MODULE 1

INTRODUCTION

CAD/CAM

CAD/CAM is a term which means computer-aided design and computer-aided manufacturing. It is the technology concerned with the use of digital computers to perform certain functions in design and production. This technology is moving in the direction of greater integration of design and manufacturing, two activities which have traditionally been treated as distinct and separate functions in a production firm. Ultimately, CAD/CAM will provide the technology base for the computer-integrated factory of the future.

Computer-aided design (CAD) can be defined as the use of computer systems to assist in the creation, modification, analysis, or optimization of a design. The computer systems consist of the hardware and software to perform the specialized design functions required by the particular user firm. The CAD hardware typically includes the computer, one or more graphics display terminals, keyboards, and other peripheral equipment. The CAD software consists of the computer programs to implement computer graphics on the system plus application programs to facilitate the engineering functions of the user company. Examples of these application programs include stress-strain analysis of components, dynamic response of mechanisms, heat-transfer calculations, and numerical control part programming. The collection of application programs will vary from one user firm to the next because their product lines, manufacturing processes, and customer markets are different. These factors give rise to differences in CAD system requirements.

Computer-aided manufacturing (CAM) can be defined as the use of computer systems to plan, manage, and control the operations of a manufacturing plant through either direct or indirect computer interface with the plant's production resources. As indicated by the definition, the applications of computer-aided manufacturing fall into two broad categories:

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1. ***Computer monitoring and control.*** These are the direct applications in which the computer is connected directly to the manufacturing process for the purpose of monitoring or controlling the process.

2. ***Manufacturing support applications.*** These are the indirect applications in which the computer is used in support of the production operations in the plant, but there is no direct interface between the computer and the manufacturing process.

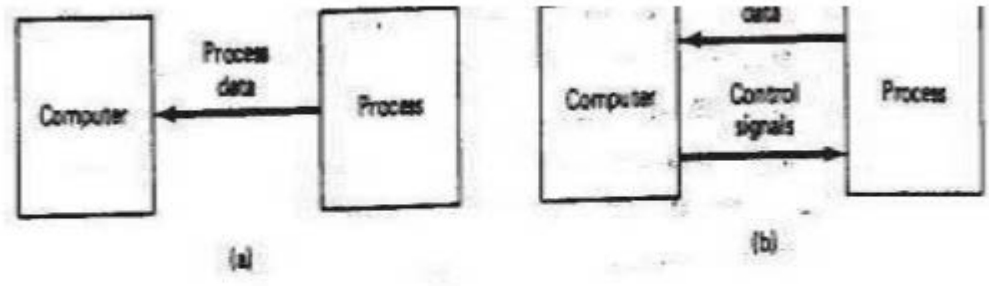
The distinction between the two categories is fundamental to an understanding of computer-aided manufacturing. It seems appropriate to elaborate on our brief definitions of the two types.

Computer monitoring and control can be separated into monitoring applications and control applications. Computer process monitoring involves a direct computer interface with the manufacturing process for the purpose of observing the process and associated equipment and collecting data from the process. The computer is not used to control the operation directly. The control of the process remains in the hands of human operators, who may be guided by the information compiled by the computer.

Computer process control goes one step further than monitoring by not only observing the process but also controlling it based on the observations. The distinction between monitoring and control is displayed in Figure. With computer monitoring the flow of data between the process and the computer is in one direction only, from the process to the computer. In control, the computer interface allows for a two-way flow of data. Signals are transmitted from the process to the computer, just as in the case of computer monitoring. In addition, the computer issues command signals directly to the manufacturing process based on control algorithms contained in its software.

In addition to the applications involving a direct computer-process interface for the purpose of process monitoring and control, computer-aided manufacturing also includes indirect applications in which the computer serves a support role in the manufacturing operations of the plant. In these applications, the computer is not linked directly to the manufacturing process.

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Computer monitoring versus computer control: (a) computer monitoring, (b) computer control.

Computer monitoring versus computer control: (a) computer monitoring;

(b) computer control.

Instead, the computer is used "off-line" to provide plans, schedules, forecasts, instructions, and information by which the firm's production resources can be managed more effectively. The form of the relationship between the computer and the process is represented symbolically in Figure. Dashed lines are used to indicate that the communication and control link is an off-line connection, with human beings often required to consumate the interface. Some examples of CAM for manufacturing support that are discussed in subsequent chapters of this book include:

Numerical control part programming by computers. Control programs are prepared for automated machine tools.

Computer-automated process planning. The computer prepares a listing of the operation sequence required to process a particular product or component.

Computer-generate work standards. The computer determines the time standard for a particular production operation.

Production scheduling. The computer determines an appropriate schedule for meeting production requirements.

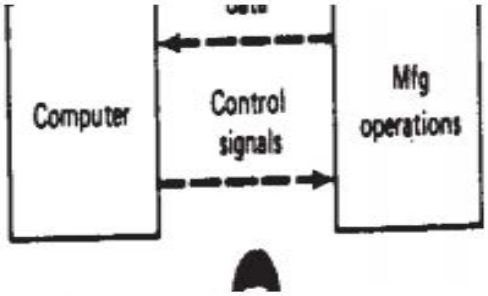
Material requirements planning. The computer is used to determine when to order raw materials and purchased components and how many should be ordered to achieve the production schedule.

Shop floor control. In this CAM application, data are collected from the factory to determine progress of the various production shop orders.

In all of these examples, human beings are presently required in the

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application either to provide input to the computer programs or to interpret the computer output and implement the required action.



CAM for manufacturing support.

CAM for manufacturing support.

THE PRODUCT CYCLE AND CAD/CAM

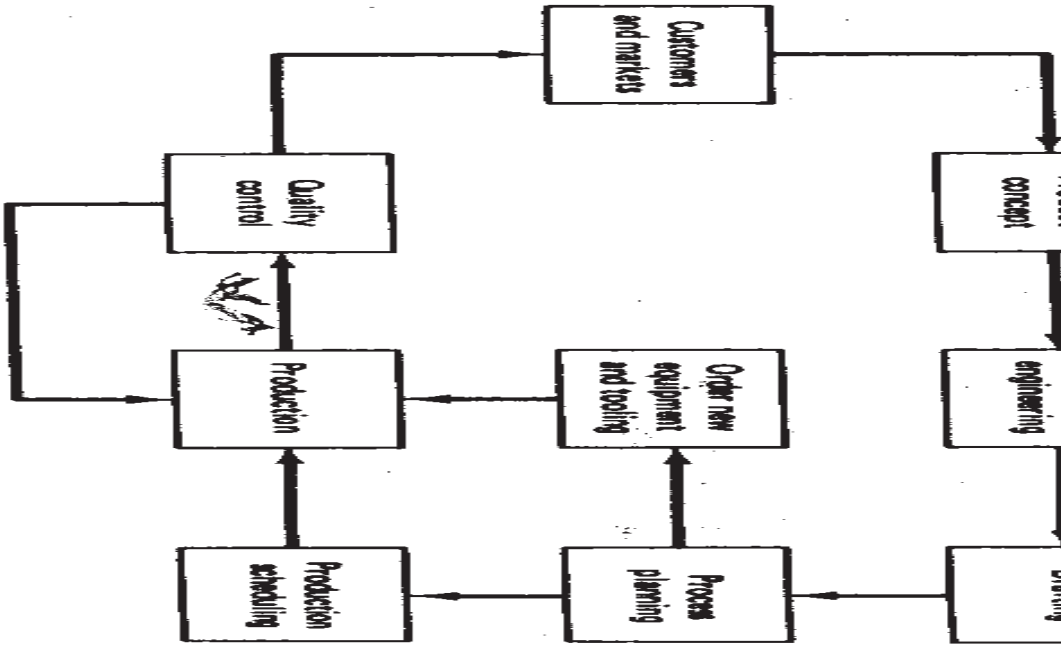
For the reader to appreciate the scope of CAD/CAM in the operations of a manufacturing firm, it is appropriate to examine the various activities and functions that must be accomplished in the design and manufacture of a product. We will refer to these activities and functions as the product cycle.

A diagram showing the various steps in the product cycle is presented in Figure. The cycle is driven by customers and markets which demand the product. It is realistic to think of these as a large collection of diverse industrial and consumer markets rather than one monolithic market. Depending on the particular customer group, there will be differences in the way the product cycle is activated. In some cases, the design functions are performed by the customer and the product is manufactured by a different firm. In other cases, design and manufacturing is accomplished by the same firm. Whatever the case, the product cycle begins with a concept, an idea for a product. This concept is cultivated, refined, analyzed, improved, and translated into a plan for the product through the design engineering process. The plan is documented by drafting Ii set of engineering drawings showing how the product is made and providing a set of specifications indicating how the product should perform.

Except for engineering changes which typically follow the product throughout its life cycle, this completes the design activities in Figure. The next activities involve the manufacture of the product. A process plan is formulated which

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specifies the sequence of production operations required to make the product. New equipment and tools must sometimes be acquired to produce the new product. Scheduling provides a plan that commits the company to the manufacture of certain quantities of the product by certain dates. Once all of these plans are formulated, the product goes into production, followed by quality testing, and delivery to the customer.



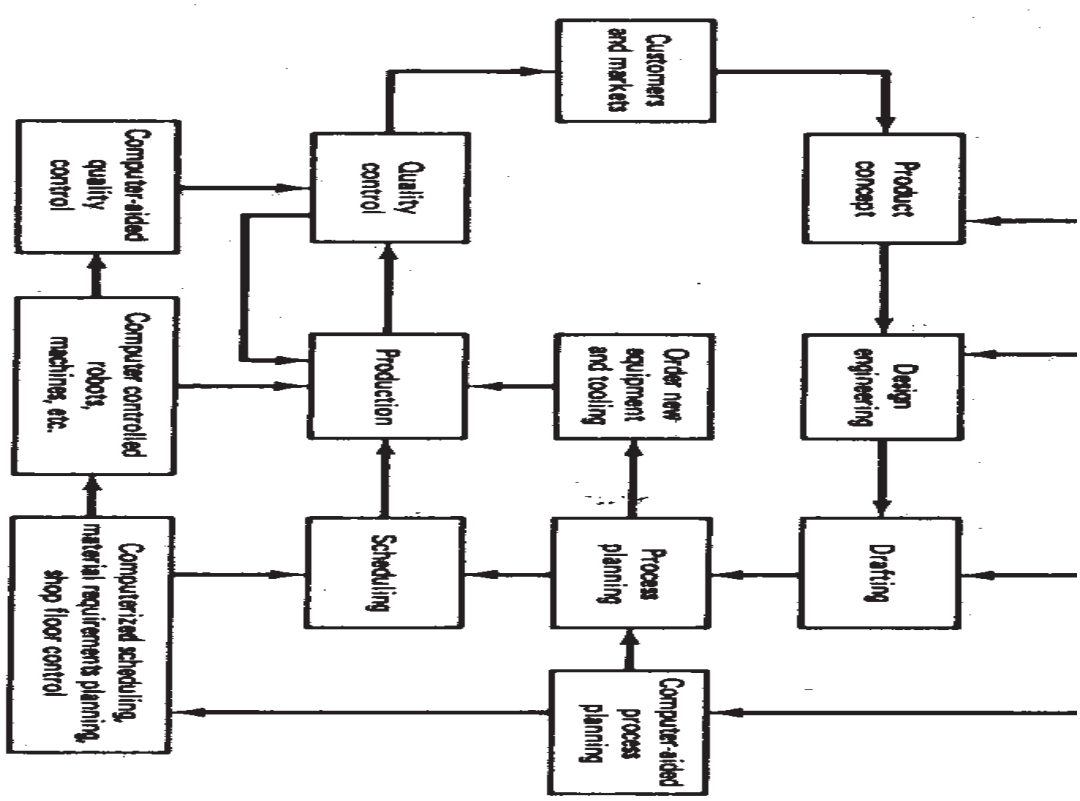
Product cycle (design and manufacturing).

The impact of CAD/CAM is manifest in all of the different activities in the product cycle, as indicated in Figure. Computer-aided design and automated drafting are utilized in the conceptualization, design, and documentation of the product. Computers are used in process planning and scheduling to perform these functions more efficiently. Computers are used in production to monitor and control the manufacturing operations. In quality control, computers are used to perform inspections and performance tests on the product and its components.

As illustrated in Figure, CAD/CAM is overlaid on virtually all of the activities and functions of the product cycle. In the design and production operations of a modem manufacturing firm, the computer has become a pervasive, useful, and indispensable tool. It is strategically important and competitively imperative that manufacturing firms and the people who are employed by them understand CAD/

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CAM.



Product cycle revised with CAD/CAM overlaid.

AUTOMATION AND CAD/CAM

Automation is defined as the technology concerned with the application of complex mechanical, electronic, and computer-based systems in the operation and control of production. It is the purpose of this section to establish the relationship between CAD/CAM and automation.

