

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
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1. REPORT DATE (DD-MM-YYYY) 16-09-2008		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 1-Sep-2002 - 31-Aug-2007	
4. TITLE AND SUBTITLE Final Report for ARO Grant: " Handling Massive Models: Representation, Real-Time Display and Interaction"			5a. CONTRACT NUMBER DAAD19-02-1-0390		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 611102		
6. AUTHORS Dinesh Manocha, Ming C. Lin			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of North Carolina - Chapel Hill Office of Sponsored Research 104 Airport Drive, Suite 2200, CB 1350 Chapel Hill, NC 27599 -1350			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 43066-MA.1		
12. DISTRIBUTION AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT See attachment					
15. SUBJECT TERMS massive models, interactive simulation and visualization, Computer generated forces					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Dinesh Manocha
a. REPORT UU	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER 919-962-1749

**Report Title**

Final Report for ARO Grant:  
" Handling Massive Models: Representation, Real-Time Display  
and Interaction"

**ABSTRACT**

See attachment

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**List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:**

**(a) Papers published in peer-reviewed journals (N/A for none)**

Number of Papers published in peer-reviewed journals: 19.00

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**(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)**

Number of Papers published in non peer-reviewed journals: 11.00

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**(c) Presentations**

Number of Presentations: 6.00

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**Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 8

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**Peer-Reviewed Conference Proceeding publications (other than abstracts):**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 33

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**(d) Manuscripts**

Number of Manuscripts: 0.00

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**Number of Inventions:**

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**Graduate Students**

<b>NAME</b>	<b><u>PERCENT_SUPPORTED</u></b>
See Attachment	
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	1

**Names of Post Doctorates**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

**Names of Faculty Supported**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Ming C Lin	0.10	No
Dinesh Manocha	0.10	No
<b>FTE Equivalent:</b>	<b>0.20</b>	
<b>Total Number:</b>	<b>2</b>	

**Names of Under Graduate students supported**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

**Student Metrics**

This section only applies to graduating undergraduates supported by this agreement in this reporting period

- The number of undergraduates funded by this agreement who graduated during this period: ..... 1.00
- The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00
- The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00
- Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 1.00
- Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00
- The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ..... 0.00
- The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:..... 0.00

**Names of Personnel receiving masters degrees**

<u>NAME</u>
<b>Total Number:</b>

**Names of personnel receiving PHDs**

<u>NAME</u>
See Attachment
<b>Total Number:</b>

**Names of other research staff**

NAME

PERCENT SUPPORTED

**FTE Equivalent:**

**Total Number:**

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**Sub Contractors (DD882)**

**Inventions (DD882)**

PROJECT TITLE: Handling Massive Models: Representation, Real-Time Display and Interaction

INTERIM PROJECT REPORT

Contract Number: DAAD19-02-1-0390

Name(s) of Principal Investigator(s): Dinesh Manocha  
Ming C. Lin

Name of Organization: University of N. Carolina at Chapel Hill

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## 1. Technical Objectives and Motivation

We propose to address some fundamental research issues in handling and visualizing massive models, composed of millions of primitives. These include efficient representations, interactive display and real-time interaction. These models arise in many applications, including computer-aided design, simulation-based design, lethality and vulnerability analysis, medical simulation, surgical training and scientific visualization.

Our goal is to develop efficient algorithms and systems, and demonstrate their performance on massive environments composed of millions of primitives. The set of research problems that we worked on included:

1. Hierarchical and multiresolution representations of models for fast display.
2. Interactive display of large polygonal, sculptured, sampled or solid models on current graphics systems.
3. Interactive proximity queries and collision response between rigid and deformable models in a large, complex environment.
4. Real-time interaction with the virtual world.

## 2. Approach

We used a number of techniques from algebraic geometry, approximation theory, computational geometry, numerical analysis, computer-aided geometric

design and computer graphics to investigate the underlying mathematical concepts and to develop more efficient and robust geometric algorithms. This included algorithms and systems for representing massive models, rendering them at interactive rates, collision detection and interaction.

### 3. Significant Accomplishments

The PI and his student developed novel algorithms for boundary computation, model simplification, fast display and interference detection, model representation, ray tracing, physical simulation and multiresolution techniques

The resulting algorithms and systems have been applied to a number of applications and the technology has been transferred to a number of research and DOD labs as well as commercial vendors.

