Report on NSF Workshop on Manufacturing and Computational Geometry

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Abstract

This is a summary of the *NSF Workshop on Manufacturing and Computational Geometry*, held at the Courant Institute of Mathematical Sciences, New York University, on April 1–2, 1994. The meeting brought together about 30 participants from both the manufacturing and the computational geometry communities for the purposes of

- discussing current trends in the two communities,
- identifying areas of mutual interest, and
- proposing future joint activities.

1 Introduction

Recent geopolitical factors have led to a shift from defense-based industries to consumer-based production. Manufacturing has been recognized as a priority for US competitiveness in the new global economy. There have been recent initiatives on manufacturing, both at the Federal and various state levels. In this context, the workshop is timely and strategic.

One aspect of improving manufacturing is through an increased use of high technology at every level. This means that the manufacturing process must become more flexible and more automated. Traditionally, automation of a process often reduces its flexibility. But the goal of "flexible automation" seeks to combine both goals through manufacturing systems which are programmable and intelligent. This implies a high level of sophistication in manufacturing design. High level tools are essential in the design and prototyping of manufacturing. It involves many aspects of expertise, but an ubiquitous feature is the use of geometry. Geometry appears at two distinct levels: in the design of the manufacturing *process* as well as in the manufactured *products*.

The computational geometry (CG) community has been very active in developing many tools, both analytical and algorithmic, for geometric problems. Although much of this work has potential applications in manufacturing, the lack of interaction between the two communities meant that this potential is largely unrealized. Although we have notable examples of such interaction, there have also been many missed opportunities. The interaction will benefit both communities – manufacturing will become more aware of the available results in CG, and CG can direct attention to problems of manufacturing relevance.

Organization. The workshop was organized by a steering committee comprising David Dobkin, Harry Stephanou and the author. The technical program (see Appendix B) was organized around two sets of talks. On the first day, we heard general talks describing some relevant trends in current manufacturing and CG. On the second day, we heard from several experts concerning geometric issues in manufacturing.

The workshop was strategic rather than technical in nature. Thus the meeting was informal and technical talks were intended to provide context for interaction and discussion. One-page abstracts of the talks were pre-distributed. We divided the participants into three groups that met each day, after the talks. Their discussions were led by a group leader and recorded by a group scribe. Copies of a preliminary NRC report on Manufacturing and Information Technology [3] were distributed to participants for discussion. The final event of the workshop was a panel in which a representative from each group reported their findings.

2 Discussion Summary

The following summarizes the group discussions and panel presentations.

Geometry in Manufacturing. Geometry is truly ubiquitous in manufacturing. It should be emphasized that most of what we mean by "geometry" is "form geometry". There are higher geometric concepts that may become more important in the future. For instance, current geometric modeling systems deal exclusively with rigid solid shapes – but flexible material and nonrigid models are completely open. Ultimately, physical properties must come in. For instance, how do we model a huge propeller blade that deforms under its own weight? Presently, such physics are too difficult to model although we can sometimes substitute with "geometric operators", giving approximately the same effects.

While we may agree on what constitutes geometric concepts, the definition of "computational geometry" seems to have a more diverse interpretation. One view is that it is the study of the combinatorial complexity of algorithms for precisely-defined geometric problems. While this may correctly describe the dominant activity in a conference such as the *ACM Symposium on Computational Geometry*, it is clearly too narrow. No one seriously wishes to exclude from CG a variety of activities such as computer-aided design and modeling, finite element analysis and geometric issues in the computational sciences. The term "CG" is taken in this more inclusive sense in this report.

Problem Areas. The following list of problems in manufacturing has significant geometric content. It is only a partial list, culled from abstracts of talks presented at the workshop. Clearly, some problems can be classified under more than one heading. We do not attempt to define these problems so they must remain necessarily vague for the uninitiated. Still it can serve to indicate the range of geometric issues.

General issues: non-robustness, software library.