As indicated in previous Section, there are differences in the way the product cycle is implemented for different firms involved in production. Production activity can be divided into four main categories:

1. Continuous-flow processes
2. Mass production of discrete products
3. Batch production
4. Job shop production

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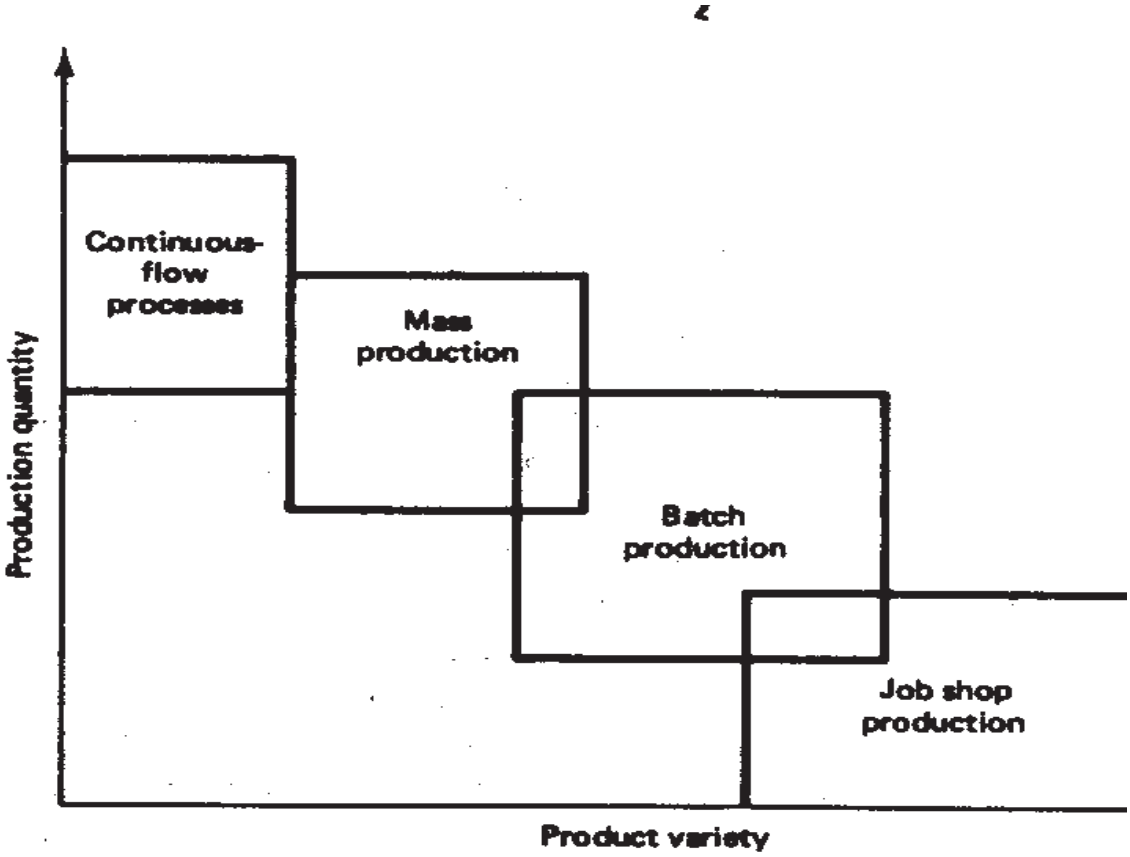
The definitions of the four types are given in Table. The relationships among the four types in terms of product variety and production quantities can be conceptualized as shown in Figure. There is some overlapping of the categories as the figure indicates. Table provides a list of some of the notable achievements in automation technology for each of the four production types.

One fact that stands out from Table is the importance of computer technology in automation. Most of the automated production systems implemented today make use of computers. This connection between the digital computer and manufacturing automation may seem perfectly logical to the reader. However, this logical connection has not always existed. For one thing, automation technology

TABLE Four Types of Production

Category	Description
1. Continuous-flow processes	Continuous dedicated production of large amounts of bulk product. Examples include continuous chemical plants and oil refineries
2. Mass production of discrete products	Dedicated production of large quantities of one product (with perhaps limited model variations). Examples include automobiles, appliances, and engine blocks.
3. Batch production	Production of medium lot sizes of the same product or component. The lots may be produced once or repeated periodically. Examples include books, clothing, and certain industrial machinery.
4. Job shop production	Production of low quantities, often one of a kind, of specialized products. The products are often customized and technologically complex. Examples include prototypes, aircraft, machine tools, and other equipment.

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Four production types related to quantity and product variation

TABLE Automation Achievements for the Four Types of Production

Category	Automation achievements
1. Continuous-flow processes	Flow process from beginning to end Sensor technology available to measure important process variables Use of sophisticated control and optimization strategies Fully computer-automated plants
2. Mass production of discrete products	Automated transfer machines Dial indexing machines Partially and fully automated assembly lines Industrial robots for spot welding, parts handling, machine loading, spray painting, etc.

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	Automated materials handling systems Computer production monitoring
3. Batch production	Numerical control (NC), direct numerical control (DNC), computer numerical control (CNC) Adaptive control machining Robots for arc welding, parts handling, etc. Computer-integrated manufacturing systems
4. Job shop production	Numerical control, computer numerical control

FUNDAMENTALS OF CAD

INTRODUCTION

The computer has grown to become essential in the operations of business, government, the military, engineering, and research. It has also demonstrated itself, especially in recent years, to be a very powerful tool in design and manufacturing. In this and the following two chapters, we consider the application of computer technology to the design of a product. This secton provides an overview of computer-aided design.

The CAD system defined

As defined in previous section, computer-aided design involves any type of design activity which makes use of the computer to develop, analyze, or modify an engineering design. Modem CAD systems (also often called CAD/CAM systems) are based on interactive computer graphics (ICG).Interactive computer graphics denotes a user-oriented system in which the computer is employed to create, transform, and display data in the form of pictures or symbols. The user in the computer graphics design system is the designer, who communicates data and commands to the computer through any of several input devices. The computer communicates with the user via a cathode ray tube (CRT). The designer creates an image on the CRT screen by entering commands to call the desired software sub-routines stored in the computer. In most systems, the image is constructed out of basic geometric elements- points, lines, circles, and so on. It can be modified according to the commands of the designer- enlarged, reduced in size, moved to another location on the screen, rotated,

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and other transformations. Through these various manipulations, the required details of the image are formulated.

The typical ICG system is a combination of hardware and software. The hardware includes a central processing unit, one or more workstations (including the graphics display terminals), and peripheral devices such as printers. Plotters, and drafting equipment. Some of this hardware is shown in Figure. The software consists of the computer programs needed to implement graphics processing on the system. The software would also typically include additional specialized application programs to accomplish the particular engineering functions required by the user company.

It is important to note the fact that the ICG system is one component of a computer-aided design system. As illustrated in Figure, the other major component is the human designer. Interactive computer graphics is a tool used by the designer to solve a design problem. In effect, the ICG system magnifies the powers of the designer. This bas been referred to as the synergistic effect. The designer performs the portion of the design process that is most suitable to human intellectual skills (conceptualization, independent thinking); the computer performs the task: best suited to its capabilities (speed of calcu1ations, visual display, storage of large 8IWWIts of data), and the resulting system exceeds the sum of its components.

There are several fundamental reasons for implementing a computer-aided design system.

1. To increase the productivity of the designer. This is accomplished by helping the designer to the product and its component subassemblies and parts; and by reducing the time required in synthesizing, analyzing, and documenting the design. This productivity improvement translates not only into lower design cost but also into shorter project completion times.

2. To improve the quality of design. A CAD system permits a more thorough engineering analysis and a larger number of design alternatives can be investigated. Design errors are also reduced through the greater accuracy provided by the system. These factors lead to a better design.

3. To improve communications. Use of a CAD system provides better

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engineering drawings, more standardization in the drawings, better documentation of the design, fewer drawing errors and greater legibility.

4. To create a database for manufacturing. In the process of creating the documentation for the product design (geometries and dimensions of the product and its components, material specifications for components, bill of materials, etc.), much of the required database to manufacture the product is also created.

THE DESIGN PROCESS

Before examining the several facets of computer-aided design, let us first consider the general design process. The process of designing something is characterized by Shigley as an iterative procedure, which consists of six identifiable steps or phases:-

1. Recognition of need
2. Definition of problem
3. Synthesis
4. Analysis and optimization
5. Evaluation
6. Presentation

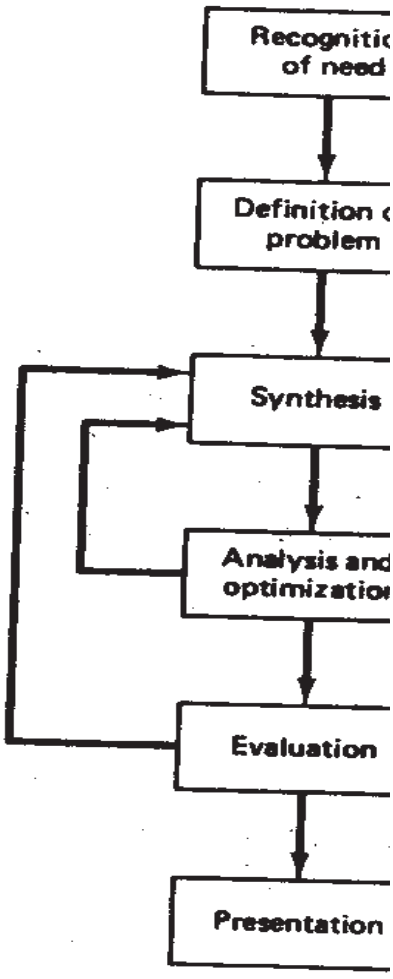
Recognition of need involves the realization by someone that a problem exists for which some corrective action should be taken. This might be the identification of some defect in a current machine design by an engineer or the perception of a new product marketing opportunity by a salesperson. Definition of the problem involves a thorough specification of the item to be designed. This specification includes physical and functional characteristics, cost, quality, and operating performance.

Synthesis and analysis are closely related and highly interactive in the design process. A certain component or subsystem of the overall system is conceptualized by the designer, subjected to analysis, improved through this analysis procedure, and redesigned. The process is repeated until the design has been optimized within the constraints imposed on the designer. The components and

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subsystems are synthesized into the final overall system in a similar interactive manner.

Evaluation is concerned with measuring the design against the specifications established in the problem definition phase. This evaluation often requires the fabrication and testing of a prototype model to assess operating performance, quality, reliability, and other criteria. The final phase in the design process is the presentation of the design. This includes documentation of the design by means of drawings, material specifications, assembly lists, and so on. Essentially, the documentation requires that a design database be created. Figure illustrates the basic steps in the design process, indicating its iterative nature.



The general design process as defined by Shigley .

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Engineering design has traditionally been accomplished on drawing boards, with the design being documented in the form of a detailed engineering drawing. Mechanical design includes the drawing of the complete product as well as its components and subassemblies, and the tools and fixtures required to manufacture the product. Electrical design is concerned with the preparation of circuit diagrams, specification of electronic components, and so on. Similar manual documentation is required in other engineering design fields (structural design, aircraft design, chemical engineering design, etc.). In each engineering discipline, the approach has traditionally been to synthesize a preliminary design manually and then to subject that design to some form of analysis. The analysis may involve sophisticated engineering calculations or it may involve a very subjective judgment of the aesthete appeal possessed by the design. The analysis procedure identifies certain improvements that can he made in the design. As stated previously, the process is iterative. Each iteration yields an improvement in the design. The trouble with this iterative process is that it is time consuming. Many engineering labor hours are required to complete the design project.

THE APPLICATION OF COMPUTERS FOR DESIGN

The various design-related tasks which are performed by a modem computer-aided design-system can be grouped into four functional areas:

1. Geometric modeling
2. Engineering analysis
3. Design review and evaluation
4. Automated drafting

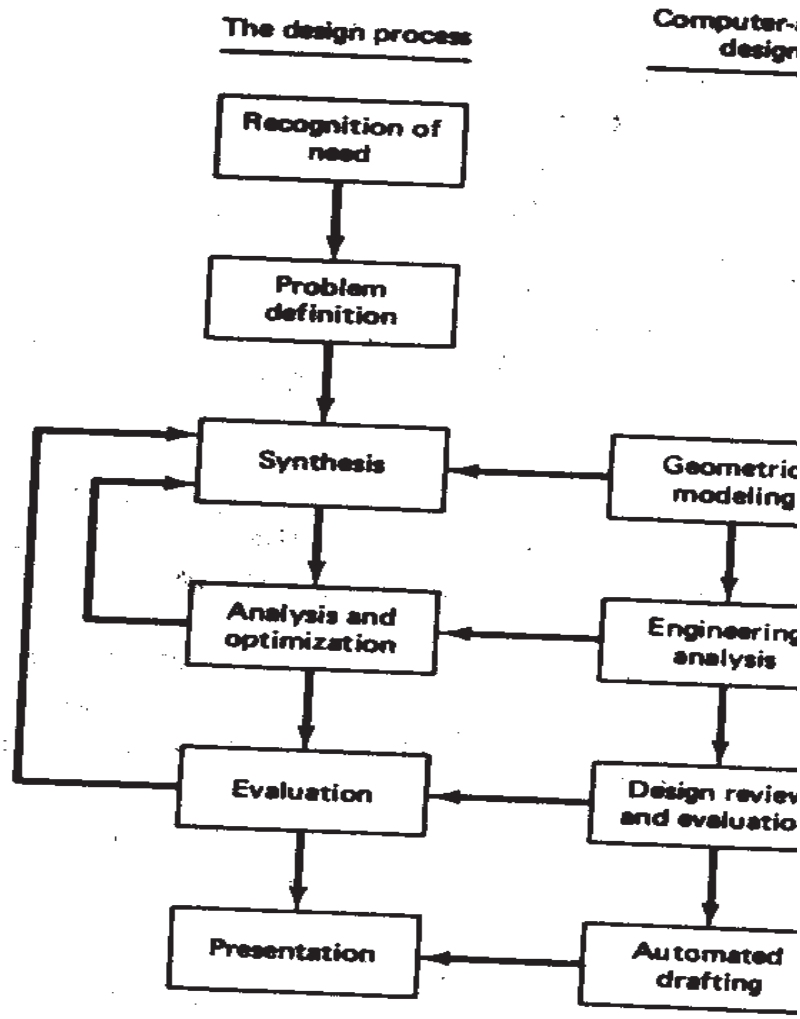
These four areas correspond to the final four phases in Shigley's general design process, illustrated in Figure. Geometric modeling corresponds to the synthesis phase in which the physical design project takes form on the ICG system. Engineering analysis corresponds to phase 4, dealing with analysis and optimization. Design review and evaluation is the fifth step in the general design procedure. Automated drafting involves a procedure for converting the design image data residing in computer memory into a hard-copy document. It represents an important

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method for presentation (phase 6) of the design. The following four sections explore each of these four CAD functions.

Geometric modeling

In computer-aided design, geometric modeling is concerned with the computer-compatible mathematical description of the geometry of an object. The mathematical description allows the image of the object to be displayed and manipulated on a graphics terminal through signals from the CPU of the CAD system. The software that provides geometric modeling capabilities must be designed for efficient use both by the computer and the human designer.



To use geometric modeling, the designer constructs, the graphical image of the object on the CRT screen of the ICG system by inputting three types of

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commands to the computer. The first type of command generates basic geometric elements such as points, lines, and circles. The second command type is used to accomplish scaling, rotating, or other transformations of these elements. The third type of command causes the various elements to be joined into the desired shape of the object being creaed on the ICG system. During the geometric modeling process, the computer converts the commands into a mathematical model, stores it in the computer data files, and displays it as an image on the CRT screen. The model can subsequently be called from the data files for review, analysis, or alteration.

