Real-Time Interaction in Virtual Environments *

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Summary
We propose to develop computational approaches to enable real-time physically-based interaction between a user and a virtual reality (VR) training system. The resulting algorithms and systems will provide capabilities of real-time collision detection and contact response, so that a user can interact with the virtual environment (VE) in a direct, natural and intuitive manner. Specifically the proposed research will focus on (1) Designing interactive collision detection algorithms for large and complex virtual environments; (2) Developing fast dynamic simulation programs to generate realistic contact response; (3) Implementing physically-based VR interfaces for handling virtual contacts; (4) Performing user studies to evaluate the effectiveness of alternative feedback techniques.

We plan to collaborate closely with Dr. Jim Templeman and other researchers at NRL. Our collaborators at NRL will have the first access to all the technologies developed under this project at no additional cost. Furthermore, we will also assist in the integration of our systems with the locomotion simulator developed at NRL. The proposed research is expected to lay the scientific foundation and empirical analysis for high-quality interaction with the VEs. The resulting system should enhance perceived realism and provide a better sense of presence in an immersive virtual environment.

1 Motivation and Problem Statements

Motion is ubiquitous within both the virtual world and the physical environment. The problems of collision detection and contact response are central to many tasks involving motion in virtual environments, computer animation, robotics, simulation-based design, electronic prototyping, acquisition, evaluation and testing, war-gaming, etc. In many of these applications, motion among different entities is often simulated by modeling the contact constraints and impact dynamics. This is especially important in creating an immersive virtual environment for training and mission rehearsal.

One of the driving applications for our research is in the area of training dismounted infantry in maneuver warfare. The soldiers need to move freely within and between multi-story buildings, covering several city blocks. Dr. Jim Templeman has proposed a virtual locomotion technique, called Gaiter, for walking in place to move around in such a VE. This technique provides a more responsive and expressive range of motion. However, as the user can now move around more effectively in a VE, there is a need for the user to interact with the carried weapons, objects in the surrounding environment, and other avatars or trainees. Given the position and orientation of the user using full body tracking technology, real-time physically-based modeling techniques can be used to simulate the interaction between the user and the virtual world, as well as the interaction among virtual objects and the avatar. The simulated behavior should emulate what we expect in the real world. This requires complex modeling of all types of possible motion encountered in such a scenario.

As part of the user’s body penetrates a purely virtual object, several body surfaces may come into contact with it. We must determine where and how much penetration has occurred to compute the collision response. Given the contact information, the dynamic simulation module will need to determine the reaction of the bodies (i.e. sliding over the virtual object, bouncing back, etc.) and how the virtual objects are effected by each other. Each virtual object has its own material properties which need to be taken into consideration. These physical properties govern the behaviors of both the virtual object as well as that of the user upon impact.

Despite the wealth of literature and the development in the CAD/CAM/VR/Graphics industry, the current state of art in modeling, simulation and VR still does not provide a satisfactory solution for the much needed interaction with a virtual environment. This is probably due to the real-time performance requirements of VR, the complexity of usable and interesting VEs, as well as limited device technology for providing the much needed feedback response.

2 Research Objectives

Realizing the importance of providing intuitive, real-time interaction with the VEs, several industrial sectors and research laboratories are working on the development of better sensors, more accurate (and wireless) trackers, wearable haptic devices, higher resolution HMDs, large and immersive display, etc. However, there is still insufficient progress to develop the much needed algorithms, software and systems to support the use of these VR devices, in order to realize high-quality

* Due to the page limit, we are confining the citations in this white paper to the web page references, not the actual citation.
interaction with the VEs. One of the many challenges is the design of computational methods for detecting contact and computing realistic response in highly complex environments at interactive rates to enable real-time mobile interaction.

Aiming to improve the quality of interaction provided by the VEs, we proposed to address the following: (1) designing interactive collision detection algorithms for modeling motion within a complex virtual environment; (2) developing fast dynamic simulation systems to generate realistic contact response for interaction with the VEs; (3) implementing physically-based VR interface for handling virtual contacts; (4) performing preliminary user studies to evaluate the effectiveness of alternative feedback techniques.

