THE EMERGING TECHNOLOGY OF CAD/CAM

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Abstract

Computer-Aided Design and Manufacture (CAD/CAM) represents a merging of technological advances in computer hardware and software with pressing needs in manufacturing industries. Integrated manufacturing systems--from computer graphics-aided design through engineering analysis and automated fabrication--are only now beginning to fulfill nearly twenty-five-year old promises of increased production efficiency. This paper summarizes CAD/CAM's evolution and its current state and then describes some areas that will experience significant change in the next decade.

Introduction

For more than fifteen years, Computer-Aided Design and Manufacture (CAD/CAM) has been a field filled with great promise: more efficient manufacturing through completely automated factories, greater industrial productivity, superior products through computer-assisted testing and fabrication, better working conditions for designers and manufacturers, among others. But CAD/CAM is only now beginning to fulfill these promises. Initially, traditional paper and pencil drafting was computerized in the form of two dimensional CAD systems. Three dimensional systems evolved to overcome some of the limitations inherent in such two dimensional representations and thereby introduced design methods not possible without computers. Computers also assisted machinists by driving cutting machines and automating process control, thereby establishing the foundations of CAM. Since that time, CAM and CAD have remained essentially separate; many of the cliched "bridges" between CAM and CAD do not yet fully exist, and integrated manufacturing environments remain elusive and ever more desirable goals. We strongly feel that in the next decade, CAD/CAM will finally fulfill its promises and become a dominant force both technologically and socially.

The first section of this paper provides a historical perspective of the field so that we can better assess its directions. Subsequently, brief clarifications of relevant terminology and summaries of several current approaches to geometric modeling in CAD systems are given. We then examine hardware and software trends of the late 1970's and early 1980's and offer our proposal of a CAD/CAM system architecture that we feel will prevail late in this decade.

A Short History of CAD/CAM

Ivan Sutherland's Sketchpad of the early 1960's is often considered the basis of interactive computer graphics. Although graphics are perhaps the most visible aspect of CAD/CAM, the field traces its beginnings to computer-aided machining of nearly a decade earlier. The result of joint work between the Massachusetts Institute of Technology and IBM was the APT language (for Automatically Programmed Tools) that supported high-level definition of parts' geometry in order to construct cutter paths for numerically controlled machine tools. An APT program provided a "batch" definition of an object; for example, Figure 1a is an APT definition of the outer contour of the part drawn in Figure 1b. The APT language is, in a sense, the first CAD system, although its primary goal was CAM.

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P1 = POINT/0,0,0
P2 = POINT/5,0,0
P3 = POINT/5,1,0
P4 = POINT/3,4,0
P5 = POINT/0,4,0
L1 = LINE/P1,P2
C1 = CIRCLE/CENTER,P3,RADIUS,1
L2 = LINES/P4,LEFT,TANTO,C1
L3 = LINE/P4,P5
L4 = LINE/P5,P1
PL1 = PLANE/P1,P2,P3
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Figure 1a. APT part program

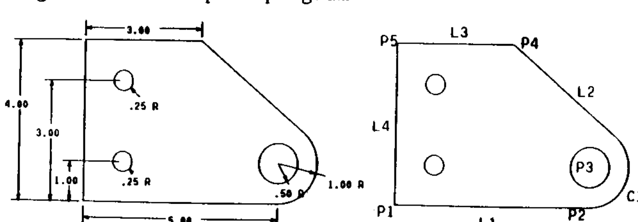


Figure 1b. Engineering drawing and feature labeling

Subsequently, both aerospace and automobile industries have led CAD/CAM research, with Lockheed, McDonnell-Douglas, General Motors, and a few other companies developing systems during the next decade. In the 1970's, specialized CAD/CAM companies emerged (notably Computervision) and developed systems, most of which use wire-frame models as discussed below. More complex three dimensional modeling schemes were developed at the University of Rochester (PADL-1, [10]), MAGI (Synthavision, [6]), and elsewhere. These are catergorized as "solid modeling" systems since they model objects as unambiguous, informationally-complete volumes rather than as the points, edges, or curves that the bound objects.

Design, Drafting, and Graphics

Until only recently, much literature on "CAD" concerned not computer-aided design, but rather computer-aided drafting. Ironically, design may involve no drafting at all. Furthermore, much of this literature could better be characterized as computer graphics. Since the terms "design," "drafting," and "graphics" are often used interchangeably, we offer brief definitions.

Graphics is the art of making drawings; in certain applications, computers can assist in producing drawings that would be difficult or impossible to create by manual methods.