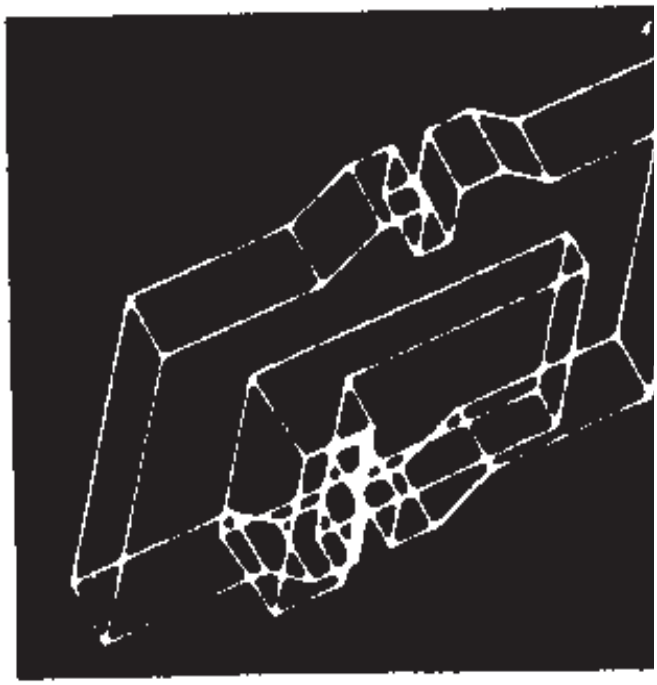
There are several different methods of representing the object in geometric modeling. The basic form uses wire frames to represent the object. In this form, the object is displayed by interconnecting lines as shown in Figure. Wire frame geometric modeling is classified into three types depending on the capabilities of the ICG system. The three types are:

1. 2D. Two-dimensional representation is used for a flat object.

2. 2½D. This goes somewhat beyond the 2D capability by permitting a three-dimensional object to be represented as long as it has no side-wall details.

3. 3D. This allows for full three-dimensional modeling of a more complex geometry.

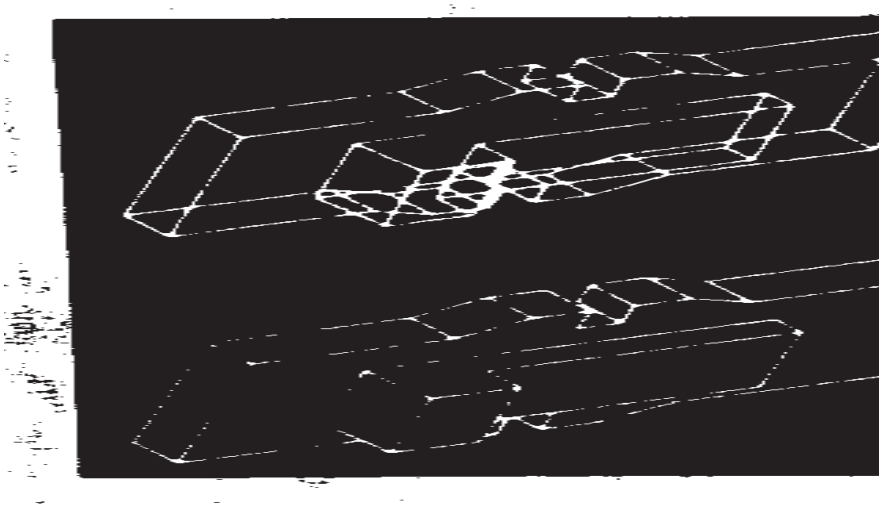
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Example of wire-frame drawing of a part.

Even three-dimensional wire-frame representations of an object are sometimes inadequate for complicated shapes. Wire-frame models can be enhanced by several different methods. Figure shows the same object shown in the previous figure but with two possible improvements. 1be first uses dashed lines to portray the rear edges of the object, those which would be invisible from the front. 1be second enhancement removes the hidden lines completely, thus providing a less cluttered picture of the object for the viewer. Some CAD systems have an automatic "hidden-line removal feature," while other systems require the user to identify the lines that are to be removed from view. Another enhancement of the wire-frame model involves providing a surface representation which makes the object appear solid to the viewer. However, the object is still stored in the computer as a wire-frame model.

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Same workpart as shown in Figure 4.4 but with (a) dashed lines 10 show rear edges of part, and (b) hidden-line removal. (Courtesy of Computervision Corp.)



Solid model of yoke part as displayed on a computer graphics system. (Courtesy of Computervision Corp.)

The most advanced method of geometric modeling is solid modeling in three dimensions. This method, illustrated in Figure, typically uses solid geometry shapes called primitives to construct the object.

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Another feature of some CAD systems is color graphics capability. By means of colour, it is possible to display more information on the graphics screen. Colored images help to clarify components in an assembly, or highlight dimensions, or a host of other purposes.

Engineering analysis

In the formulation of nearly any engineering design project, some type of analysis is required. The analysis may involve stress-strain calculations, heat-transfer computations, or the use of differential equations to describe the dynamic behavior of the system being designed. The computer can be used to aid in this analysis work. It is often necessary that specific programs be developed internally by the engineering analysis group to solve a particular design problem. In other situations, commercially available general-purpose programs can be used to perform the engineering analysis.

Turnkey CAD/CAM systems often include or can be interfaced to engineering analysis software which can be called to operate on the current design model.

We discuss two important examples of this type:

Analysis of mass properties

Finite-element analysis

The analysis of mass properties is the analysis feature of a CAD system that has probably the widest application. It provides properties of a solid object being analyzed, such as the surface area, weight, volume, center of gravity, and moment of inertia. For a plane surface (or a cross section of a solid object) the corresponding computations include the perimeter, area, and inertia properties.

Probably the most powerful analysis feature of a CAD system is the finite-element method. With this technique, the object is divided into a large number of finite elements (usually rectangular or triangular shapes) which form an interconnecting network of concentrated nodes. By using a computer with significant computational capabilities, the entire Object can be analyzed for stress-strain, heat transfer, and other characteristics by calculating the behavior of each node. By determining the interrelating behaviors of all the nodes in the system, the behavior of

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the entire object can be assessed.

Some CAD systems have the capability to define automatically the nodes and the network structure for the given object. 1be user simply defines certain parameters for the finite-element model, and the CAD system proceeds with the computations.

The output of the finite-element analysis is often best presented by the system in graphical format on the CRT screen for easy visualization by the user, For example, in stress-strain analysis of an object, the output may be shown in the form of a deflected shape superimposed over the unstressed object. This is illustrated in Figure. Color graphics can also be used to accentuate the comparison before and after deflection of the object. This is illustrated in Figure for the same image as that shown in Figure . If the finite-element analysis indicates behavior of the design which is undesirable, the designer can modify the shape and recompute the finite-element analysis for the revised design.



Finite-element modeling for stress-strain analysis. Graphics display shows strained part superimposed on unstrained part for comparison.

Design review and evaluation

Checking the accuracy of the design can be accomplished conveniently on the graphics terminal. Semiautomatic dimensioning and tolerancing routines which assign size specifications to surfaces indicated by the user help to reduce the possibility of dimensioning errors. The designer can zoom in on part design details

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and magnify the image on the graphics screen for close scrutiny.

A procedure called layering is often helpful in design review. For example, a good application of layering involves overlaying the geometric image of the final shape of the machined part on top of the image of the rough casting. This ensures that sufficient material is available on the casting to acccomplish the final machined dimensions. This procedure can be performed in stages to check each successive step in the processing of the part.

Another related procedure for design review is interference checking. This involves the analysis of an assembled structure in which there is a risk that the components of the assembly may occupy the same space. This risk occurs in the design of large chemical plants, air-separation cold boxes, and other complicated piping structures.

One of the most interesting evaluation features available on some computer-aided design systems is kinematics. The available kinematics packages provide the capability to animate the motion of simple designed mechanisms such as hinged components and linkages. This capability enhances the designer's visualization of the operation of the mechanism and helps to ensure against interference with other components. Without graphical kinematics on a CAD system, designers must often resort to the use of pin-and-cardboard models to represent the mechanism. commercial software packages are available to perform kinematic analysis. Among these are programs such as ADAMS (Automatic Dynamic Analysis of Mechanical Systems), developed at the University of Michigan. This type of program can be very useful to the designer in constructing the required mechanism to accomplish a specified motion and/or force.

Automated drafting

Automated drafting involves the creation of hard-copy engineering drawings directly from the CAD data base. In some early computer-aided design departments, automation of the drafting process represented the principal justification for investing in the CAD system. Indeed, CAD systems can increase productivity in the drafting function by roughly five times over manual drafting.

Some of the graphics features of computer-aided design systems lend them-

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selves especially well to the drafting process. These features include automatic dimensioning, generation of crosshatched areas, scaling of the drawing, and the capability to develop sectional views and enlarged views of particular path details. The ability to rotate the part or to perform other transformations of the image (e.g., oblique, isometric, or perspective views), as illustrated in Figure, can be of significant assistance in drafting. Most CAD systems are capable of generating as many as six views of the part. Engineering drawings can be made to adhere to company drafting standards by programming the standards into the CAD system. Figure shows an engineering drawing with four views displayed. This drawing was produced automatically by a CAD system. Note how much the isometric view promotes a higher level of understanding of the object for the user than the three orthographic views.

Parts classification and coding

In addition to the four CAD functions described above, another feature of the CAD data base is that it can be used to develop a parts classification and coding system. Parts classification and coding involves the grouping of similar part designs into classes, and relating the similarities by mean of a coding scheme. Designers can use the classification and coding system to retrieve existing part designs rather than always redesigning new parts.

CREATING THE MANUFACTURING DATA BASE

Another important reason for using a CAD system is that it offers the opportunity to develop the data base needed to manufacture the product. In the conventional manufacturing cycle practiced for so many years in industry, engineering drawings were prepared by design draftsmen and then used by manufacturing engineers to develop the process plan (i.e., the "route sheets"). The activities involved in designing the product were separated from the activities associated with process planning. Essentially, a two-step procedure was employed. This was both time consuming and involved duplication of effort by design and manufacturing personnel. In an integrated CAD/CAM system, a direct link is established between product design and manufacturing: It" is the goal of CAD/CAM not only to automate certain phases of design and certain phases of manufacturing,

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but also to automate the transition from design to manufacturing. Computer-based systems have been developed which create much of the data and documentation required to plan and manage the manufacturing operations for the product.

The manufacturing data base is an integrated CAD/CAM data base. It includes all the data on the product generated during design (geometry data, bill of materials and parts lists, material specifications, etc.) as well as additional data required for manufacturing much of which is based 011 the product design. Figure 4.10 shows how the CAD/CAM data base is related to design and manufacturing in a typical production-oriented company.

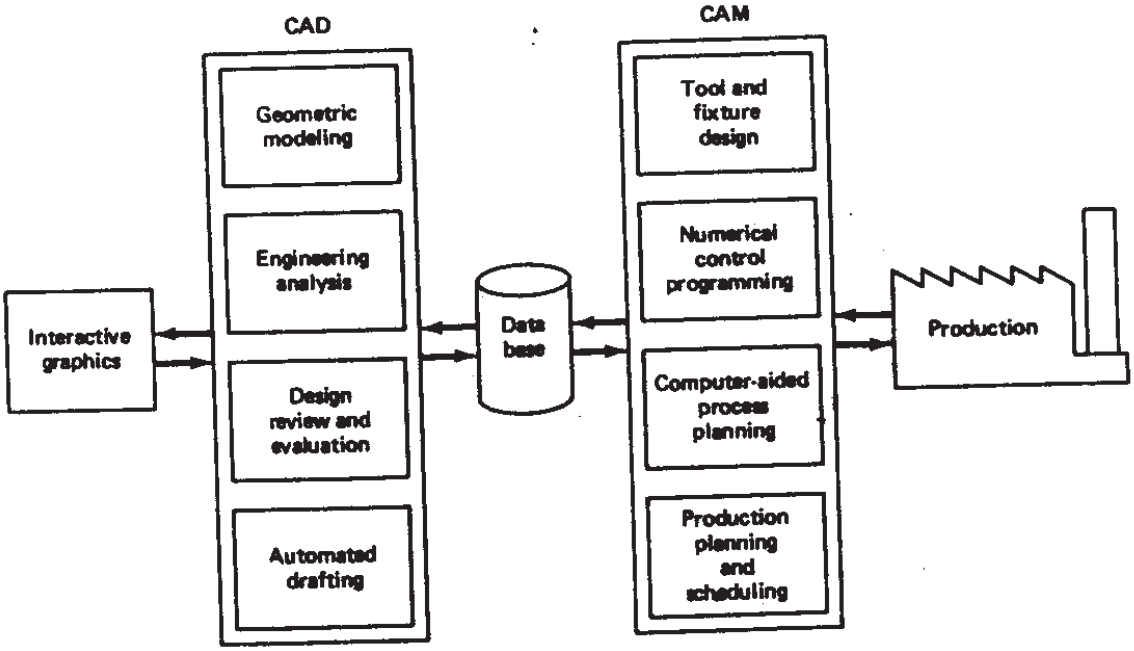


FIGURE Desirable relationship of CAD/CAM data base to CAD and CAM.

BENERTS OF COMPUTER-AIDED DESIGN

There are many benefits of computer-aided design, only some of which can be easily measured. Some of the benefits are intangible, reflected in improved work quality, more pertinent and usable information, and improved control, all of which are difficult to quantify. Other benefits are tangible, but the savings from them show up far downstream in the production process, so that it is difficult to assign a dollar figure to them in the design phase. Some of the benefits that derive from implementing CAD/CAM can be directly measured. Table provides a checklist of

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potential benefits of an integrated CAD/CAM system. In the subsections that follow, we elaborate on some of these advantages.

Productivity improvement in design

Increased productivity translates into a more competitive position for the firm because it will reduce staff requirements on a given project. This leads to lower costs in addition to improving response time on projects with tight schedules.

Surveying some of the larger CAD/CAM vendors, one finds that the Productivity improvement ratio for a designer/draftsman is usually given as a range, typically from a low end of 3: 1 to a high end in excess of 10: 1 (often far in excess of that figure). There are individual cases in which productivity has been increased by a factor of 100, but it would be inaccurate to represent that figure as typical.

