu of the control area. There are three types of display modes, corresponding to the point, line, and face modes. You can also rotate, translate and zoom the view port. In the data area, the coordinate of the end of the virtual arm and the magnitude of virtual force can be shown. The graphic area shows the virtual Motoman robot manoeuvred by the master arm; and the geometrical information from the graphic display is renewed through sensing the configuration of the master arm. When the virtual slave manipulator is interacting with the virtual object, the simulator calculates the interaction depths and estimates the contact forces, and then the master arm with force feedback, can generate a contacted signal to the hand of human operator. The force column graphic varies as the grasp force changes. In the meantime, the calculated force is sent back to the master manipulator through a D/A card and commands the motor to produce force acting on the human operator.

5 Conclusion

We present our virtual environment system with virtual force display and explain this implementation in detail. The system we performed is a basic interface between a human and robotic system. Therefore, we are able to apply this technique to many robot systems such as tele-operation system that use environment models, and to the artificial reality system. Our future work will focus on the collision detection calculation between complex surface and massive models. Hierarchical methods and subdivision techniques will be used. Another aspect is the representation of a surface. The rigid body and elastic body are quite different in contact force, motion, and deformation generation. A more refined and efficient method for detection and resolving collisions should be implemented.

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一个基于主手的力觉再现和反馈的机器人仿真系统

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摘　要　介绍了基于5自由度力觉再现装置的虚拟力觉仿真系统的实现方法.此系统中,操作者通过主手控制虚拟环境中的从手与虚拟物体相作用,虚拟环境中的接触情况如碰撞响应、形变在图形界面仿真,虚拟力通过主手装置表达.该研究有利于提高遥操作机器人的性能和增强操作者的沉浸感.

关键词　虚拟现实; 力觉再现; 接触检测; 接触响应

中图分类号　TP24