Drafting is a realization of projective geometry and attempts to provide complete, unambiguous representations of three dimensional solid objects within the constraints of two dimensions. Drafting, therefore, is formal pictorial "language," and drafted engineering drawings traditionally have been the usual medium of communication between designers and manufacturers.

On the other hand, design, whether computer-assisted or completely manual, involves conceptualizing, planning, and defining. The result usually is documented in various ways, including model building, prototyping, and drawing. Although CAD/CAM systems provide computer models as additional modes of documenting, drafted engineering drawings remain "state-of-the-art."

The distinction between modeling and drafting is critical. Designers model objects in order to define them; they may then document their design, perhaps by drafting, in order to provide manufacturers with sufficient information. Despite our view of computer-aided drafting as primarily computer-assisted documentation (just as word processing is computer-assisted typing), we include it as a modeling approach in the next section because of its prevalence in industry and its relationship to three dimensional modeling.

Approaches to Modeling

The primary aim of a designer's model of an object is to provide information required to manufacture that object, and the completeness and non-ambiguity of the model contribute heavily toward an object's efficient manufacture. The approaches described below offer alternative means of modeling; only the first approach is practical without computer assistance. For more detailed descriptions of these approaches, see [1].

Engineering Drawings

Engineering drawings are, of course, the traditional and predominant form of object definition. Drawings are two dimensional projections of objects' outlines, and designers attempt to provide an adequate number of such projections to define these objects (and manufacturers generally agree that designers never do) . Multiple view engineering drawings suffer major deficiencies: possible inconsistencies among views, ambiguities, little if any direct information for automated process planning and manufacturing, and possible deviations from projective geometry in the form of sanctioned "lies" called "drafting conventions." Figure 2 provides an example of a computer-assisted engineering drawing from Lockheed's CADAM system.

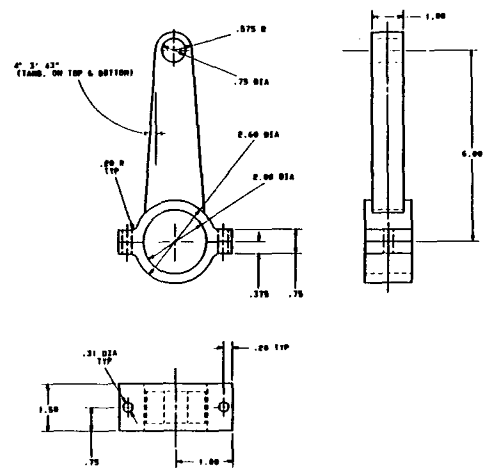


Figure 2: CADAM drawing

Computer-aided drafting offers considerable advantage over manual drafting, including semi-automatic projections of auxiliary views from a principal view, some physical property calculation facilities, ease of dimensioning, and much more efficient engineering change incorporation. This approach is inherently limited by its two dimensional view of our three dimensional world, and despite its overwhelming prevalence, it will eventually be supplanted by three dimensional computer-aided modeling.

Wire-frames

Just as drafting relies on "outlines," wire-frames model objects as collections of three dimensional bounding edges. These edges are either actual "hard" edges along which a surface derivative is discontinuous or "soft" (i.e. nonexistent) edges which may have been added to model curved surfaces. Wire-frame modeling is the

three dimensional analog to drafting and requires computer assistance; wire-frame CAD systems have drafting-like interfaces that are easy to learn and use, and the majority of commercial CAD systems are wire-frame based. Figure 3 is an example of a wire-frame model with hidden lines dashed for clarity.

Because their underlying data models do not contain information regarding surfaces enclosed by edges or volumes contained by surfaces, wire-frame systems cannot provide unambiguous or complete models of objects. They therefore may not provide adequate physical property calculation or display (e.g. hidden line supression) facilities. Furthermore, the incompleteness of wire-frame models limits their value for manufacturing.

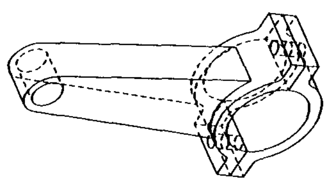
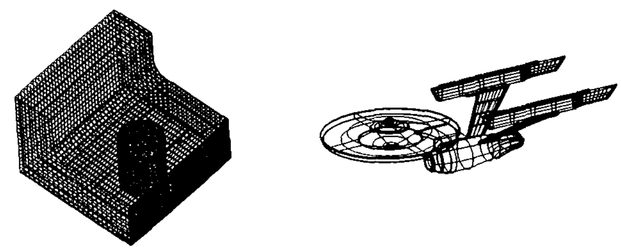


Figure 3. Wire-frame model

Both two dimensional and wire-frame models "outline" objects and therefore cannot directly support the concept of contained volume. Solid or volumetric modeling systems, however, unambiguously and completely define objects by basing their descriptions on volume-containing entities in any of several ways; [8] presents a thorough discussion of approaches to solid modeling, while [9] provides a survey and discussion of currently-available solid modeling systems. The most common and probably most useful approaches to solid modeling--surface representation, constructive solid geometry, and sweeping--are described below.