TABLE Potential Benefits That May Result from implementing CAD as Part of an Integrated CAD/CAM System.

1. Improved engineering productivity
2. Shorter lead times
3. Reduced engineering personnel requirements
4. Customer modifications are easier to make
5. Faster response to requests for quotations
6. Avoidance of subcontracting to meet schedules
7. Minimized transcription errors
8. Improved accuracy of design
9. In analysis, easier recognition of component interactions
10. Provides better functional analysis to reduce prototype testing
11. Assistance in preparation of documentation
12. Designs have more standardization
13. Better designs provided
14. Improved productivity in tool design
15. Better knowledge of costs provided
16. Reduced training time for routine drafting tasks and NC part programming
17. Fewer errors in NC part programming
18. Provides the potential for using more existing parts and tooling
19. Helps ensure designs are appropriate to existing manufacturing techniques
20. Saves materials and machining time by optimization algorithms

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21. Provides operational results on the status of work in progress
22. Makes the management of design personnel on projects more effective
23. Assistance in inspection of complicated parts
24. Better communication interfaces and greater understanding among engineers, designers, drafters, management, and different project groups.

Productivity improvement in computer-aided design as compared to the traditional design process is dependent on such factors as:

Complexity of the engineering drawing

Level of detail required in the drawing

Degree of repetitiveness in the designed parts

Degree of symmetry in the parts

Extensiveness of library of commonly used entities

As each of these factors is increased. the productivity advantage of CAD will tend to increase

Shorter lead times

Interactive computer-aided design is inherently faster than the traditional design. It also speeds up the task of preparing reports and lists (e.g., the assembly lists) which are normally accomplished manually. Accordingly, it is possible with a CAD system to produce a finished set of component drawings and the associated reports in a relatively short time. Shorter lead times in design translate into shorter elapsed time between receipt of a customer order and delivery of the final product. The enhanced productivity of designers working with CAD systems will tend to reduce the prominence of design, engineering analysis, and drafting as critical time elements in the overall manufacturing lead time.

Design analysis

The design analysis routines available in a CAD system help to consolidate the design process into a more logical work pattern. Rather than having a back- and-forth exchange between design and analysis groups, the same person can perform the analysis while remaining at a CAD workstation. This helps to improve the

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concentration of designers, since they are interacting with their designs in a real-time sense. Because of this analysis capability, designs can be created which are closer to optimum. There is a time saving to be derived from the computerized analysis routines, both in designer time and in elapsed time. This saving results from the rapid response of the design analysis and from the tune no longer lost while the design finds its way from the designer's drawing board to the design analyst's queue and back again.

Fewer design errors

Interactive CAD systems provide an intrinsic capability for avoiding design, drafting, and documentation errors. Data entry, transposition, and extension errors that occur quite naturally during manual data compilation for preparation of a bill of materials are virtually eliminated. One key reason for such accuracy is simply that

No manual handling of information is required once the initial drawing has been developed. Errors are further avoided because interactive CAD systems perform time-consuming repetitive duties such as multiple symbol placement, and sorts by area and by like item, at high speeds with consistent and accurate results. Still more errors can be avoided because a CAD system, with its interactive capabilities, can be programmed to question input that may be erroneous. For example, the system might question a tolerance of 0.00002 in. It is likely that the user specified too many zeros. The success of this checking would depend on the ability of the CAD system designers to determine what input is likely to be incorrect and hence, what to question.

Greater accuracy in design calculations

There is also a high level of dimensional control, far beyond the levels of accuracy attainable manually. Mathematical accuracy is often to 14 significant decimal places. The accuracy delivered by interactive CAD systems in three-dimensional curved space designs is so far behind that provided by manual calculation methods that there is no real comparison.

Computer-based accuracy pays off in many ways. Parts are labeled by the same recognizable nomenclature and number throughout all drawings. In some CAD systems, a change entered on a single item can appear throughout the entire

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documentation package, effecting the change on all drawings which utilize that part. The accuracy also shows up in the form of more accurate material and cost estimates and tighter procurement scheduling. These items are especially important in such cases as long-lead-time material purchases.

Standardization of design, drafting, and documentation procedures

The single data base and operating system is common to all workstations in the CAD system: Consequently, the system provides a natural standard for design/drafting procedure -With interactive computer-aided design, drawings are “standardized” as they are drawn; there is no confusion as to proper procedures because the entire format is "built into" the system program.

Drawings are more understandable

Interactive CAD is equally adept at creating and maintaining isometrics and oblique drawings as well as the simpler orthographies. All drawings can he generated and updated with equal ease. Thus an up-to-date version of any drawing type can always he made available.

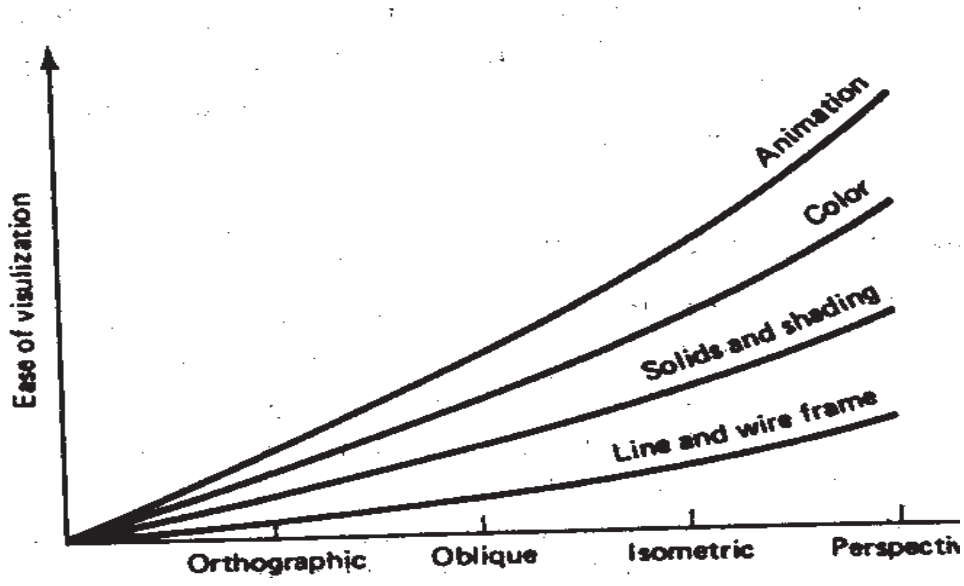


FIGURE Improvement in visualization of images for various drawing types and computer graphics features.

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In general, ease of visualization of a drawing relates directly to the projection used. Orthographic views are less comprehensible than isometrics. An isometric view is usually less understandable than a perspective view. Most actual construction drawings are "line drawings." The addition of shading increases comprehension. Different colors further enhance understanding. Finally, animation of the images on the CRT screen allows for even greater visualization capability. The various relationships are illustrated in Figure..

Improved procedures for engineering changes

Control and implementation of engineering changes is significantly improved with computer-aided design. Original drawings and reports are stored in the data base of the CAD system. This makes them more accessible than documents kept in a drawing vault. They can be quickly checked against new information. Since data storage is extremely compact, historical information from previous drawings can be easily retained in the system's data base, for easy comparison with current design/drafting needs.

Benefits in manufacturing

The benefits of computer-aided design carry over into manufacturing. As indicated previously, the same CAD/CAM data base is used for manufacturing planning and control, as well as for design. These manufacturing benefits are found in the following areas:

Tool and fixture design for manufacturing

Numerical control part programming

Computer-aided process planning

Assembly lists (generated by CAD) for production

Computer-aided inspection

Robotics planning

Group technology

Shorter manufacturing lead times through better scheduling

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These benefits are derived largely from the CAD/CAM data base, whose initial framework is established during computer-aided design. We will discuss the many facets of computer-aided manufacturing in later chapters. In the remainder of this chapter, let us explore several applications that utilize computer graphics technology to solve various problems in engineering and related fields.

HARDWARE IN COMPUTER-AIDED DESIGN

INTRODUCTION

Hardware components for computer-aided design are available in a variety of sizes, configurations, and capabilities. Hence it is possible to select a CAD system that meets the particular computational and graphics requirements of the user firm. Engineering firms that are not involved in production would choose a system exclusively for drafting and design-related functions. Manufacturing firms would choose a system to be part of a company-wide CAD/CAM system. Of course, the CAD hardware is of little value without the supporting software for the system, and we shall discuss the software for computer-aided design in the following chapter.

a modem computer-aided design system is based on interactive computer graphics (ICG). However, the scope of computer-aided design includes other computer systems as well. For example, computerized design has also been accomplished in a batch mode, rather than interactively. Batch design means that data are supplied to the system (a deck of computer cards is traditionally used for this purpose) and then the system proceeds to develop the details of the design. The disadvantage of the batch operation is that there is a time lag between when the data are submitted and when the answer is received back as output. With interactive graphics, the system provides an immediate response to inputs by the user. The user and the system are in direct communication with each other, the user entering commands and responding to questions generated by the system.

Computer-aided design also includes nongraphic applications of the computer in design work. These consist of engineering results which are best displayed in other than graphical form. Nongraphic hardware (e.g., line printers) can be employed to create rough images on a piece of paper by appropriate combinations of characters and symbols. However, the resulting pictures, while they may create

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interesting wall posters, are not suitable for design purposes.

The hardware we discuss in this chapter is restricted to CAD systems that utilize interactive computer graphics. Typically, a stand-alone CAD system would include the following hardware components:

One or more design workstations. These would consist of:

A graphics terminal

Operator input devices

One or more plotters and other output devices

Central processing unit (CPU)

Secondary storage

These hardware components would be arranged in a configuration as illustrated in Figure. The following sections discuss these various hardware components and the alternatives and options that can be obtained in each category.

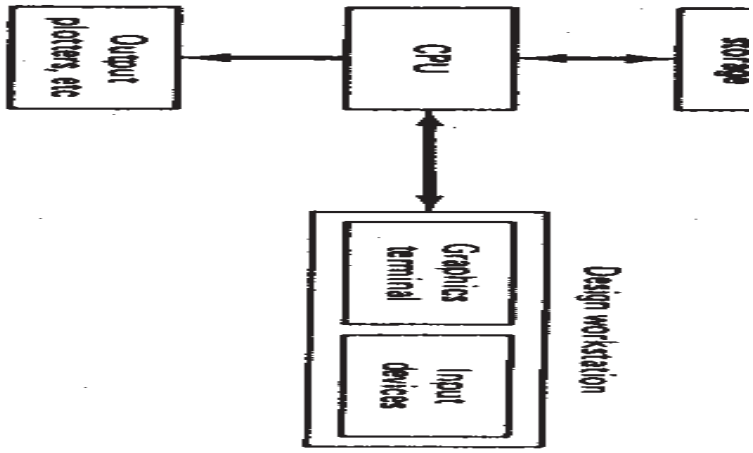


FIGURE Typical configuration of hardware components in a stand-alone CAD system. There would likely be more than one design workstation.

THE DESIGN WORKSTATION

The CAD workstation is the system interface with the outside world. It represents a significant factor in determining how convenient and efficient it is for a designer to use the CAD system. The workstation must accomplish five functions:

1. It must interface with the central processing unit.

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2. It must generate a steady graphic image for the user.

3. It must provide digital descriptions of the graphic image.

4. It must translate computer commands into operating functions.

5. It must facilitate communication between the user and the system]

The use of interactive graphics has been found to be the best approach to accomplish these functions. A typical interactive graphics workstation would consist of the following hardware Components:

A graphics terminal

Operator input devices

A graphics design workstation showing these components is illustrated in Figure.



FIGURE Interactive graphics design workstation showing graphics terminal and two input devices: alphanumeric keyboard and electronic tablet and pen.

THE GRAPHICS TERMINAL

'There are various technological approaches which have been applied to the development of graphics terminals. The technology continues to evolve as CAD

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system manufactures attempt to improve their products and reduce their costs. In this section we present a discussion of the current technology in interactive computer graphics terminals.

Image generation in computer graphics

Nearly all computer graphics terminals available today use the cathode ray tube (CRT) as the display device. Television sets use a form of the same device as the picture tube. 'The operation of the CRT is illustrated in Figure. A heated cathode emits a high-speed electron beam onto a phosphor-coated glass screen. 'The electrons energize the phosphor coating, causing it to glow at the points where the beam makes contact. By focusing the electron beam, changing its intensity, and controlling its point of contact against the phosphor coating through the use of a deflector system, the beam can be made to generate a picture on the CRT screen.

There are two basic techniques used in current computer graphics terminals for generating the image on the CRT screen. They are:

1. Stroke writing

2. Raster scan

Other names for the stroke-writing technique include line drawing, random position, vector writing, stroke writing, and directed beam. Other names for the raster scan technique include digital TV and scan graphics.

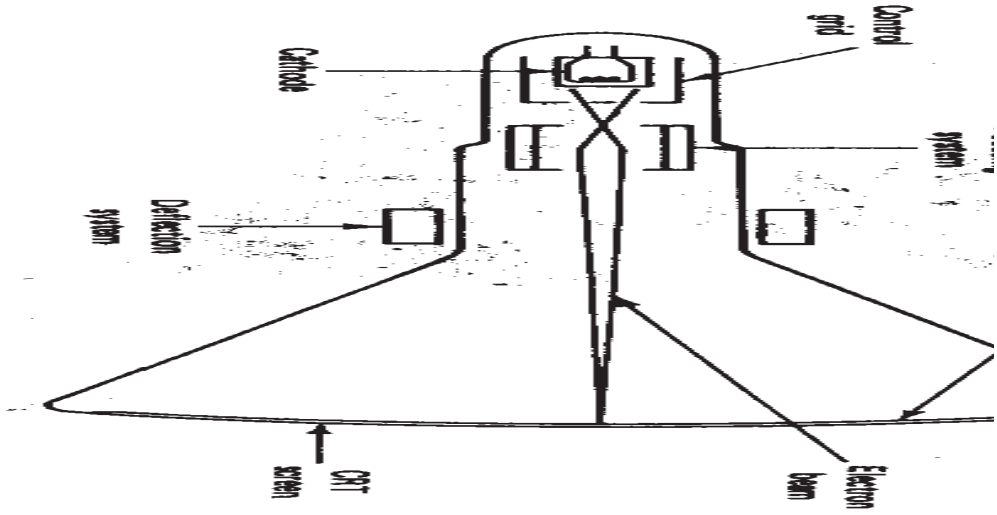


FIGURE Diagram of cathode ray tube (CRT).