Manufacturing process: NC-machining, molding, casting, milling, bending, cutting, gravity casting, injection molding, stereolithography, photochemical machining, laminated object manufacturing, inspection planning, geometric databases, workspace design.

Geometric and Mechanical Design: mesh generation, routing and placement, packing and material layout.

Virtual Reality: simulation, accessibility verification, geometric interference detection, virtual factory and manufacturing.

Robotics and automation: position tracking, feature recognition, parts feeder design, automatic fixturing, visual and other sensor data processing.

Geometric modeling: feature-based design, problems in structural biology, constraint solving.

Computational metrology: sampling strategy, best-fit problems, actual value estimation, tolerance checking, reference software construction, statistical tolerancing, coordinate-measuring machine modeling.

Manufacturing versus CG. There is a major cultural difference between the two communities. Manufacturing is engineering oriented and largely interested in solving concrete problems; CG studies theoretical issues and is interested in general tools. The use of these tools in manufacturing problems requires an additional level of non-trivial effort that has so far been largely neglected. To indicate the kind of cultural transformation awaiting CGer's, we mention a challenge of Herb Voelcker: CGer's like convenient models of physical geometry such as the usual polyhedral domains. But are CGer's willing to work with models which may be more natural for research engineers, such as the one for NC machining in [2]?

Academia versus Industry. A related cultural difference can be seen between academia and industry. Here, manufacturing itself can be split between the academic approach and the shop-floor approach. The VLSI area is cited as an example where the two can find common ground: For some time, industry and academia went their separate ways. Then Mead and Conway [1] put VLSI on a sound footing (they simplified many issues, like good academic researchers, but it was realistic enough to form the basis of real work). We should remember that manufacturing is rather diverse, and each domain of manufacturing requires its own Mead-Conway approach.

The difference between theoretical and industrial approaches to a problem is illustrated in several ways.

- Problem of pipe routing. The main criteria is that the pipe be self-avoiding. In industry, the code to solve this problem is rather simple, but hardly efficient or sophisticated, in contrast to the usual hallmark of CG solutions. Basically, industry prefers to throw a huge number of computing cycles at the problem, sacrificing robustness and correctness for simplicity of coding.
- Bandwidth in telecommunications. Data compression has a deep mathematical basis and many coding algorithms have been proposed. But the channel providers solve this bandwidth

problem by just providing thicker cables. But the retort, "why do we still not have video phones?", points out limitations of such brute force solutions.

- In geometric algorithms, industry prefers simple heuristics to the fool-proof techniques of CG. E.g., to cut down on many geometric searches, bounding boxes are quite effective but they have no theoretical guarantees. To compound the problem, CG solutions are usually abstractly described and non-experts (even experts!) find it hard to implement these solutions.

Practitioners must not expect CG to ignore its real strength, which is theoretical analysis. There should be a place for the advancement of theory that does not have immediate relevance. Consider the dilemma of too pragmatic an approach: it is pointed out that manufacturing gives the appearance of solving the same problems over and over. Thus many papers have claimed "we are solving the *process planning problem*", without any apparent sense of finality. It is fatal for a scientific discipline not to have a definite measure of progress. In contrast, standard CG methods of judging algorithms by their efficiency (space or time, worst-case or otherwise) allow the field to measure progress in various computational problems. There is nothing wrong with this *per se* and, in fact, much to recommend it. But this successful research paradigm also starts to drive out or inhibit the development of useful algorithms that may be inferior by these traditional measures. We would like CG to admit simple yet effective solutions that may not have asymptotically optimal behavior. In short, CG must modify some of its normative values for doing research. We believe that this behavioral change can come about when CG has closer contacts with various application areas.

What can be done to improve interaction? We must separately address the two dichotomies noted above: academia versus industry, and manufacturing versus CG.