Surface Representation

Surface-representing systems (also known as boundary- or boundary surface-representating systems) model objects as collections of surfaces that form their topological boundaries. Objects are considered as defined by mathematical representations of adjacent faces or patches, and solid modeling surface-representing systems can automatically or semi-automatically identify an enclosed volume by, perhaps, giving faces an "inside" and an "outside." Surface-representing systems are most appropriate for designing complex sculptured surfaces like airplane fuselages and car bodies; physical property calculation is generally strongly supported in such systems. However, it is often difficult to check the validity of surface models, and user interfaces tend to be awkward since they often require tedious keying of curve or surface coordinates. Figure 4 shows models created using IBM's Numerical Geometry System [3]; Figure 4a is an L-bracket with a hole, while Figure 4b is a complex aircraft's wetted surface.

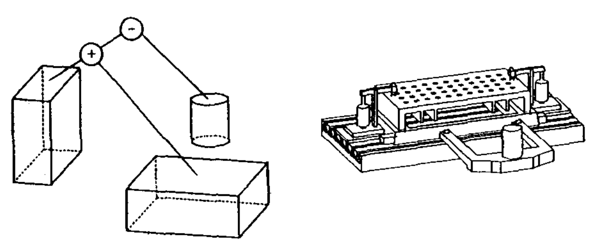


(a) (b)

Figure 4. Surface models on NGS

Constructive Solid Geometry

Constructive Solid Geometry (CSG) models objects as sums and differences of simpler objects. Typically, CSG systems provide a set of primitive simple objects such as blocks, cylinders, and cones; a set of operators similar to set union, intersection, and difference is used to combine objects to form more complex objects. Figure 5a shows the simple bracket of Figure 4a modeled as a combination of primitive objects, while Figure 5b is part of a robotic assembly line modeled and simulated on IBM's GDP/GRIN [4]. Many systems based on CSG are in use, including PADL, GMSOLID [2], GDP/GRIN, and Synthavision. CSG systems suffer from several deficiencies: their models are not unique (i.e. an object may have many CSG models), they are mathematically complex and therefore cannot always provide the desired level of interactivity, their user interfaces are untraditional and often counter-intuitive, and they cannot easily model objects with sculptured (doubly-curved) surfaces. (An alternative modeling scheme similar to CSG, but using abstracted manufacturing operators rather than set operators, has been proposed in [1].) However, since CSG models are "semantically rich," they potentially can contribute to objects' automated manufacture; for example, CSG models may provide automated process planning and fabricating and assembly information.



(a) (b)

Figure 5. CSG models

Sweeping

A third approach, sweeping, models objects as sets of points translated along a straight line segment or rotated around an axis; the resulting point sets define solid objects. Sweeping is, of course, limited (as is its manufacturing analog, extrusion), and it is often combined with other modeling approaches like CSG; the Medusa CAD system [5] typifies sweeping-oriented solid modelers.

A Hardware Revolution

CAD systems for mechanical design typically have resided on mini and mainframe computers, and inital system cost ranges from $30,000 to more than $150,000 per workstation when terminal, processor, peripheral, and software expenditures are considered. Eventually, after training periods, substantially increased productivity offsets this large inital investment and recurring costs. Within the next year or so, however, microprocessor- based systems will approach much larger and more costly computers' power, and sophisticated modeling software will be available in support of this new hardware.

Powerful workstations with 32-bit microprocessors, large main and secondary memories, hardware graphics support, and communication to other workstations or to a mainframe are becoming available, but their capabilities are not yet fully utilized in CAD/CAM systems. Here, the distinction between stand-alone microcomputer and (very) intelligent terminal becomes mute; complex CAD software could be executed directly by a workstation, or, perhaps "simple" geometric definition, manipulation, and display graphics could be done locally, while more complex operations would invoke a mainframe's processor.

Over the past decade, graphics terminals have shown a gradual, but distinct, transition from storage tube technology to vector refresh and color raster. As main memory costs decrease and speed increases, color raster monitors will become the dominant technology, and resolutions will approach 2000 by 2000 picture elements with thousands of colors. Low cost graphics workstations are also beginning to appear. As an example of current technology, Figure 6 shows recent work on an IBM PCXT microcomputer with commercially-available graphics enhancements. The figure was generated by a stand-alone three dimensional CAD system developed by the MicroCAD Group at UCLA and was displayed on a medium resolution color raster monitor. Both the speed and the quality of the graphics compare favorably with mainframe-oriented systems.