### 4. Cooperation with and Technology Transfer to Army Laboratories and Other Organizations

A: Army Research Labs, Aberdeen, MD: The PI and his graduate students are integrating our solid modeler, BOOLE, with the BRL-CAD solid modeling system developed by researchers at Army Research Labs, Aberdeen. BRL-CAD is primarily used for vulnerability analysis at ARL and it has more than \$1600\$ users worldwide. BOOLE has been used for performing boolean operations on curved surfaces.

B: Collision Detection System: More than 15000 users all over the world have copied the source code of the I-COLLIDE, V-COLLIDE, SWIFT, SWIFT++, DeformCD and PQP collision detection systems. Some of the prominent users are at Sandia National Labs, Lockheed Martin, Ford Motor Company, Division, Engineering Animation, Army Research Labs, Evans and Sutherland, etc. More than 40 commercial organizations have licensed these technologies.

C: We have been collaborating closely with RDECOM STTC at Orlando, FL on incorporating our GPU-based technologies and new algorithms for dynamic terrains into OneSAF and Computer-Generated Force Systems. Earlier some of our algorithms for LOS and route planning were incorporated into OOS. We also worked with ARA, SAIC and Future Combat Systems (FCS) to incorporate our technologies for dynamic datasets and dynamic terrains into OneSAF. We have demonstrated these technologies at PEO-STRI, I/ITSEC 2007 and Capitol Hill demonstration in February 2007.

### 5. Publications in Refereed Journals and Conference Proceedings

V. Kwatra, D. Adalsteinsson, T. Kim, N. Kwatra, M. Carlson, and M. Lin, "Texturing Fluids", IEEE Trans. on Visualization and Computer Graphics, p. , vol. , (2007). Accepted,

T. Kim and M. Lin, ""Stable Advection-Reaction-Diffusion with Arbitrary Anisotropy"", Journal of Computer Animation and Virtual World, Special Issue, p. , vol. , (2007). Published,

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T. Kim, J. Sewall, A. Sud, and M. Lin, ""Fast Simulation of Laplacian Growth"", IEEE Computer Graphics and Applications, p. , vol. , (2007). Published,

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Y. Kim, S. Redon, M. Lin, D. Manocha, and J. Templeman, ""Interactive Continuous Collision Detection using Swept Volume for Avatars", Presence, p. , vol. 16, (2007). Published,

N. Raghuvanshi and M. Lin, ""Physically-based Sound Synthesis for Large-Scale Virtual Environments"", IEEE Computer Graphics and Applications, p. 14, vol. 27, (2007). Published,

J. Wendt, W. Baxter, I. Oguz, and M. Lin, ""Finite-Volume Flow Simulations in Arbitrary Domains"", Graphical Models, p. 19, vol. 69, (2007). Published,

M. A. Otaduy and M. C. Lin, ""A Haptic Rendering Pipeline for Stable and Responsive Six-Degree-of-Freedom Manipulation", IEEE Trans. on Robotics, p. 751f, vol. 22, (2006). Published,

S. Redon and M. Lin, ""An Efficient, Error-Bounded Approximation Algorithm for Simulating Quasi-Statics of Complex Linkages"", Computer Aided Design (Invited submission), p. 300, vol. 38, (2006). Published,

N. Govindaraju, M. Lin, and D. Manocha, ""Efficient Collision Culling among Deformable Objects using Graphics Processors"", Presence, p. 62, vol. 15, (2006). Published,

N. Govindaraju, M. Lin, and D. Manocha, ""Fast and Reliable Collision Culling using Graphics Hardware"", IEEE Trans on Visualization and Computer Graphics (invited paper), p. 143, vol. 12, (2006). Published,

S. Redon and M. Lin, ""A Fast Method for Local Penetration Depth Computation"", Journal of Graphical Tools, p. 37, vol. 11, (2006). Published,

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Gokul Varadhan, Dinesh Manocha, "Star-shaped Roadmaps - A Deterministic Sampling Approach for Complete Motion Planning", International Journal of Robotics Research, p. , vol. , (2007). Published,

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Sean Curtis, Rasmus Tamstorf, Dinesh Manocha, "Fast Collision Detection for Deformable Models using Representative-Triangles", Symposium on Interactive 3D Graphics and Games, p. , vol. , (2008). Published,