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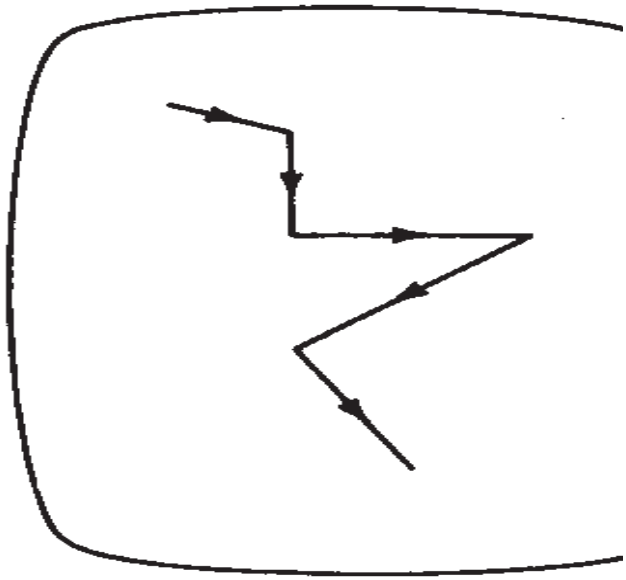


FIGURE Stroke writing for generating images in computer graphics.

The stroke-writing system uses an electron beam which operates like a pencil to create a line image on the CRT screen. The image is constructed out of a sequence of straight-line segments. Each line segment is drawn on the screen by directing the beam to move from one point on the screen to the next, where each point is defined by its x and y coordinates. The process is portrayed in Figure . Although the procedure results in images composed of only straight lines, smooth curves can be approximated by making the connecting line segments short enough.

In the raster scan approach, the viewing screen is divided into a large number of discrete phosphor picture elements, called pixels. The matrix of pixels constitutes the raster. The number of separate pixels in the raster display might typically range from 256 × 256 (a total of over 65,(00) to 1024 × 1024 (a total of over 1,000,000 points). Each pixel on the screen can be made to glow with a different brightness. Color screens provide for the pixels to have different colors as well as brightness. During operation, an electron beam creates the image by sweeping along a horizontal line on the screen from left to right and energizing the pixels in that line during the sweep. When the sweep of one line is completed, the electron beam moves to the next line below and proceeds in a fixed pattern as indicated in Figure. After sweeping the entire screen the process is repeated at a rate of 30 to 60 entire scans of the screen per second:)

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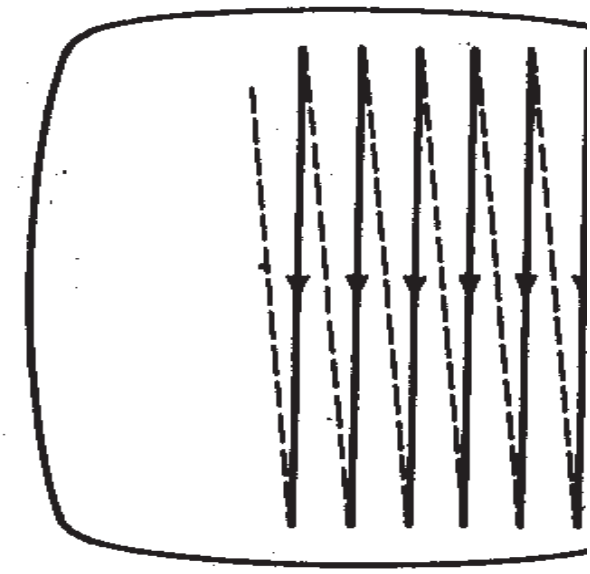


FIGURE Raster scan approach for generating images in computer graphics.

Graphics terminals for computer-aided design

The two approaches described above are used in the overwhelming majority of current-day CAD graphics terminals. There are also a variety of other technical factors which result in different types of graphics terminals. These factors include the type of phosphor coating on the screen, whether color is required, the pixel density, and the amount of computer memory available to generate the picture. We will discuss three types of graphics terminals, which seem to be the most important today in commercially available CAD systems. The three types are:

1. Directed-beam refresh

2. Direct-view storage tube (DVST)

3. Raster scan (digital TV)

The following paragraphs describe the three basic types. We then discuss some of the possible enhancements, such as color and animation.

DIRECTED-BEAM REFRESH. The directed-beam refresh terminal utilizes the stroke-writing approach to generate the image on the CRT screen. The term "refresh" in the name refers to the fact that the image must be regenerated many times per second in order to avoid noticeable flicker of the image. The phosphor

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elements on the screen surface are capable of maintaining their brightness for only a short time (sometimes measured in microseconds). In order for the image to be continued, these picture tubes must be refreshed by causing the directed beam to retrace the image repeatedly. On densely filled screens (very detailed line images or many characters of text), it is difficult to avoid flickering of the image with this process. On the other hand, there are several advantages associated with the directed-beam refresh systems. Because the image is being continually refreshed, selective erasure and alteration of the image is readily accomplished. It is also possible to provide animation of the image with a refresh tube.

The directed-beam refresh system is the oldest of the modem graphics display technologies. Other names sometimes used to identify this system include vector refresh and stroke-writing refresh. Early refresh tubes were very expensive. but the steadily decreasing cost of solid-state circuitry has brought the price of these graphics systems down to a level which is competitive with other types.

DIRECT-VIEW STORAGE TUBE (DVST). DVST terminals also use the stroke-writing approach to generate the image on the CRT screen. The term storage tube refers to the ability of the screen to retain the image which has been projected against it, thus avoiding the need to rewrite the image which has been projected against it, thus avoiding the need to rewrite the image constantly. What makes this possible is the use of an electron flood gun directed at the phosphor coated screen which keeps the phosphor elements illuminated once they have been energized by the stroke-writing electron beam. The resulting image on the CRT screen is flicker-free. Lines may be readily added to the image without concern over their effect on image density or refresh rates. However, the penalty associated with the storage tube is that individual lines cannot be selectively removed from the image.

Storage tubes have historically been the lowest-cost terminals and are capable of displaying large amounts of data, either graphical or textual. Because of these features, there are probably more storage tube terminals in service in industry at the time of this writing than any other graphics display terminal. The principal disadvantage of a storage CRT is that selective erasure is not possible. Instead, if the user wants to change the picture, the change will not be manifested on the screen

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until the entire picture is regenerated. Other disadvantages include its lack of color capability, the inability to use a light pen as a data entry, and its lack of animation capability.

RASTER SCAN TERMINALS. Raster scan terminals operate by causing an electron beam to trace a zigzag pattern across the viewing screen, as described earlier. The operation is similar to that of a commercial television set. The difference is that a TV set uses analog signals originally generated by a video camera to construct the image on the CRT screen, while the raster scan ICG terminal uses digital signals generated by a computer. For this reason, the raster scan terminals used in computer graphics are sometimes called digital TVs.

The introduction of the raster scan graphics terminal using a refresh tube had been limited by the cost of computer memory. For example, the simplest and lowest-cost terminal in this category uses only two beam intensity levels, on or off. This means that each pixel in the viewing screen is either illuminated or dark. A picture tube with 256 lines of resolution and 256 addressable points per line to form the image would require 256 × 256 or over 65,000 bits of storage. Each bit of memory contains the on/off status of the corresponding pixel on the CRT screen. This memory is called the frame buffer or refresh buffer. The picture quality can be improved in two ways: by increasing the pixel density or adding a gray scale (or color). Increasing pixel density for the same size screen means adding more lines of resolution and more addressable points per line. A 1024 × 1024 raster screen would require more than 1 million bits of storage in the frame buffer. A gray scale is accomplished by expanding the number of intensity levels which can be displayed on each pixel. This requires additional bits for each pixel to store the intensity level. Two bits are required for four levels, three bits for eight levels, and so forth. Five or six bits would be needed to achieve an approximation of a continuous gray scale. For a color display, three times as many bits are required to get various intensity levels for each of the three primary colors: red, blue, and green. (We discuss color in the following section.) A raster scan graphics terminal with high resolution and gray scale can require a very large capacity refresh buffer. Until recent developments in memory technology, the cost of this storage capacity was prohibitive for a terminal with good picture quality. The capability to achieve color and animation was not

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possible except for very low resolution levels.

TABLE Comparison of Graphics Terminal Features

	Directed-beam refresh	**DVST**	**Raster scan**
Image generation	Stroke writing	Stroke writing	Raster scan
Picture quality	Excellent	Excellent	Moderate to good
Data content	Limited	High	High
Selective erase	Yes	No	Yes
Gray scale	Yes	No	Yes
Color capability	Moderate	No	Yes
Animation capability	Yes	No	Moderate

It is now possible to manufacture digital TV systems for interactive computer graphics at prices which are competitive with the other two types. The advantages of the present raster scan terminals include the feasibility to use low-cost TV monitors, color capability, and the capability for animation of the image. These features, plus the continuing improvements being made in raster scan technology, make it the fastest-growing segment of the graphics display market.

The typical color CRT uses three electron beams and a triad of color dots an the phosphor screen to provide each of the three colors, red, green, and blue. By combining the three colors at different intensity levels, a variety of colors can be created on the screen. It is mare difficult to fabricate a stroke-writing tube which is precise enough far color because of the technical problem of getting the three beams to. converge properly against the screen .

The raster scan approach has superior color graphics capabilities because of the developments which have been made over the years in the color television industry. Color raster scan terminals with 1024 × 1024 resolution are commercially available for computer graphics. The problem in the raster terminals is the memory requirements of the refresh buffer. Each pixel on the viewing screen' may require up to 24 bits of memory in the refresh buffer in order to display the full range of color

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tones. When multiplied by the number of pixels in the display screen, this translates into a very large storage buffer.

The capability for animation in computer graphics is limited to display methods in which the image can be quickly redrawn. This limitation excludes the storage tube terminals Both the directed-beam refresh and the raster scan systems are capable of animation. However, this capability is not automatically acquired .with these systems. It must be accomplished by means of a powerful and fast CPU interfaced to the graphics terminal to process the large volumes of data required for animated images In computer-aided design, animation would be a powerful feature in applications where kinematic simulation is required. The analysis of linkage mechanisms and other mechanical behavior would be examples. In computer-aided manufacturing, the planning of a robotic work cycle would be improved through the use of an animated image of the robot simulating the motion of the arm during the cycle. The popular video games marketed by Atari and other manufacturers for use with home TV sets are primitive examples of animation in computer graphics. Animation in these TV games is made possible by sacrificing the quality of the picture. This keeps the price of these games within an affordable range.

OPERATOR INPUT DEVICES

Operator input devices are provided at the graphics workstation to facilitate convenient communication between the user and the system. Workstations generally have several types of input devices to allow the operator to select the various preprogrammed input functions. These functions permit the operator to create or modify an image on the CRT screen or to enter alphanumeric data into the system. This results in a complete part on the CRT screen as well as complete geometric description of the part m the CAD data base.

Different CAG system vendors offer different types of operator input devices. These devices can be divided into three general categories:

1. Cursor control devices
2. Digitizers
3. Alphanumeric and other keyboard terminals

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Of the three, cursor control devices and digitizers are both used for graphical interaction with the system. Keyboard terminals are used as input devices for commands and numerical data.

There are two basic types of graphical interaction accomplished by means of cursor control and digitizing:

Creating and positioning new items on the CRT screen

Pointing at or otherwise identifying locations on the screen, usually associated with existing images

Ideally, a graphical input device should lend itself to both of these functions. However, this is difficult to accomplish with a single unit and that is why most workstations have several different input devices.

Cursor control

The cursor normally takes the form of a bright spot on the CRT screen that, indicates where lettering or drawing will occur. The computer is capable of reading the current position of the cursor. Hence the user's capability to control the cursor position allows locational data to be entered into the CAD system data base. A typical example would be for the user to locate the cursor to identify the starting point of a line. Another, more sophisticated case, would be for the user to position the cursor to select an item from a menu of functions displayed on the screen. For instance, the screen might be divided into two sections, one of which is an array of blocks which correspond to operator input functions. The user simply moves the cursor to the desired block to execute the particular function.

There are a variety of cursor control devices which have been employed in CAD systems. These include:

Thumbwheels

Direction keys on a keyboard terminal

Joysticks

Tracker ball

Light pen

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Electronic tablet/pen

The first four items in the list provide control over the cursor without any direct physical contact of the screen by the user. The last two devices in the list require the user to control the cursor by touching the screen (or some other flat surface which is related to the screen) with a pen-type device.

The thumbwheel device uses two thumbwheels, one to control the horizontal position of the cursor, the other to control the vertical position. This type of device is often mounted as an integral part of the CRT terminal. The cursor in this arrangement is often represented by the intersection of a vertical line and a horizontal line displayed on the CRT screen. The two lines are like crosshairs in a gunsight which span the height and width of the screen.

Direction keys on the keyboard are another basic form of cursor control used not only for graphics terminals but also for CRT terminals without graphics capabilities. Four keys are used for each of the four directions in which the cursor can be moved (right or left, and up or down).

The joystick apparatus is pictured in Figure. It consists of a box with a vertical toggle stick that can be pushed in any direction to cause the cursor to be moved in that direction. The joystick gets its name from the control stick that was used 10 old airplanes.

The tracker ball is pictured in Figure. Its operation is similar to that of the joystick except that an operator-controlled ball is rotated to move the cursor in the desired direction on the screen.