3 Background

The problems of contact computation and physically-based response have been explored in computer graphics, robotics, computational geometry, computer animation, and physically-based modeling. For collision detection, numerous approaches based on geometric reasoning, bounding volume hierarchy, spatial representation, numerical methods, and analytical approaches have been proposed. However, many of these algorithms do not satisfy the demanding requirements of general-purpose collision detection for virtual environments. See a recent survey by the PI [Lin98].

The PIs have been working in this area for more than a decade and had developed one of the first collision detection system, I-Collide, for real-time interaction with simulated environments in 1995. Over the last 5 years, we have continued to design novel algorithms and develop new systems, including RAPID, V-Collide, S-Collide, PQP and H-Collide. However, our current system can only perform interaction between a user’s hand (or a simplified avatar with few DoFs) and a reasonably complex environment in real time. Furthermore, there is relatively little work on detecting contacts between deformable models, e.g. flexible muscles or cloth. We need to continue pushing the frontier of collision detection to design real-time algorithms suitable for handling complex articulated and deformable bodies.

Physical simulation has been extensively used for engineering applications like virtual prototyping as well as generating “plausible” motion for computer graphics and animation. However, their application to virtual environments and training simulators has been restricted. Current algorithms and systems are unable to simulate real-time dynamics for large, complex environments, while maintaining the desired rendering frame rate.

4 Proposed Approaches

Since the interaction techniques depend on the algorithms for handling virtual contacts, we will first focus on collision detection and contact response. Then, we will design interaction techniques to interface with the VEs, evaluate their effectiveness, and refine our computational methods for modeling virtual contact accordingly.

4.1 Collision Detection

We propose three novel approaches for contact determination:

- **Accelerated Proximity Queries Using Multiresolution Techniques**

  Multiresolution methods and level-of-detail modeling have received considerable attention in computer graphics for faster rendering of complex environments. Our goal is to utilize these representations to accelerate collision queries between complex models. The resulting algorithm will pre-compute a series of bounded-errors approximations (LoDs) for objects in the environment. The LoDs for each object form a new hierarchy to be used in a progressive refinement framework for proximity queries. The proposed framework will allow the applications to progressively refine the result of a collision query to suit their needs (e.g. articulation), while optimizing the overall performance.

- **Fast Swept Volume Computation using Hybrid Hierarchies**

  Nearly all the collision detection algorithms consider only the contact status at each discrete simulation state. Penetration can be possibly missed between successive checks. To avoid such a situation, swept volumes of the objects over time need to be computed and checked for intersection. However, it is extremely difficult to compute them in real-time for complex models. We propose to use hybrid hierarchies of swept sphere bounding volumes (SSBV) to simplify the computation of swept volumes. The SSBV are a family of bounding volumes defined by sweeping a spherical volume around a core shape. The set of core shapes include a point, a line and a rectangle slab. Given the discrete positions of the avatar and/or other moving objects in the virtual environment, we propose to compute approximations of the swept volume using SSBV and check for collisions between the swept volume and the the environment.

- **Rapid Contact Determination for Deformable Models with Distance Fields**

  We propose to use distance fields for detecting contacts among deformable models. The distance fields can be computed dynamically using graphics hardware or precomputed using fast marching level-set methods along with non-linear interpolation schemes. As the objects undergo deformation, the distance fields can be deformed accordingly and used to calculate penetration depth for contact force computation.
4.2 Contact Response
A key component of interaction with virtual environments is the computation of appropriate response between the moving avatars or objects and the rest of the virtual environment. Given the computational costs of dynamic simulation in a complex environment, we propose to investigate two novel approaches to attain real-time performance:

- **Accelerated Computations using Graphics Hardware**
  Recently we introduced the idea of using polygon rasterizing graphics hardware for accelerated proximity computations (SIGGRAPH 1999). This includes computation of generalized Voronoi diagrams (GVD) and using them for real-time motion planning in dynamic environments. More details are available at: http://www.cs.unc.edu/~geom/voronoi/
  Our algorithm appears to provide the first known practical solution to these hard problems. We propose to develop a similar approach for real-time dynamics simulation in a complex environment. It involves computation of contact information and dynamics response by rendering distance functions, multi-pass techniques that requires reading back the frame buffer and the depth buffer, and finally computing the response.