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Min Tang, Sean Curtis, Sung-Eui Yoon, Dinesh Manocha, "Interactive Continuous Collision Detection between Deformable Models using Connectivity-Based Culling", Proceedings of SPM08 (ACM Solid and Physical Modeling Symposium), p. 25, vol. , (2008). Published,

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Christian Lauterbach, Sung-Eui Yoon, Min Tang, Dinesh Manocha, "ReduceM: Interactive and Memory Efficient Ray Tracing of Large Models", Computer Graphics Forum (Proc. EGSR 2008), Vol. 27 Issue 3, 2008, p. , vol. 27, (2008). Published,

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Rahul Narain, Vivek Kwatra, Huai-Ping Lee, Theodore Kim, Mark Carlson, Ming C. Lin, "Feature-guided Dynamic Texture Synthesis on Continuous Flows", Eurographics Symposium on Rendering, p. , vol. , (2007). Published,

Nico Galoppo, Serhat Tekin, Miguel A. Otaduy, Markus Gross, Ming C. Lin, "Haptic Rendering of High-Resolution Deformable Objects", 12th International Conference on Human-Computer Interaction, Beijing, China, p. , vol. , (2007). Published,

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Sung-Eui Yoon, Sean Curtis, Dinesh Manocha, "Ray Tracing Dynamic Scenes using Selective Restructuring", Eurographics Symposium on Rendering, p. , vol. , (2007). Published,

Christian Lauterbach, Sung-Eui Yoon, Dinesh Manocha, "Ray-Strips: A Compact Mesh Representation for Interactive Ray Tracing", IEEE Symposium on Interactive Ray Tracing, p. , vol. , (2007). Published,

Russell Gayle, Avneesh Sud, Ming C. Lin, Dinesh Manocha, "Reactive Deforming Roadmaps: Motion Planning of Multiple Robots in Dynamic Environments", IEEE/RSJ International Conference On Intelligent Robots and Systems (IROS), p. , vol. , (2007). Published,

David Kasik, Dinesh Manocha, Philipp Slusallek, "Real-Time Interaction with Complex Models", IEEE Computer Graphics and Applications, p. , vol. , (2007). Published,

Avneesh Sud, Russell Gayle, Stephen Guy, Erik Andersen, Ming C. Lin, Dinesh Manocha, "Real-time Navigation of Independent Agents Using Adaptive Roadmaps", Proc. ACM Symposium VRST, p. , vol. , (2007). Published,

Avneesh Sud, Erik Andersen, Sean Curtis, Ming C. Lin, Dinesh Manocha, "Real-time Path Planning for Virtual Agents in Dynamic Environments", IEEE Virtual Reality, p. , vol. , (2007). Published,

Nikunj Raghuvanshi, Christian Lauterbach, Anish Chandak, Dinesh Manocha, Ming C. Lin, "Real-time sound synthesis and propagation for games", Communications of ACM. Special Issue on Games, p. , vol. , (2007). Published,

Nico Galoppo, Miguel A. Otaduy, Serhat Tekin, Markus Gross, Ming C. Lin, "Soft Articulated Characters with Fast Contact Handling", ACM SIGGRAPH/Eurographics Conference, Vienna, p. , vol. , (2007). Published,

Avneesh Sud, Naga K. Govindaraju, Russell Gayle, Erik Andersen, Dinesh Manocha, "Surface Distance Maps", Graphics Interface, p. , vol. , (2007). Published,

Miguel A. Otaduy and Ming C. Lin, ""High-Fidelity Haptic Rendering"", (2006). Book, Published  
Bibliography: Morgan-Claypool

Nico Galoppo, M. Otaduy, S. Tekin, M. Gross, and M. Lin, "Fast Contact Dynamics for Deformable Articulated Characters", (2007). Proc. of Eurographics, Accepted

R. Gayle, A. Sud, M. Lin, and D. Manocha, "Reactive Deformation Roadmaps: Motion Planning of Multiple Robots in Dynamic Environments", (2007). Proc. of IROS 2007, Published

J. Sewall, P. Mecklenburg, S. Mitran, and M. Lin, "Fast Flow Simulation Using Residual Distribution Schemes", (2007). , Published  
Collection: Proc. of Eurographics Workshop on Natural Phenomena

