Simulation and Visualization of Mechanical Systems in Immersive Virtual Environments[1]

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Abstract

A prototype for doing real-time simulation of mechanical systems in immersive virtual environments has been developed to run in the CAVE and on the ImmersaDesk at Argonne National Laboratory. This system has three principal software components: a visualization component for rendering the model and providing a user interface, communications software, and mechanics simulation software. The system can display the three-dimensional objects in the CAVE and project various scalar fields onto the exterior surface of the objects during real-time execution.

Introduction

Over the past few years a number of CAVE [3] applications have been developed to enable the use of immersive visualization in applied mechanics simulations. Example applications include multibody dynamics, stress analysis, crash simulation and fluid dynamics. Most of these simulations have been used to demonstrate a capability and to do experiments. In a few instances these demonstrations have evolved into useful tools, e.g., the Boilermaker (Diachin et. al. 1996). More often the results of these demonstrations were most useful in pointing out the limitations of the technology, its strengths and its weaknesses. At present some degree of success has been achieved in modeling mechanical systems in real-time using the CAVE and a networked connected parallel supercomputer.

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[3] The CAVE and the ImmersaDesk™ are trademarks of the Electronic Visualization Laboratory of the University of Illinois at Chicago.

DISCLAIMER

The purpose of this paper is to describe the computing environment used to test virtual prototyping concepts and report on current progress on real-time mechanics simulation using finite-elements.

Computing Environment

Futures Laboratory/Distributed Supercomputing Laboratory. Two research centers facilities at Argonne National Laboratory have helped to create a unique environment for doing research on virtual prototyping concepts and the use of immersive virtual environments in scientific applications. These facilities are the Futures Laboratory and the Distributed Systems Laboratory. The Futures Laboratory was set up to investigate advanced visualization and collaborative multimedia technology. The CAVELab was established under the Futures Laboratory in 1996 to provide a development environment for virtual reality research at ANL and to support the I-WAY Project (Defanti et. al. 1996). The Distributed Systems Laboratory was established to in the following year after successful demonstration of the I-Way advanced networking project at SuperComputing '96 in San Diego. The Distributing Systems Laboratory is doing research on enabling tools for distributed supercomputing based on NEXUS (Foster et. al., 1994) software developed for I-WAY.

QUAD Computing Environment. Recently, Argonne National Laboratories has upgraded to its computational infrastructure to establishing a highly flexible and balanced computer environment for doing advanced scientific simulations. This hybrid computing environment is referred to as the QUAD machine, supporting both distributed-memory and shared-memory parallel computing paradigms. The compute engines are connected via high-speed network switches and share high-capacity, high-bandwidth storage servers with three disks farms totaling 432 GB and six 3495 tape robots that can store 200 TB. In the past year, an SGI Origin 2000/Reality Monster visualization server has been acquired and substantial upgrades have been made to the IBM SP, which provides the bulk of the parallel compute cycles. The current system configuration is summarized as follows:

Processor	Number	Memory (MB)	Memory Banks	Clock (MHz)	Disk (GB/node)
SP1	64	128		60	1
SP2 (thin)	80	256	2	120	9
SP2 (thin)	8	512	4	120	9
SP2 (wide)	2	512	4	135	9
8-Way SMP 970B server	7	1024		-	6
Origin/20000 R10000	16	4096		195	32
Infinite RealityEngine2	4				

The networking component provides both internal and external communications capacity. The internal network is built on IBM's high-performance switch, which can support speeds of up to 300 MB/s. External high-speed network connections are made through an IBM high-performance gateway node, which interconnects the high-performance switch with ATM and HIPPI.

CAVE/ImmersaDesk. Virtual reality research at ANL has concentrated on immersive visualization performed in the CAVE or on an ImmersaDesk. The CAVE (Cruz et. al. 1993) is a multiperson, room-sized (10'x 10' x 9'), high-resolution, three-dimensional video and audio environment made up of three rear-projection screens for walls and a down-projection screen for the floor (see Figure 1). Electrohome 8000 projectors throw full-color workstation images onto the screens at 96 Hz, giving 2000 x 2000 linear pixel resolution to the surrounding composite image. Computer-controlled audio provides sound to multiple speakers within the CAVE™. A user's movements are tracked with tethered electromagnetic sensors: one sensor tracks head movements, the other a hand-held wand. Stereographic LCD stereo shutter glasses are used to separate the alternate fields going to the eyes. The ImmersaDesk is a lower-cost, more portable, and smaller alternative to the CAVE. The ImmersaDesk provides the illusion of data immersion on a single large 4 x 6 foot screen with a resolution of 1024 x 768 pixels with head tracking and a hand-held wand.