- **Porting to Game Console Hardware**: Some of the upcoming 128-bit game consoles like Sony PlayStation II, Microsoft Xbox and Nintendo Dolphin system have extremely powerful graphics rendering capabilities. For example, the graphics system in a Xbox is expected to render up to 200 million triangles per second. Furthermore, they seem to provide much better control over the frame buffer (as compared to current PC graphics card and SGI workstations).
  Therefore, we propose to investigate the use of graphics hardware available in these consoles for real-time contact response computations. A major challenge is dealing with the memory limitations, e.g. the Sony PS/2 has only 32 MB memory and Xbox has 64MB memory, and the lack of advanced programming environments. Our research group has strong ties with Intel, Sony and NVidia. The Sony PlayStation group will provide the PIs with an advanced developer’s toolkit and have also offered us technical support to evaluate portability of these algorithms.

- **Simplification of Complex Dynamical Systems**
  One of main challenges in this area is to design simulation systems than can effectively choose appropriately motion models and algorithms for the given situation. Perhaps a rigid body model is a reasonable approximation, or maybe a linear or even non-linear deformable model is needed. Inertial effects may or may not be negligible. There are a variety of ways to model friction with different properties and computational costs. Even after the model has been chosen, there might be alternative algorithms. For example, there are at least three families of methods for modeling rigid body contact (analytic/LCP formulations, penalty methods, and impulse-based methods), each with different strengths and weaknesses. By and large, today’s simulation systems use a single model and a single algorithm for a given class of dynamic objects.

  Our goal is to develop a simulation system that can appropriate choose among motion models and algorithms on the fly. Given a user’s application needs, this system will take into account important results of the simulation, the environment, the allowable tolerances, the sources of error in each algorithm, the bounds on the errors, and how they propagate over time. This dynamics simplification framework should be applicable to simulation of natural phenomenon (e.g. fog, smoke, fluid) as well.

4.3 Interaction Techniques
One of the most well-known “illusion breakers” is that often the virtual objects in the VE do not behave as one would expect in a real world. Thus, it is important to develop appropriate feedback strategies and techniques for direct interaction with the virtual world. The feedback strategies and interaction techniques depend highly on the application requirements, the environment, computational techniques used for collision response and behaviors associated with the avatars. Some of the well known approaches include color coding of colliding objects or adjusting their position so that there is no contact. If the user in the VE has no sense of touch on contact with the virtual objects, this often results in a sensory conflict.

  We propose to investigate techniques that give users more control over the VE and takes into account environmental constraints like the walls, ceiling or gravity. We plan to interact closely with Dr. Templeman and other researchers at NRL to exchange our results and collaborate on the design of appropriate interaction techniques. This will also provide the base to further improve our computational models.

  We also believe that force display from wearable haptics will be essential in several scenarios (e.g. moving against the wall) where the user cannot visualize the contacts or enhance the sense of immersion when manipulating objects in a VE. The proposed research can be potentially integrated with wearable haptics to generate a better haptic response (to be described in Section 4.5). We request additional support as an optional task to integrate the use of wearable haptics, which requires specialized optimization for it to achieve the desired performance.

  Another feedback alternative to virtual contacts is auditory display. It involves appropriate generation of sound and rendering it based on physical interaction in a complex environment. Many academic and industrial research groups have developed techniques for acoustic simulation and we will investigate their effectiveness as a feedback strategy.
4.4 Evaluation
We will assess the effectiveness of alternative interaction techniques developed in the context of mobile activities (e.g. walking, running or maneuvering through a new environment). We hope to work closely with researchers at NRL and utilize their unique experience in designing interaction techniques based on principles of human perception and motor control. Our goal is to evaluate if the dynamics and kinematics constraints imposed provide a satisfactory interaction with the VEs. Based on user studies, we will refine and modify our designs of physically-based interface with the VE accordingly.