To improve contacts between industry and academia, industry must be willing to open up by providing data, software and hardware and expertise. Academia must change its traditional reward system – for instance, CG should develop publication criteria for implementation work (such work is mostly unpublishable in current journals). Funding agencies can sponsor exchange programs between academic and industrial researchers. The use of graduate students and postdocs in such exchanges is not only cost effective but can imbue many young careers with a sense of connectedness between theory and practice. It is also a pathway to job opportunities and to the sources of real world problems. Difficult problems of intellectual property and trade secrets remain; without resolving this issue, we note that not every contact between industry and academia involves such problems. Manufacturing as a whole is too broad – the contacts must be carefully targeted.

It is agreed that we must bring CG into mainstream manufacturing. For this, CG must become more experimental and get onto the shop floors. A practical project that will make many of the paper algorithms in CG accessible is to set up a software database or library, similar to the successful bibliography project in CG.

We should encourage the formation of a subgroup of researchers that sits on the interface between CG and manufacturing – each researcher will probably have a major affiliation to one or the other community, but they can be the agents of information transfer between the communities. Funding agencies can programmatically nurture such an interface community. The NSF *Grant Opportunities for Academic Liaison with Industry* (GOALI) initiated in FY 1994 is an example. What defines any (sub)community are activities such as workshops, conferences and publication outlets.

What about HPCC? Some participants feel that the use of parallelism (or specialized hardware) to speed up algorithms in CG would solve many problems. For instance, if we can efficiently perform exact numerical computations, it would sidestep the non-robustness issues. The effort and cost to exploit parallelism is a deterrent: no one seems willing to look beyond hooking up clusters of workstations to solve their problems in CG/manufacturing. Another example is Boeing company – it needs many cycles for virtual reality applications yet it is not ready to invest in parallel architecture. The panel concluded that the triple intersection of CG, manufacturing and HPCC is small. If parallelism is easily available, manufacturing might use it, but we should not expect it to spearhead the creation of parallel machines and software.

Suggestions for Future Action.
(i) A possible follow-up to this workshop is to have an open technical meeting, perhaps attached to one of the regular conferences in manufacturing or CG. One suggestion is to hold special sessions at the *IEEE Conference on Robotics and Automation* or a special workshop attached to the *ACM Symposium on Computational Geometry.*
(ii) Special meetings could be organized to extract and define critical problems of "geometric manufacturing/engineering". The publication of a list of such problems can give a powerful impetus to progress. Two promising new areas of focus are *computational metrology* and *virtual reality.* For instance, Boeing has a 20-year program to do virtual manufacturing. This will surely generate a broad range of new problems and a specialized conference may help to articulate the issues.
(iii) A newsgroup and/or a mailing list for researchers in "geometric-engineering" may be useful for interaction and the dissemination of ideas. Other ideas include a working group or a newsletter.
(iv) The traditional CG community should espouse a viable experimental component[1]. Establishment of a CG software database can serve as a catalyst.

3 Conclusion

Geometry is a key component of manufacturing. Within the manufacturing and computational geometry communities, there is a subgroup of researchers who are interested in problems in this interface. CG has insights and tools that could be applied to manufacturing problems, but this is by no means routine. The cultivation of a "geometric-engineering" subcommunity who understands both disciplines will help to port, validate and develop these tools for manufacturing. We proposed some activities, programs and funding initiatives towards this end.

ACKNOWLEDGEMENTS

The steering committee would like to thank each member of the workshop for their full participation and contributions. The above summary is really their joint product. In particular, we thank the group leaders (Souvaine, Woo and Mishra) and group scribes (Mitchell, Trinkle, O'Rourke, Piatko, Milenkovic) for leading the discussions; Joe O'Rourke for moderating the panel; Herb Voelcker and Pradeep Khosla for joining the panel (in addition to the group presenters); Joe Mitchell, Bud Mishra, Joe O'Rourke and Ari Requicha for suggestions in the early planning; Greg Medallie from National Research Council for sending some timely literature on manufacturing. This report has benefited from critical and insightful remarks of Herb Voelcker and also Joe Mitchell. Finally, this project would not have been possible without the enthusiastic support of NSF and especially Kamal Abdali who first suggested the workshop.

