DIMACS Center
Rutgers University

Workshop on Computer Aided Design and Manufacturing

Final Report

October 2004

Ia. Participants from the program

Participants:

PI: Fred Roberts

Workshop Organizers:

Deba Dutta, University of Michigan, Ann Arbor
Ravi Janardan, University of Minnesota, Minneapolis
Michiel Smid, Carleton University

Ib. Participating Organizations

Telcordia Technologies: Collaborative Research
Partner organization of DIMACS. Individuals from the organization participated in the program planning.

AT&T Labs - Research: Collaborative Research
Partner organization of DIMACS. Individuals from the organization participated in the program planning and workshop.

NEC Laboratories America: Collaborative Research
Partner organization of DIMACS. Individuals from the organization participated in the program planning.

Lucent Technologies, Bell Labs: Collaborative Research
Partner organization of DIMACS. Individuals from the organization participated in the program planning.

Princeton University: Collaborative Research
Partner organization of DIMACS. Individuals from the organization participated in the program planning.

Avaya Labs: Collaborative Research
Partner organization of DIMACS. Individuals from the organization participated in the program planning.

HP Labs: Collaborative Research
Partner organization of DIMACS. Individuals from the organization participated in the program planning.

IBM Research: Collaborative Research
Partner organization of DIMACS. Individuals from the organization participated in the program planning.

Microsoft Research: Collaborative Research
Partner organization of DIMACS. Individuals from the organization participated in the program planning.

1c. Other Collaborators

The project involved scientists from numerous institutions in numerous countries. The resulting collaborations also involved individuals from many institutions in many countries.

II. Project Activities

DIMACS Workshop on Computer Aided Design and Manufacturing was held on October 7 - 9, 2003 at the DIMACS Center, CoRE Building, Rutgers University, Piscataway, NJ. There were 54 participants, including 25 faculty, 6 researchers, 19 students, 2 post-doctoral fellows, and 2 others.

Computer-Aided Design and Manufacturing (CAD/CAM) is concerned with all aspects of the process of designing, prototyping, manufacturing, inspecting, and maintaining complex geometric objects under computer control. As such, there is a natural synergy between this field and Computational Geometry (CG), which involves the design, analysis, implementation, and testing of efficient algorithms and data representation techniques for geometric entities such as points, polygons, polyhedra, curves, and surfaces. On the one hand, CG can bring about significant performance improvements in CAD/CAM, while, on the other hand, CAD/CAM can be a rich source of interesting new problems that provide new impetus to research in CG. Indeed, such two-way interaction has already been witnessed in recent years in areas such as numerically-controlled machining, casting and injection molding, rapid prototyping and layered manufacturing, metrology, and mechanism/linkage design, to name just a few.

The purpose of this workshop was to further promote this interaction by bringing together researchers from both sides of the aisle to assess the current state of work at the interface of the two fields, to identify research needs, and to establish directions for collaborative future work. There was a combination of invited talks and contributed papers.

Topics addressed included, but were not limited to, geometric aspects of manufacturing processes (from traditional machining to layered manufacturing to nanoscale manufacturing), process planning and control, rapid prototyping technologies, computational metrology and tolerancing, geometric problems in mechanism design, geometric constraint systems, geometric modeling related to manufacturing, computer vision and robotics related to manufacturing, and geometric issues in standards development.

The workshop began with a keynote lecture on the elements of computational metrology by Vijay Srinivasan of IBM Corporation and Columbia University. Srinivasan explained that the past decade has seen the emergence of computational metrology as a separate discipline. He defined it as the field that deals with fitting and filtering discrete geometric data that are obtained by measurements made on manufactured parts. Computational metrology plays an important role

in the manufacturing industry. A manufactured part may be measured to characterize the manufacturing process that produced it or to assess the conformance of the part to designer-specified tolerances. In either case, measurements are made on the surface of the part and the measured data are then reduced to a few numbers or attributes by increasingly sophisticated computational techniques. Srinivasan stated that there are two basic facts about manufacturing and measurement. First, all manufacturing processes are inherently imprecise and produce parts that vary. Second, no measurement can be absolutely accurate and with every measurement there is some finite uncertainty about the measured attribute or measured value. To model reality more closely, both axioms should be considered operative. With these preliminaries, Srinivasan then proceeded to address fitting and filtering problems. Fitting is the task of associating ideal geometric forms to non-ideal forms (such as, for example, discrete set of points sampled on a manufactured surface). For example, an engineer may want to find the smallest cylinder (that is, a cylinder with the smallest diameter) that encloses a set of points in space because it gives him or her some quantitative information about how a part will fit in an assembly. This can be easily posed as a minimization problem, but computational methods to solve this problem are not simple. Filtering is the task of obtaining scale-dependent information from measured data. The computational scheme used for filtering is one of convolution. Srinivasan believes that recent developments in wavelets seem to indicate that the scale-dependent information can be processed more effectively using wavelet filters.