4.5 Wearable Haptics
The proposed research is interwined with our research interests on haptic display. We have been focusing on contact force and torque display at KHz rates for using desktop 3-DoF (degree of freedom) and 6-DoF haptic devices. We have currently integrated our initial algorithm with a 6-DoF PHANToM to feel the mechanical interaction of gears, force fields, and object manipulation in a multi-object dynamic scene. The preliminary results are very encouraging. Our research can be potentially integrated with a glove-like force feedback device, given some specialization and optimization. For more information, please refer to:

http://www.cs.unc.edu/~geom/6DHaptics/

Given our experience on haptic display and the anticipated results in the proposed research project, we can also develop the required algorithms and software to support wearable haptic devices. With the additional support, we can continue along our current research direction and collaborate with the industry, NRL and/or other Navy organizations to investigate the design of wearable haptic devices and enabling software systems for real-time interaction in a training VE.

5 Significance to Navy/Marine Corps & Anticipated Benefits
The proposed research is motivated by the need to improve the interaction with a computer generated virtual environment. It will complement and enhance the research on Mobility Interface Project at NRL by providing the computational methods for incorporating virtual contacts into the locomotion simulator. Furthermore, the underlying techniques can also provide the algorithms, software and system support for wearable haptic devices. The basic principles of our approaches are not limited to training and mission rehearsal in VEs, but acquisition, testing and evaluation of weapon systems as well.

The proposed research is expected to lay the scientific foundation and empirical analysis for real-time physically-based mobile interaction with the VEs. The resulting algorithms and software system should enhance perceived realism as the user moves in the virtual environment and manipulates the virtual objects, and thereby providing a better sense of presence in an immersive virtual environment.

In addition to publishing and disseminating our research results at international conferences and archival journals, we will also provide our software systems to enable intuitive, realistic mobile interaction with the VEs for training and mission planning. This is one of the primary goals of both VIRTE/IVE programs at ONR.

6 Collaboration with NRL and other UNC Researchers
We will be integrating our research with related projects at UNC on interactive walkthrough of complex datasets, tracking, large displays and evaluating presence in virtual environments. UNC has one of the largest academic VR research programs and we collaborate closely on large projects. Our laboratory is equipped with state of the art equipment on display technologies, optical tracking and graphics systems. Furthermore, we have a long tradition of working with collaborators in other departments at UNC, researchers in industrial, DoD/DoE labs and commercial vendors.

The algorithms and software systems developed will be integrated into the Locomotion Simulator developed by Dr. Templeman’s group at NRL. While we plan to conduct some preliminary user studies at UNC to evaluate alternative feedback techniques for real-time interactions, we will rely on the expertise of our collaborators at NRL to design interaction modes that offer a consistent, intuitively controllable interface with the Locomotion simulator. This will include analyzing how virtual locomotion and virtual contacts interact with each other.

7 Qualifications/Experience of Key Personnel
Prof. Ming C. Lin received her B.S., M.S., Ph.D. degrees in Electrical Engineering and Computer Science in 1988, 1991, 1993 respectively from the University of California, Berkeley. She is currently an assistant (associate effective Jan. 2001) professor in the Computer Science Department at the University of North Carolina (UNC), Chapel Hill. Prior to joining UNC, she was an assistant professor in the Computer Science Department at both Naval Postgraduate School and North Carolina A&T State University, and a Program Manager at the U.S. Army Research Office. She received the NSF Young Faculty Career Award in 1995, Honda Research Initiation Award in 1997, and IBM/UNC Junior Faculty Award in 1999.
Her research interests include real-time 3D graphics for virtual environments, physically-based modeling, geometric computing, and robotics. She has published over 50 refereed articles (see \url{http://www.cs.unc.edu/~lin/}) in top international conferences and journals. Most of her publications are in the area of physically-based modeling and interaction, with focus on collision detection, contact determination and response. She has served as a conference chair, program committee and editor for many leading conferences and journals on virtual reality, computer graphics, robotics, and computational geometry. She is currently leading a team of 7 Ph.D. students and 3 M.S. students in the area of Geometric and Physically-Based Modeling and Interaction with Virtual Environments. She has been frequently invited to lecture at the annual Computer Game Developer’s Conference and other meetings.