Application

The dynamic systems of interest involve motion in near real-time and where frictional contact is important. Examples include machines that do robotic assembly operations, braking systems and various types of machines that do grinding, honing, and lapping. A parallel program, FIFEA, has been written to simulate these complex mechanical systems. MPI (Gropp et. al. 1994) is used to do low-level communications using a distributed memory computational model. This approach permits the program to be run on both shared and distributed memory parallel supercomputers. PETSc (Balay et. al. 1995) is used to manage the parallel data structures and to do parallel gather/scatter operations on the parallel vectors and the sparse matrices. BlockSolve95 (Jones and Plassmann, 1996) is invoked within PETSc to solve the algebraic equations.

The program uses a hybrid finite-element method to do the thermal-stress analysis of these complex mechanical systems. In this method the large displacement multibody dynamics problem is decoupled from the small-strain thermal-stress problem. The finite element model is used to determine the inertial characteristics of each distinct body. Contact forces due to interactions between the bodies provide the driving force for the multibody dynamics equations. This small system of nonlinear equations is then solved to determine the motion of the rigid bodies. The accelerations derived from the motion of the *rigid bodies* give rise to inertial forces in the large set of finite element equations for the dynamic thermal-stress problem. These equations are then integrated by using a stable implicit Newmark-β time integration to allow large time steps. The result is a large system of algebraic equations that are both sparse and symmetric. The solution of this set of equations determines the displacements and temperatures that produce the thermal-elastic stresses and strains in the bodies.

The display program runs in the CAVE or on the ImmersaDesk. This program communicates with the simulation program running locally or at a remote location. The results are displayed as a three-dimensional scene by using OpenGL. The CAVELib

(Cruz et. al. 1993) performs transformations to display the scene on the walls based upon the current location and orientation of the head-tracking device. Two-way communications between the simulation program and the display program are currently provided by the CAVEcomm (Disz et. al. 1995) library. This two-way communication enables the display program to control various aspects of the simulation program and the simulation program to send data to the display program.

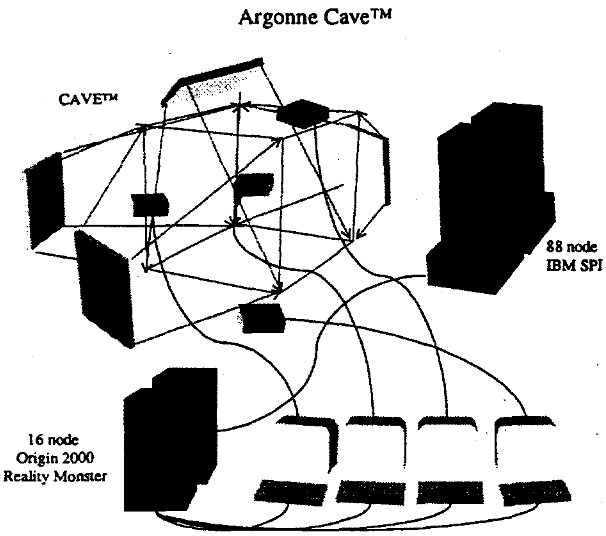

Figure 1 Configuration of the CAVE at Argonne National Laboratory.

The CAVE Grinder used a simple finite element model to calculate the heat generation and conduction heat transfer in a simple grinding application. In this simulation 788 nodes and 433 elements to create an annular shaped grinding wheel, small rectangular workpiece, and the moving rectangular table. The motion of the table was controlled interactively by the wand. The calculation was done remotely on SP supercomputer and the results displayed in the CAVE. The results were encouraging and demonstrated the potential for true interaction between a physical model and the CAVE.