Nancy Amato, Department of Computer Science, Texas A&M University, presented her joint work with O. Burchan Bayazit, Jyh-Ming Lien, and Guang Song, on the applications of randomized motion planning in intelligent CAD. Motion planning arises in a diverse set of application domains such as robotics, computer animation (digital actors), intelligent CAD (virtual prototyping and training), and even computational biology (protein folding or drug design). As one example, a motion planner could be used to find a part removal path in a mechanical assembly. This path could be archived and used in a VR training system for mechanics, or as on-line aid during actual task execution in a mixed reality environment. A typical mechanical assembly consisting of both rigid and flexible parts arranged in a compact design would yield a very difficult, high degree of freedom motion planning problem. Amato said that, surprisingly, a single class of planners, called probabilistic roadmap methods (PRMs), have proven effective on challenging motion planning problems from all domains. She described the PRM framework and give an overview of several PRM variants developed in the research group that are relevant to CAD, including planners for systems containing foldable objects, deformable objects, or closed kinematic chains. For virtual prototyping scenarios, she presented preliminary results of a planner for disassembly sequencing and showed that in some cases a hybrid system incorporating both an automatic planner and haptic user input can solve more difficult problems faster than a fully automatic system.

Yuan-Shin Lee, Department of Industrial Engineering, North Carolina State University, focused on the analytical and geometric processing technologies for design and manufacturing of complex surfaces. He discussed research on topics involving interesting geometry and dealing with real industrial problems with a close connection to CAD/CAM and multi-axis NC machining, sculptured surface machining (SSM) and shape interrogation, high speed machining (HSM) and NC tool path optimization, rapid prototyping of complex surfaces, and virtual sculpting and haptic rendering of complex surfaces.

Ram D. Sriram, Design and Process Group in the Manufacturing Systems Integration Division at the National Institute of Standards and Technology, discussed issues in product modeling that go beyond geometry. Sriram observed that the early part of this millennium has witnessed the emergence of an Internet-based engineering marketplace, where engineers, designers, and manufacturers from small and large companies are collaborating through the Internet to participate in various product development and marketing activities. He forecast that this will be further enhanced by the next generation manufacturing environment, which will consist of a network of engineering applications, where state of the art multi-media tools and techniques will enhance closer collaboration between geographically distributed applications, virtual reality tools will allow visualization and simulation in a synthetic environment, and information exchange standards will facilitate seamless interoperation of heterogeneous applications. To support such an environment, a product representation scheme that goes beyond the geometric-centric approach of traditional CAD systems is needed. Sriram described two major efforts over the last two decades to achieve such a product representation scheme.

The program of talks was as follows:

Elements of computational metrology
Vijay Srinivasan, IBM Research, New York, and Columbia University

Geometric tolerance analysis methods for imperfect-form assemblies
Scott Pierce, M.I. Technologies, Georgia, and Georgia Tech.

Outstanding problems in geometric constraint solving for CAD
Meera Sitharaman, University of Florida

Immobilizing chains of hinged polygons
Frank van der Stappen, Utrecht Univ., the Netherlands

On computing all immobilizing grasps of a simple polygon with few contacts
Jae-Sook Cheong, Utrecht Univ., the Netherlands

Applications of randomized motion planning in intelligent CAD
Nancy Amato, Texas A&M Univ.

Why cutting path planning is different from robotic planning
Sanjay Sarma, MIT

Computational geometry in design and manufacturing of free-form surfaces
Yuan-Shin Lee, North Carolina State University

Zigzag toolpath generation for sculptured surface finishing
Debananda Misra, GE Global Research Center, India

Multiple clothing part placement

Victor Milenkovic, University of Miami

Fast discretized algorithms for arrangement computations
Dinesh Manocha, University of North Carolina

Applications of computational topology of swept volumes
Denis Blackmore, New Jersey Institute of Technology

Mass properties of the union of millions of polyhedra
Wm. Randolph Franklin, Rennsselaer Polytechnic Institute

Stochastic geometry for bio-medical CAD
William Regli, Drexel University

Algebraic and geometric approximation of waves as Voronoi Diagrams in time
Tony Woo, University of Washington

Beyond geometry: Issues in product modeling
Ram Sriram, National Institute of Standards and Technology

Theory of design
Michael Leyton, DIMACS

Geometric algorithms for Layered Manufacturing: Part I
Michiel Smid, Carleton Univ., Canada

Geometric algorithms for Layered Manufacturing: Part II
Ravi Janardan, University of Minnesota

Software error compensation of rapid prototyping
Sanjay Joshi, Pennsylvania State University

Computing shapes and their features from point samples
Tamal Dey, The Ohio State University