Prof. Dinesh Manocha is currently an associate (full effective Jan. 2001) professor of computer science at the University of North Carolina at Chapel Hill. He received his B.Tech. degree in computer science and engineering from the Indian Institute of Technology, Delhi in 1987; M.S. and Ph.D. in computer science at the University of California at Berkeley in 1990 and 1992, respectively. He received Alfred and Chella D. Moore fellowship and IBM graduate fellowship in 1988 and 1991, respectively, and a Junior Faculty Award in 1992. He was selected an Alfred P. Sloan Research Fellow, received NSF Career Award in 1995 and Office of Naval Research Young Investigator Award in 1997, and Hettleman Prize for scholarly achievement at UNC Chapel Hill in 1998.

His research interests include interactive computer graphics, geometric and solid modeling, virtual environments, physically-based modeling, and scientific computation. His research has been sponsored by DARPA, NSF, ARO, ONR, Sloan Foundation, Intel, Ford and Honda. He has published more than 100 papers (see \url{http://www.cs.unc.edu/~dm}) in leading conferences and journals on computer graphics, geometric and solid modeling, robotics, symbolic and numeric computation, virtual reality, molecular modeling and computational geometry. He has served as a program chair, committee member and editors for many leading conferences and journals on virtual reality, computer graphics, computational geometry, geometric and solid modeling. He is the co-leader of the Geometric Computing Group and is the PI of our Walkthrough & Massive Model Rendering and Interaction Project.

**Technology Transition:** Over the years we have established strong relationships with several research laboratories and commercial vendors involved in developing technology for contact computation, simulation and virtual environments. More than 35 commercial vendors have licensed our technology. These include Kawasaki (one of the major developers of robots in the world), Intel, Sony, Ford, ADAC Lab (has the largest world share of Magnetic Resonance Imaging market), Transom (now part of Engineering Animation), Division, Prosolvia, Knowledge Revolution (now part of the MSC, a world’s leading company on simulation), Mechanical Dynamics Inc., Boeing (McDonnell Douglas), Holometric, Amada etc. Many scientists at research labs and academia (including Sandia National Laboratory, MIT, CMU, Stanford, UPenn, Rice, Brown, CalTech, University of Washington, University of Maryland, etc.) across the world have also used our algorithms and systems. The applications range from underwater simulation, CAD/CAM design, path planning of deformable plates, real-time 3D interaction, human articulation, simulation for missile testing, haptics and many other VR applications. In addition to interaction technologies, we have also collaborated closely with a number of industrial and DOD labs on interactive walk-throughs of very large datasets. These include Electric Boat Division of General Dynamics, Newport News Shipbuilding, Army Research Labs at Aberdeen Proving Ground, Engineering Animation, ABB Engineering etc.

## 8 Proposed Budget & Justification

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**Justification:** For each of the subtasks (collision detection, contact response and interface), we request 1 month of support for Prof. Ming Lin and 1/2 month of support for Prof. Dinesh Manocha. The evaluation subtask requires 1/2 month of support for Prof. Mary Whitton for Year 2 and Year 3. Prof. Ming Lin will also be involved in the design and analysis of the experiments for evaluation of various interface alternatives. However, due to the budgetary constraints, she will not ask any additional support for these tasks. The entire research project requests 2 Research Assistants (RAs) for Year 1 and 3 RAs for Year 2 and Year 3. The requested funds also include travel support to visit NRL and present papers at leading conferences in computer graphics and virtual environments. The total budget required to conduct the proposed research is $645K. However, the University will provide $45K in matching fund for personnel support and minor equipment purchasing. Therefore, we are only requesting $600K over 3 years. We also include an optional support of $165K for extending the proposed research and integrated it with wearable haptic devices to provide even more natural, high-quality interaction with the VE.