The light pen is a pointing device in which the computer seeks to identify the

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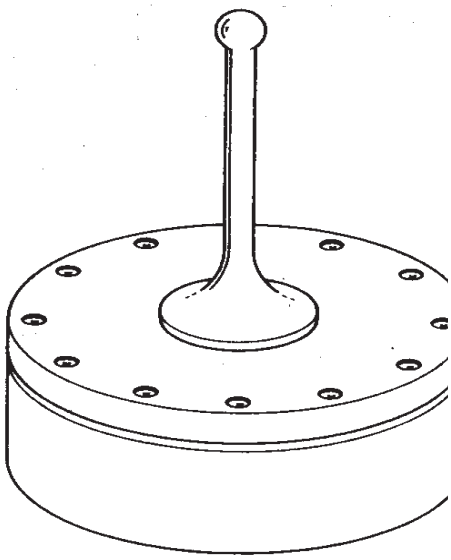


FIGURE Joystick input device for interactive computer graphics

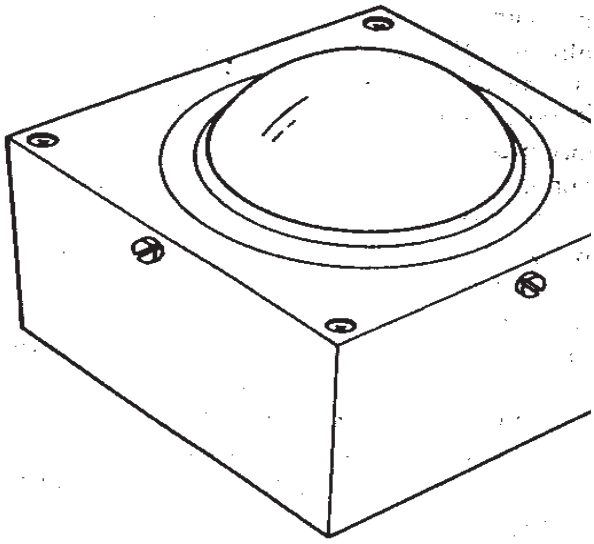


FIGURE Tracker ball input device for interactive computer graphics.

position where the light pen is in contact with the screen. Contrary to what its name suggests, the light pen does not project light. Instead, it is a detector of light on the CRT screen and uses a photodiode, phototransistor, or some other form of light sensor. The light pen can be utilized with a refresh-type CRT but not with a storage tube. This is because the image on the refresh tube is being generated in time sequence. The time sequence is so short that the image appears continuous to the human eye. However, the computer is capable of discerning the time sequence and it

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coordinates this timing with the position of the pen against the screen. In essence, the system is performing as an optical tracking loop to locate the cursor or to execute some other input function. The tablet and pen in computer graphics describes an electronically sensitive tablet used in conjunction with an electronic stylus. The tablet is a flat surface, separate from the CRT screen, on which the user draws with the penlike stylus to input instructions or to control the cursor

It should be noted that thumbwheels, direction keys, joysticks, and tracker balls are generally limited in their functions to cursor control. The light pen and tablet/pen are typically used for other input functions as well as cursor control. Some of these functions are:

Selecting from a function menu

Drawing on the screen or making strokes on the screen or tablet which indicate what image is to be drawn

Selecting a portion of the screen for enlargement of an existing image

Digitizers

The digitizer is an operator input device which consists of a large, smooth board (the appearance is similar to a mechanical drawing board) and an electronic tracking device which can be moved over the surface to follow existing lines. It is a common technique in CAD systems for taking x, y coordinates from a paper drawing. The electronic tracking device contains a switch for the user to record the desired x and y coordinate positions. The coordinates can be entered into the computer memory or stored on an off-line storage medium such as magnetic tape. High-resolution digitizers, typically with a large board (e.g., 42 in by 60 in.) can provide resolution and accuracy on the order of 0.001 in. It should be mentioned that the electronic tablet and pen, previously discussed as a cursor control device, can be considered to be a small, low-resolution digitizer.

Not all CAD systems would include a digitizer as part of its core of operator input devices. It would be inadequate, for example, in three-dimensional mechanical design work since the digitizer is limited to two dimensions. For two-dimensional drawings, drafters can readily adapt to the digitizer because it is similar to their drafting boards. It can be tilted, raised, or lowered to assume a comfortable position

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for the drafter.

The digitizer can be used to digitize line drawings. The user can input data from a rough schematic or large layout drawing and edit the drawings to the desired level of accuracy and detail. The digitizer can also be used to freehand a new design with subsequent editing to finalize the drawing.

Keyboard terminals

Several forms of keyboard terminals are available as CAD input devices. The most familiar type is the alphanumeric terminal which is available with nearly all interactive graphics systems. The alphanumeric terminal can be either a CRT or a hard copy terminal, which prints on paper. For graphics, the CRT has the advantage because of its faster speed, the ability to easily edit, and the avoidance of large volumes of paper. On the other hand, a permanent record is sometimes desirable and this is most easily created with a hard-copy terminal. Many CAD systems use the graphics screen to display the alphanumeric data, but there is an advantage in having a separate CRT terminal so that the alphanumeric messages can be created without disturbing or overwriting the image on the graphics screen.

The alphanumeric terminal is used to enter commands, functions, and supplemental data to the CAD system. This information is displayed for verification on the CRT or typed on paper. The system also communicates back to the user in a similar manner. Menu listings, program listings, error messages, and so forth, can be displayed by the computer as part of the interactive procedure.

These function keyboards are provided to eliminate extensive typing of commands, or calculate coordinate positions, and other functions. The number of function keys varies from about 8 to 80. The particular function corresponding with each button is generally under computer control so that the button function can be changed as the user proceeds from one phase of the design to the next. In this way the number of alternative functions can easily exceed the number of but tons on the keyboard.

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Also, lighted buttons are used on the keyboards to indicate which functions are possible in the current phase of design activity. A menu of the various function alternatives is typically displayed on the CRT screen for the user to select the desired function.

PLOTTERS AND OTHER OUTPUT DEV CES

There are various types of output devices used in conjunction with a computer-aided design system. These output devices include:

Pen plotters

Hard-copy units

Electrostatic plotters Computer-output-to-microfilm (COM) units

We discuss these devices in the following sections.

Pen plotters

The accuracy and quality of the hard-copy plot produced by a pen plotter is considerably greater than the apparent accuracy and quality of the corresponding image on the CRT screen. In the case of the CRT image, the quality of the picture is degraded because of lack of resolution and because of losses in the digital-to-analog conversion through: the display generators. On the other hand, a high-precision pen plotter is capable of achieving a hard-copy drawing whose accuracy is nearly consistent with the digital definitions in the CAD data base.

The pen plotter uses a mechanical ink pen (either wet ink or ballpoint) to write on paper through relative movement of the pen and paper. There are two basic types of pen plotters currently in use:

Drum plotters

Fiat-bed plotters

Hard-copy unit

A hard-copy unit is a machine that can make copies from the same image data layed on the CRT screen. The image on the screen can be duplicated in a matter of seconds. The copies can be used as records of intermediate steps in the design process or when rough hard copies of the screen are needed quickly. The hard copies

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produced from these units are not suitable as final drawings because the accuracy and quality of the reproduction is not nearly as good as the output of a pen plotter.

Most hard-copy units are dry silver copiers that use light-sensitive paper exposed through a narrow CRT window inside the copier. The window is typically 8½ in. (216 mm), corresponding to the width of the paper, by about ½ in. (12 mm) wide. The paper is exposed by moving it past the window and coordinating the CRT beam to gradually transfer the image. A heated roller inside the copier is used to develop the exposed paper. The size of the paper is usually limited on these hard-copy units to 8½ by II in. Another drawback is that the dry silver copies will darken with time when they are left exposed to normal light.

Electrostatic plotters

Hard-copy units are relatively fast but their accuracy and resolution are poor. Pen plotters are highly accurate but plotting time can take many minutes (up to a half-hour or longer for complicated drawings). The electrostatic plotter offers a compromise between these two types in terms of speed and accuracy. It is almost as fast as the hard-copy unit and almost as accurate as the pen plotter.

The electrostatic copier consists of a series of wire styli mounted on a bar which spans the width of the charge-sensitive paper. The styli have a density of up to 200 per linear inch. The paper is gradually moved past the bar and certain styli are activated to place dots on the paper. By coordinating the generation of the dots with the paper travel, the image is progressively transferred from the data base into hard-copy form. The dots overlap each other slightly to achieve continuity. For example, a series of adjacent dots gives the appearance of a continuous line.

A limitation of the electrostatic plotter is that the data must be in the raster format (i.e., in the same format used to drive the raster-type CRT) in order to be readily converted into hard copy using the electrostatic method. If the data are not in raster format, some type of conversion is required to change them into the required format. The conversion mechanism is usually based on a combination of software and hardware.

An advantage of the electrostatic plotter which is shared with the drum-type

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pen plotter is that the length of the paper is virtually unlimited. Typical plotting widths might be up to 6 ft (1.83 m). Another advantage is that the electrostatic plotter can be utilized as a high-speed line printer, capable of up to 1200 lines of text per minute.

THE CENTRAL PROCESSING UNIT

The CPU operates as the central "brain" of the computer-aided design system. It is typically a minicomputer. It executes all the mathematical computations needed to accomplish graphics and other functions, and it directs the various activities within the system.

COMPUTER GRAPHICS SOFTWARE AND DATA BASE

INTRODUCTION

The graphics software is the collection of programs written to make it convenient for a user to operate the computer graphics system. It includes Programmes to generate images on the CRT screen, to manipulate the images, and to accomplish various types of interaction between the user and the system. In addition to the graphics software, there may be additional programs for implementing certain specialized functions related to CAD/CAM. These include design analysis programs(e.g., finite-element analysis and kinematic simulation) and Manufacturing planning programs (e.g., automated process planning and numerical control part programming). This chapter deals mainly with the graphics software.

The graphics software for a particular computer graphics system is very much a function of the type of hardware used in the system. The software must be written specifically for the type of CRT and the types of input devices used in the system. The details of the software for a stroke-writing CRT would be different than for a raster scan CRT. The differences between a storage tube and a refresh tube would also influence the graphics software. Although these differences in software may be invisible to the user to some extent, they are important considerations in the design of an interactive computer graphics system.

Newman and Spoull list six “ground rules” that should be considered in designing graphics software:

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1. Simplicity. The graphics software should be easy to use.

2. Consistency . The package should operate in a consistent and predictable way to the user.

3. Completeness. There should be no inconvenient omissions in the set of graphics functions.

4. Robustness. The graphics system should be tolerant of minor instances of misuse by the operator.

5. Performance. Within limitations imposed by the system hardware, the performance should be exploited as much as possible by software. Graphics programs should be efficient and speed of response should be fast and consistent.

6. Economy. Graphics programs should not be so large or expensive as to make their use prohibitive.

THE SOFTWARE CONFIGURATION OF A GRAPHICS SYSTEM

In the operation of the graphics system by the user, a variety of activities take place, which can be divided into three categories:

1. Interact with the graphics terminal to create and alter images on the screen

2. Construct a model of something physical out of the images on the screen. the models are sometimes called application models.

3. Enter the model into computer memory and/or secondary storage.

In working with the graphics system the user performs these various activities in combination rather than sequentially. The user constructs a physical model and inputs it to memory by interactively describing images to the system. This is done without any thought about whether the activity falls into category 1, 2, or 3.

The reason for separating these activities in this fashion is that they correspond to the general configuration of the software package used with the interactive computer graphics (ICG) system. The graphics software can be divided

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into three modules according to a conceptual model suggested by Foley and Van Dam:

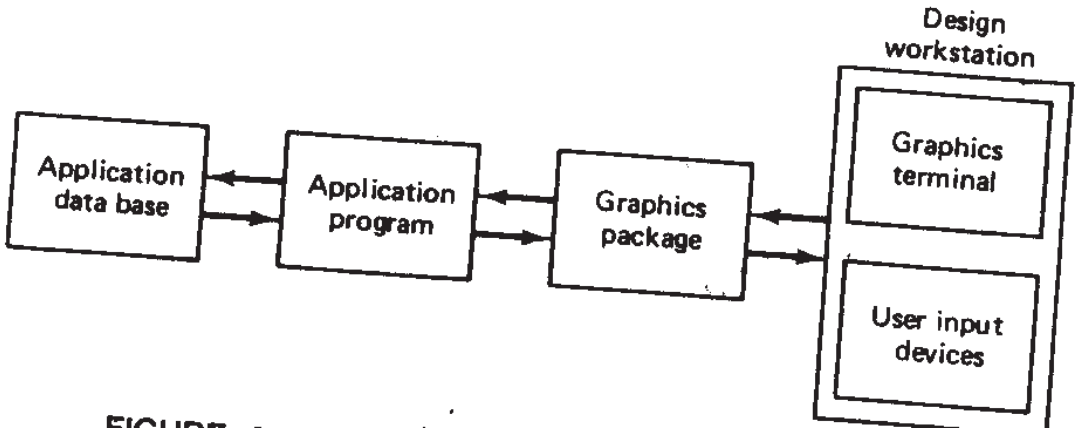
1. The graphics package (Foley and Van Dam called this the graphics system)

2. The application program

3. The application data base

This software configuration is illustrated in Figure. The central module is the application program. It controls the storage of data into and retrieves data out of the application data base. The application program is driven by the user through the graphics package.

The application program is implemented by the user to construct the model of a physical entity whose image 'is to be viewed on the graphics-screen. Application programs are written for particular problem areas. Problem areas in engineering design would include architecture, construction, mechanical components, electronics, chemical engineering, and aerospace engineering. Problem areas other than design would include flight simulators, graphical display of data, mathematical analysis, and even artwork. In each case, the application software is developed to deal with images and conventions which are appropriate for that field.



The graphics package is the software support between the user and the graphics terminal. It manages the graphical interaction between the user and the system. It also serves as the interface between the user and the application software. The graphics package consists of input subroutines and output subroutines. The input

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routines accept input commands and data from the user and forward them to the application program. The output subroutines control the display terminal (or other output device) and converts the application models into two-dimensional or three-dimensional graphical pictures.