The Porshe in the CAVE (Automotive Disk Brake) was a more ambitious attempt to use parallel supercomputing in conjunction with the CAVE. A complete finite-element model of the automotive disk brake consisting of 5636 nodes and 3790 elements was constructed to model the rotor and two disk pads. The simulation was run in parallel on the IBM SP at ANL and the results displayed in the CAVE. The simulation calculated the velocities, displacements and temperature fields during a braking by solving the 30 nonlinear equations for the multibody dynamics of the three components and the 22544 algebraic equations for the finite elements. The simulation component demonstrated good parallel speed-up: 4.0 on 8 processors of the IBM SP1 and 4.8 on 8 processors of the SGI PowerChallenge. However, the best lag times for startup (57.8 sec) processors of the SP1) and simulation update (51.9 sec) were to long for reasonable interactions in the CAVE.

Figure 2 shows how the same software can do simulations of various sizes. In this particular case the model consists of 612 nodes and 346 elements. The velocity of the middle slab is initialized in a direction parallel to the planes of the three plates, the two smaller slabs are held in contact by application of normal forces and one of the smaller slabs is also rotating. Heat is generated at the interfaces due to friction. The resulting temperatures are displayed on the exterior surface of the model.

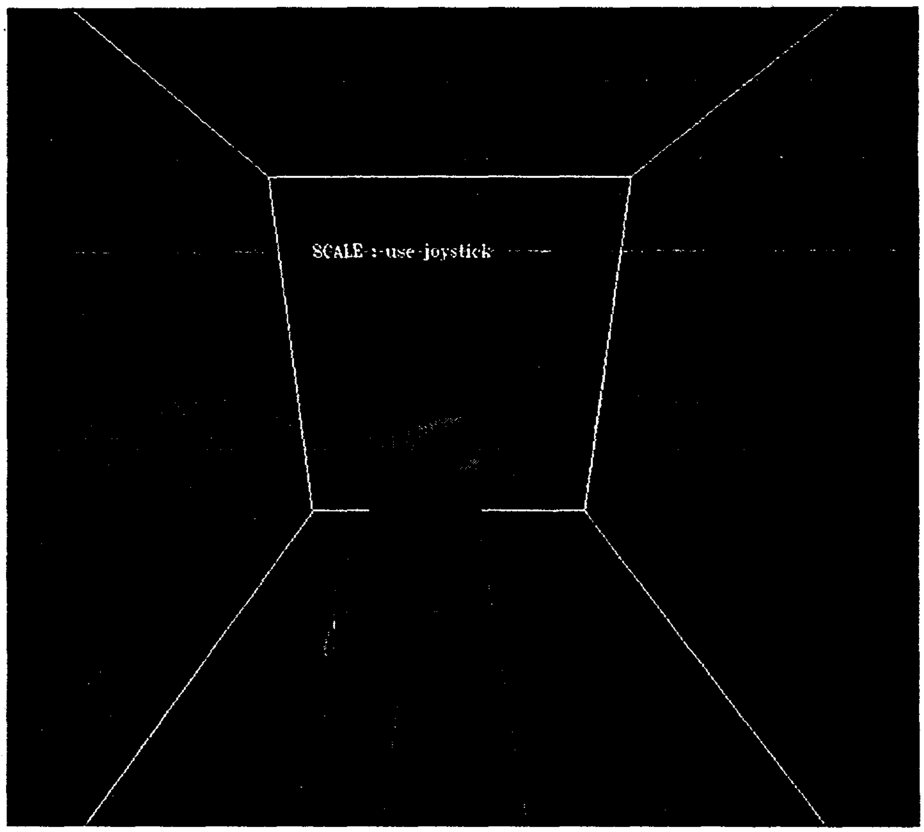

Figure 2 Finite element model in the CAVE.

Conclusions

The current version of the program uses hexahedral finite elements to model all of the system components (see Figure 2). Simulations have been performed on high-performance computer systems and displayed in the CAVE or on the ImmersaDesk. However, the size and complexity of the problem are still a limiting factor. Models with a few hundred elements (as shown in Figure 2.) can be run in computational time with no serious lag effects. This is sufficient to model modest-sized building structures with frame and truss elements. However, when number of elements is increased to a point that simulation time to update a scene exceeds 20 seconds, lag time becomes unacceptable (V. Taylor et. al.1995).

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