Hardware technology can allow better user interfaces through, for example, dynamic and application-oriented menus, multi-processing windows, communication, and improved pick and pointing devices. Furthermore, local computing power provides reliability and the potential for much reduced down time since dependence on a mainframe may be unnecessary. Such power will not be prohibitively expensive; more workstations and consequently better working environments therefore may be possible.

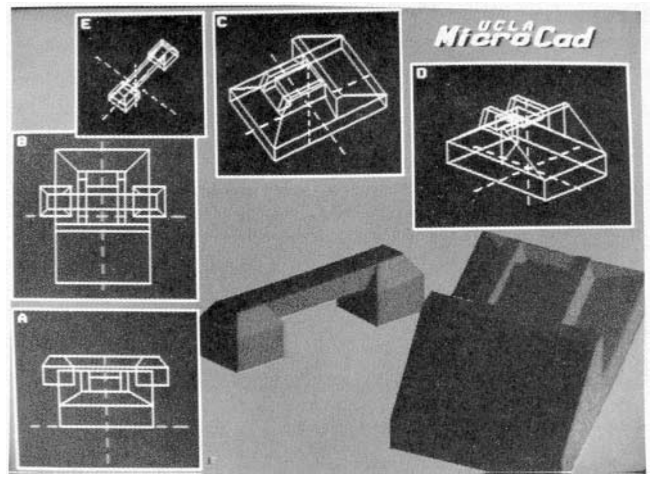


Figure 6. Microcomputer-based CAD

A Software Evolution

Analogous to the hardware revolution that is just beginning, we also see a software evolution involving both geometric modeling techniques and human factors. Design engineers are as intolerant of unresponsive computers as are other classes of computer users. It is unacceptable for a computer to take minutes to accomplish what a designer could do manually in seconds. In fact, the proliferation of computer-aided drafting systems is due in large part to response time requirements. Interactive response times of solid modeling systems developed over the last ten years generally suffer severely due to their inherent mathematical complexity. With more powerful hardware, such modeling systems become practical. A related deficiency of many current CSG systems is their dependence on approximation; for example, straight lines may approximate curves, and planar faces may approximate curved surfaces. A significant breakthrough made possible by new hardware which we foresee in the near future is software that operates on analytic representations of solid geometric entities (rather than on more mathematically-tractable approximations) and still provides adequate interactive response times.

Within the next two or three years, solid modeling systems will integrate sculptured surface capability (with analytic representations) and CSG operations and thereby greatly increase their ranges of application. Examples include container design with volume and shape constraints and automated blending and filleting. User interfaces will also change; geometric editing and variational geometry will provide true family of parts capabilities as well as much more efficient engineering change incorporation.

With current and anticipated hardware technologies, solid modeling will overcome the inertia of tradition and displace computer-aided drafting as the predominant modeling approach. Benefits will include integration of design and analysis phases of the manufacturing cycle, much reduced prototyping, and enforcing of manufacturing constraints during design (e.g. cost, shop floor

scheduling, robotic fabrication). Automated process plan generation, manufacturing process control, and better utilization of available manufacturing resources should result; significant advantages will include much reduced design-to-manufacture times and smaller required inventories. Related areas will also be automated; for example, forging dies and casting models will be derived from parts' CAD definitions. In summary, CAD/CAM will begin to fulfill its well-advertised promises by exploiting new hardware with complex software.

Trends in CAD/CAM

Integrated System Architecture

Advancements in hardware and software technologies provide the bases for integrating the many facets of manufacturing. During the next decade, computer networks will surround manufacturing databases, and we foresee such distributed systems as the beginning of integrated CAD/CAM. Just as this is the decade of home and office computerization, the next decade promises to produce integrated, computerized environments, with databases and information networks promoting knowledgeable communication. For CAD/CAM, such integration is the key to productivity; an entire manufacturing cycle--from conceptual design through analysis and fabrication, and on to sales and support--must flow through a computer network (rather than repeatedly from person-to-paper-to-machine). One proposal is a hierarchical network with CAD workstations, machine tool and robot controllers, and communication to databases, management, sales, training, and support, as shown conceptually in Figure 7. For example, with a distributed architecture, iterations between design and manufacturing could pass through the network, avoiding proliferation of (perhaps inconsistent) engineering change documents, encouraging stanardization of parts, and allowing inventories to be checked for subassembly parts' availability.