The third module in the ICG software is the data base. The data base contains mathematical, numerical, and logical definitions of the application models, such as electronic circuits, mechanical components, automobile bodies, and so forth. It also includes alphanumeric information associated with the models, such as bills of materials, mass properties, and other data. The contents of the data base can be readily displayed on the CRT or plotted out in hard-copy form. Section

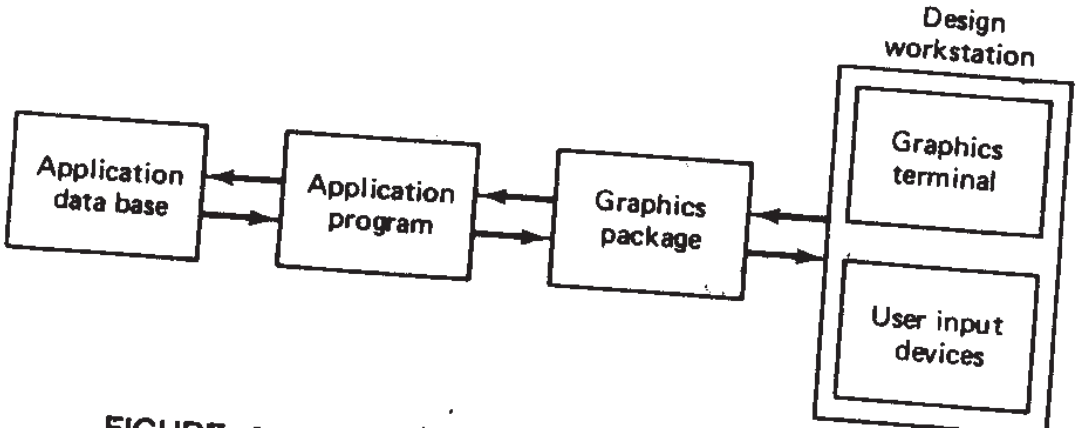


FIGURE Model of graphics software configuration .

FUNCTIONS OF A GRAPHICS PACKAGE

To fulfill its role in the software configuration, the graphics package must perform a variety of different functions. these functions can be grouped into function sets. Each set accomplishes a certain kind of interaction between the user and the system. Some of the common function sets are:

Generation of graphic elements

Transformations

Display control and windowing functions

Segmenting functions

User input functions

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TRANSFORMATIONS

Many of the editing features involve transformations of the graphics elements or cells composed of elements or even the entire model. In this section we discuss the mathematics of these transformations. Two-dimensional transformations are considered first to illustrate concepts. Then we deal with three dimensions.

Two-dimensional transformations

To locate a point in a two-axis cartesian system, the x and y coordinates are specified. These coordinates can be treated together as a 1x1 matrix: (*x,y*). For example, the matrix (2, 5) would be interpreted to be a point which is 2 units from the origin in the x-direction and 5 units from the origin in the y-direction.

This method of representation can be conveniently extended to define a line as a 2 x 2 matrix by giving the x and y coordinates of the two end points of the line. The notation would be

$$L = \begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \end{bmatrix}$$

Using the rules of matrix algebra, a point or line (or other geometric element represented in matrix notation) can be operated on by a transformation matrix to yield a new element.

There are several common transformations used in computer graphics. We will discuss three transformations: translation, scaling, and rotation.

TRANSLATION. Translation involves moving the element from one location to another. In the case of a point, the operation would be

$x' = x + m, \qquad y' = y + n$

where x', y' = coordinates of the translated point

x, y = coordinates of the original point

m, n = movements in the x and y directions, respectively

In matrix notation this can be represented as

$(x', y') = (x, y) + T$

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where

T = (m,n), the translation matrix

Any geometric element can be translated in space by applying Eq. to each point that defines the element. For a line, the transformation matrix would be applied to its two end points.

SCALING. Scaling of an element is used to enlarge it or reduce its size. The scaling need not necessarily be done equally in the x and y directions. For example, a circle could be transformed into an ellipse by using unequal x and y scaling factors.

The points of an element can be scaled by the scaling matrix as follows:

(x' ,y') = (x,y)S

where

$$s = \begin{bmatrix} m & 0 \\ 0 & n \end{bmatrix}$$ the scaling matrix

This would produce an alteration in the size of the element by the factor m in the x-direction and by the factor n in the y direction. It also has the effect of repositioning the element with respect to the cartesian system origin. If the scaling factors are less than I, the size of the element is reduced and it is moved closer to the origin. If the scaling factors are larger than I, the element is enlarged and removed farther from the origin.

ROTATION. In this transformation, the points of an object are rotated about the origin by an angle O. For a positive angle, this rotation is in the counterclockwise direction. This accomplishes rotation of the object by the same angle, but it also moves the object. In matrix notation, the procedure would be as follows:

(x',y') = (x,y)R

where

$$R = \begin{bmatrix} \cos 0 & \sin 0 \\ -\sin 0 & \cos 0 \end{bmatrix}$$ the rotation matrix

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EXAMPLE 6.1

As an illustration of these transformations in two dimensions, consider the line defined by

$$L = \begin{bmatrix} 1 & 1 \\ 2 & 4 \end{bmatrix}$$

Let us suppose that it is desired to translate the line in space by 2 units in the x direction and 3 units in the y direction. This would involve adding 2 to the current x value and 3 to the current y value of the end points defining the line. That is,

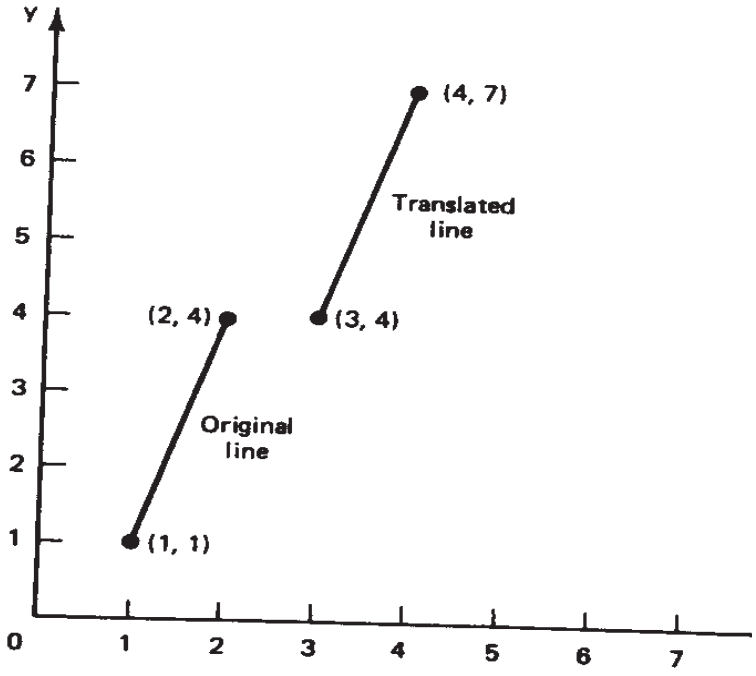


FIGURE. Results of translation in Example 6.1.

$$\begin{bmatrix} 1 & 1 \\ 2 & 4 \end{bmatrix} + \begin{bmatrix} 2 & 3 \\ 2 & 3 \end{bmatrix} = \begin{bmatrix} 3 & 4 \\ 4 & 7 \end{bmatrix}$$

The new line would have end points at (3, 4) and (4, 7). The effect of the transformation is illustrated in Figure 6.3.

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EXAMPLE

For the same original line as in Example 6.1, let us apply the scaling factor of 2 to the line. The scaling matrix for the 2 x 2 line definition would therefore be

$$T = \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix}$$

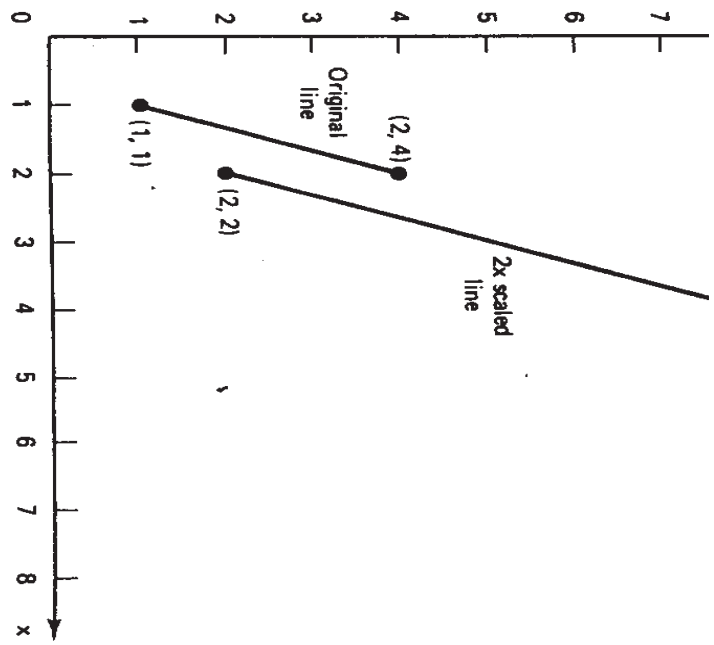
The resulting line would be determined by Eq. as follows:

$$\begin{bmatrix} 1 & 1 \\ 2 & 4 \end{bmatrix} - \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix} = \begin{bmatrix} 2 & 4 \\ 4 & 8 \end{bmatrix}$$

The new line is pictured in Figure .

EXAMPLE

We will again use our same line and rotate the line about the origin by 30°. Equation would be used to determine the transformed line where the rotation matrix would be:



FigureResults of scaling in Example .

$$R = \begin{bmatrix} \cos 30 & \sin 30 \\ -\sin 30 & \cos 30 \end{bmatrix} = \begin{bmatrix} 0.866 & 0.500 \\ -0.500 & 0.866 \end{bmatrix}$$

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The new line would be defined as:

$$\begin{bmatrix} 1 & 1 \\ 2 & 4 \end{bmatrix} \begin{bmatrix} 0.866 & 0.500 \\ -0.50 & 0.866 \end{bmatrix} = \begin{bmatrix} 0.366 & 1.366 \\ -0.268 & 4.464 \end{bmatrix}$$

The effect of applying the rotation matrix to the line is shown in Figure.

Three-dimensional transformations

Transformations by matrix methods can be extended to three-dimensional space. We consider the same three general categories defined in the preceding section. The same general procedures are applied to use these transformations that were defined for the three cases by Eqs. TRANSLATION. The translation matrix for a point defined in three dimensions would be

T = (m. n, p)

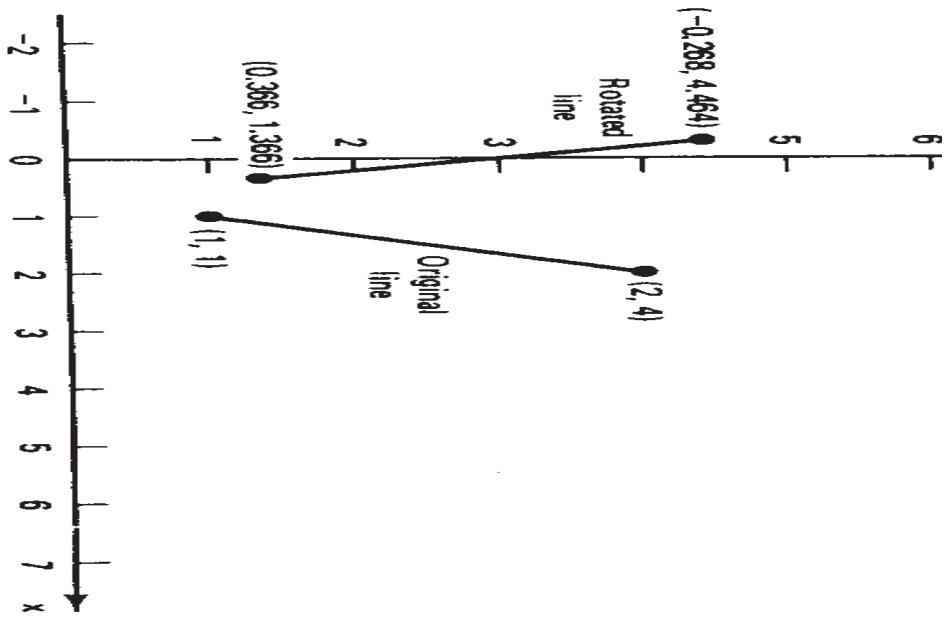


FIGURE Results of rotation in Example

and would be applied by adding the increments m, n, and p to the respective coordinates of each of the points defining the three-dimensional geometry element.

SCALING. The scaling transformation is given by

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$$S = \begin{bmatrix} m & 0 & 0 \\ 0 & n & 0 \\ 0 & 0 & p \end{bmatrix}$$

For equal values of m, n, and p, the scaling is linear.

ROTATION. Rotation in three dimensions can be defined for each of the axes.

Rotation about the z axis by an angle θ is accomplished by the matrix

$$R_z = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Rotation about the y axis by the angle 6 is accomplished similarly.

$$R_y = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$$

Rotation about the x axis by the angle θ is done with an analogous transformation matrix.

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}$$

Concatenation

The previous single transformations can be combined as a sequence of transformations. This is called concatenation, and the combined transformations are called concatenated transformations.

During the editing process when a graphic model is being developed. the use of concatenated transformations is quite common. It would be unusual that only a single transformation would be needed to accomplish a desired manipulation of the image. Two examples of where combinations of transformations would be required would be: -

Rotation of the element about an arbitrary point in the element

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Magnifying the element but maintaining the location of one of its points in the same location

In the first case, the sequence of transformations would be' translation to the origin, then rotation about the origin, then translation back to the original location. In the second case, the element would be scaled (magnified) followed by a translation to locate the desired point as needed:-

The objective of concatenation is to accomplish a series of image manipulations as a single-transformation. This allows the concatenated transformation to be defined more concisely and the computation can generally be accomplished more efficiently.

Determining the concatenation of a sequence of single transformations can be fairly straightforward if the transformations are expressed in matrix form as we have done. For example. if we wanted to scale a point by the factor of 2 in a two dimensional system and then rotate it about the origin by 45°, the concatenation would simply be the product of the two transformation matrices. It is important that the order of matrix multiplication be the same as the order in which the transformations are to be carried out. Concatenation of a series of transformations becomes more complicated when a translation is involved, and we will not consider this case.