R. Narain, V. Kwatra, T. Kim, H. Lee, M. Carlson, and M. Lin, "Feature-Guided Dynamic Texture Synthesis on Continuous Flows", (2007). ,  
Collection: Proc. of Eurographics Symposium on Rendering

N. Galoppo, M. Otaduy, S. Tekin, M. Gross, and M. Lin, "Haptic Rendering Using Dynamic Deformation Textures", (2007). , Published  
Bibliography: 10 pages

I. Kabul, R. Gayle, and M. Lin, "Cable Route Planning in Complex Environments Using Constrained Sampling", (2007). , Published  
Collection: Proc. ACM Symposium on Solid and Physical Modeling and Applications

R. Gayle, M. Lin, and D. Manocha, "Efficient Motion Planning of Highly Articulated Chains using Physics-based Sampling", (2007). ,  
Collection: Proc. of IEEE International Conference on Robotics and Automotion

A. Sud, E. Andersen, S. Curtis, M. Lin, and D. Manocha, "Real-time Path Planning for Virtual Agents in Dynamic Environments", (2007).  
Collection: Proc. of IEEE Virtual Reality 2007

T. Kim, D. Adalsteinsson and M. Lin, "Modeling Ice Dynamics As a Thin-Film Stefan Problem", (2006). Cover Image Article, Published  
Collection: Proc. of ACM SIGGRAPH/Eurographics Symposium on Computer Animation

N. Galoppo, M. Otaduy, P. Mecklenburg, M. Gross, and M. Lin, "Fast Simulation of Deformable Models in Contact Using Dynamic Deformation Textures", (2006). , Published  
Collection: Proc. of ACM SIGGRAPH/Eurographics Symposium on Computer Animation

R. Gayle, M. Lin, and D. Manocha, "Adaptive Dynamics with Efficient Contact Handling for Articulated Robots", (2006). , Published  
Collection: Proc. of Robotics: Science and System

N. Govindaraju, I. Kabul, M. C. Lin, and D. Manocha, "Fast Continuous Collision Detection among Deformable Models using Graphics Processor", (2006). , Published  
Collection: Proc. of Eurographics Symposium on Virtual Environments

N. Raghuvanshi and M. Lin, "Interactive Sound Synthesis for Large Scale Environments", (2006). Cover Image Article, Published  
Collection: Proc. of ACM Symposium on Interactive 3D Graphics and Games

K. Ward, N. Galoppo, and M. Lin, "A Simulation-based VR System for Interactive Hairstyling", (2006). (Short Paper), Published  
Collection: Proc. of IEEE Virtual Reality 2006

J. Schoner, M. Falvo, S. Lord, R. Taylor II, and M. Lin, "Interactive Simulation of Fibrin Fibers in Virtual Environments", (2006). , Published  
Collection: Proc. of IEEE Virtual Reality 2006

M.C. Lin, "Collision and Proximity Queries", (2007).  
Handbook/Encyclopedia, Accepted  
Editor(s): Benjamin Walsh  
Collection: Encyclopedia of Computer Science and Engineering

## 6. HONORS and AWARDS

Best Paper Award, ACM Solid and Physical Modeling (2003)  
Best Paper Award, IEEE VR (2005)  
ACM SIGMOD Sorting Benchmark Award (2006)  
Phi Delta Theta/Mason Distinguished Professorship awarded to Dinesh Manocha (2006)  
Beverly Long Distinguished Professorship awarded to Ming C. Lin (2007)

## 7. Papers or reports in non-refereed publications

## 8. Books or book chapters published

See the publications above.

## 9. Patent/Inventions filed or granted

## 10. Number of graduate and undergraduate students supported by gender and by minority group

See the list below

11. Number of MS and Ph.D. degrees awarded to students working through the grant and their current employment status and employers

Bill Baxter, Ph.D. 2004 (male)  
Miguel Otaduy, Ph.D. 2004 (male)  
Kelly Ward, Ph.D. 2005 (female)  
Naga Govindaraju, Ph.D. 2004 (male)  
Gokul Varadhan, Ph.D. 2005 (male)  
Ted Kim, Ph.D., 2006 (male)  
Avneesh Sud, Ph.D. 2006 (male)  
Brandon Lloyd, Ph.D. 2007 (male)