[1] Even as this report is being finalized, some of the ideas here are seeing partial fulfillment. The 1995 ACM symposium on Computational Geometry strongly encourages the submission of implementation/practical papers. There is a workshop at the Geometry Center in University of Minnesota in January 1995 on geometric software.

APPENDIX A: Participants

Kamal Abdali (NSF), Isabel M. Beichl (NIST), Marshall W. Bern (Xerox PARC), John Canny (UC Berkeley), Herbert Edelsbrunner (U of I, Urbana–Champaign), Gerald L. Engel (NSF), Martin Held (SUNY Stony Brook), Christoph M. Hoffmann (Purdue), Jiawei Hong (CIMplus), Leo Joskowicz (IBM Watson), Pradeep K. Khosla (ARPA/SISTO), Victor J. Milenkovic (Harvard), Bhubaneswar Mishra (NYU), Joe Mitchell (SUNY Stony Brook), David W. Mizell (Boeing), Joseph O'Rourke (Smith), Steven D. Phillips (NIST), Christine D. Piatko (NIST), Aristides A. G. Requicha (USC), Jűrgen Sellen (NYU), Diane L. Souvaine (Rutgers), Vijay Srinivasan (IBM Watson), Jeff Trinkle (Texas A&M), Herbert B. Voelcker (Cornell), Richard Wallace (NYU), Gordon Wilfong (AT & T Bell Labs), Tony Woo (U Michigan), Michael J. Wozny (NIST), Y. Lawrence Yao (Columbia), Chee Yap (NYU).

APPENDIX B: Program

DAY 1: Perspectives and Directions

1. Herbert Voelcker (Cornell):
   Geometry in Mechanical Design and Manufacturing
2. Joseph Mitchell (SUNY Stonybrook):
   Some Geometric Problems and Issues in Design and Manufacturing
3. David Mizell (Boeing):
   Virtual and Augmented Reality in Manufacturing
4. Herbert Edelsbrunner (University of Illinois, Urbana-Champaign):
   Complexes and Modeling
5. Ari Requicha (University of Southern California)
   Geometric Computation in Mechanical Design and Manufacture
6. Michael Wozny (NIST and RPI):
   Trends in Manufacturing Research
7. Kamal Abdali (NSF):
   Trends in Funding

DAY 2: Intersections of Manufacturing and CG.

1. Christoph Hoffman (Purdue):
   Geometric Constraint Solving for Manufacturing Applications
2. Jia-Wei Hong (NYU and CIMplus):
   Computational Geometry and its Applications in Manufacturing
3. Victor Milenkovic (Harvard University):
   Multiple Containment Methods for Apparel Manufacture
4. John Canny (UC Berkeley):
   RISC Robotics

5. Vijay Srinivasan (IBM):
   Characterizing and Controlling Geometric Variations in Manufacturing

6. Gordon Wilfong (AT&T Bell Laboratory):
   Computational Geometry Applications in Layered Manufacturing Methods

7. Tony Woo (University of Michigan):
   Visibility for Design and Manufacturing

8. Jeffrey Trinkle (Texax A& M):
   Automatic Selection of Fixture Points for Frictionless Assemblies

9. Marshall Bern (Xerox PARC):
   Non-obtuse Triangulations

10. Steven Phillips (NIST):
    Geometrical Issues in Coordinate and Computational Metrology

References

[1] C. A. Mead and L. A. Conway. *Introduction to VLSI systems.* Addison-Wesley, Reading, Massachusetts, 1980.

[2] J. P. Menon and H. B. Voelcker. Toward a comprehensive formulation of NC verification as a mathematical and computational problem. *J. of Design and Manufacturing*, 3:263–277, 1993.

[3] Committee to Study Information Technology and Manufacturing. Information technology and manufacturing (preliminary report). Technical report, National Research Council, National Academy Press, 1993.