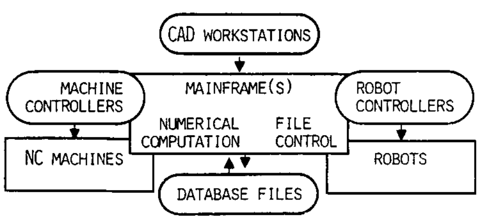


Figure 7. A distributed CAD/CAM system

Applications

Traditionally, only large companies (e.g. aerospace, automobile) have been able to afford CAD systems, upon which they depend in order to stay competitive; only recently, hardware technology has enabled medium and small companies to also consider CAD. Although CAD systems are becoming more sophisticated, powerful, and usable, initial investments can be much lower. Particularly for smaller companies, we see another important direction: in place of general-purpose design systems, customized special application systems will be developed, similar to current systems for architectural applications. Special application CAD will be more cost-effective than general purpose systems for application areas including specialized machine tool design, manufacturing line modeling, cable routing, plumbing and piping, industrial design, and space planning.

Computer-assisted engineering analysis and testing are only beginning to be incorporated into CAD/CAM systems. Automation of finite element mesh generation and interfaces to analysis programs are subjects of much current research.

Artificial Intelligence

Artificial intelligence techniques are being applied to manufacturing environments. Expert systems for machine tool programming, generative process planning [7], and optimizing of shop floor scheduling are potential areas of application.

Assembly robots are gaining visual and tactile sensory capabilities. Pattern recognition methods in conjunction with sophisticated geometric modeling may provide a key to flexible automated manufacturing lines; for example, visually sensitive robots would be able to grasp arbitrarily-oriented parts from bins or conveyors by "seeing" important geometric features of the parts.

Education

With few exceptions, both education and research in CAD/CAM has been centered in industry rather than in universities. Reasons include very high cost of equipment, the applied nature of the field, lack of cohesive "theory" under manufacturing and design, and scarcity of sufficient experienced people in the field.

As costs decrease and demand increases, technical schools, colleges, and universities are starting to teach both user- and implementer-level courses in CAD/CAM. Engineering schools are beginning to incorporate computer-aided design into their undergraduate curricula, while university computer science departments are introducing future CAD/CAM system implementers to computer graphics, data structuring, and information networks. An area that thus far has not received sufficient attention in schools is applied mathematics; graduates with knowledge of geometric modeling techniques, surface mathematics, and topology will be in great demand.

Manufacturing technology will become part of the curricla of technical schools, colleges, and universities in the next decade, and a second generation of CAD/CAM expertise should then emerge as a result of this investment in education.

Conclusions

There seems little question that the "high-technology" promises of CAD/CAM finally will be realized in the form of integrated design, engineering, and manufacturing environments. The second industrial revolution that is now automating factories will grow even faster in the next decade, and, as in the first industrial revolution, inevitable social change will occur. And the high potential benefits of these technological achievements to society--much less hazardous, tedious work together with better, less costly products--should far outweigh their detriments.

References

1. Arbab, F. "Requirements and Architecture of a CAM-oriented CAD System for Design and Manufacture of Mechanical Parts", UCLA Manufacturing Engineering Report 8201, December 1982.

2. Boyse, J.W. and Gilchrist, J.E. "GMSolid: Interactive Modeling for Design and Analysis of Solids", Computer Graphics and Applications 2, 2, March 1982.

3. Burkley, R.M. and Mayfield, J.P. "A Numerical Geometry System", Society of Manufacturing Engineers Technical Paper MS75-723, 1975.

4. Fitzgerald, W., Gracer, F., and Wolfe, R. "GRIN: Interactive Graphics for Modeling Solids", IBM J. Res. Dev. 25, 4, July 1981.

5. Foster, R.V. Medusa Design Modelling System User's Guide, Prime Computer DOC 6348-040, 1983.

6. Goldstein, R. and Malin, L. "3D Modeling with the Synthavision System", Proc 1st Annual Conf. on Computer Graphics in CAD/CAM Systems, MIT, April 1979.

7. Groover, M. and Zimmers, E. CAD/CAM: Computer-Aided Design and Manufacturing, Prentice-Hall, 1984.

8. Requicha, A.A.G. "Representations for Rigid Solids: Theory, Methods, and Systems", Computing Surveys 12, 4, December 1980.

9. Requicha, A.A.G. and Voelcker, H.B. "Solid Modeling: A Historical Summary and Contemporary Assessment", Computer Graphics and Applications 2, 2, March 1982.

10. Voelcker, H.B., et al "The PADL-1.0/2 System for Defining and Displaying Solid Objects", Computer Graphics 12, 3 (Proc. Siggraph '78), August 1978.

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