Reconstruction of a 3D object from a single freehand sketch
Hod Lipson, Cornell University

How to pick the right shape matching algorithm for your CAD data
William Regli, Drexel University

Scale-space representations and their applications to 3D matching of solid models
Ali Shokoufandeh, Drexel University

Geometric containment analysis for rotational parts
Satyandra Gupta, University of Maryland

Computational Line Geometry and Manufacturing
Bahram Ravani, University of California, Davis

How to compute exactly and efficiently with quadric surfaces
Nicola Wolpert, Max-Planck-Institut fuer Informatik, Saarbruecken, Germany

Subdivision-based representations for surface styling and design
Ioana Boier-Martin, IBM Research, New York

Sparseness in the implicit equation of rational parametric curves and surfaces
Ilias Kotsireas, Wilfrid Laurier University, Canada

Detecting degenerate object configurations with the rational univariate reduction
John Keyser, Texas A&M University

III. Project Findings

This workshop has already led to a book, "Geometric and Algorithmic Aspects of Computer-Aided Design and Manufacturing", which is to appear in the DIMACS book series published by the American Mathematical Society.

Tamar Dey explains in his article, "Sample based geometric modeling," in the workshop volume that there is a new paradigm emerging for digital modeling of physical objects from sample points due to recent advances in scanning technology. Researchers are investigating many of the traditional modeling problems in this new setting. Dey names this new area *sample based geometric modeling*. Dey demonstrates this new modeling paradigm using three basic problems, namely surface reconstruction, medial axis approximation, and shape segmentation. Dey and his collaborators developed algorithms for these three problems, which are described in the article.

The problem of switching from a rational parametric representation to an implicit, or algebraic, representation of a curve, surface, or hypersurface lies at the heart of several algorithms in computer-aided design. Ilias Kotsireas, Wilfrid Laurier University, Canada, and his collaborators have improved three implicitization algorithms (based on interpolation). More specifically, they use information on the support and certain coefficients of the toric (or sparse) resultant. The computed support of the implicit equation depends on the sparseness of the parametric expressions and is much tighter than the one predicted by degree arguments. Their Maple implementation illustrates many cases in which they obtain the exact support. Since the workshop, they have continued to improve/optimize their method of exploiting sparse structure in the problem of implicitization.

Vijay (Srini) Srinivasan, WW PLM Research, Standards, and Academic Programs, described the following outcome. "A preprint of the article ("Elements of Computational Metrology" written for the DIMACS workshop volume) was widely circulated in the ASME (American Society of Mechanical Engineers) and ISO standards committees. Parts of it will be included in the

upcoming standards from these US National and International organizations. These are the classifications of fitting problems for product conformance assessment and manufacturing process characterization."

IV. Project Training/Development

The workshop offered some 19 graduate students from Rutgers University, Drexel University, Pennsylvania State University, University of Maryland, New Jersey Institute of Technology, and University of Missouri-Rolla the opportunity to participate in an interdisciplinary workshop with senior researchers.

In addition, participants in the workshop took back to their home institutions project ideas for both student research and courses. Denis Blackmore, New Jersey Institute of Technology, said the following: "My interactions at your Workshop helped me to formulate an interesting set of problems that will form the core of the dissertation by my student Yuriy Mileyko (which should prove instrumental in starting him off on his professional career) and have led to invitations to a number of speakers in the field of computer aided design and manufacturing, including Tom Peters of UConn, in the Mathematical Sciences Colloquium series at New Jersey Institute of Technology (NJIT)."

He also said: "Your Workshop helped me to formulate theoretical questions and identify practical applications that have led to several interesting new, multidisciplinary research projects for me, and also provided me with a number of interesting new projects for the graduate students I am advising. It also stimulated my current discussions with key members of the College of Computing Sciences at NJIT about the development of a research group in the area, and a number of relevant interdisciplinary courses in the area of computer aided design and manufacturing."

V. Outreach Activities

VI. Papers/Books/Internet

Books

Geometric and Algorithmic Aspects of Computer-Aided Design and Manufacturing, Editors: Ravi Janardan, Michiel Smid, and Debasish Dutta, American Mathematical Society, DIMACS, to appear.

Internet

Main web site for the Workshop on Computer Aided Design and Manufacturing
http://dimacs.rutgers.edu/Workshops/CompAided/

Journal Articles

D. Blackmore and Y. Mileyko, "Analytical and homological interrogation of intersections," *Computer Aided Geometric Design*, submitted.

D. Blackmore, W. Regli, and Wei Sun, "Sweep modeling of bone structure," in preparation for submission to an appropriate biomedical engineering journal.

D. Blackmore and M.C. Leu, "New procedures for virtual sculpting and virtual surgery," in preparation for submission to *Computer Aided Design*)

VII. Other Products

Main web site for DIMACS 2002-2005 Special Focus on Computational Geometry and Applications
http://dimacs.rutgers.edu/SpecialYears/2002_CompGeom/

VIII. Contributions within Discipline

We ultimately expect exciting research results because of the many collaborations that were established and we expect these collaborations to flourish and be productive for years.

Nancy M. Amato, Parasol Lab, Department of Computer Science, Texas A&M University, had this to say. "I found this workshop to be very helpful in helping me learn about the breadth of research that is being performed on CAD/CAM. Due to the multidisciplinary nature of the problems, there is really no single source an interested researcher could go to educate themselves. Hence, I believe the workshop provided a valuable service by bringing together researchers who would otherwise never meet. Moreover, the workshop organizers did an excellent job in encouraging interaction - and indeed it was one of the most interactive of any workshop I have attended."

Tamal Dey reports, "This workshop motivated me to collect the results I and my co-authors have obtained in the last few years on sample based geometric modeling. This is useful since researchers in the related field of CAD/CAM benefits from such collections developed mainly in the area of computational geometry…. The workshop gathered people from areas of CAD/CAM, graphics, vision and computational geometry. The interdisciplinary interactions were helpful. For example, I got to know the needs for actual applications in CAD/CAM and I know that some people from solid modeling and vision got interested in my work related to geometric modeling."

Denis Blackmore, New Jersey Institute of Technology, reported on his collaboration with Tom Peters. "The Workshop actually played a role in the development of a strong new collaboration and the identification of at least one new problem area. To be more specific, my conversations with some of the Workshop participants led indirectly to a new and very promising collaboration of with Tom Peters of UConn., with whom I am developing a proposal on computational topology that we shall be submitting to the NSF. Discussions initiated at the Workshop led to two interesting problem areas - with a plethora of open problems - that I am currently pursuing: (1) How can handlebody decompositions of manifolds be effectively modeled using swept manifolds, and how can one develop effective programs for implementing such sweeping

procedures? (2) How can local homology calculations that are effectively computable be used to find and characterize intersections of computer rendered geometric objects?"

Finally, W. Randolph Franklin, ECSE Department, Rensselaer Polytechnic Institute, made these comments about DIMACS programs in general. "I have attended several DIMACS conferences because they are so valuable. Since they are within a few hours drive of so many universities, a large group of researchers can economically gather. They are also held relatively inexpensive for Europeans to attend, because of their location and timing. If you hold more, I will continue to come. Thank you for organizing them."

IX. Contributions -- other Disciplines

This was an inherently interdisciplinary project. Connections among computer science, mathematics, statistics, and other disciplines were brought to light. New collaborations among academic, industrial, and government researchers resulted.

Ravi Janardan, University of Minnesota, Minneapolis, reported, "In my own case, the main benefit has been learning about new research in geometric modeling for biomedical applications. I am now following up on several leads in this area."

Vijay (Srini) Srinivasan, WW PLM Research, Standards, and Academic Programs, described the following outcome. "Several industrial and academic researchers have launched investigations on the application of filtering algorithms I outlined in the article ("Elements of Computational Metrology" written for the DIMACS workshop volume). This includes a recent inquiry from Harley-Davidson on the morphological filters for assessment of ride quality based on road surface variation data."

W. Randolph Franklin, ECSE Department, Rensselaer Polytechnic Institute, commented, "The feedback from the audience at my presentation enabled me better to understand how my ideas fit in, and to refine both my research and the presentation. Those changes are incorporated both into my paper being published in a DIMACS volume, which gives implementation results, and in another paper presented at a SIAM Geometric Design conference, which may be published, giving theoretical analyses."

X. Contributions -- Human Resource Development

One of the key components of the workshop was the strong participation of students. There were 19 students from several academic institutions who attended the workshop. The workshop will have an ongoing influence on students and not just those who attended. Nancy M. Amato, Parasol Lab, Department of Computer Science, Texas A&M University, had this to say. "I have advised my students to study the work of some of the workshop attendees and we are currently working on some problems that were inspired either by talks presented at the workshop or from reading papers by workshop attendees and I expect that some publications will eventually result."

XI. Contributions to Resources for Research and Education

Vijay (Srini) Srinivasan, WW PLM Research, Standards, and Academic Programs, reports that “The article I wrote ("Elements of Computational Metrology") for the DIMACS-AMS volume is currently being used in my class at Columbia. It is the single major source of material for a graduate course, which focuses on computer-aided manufacturing issues - in this case computational issues in measurement of manufactured parts.”

Ilias Kotsireas, Wilfrid Laurier University, Canada, notes “I believe the DIMACS proceedings volume of the referred papers presented during the workshop, will be very useful for student training, when it appears.”

XII. Contributions Beyond Science and Engineering