EXAMPLE

Let us consider the example cited in the text in which a point was to be scaled by a factor of 2 and rotated by 45°. Suppose that the point under consideration was (3, 1). This might be one of several points .defining a geometric element. For purposes of illustration let us first accomplish the two transformations sequentially. First, consider the scaling.

$$(x'. y') = (x, y)S$$

$$(x', y') = (3. 1) \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix} = (6, 2)$$

Next, the rotation can be performed.

$$(x'', y'') = (x', y')R$$

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$$(x'', y'') = (6, 2)\begin{bmatrix} \cos 45 & 45 \\ -\sin 45 & \cos 45 \end{bmatrix}$$

$$= (6, 2)\begin{bmatrix} 0.7071 & 0.7071 \\ -0.7071 & 0.7071 \end{bmatrix} = (2.828.\ 5.657)$$

The same result can be accomplished by concatenating the two separate transformation matrices. The product of the two matrices would be

$$SR = \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix} - \begin{bmatrix} 0.7071 & 0.7071 \\ -0.7071 & 0.7071 \end{bmatrix}$$

$$= \begin{bmatrix} 1.414 & 1.414 \\ -1.414 & 1.414 \end{bmatrix}$$

Now, applying this concatenated transformation matrix to the original point, we have

$$(x'', y'') = (3, 1)\begin{bmatrix} 1.414 & 1.414 \\ -1.414 & 1.414 \end{bmatrix}$$

$$= (2.828, 5.657)$$

WIRE-FRAME VERSUS SOLID MODELING

The importance of three-dimensional geometry

Early CAD systems were basically automated drafting board systems which displayed a two-dimensional representation of the object being designed. Operators (e.g., the designer or drafter) could use these graphics systems to develop the line drawing the way they wanted it and then obtain a very high quality paper plot of the drawing. By using these systems, the drafting process could be accomplished in less time, and the productivity of the designers could be improved.

However, there was a fundamental shortcoming of these early systems. Although they were able to reproduce high-quality engineering drawings efficiently and quickly, these systems stored in their data files a two-dimensional record of the drawings. The drawings were usually of three-dimensional objects and it was left to the human beings who read these drawings to interpret the three-dimensional shape from the two-dimensional representation. The early CAD systems were not capable

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of interpreting the three-dimensionality of the object. It was left to the user of the system to make certain that the two-dimensional representation was correct (e.g., hidden lines removed or dashed, etc.), as stored in the data files.

More recent computer-aided design systems possess the capability to define objects in three dimensions. This is a powerful feature because it allows the designer to develop a full three-dimensional model of an object in the computer rather than a two-dimensional illustration. The computer can then generate the orthogonal views, perspective drawings, and close-ups of details in the object.

The importance of this three-dimensional capability in interactive computer graphics should not be underestimated.

Wire-Frame models

Most current day graphics systems use a form of modeling called wire-frame modeling. In the construction of the wire-frame model the edges of the objects are shown as lines. For objects in which there are curved surfaces, contour lines can be added; as shown in Figure, to indicate the contour. The image assumes the appearance of a frame constructed out of wire - hence the name “wire frame” model.

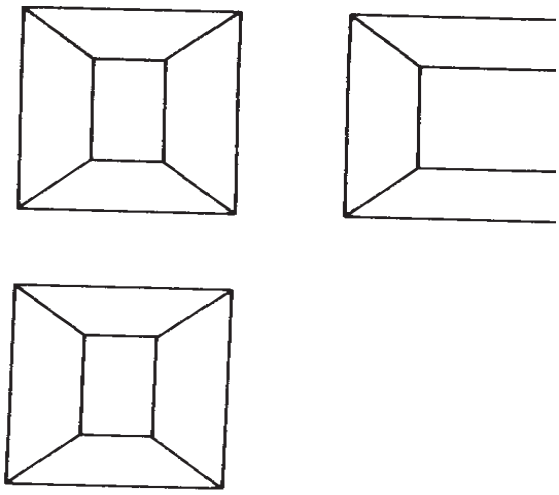


FIGURE Orthographic views of three-dimensional object without hidden- line removal.

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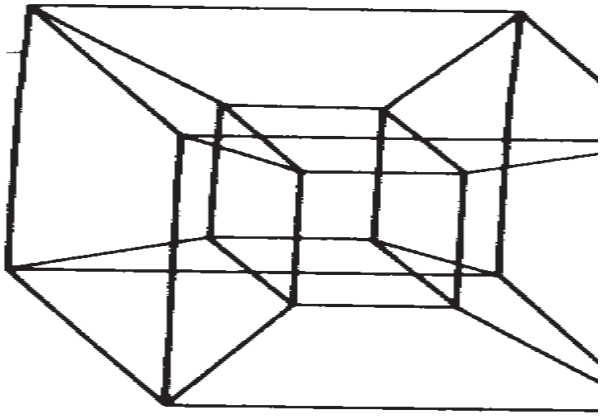


FIGURE Perspective view of three-dimensional object of Figure without hidden line removal.

There are limitations to the models which use the wire-frame approach to form the image. These limitations are, of course, especially pronounced in the case of three-dimensional objects. In many cases, wire-frame models are quite adequate for two-dimensional representation. The most conspicuous limitation is that all of the lines that define the edges (and contoured surfaces) of the model are shown in the image. Many three-dimensional wire-frame systems in use today do not possess an automatic hidden-line removal feature. Consequently, the lines that indicate the edges at the rear of the model show right through the foreground surfaces. This can cause the image to be somewhat confusing to the viewer, and in some cases the image might be interpretable in several different ways. This interpretation problem can be alleviated to some extent through human intervention in removing the hidden background lines in the image.

There are also limitations with the wire-frame models in the way many CAD systems define the model in their data bases. For example, there might be ambiguity in the case of a surface definition as to which side of the surface is solid. This type of limitation prevents the computer system from achieving a comprehensive and unambiguous definition of the object.

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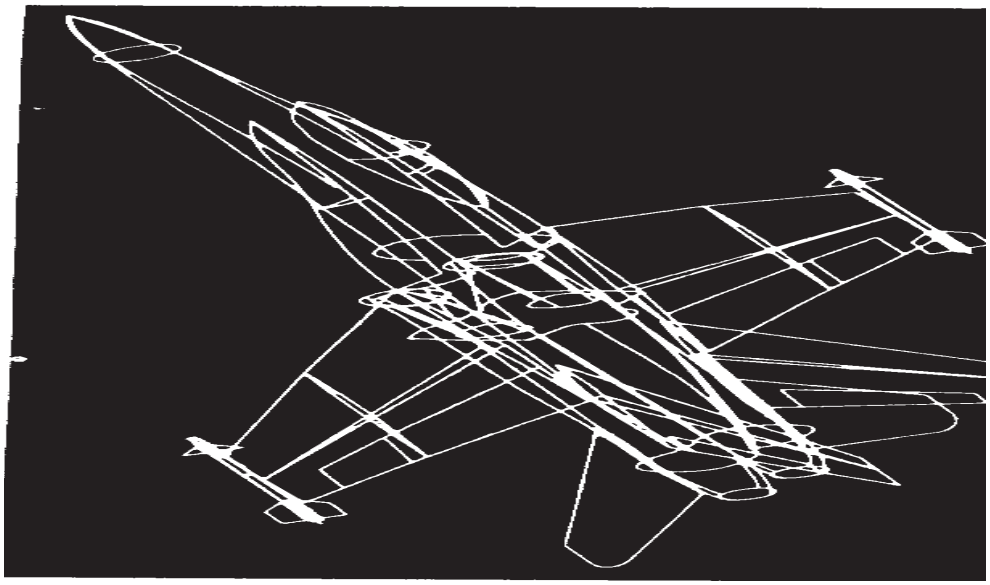


FIGURE Wireframe model of F/A-18 fighter aircraft, showing primary control curves.

Solid models

An improvement over wire-frame models, both in terms of realism to the user and definition to the computer, is the solid modeling approach. In this approach, the models are displayed as solid objects to the viewer, with very little risk of misinterpretation. When color is added to the image, the resulting picture becomes strikingly realistic. It is anticipated that graphics systems with this capability will find a wide range of applications outside computer-aided design and manufacturing. These applications will include' color illustrations in magazines and technical publications, animation in movie films, and training simulators (e.g., aircraft pilot training).

There are two factors which promote future widespread use of solid modelers (i.e., graphics systems with the capability for solid modeling). The first is the increasing awareness among users of the limitations of wire-frame systems. As powerful as today's wire-frame-based CAD systems have become, solid model systems represent a dramatic improvement in graphics technology. The second reason is the continuing development of computer hardware and software which make solid modeling possible. Solid modelers require a great deal of computational power, in terms of both speed and memory, in order to operate. The advent of

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powerful, low-cost minicomputers has supplied the needed capacity to meet this requirement. Developments in software will provide application programs which take advantage of the opportunities offered by solid modelers. Among the possibilities are more highly automated model building and design systems, more complete three-dimensional engineering analysis of the models, including interference checking, automated manufacturing planning, and more realistic production simulation models.

Two basic approaches to the problem of solid modeling have been developed:

1. Constructive solid geometry (CSG or C-rep), also called the building-block approach

2. Boundary representation (B-rep)

The CSG systems allow the user to build the model out of solid graphic primitives, such as rectangular blocks, cubes, spheres, cylinders, and pyramids. This building-block approach is similar to the methods described in Section 6.4 except that a solid three-dimensional representation of the object is produced. The most common method of structuring the solid model in the graphics data base is to use Boolean operations, described in the preceding section and pictured in Figure.

The boundary representation approach requires the user to draw the outline or boundary of the object on the CRT screen using an electronic tablet and pen or analogous procedure. The user would sketch the various views of the object (front, side, and top, more views if needed), drawing interconnecting lines among the views to establish their relationship. Various transformations and other specialized editing procedures are used to refine the model to the desired shape. The general scheme is illustrated in Figure.

The two approaches have their relative advantages and disadvantages. The C-rep systems usually have a significant procedural advantage in the initial formulation of the model. It is relatively easy to construct a precise solid model out of regular solid primitives by adding, subtracting, and intersecting the components. The building-block approach also results in a more compact file of the model in the database.

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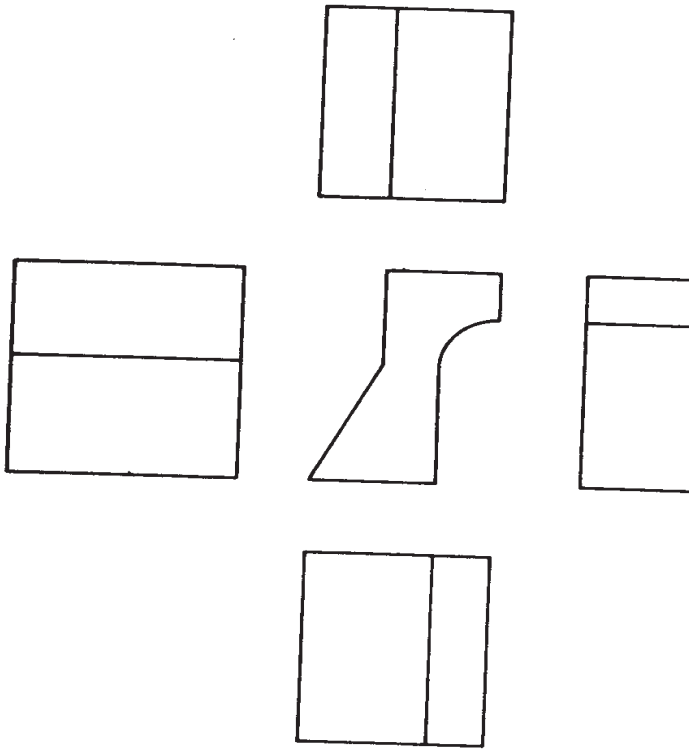


FIGURE Input views of the types required for boundary representation (B-rep) .

On the other hand, B-rep systems have their relative advantages. One of them becomes evident when unusual shapes are encountered that would not be included within the available repertoire of the CSG systems. This kind of situation is exemplified by aircraft fuselage and wing shapes and by automobile body styling. Such shapes would be quite difficult to develop with the building-block approach, but the boundary representation method is very feasible for this sort of problem.

Another point of comparison between the two approaches is the difference in the way the model is stored in the data base for the two systems. The CSG approach stores the model by a combination of data and logical procedures.

(the Boolean model). This generally requires less storage but more computation to reproduce the model and its image. By contrast, the B-rep system stores an explicit definition of the model boundaries. This requires more storage space but does not necessitate nearly the same computation effort to reconstruct the image. A related benefit of the B-rep systems is that it is relatively simple to convert back and forth between a boundary representation and a corresponding wire-frame

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model. The reason is that the model's boundary definition is similar to the wire-frame definition, which facilitates conversion of one form to the other. This makes the newer solid B-rep systems compatible with existing CAD systems out in the field.

Because of the relative benefits and weaknesses of the two approaches, hybrid systems have been developed which combine the CSG and B-rep approaches. With these systems, users have the capability to construct the geometric model by either approach, whichever is more appropriate to the particular problem.

Vector Generation

- The process of 'turning on' the pixels.

Two V.G. Algorithm (line grassing)

1. DDA (Digital Differnetial Analysers)
2. Bresenham's Algoritm.

DDA Algorithm

- Based on dy of dx

- Floating point Arithmetic , slower

- More accurate.

1. Read the endpoints co-ordinates (x_1, y_1) & (x_2, y_2) for a line
2. $dx = x_2 - x$

   $dy = y_2 - y$
3. If abs (dx) > abs (dy) then

   step = abs (dx)

   otherwise

   Step = abs (dy)

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4. x inc = dx/step

   y inc = dy/step

   $x = x_1$

   $y\ x = y_1$

5. Put pixel (x, y, colour0

6. x = x + x inc

   y = y + y inc

   Put pixel (x,y, colour)

7. Repeat step 6 until $x = x_2$

   Draw line from (1,2) to (4,6) using DDA Algorithm.

1. $x_1 = 1$ $y_1 = 2$

   $x_2 = 4$ $y_2 = 5$

2. dx = 3 dy = 4

3. Step = dt = 4

4. X inc = dx = 3 = 0.75

   Step 4

5. Plot (1_1 2)

6. x = x + x inc x = 1 y = 2

   y = y + y inc x = 1.75 y = 3

   x = 2.5 y = 4

   x = 3.25 y = 5

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x = 4 y = 6

7. Stop

[Rounded to higher value]

- Eliminating stair casing or aliasing is known as ant aliasing.

Bresenham's line Drawing Algorithm.

- Uses Integer arithmetic.

- Faster than DDA because of Integer Arithmatic.

- Separate algorithms for |m|<| & |m| ≥ |

$$m = \frac{y_2 - y_1}{x_2 - x_1}$$

for |m|<|

1. Read (x_1, y_1) and (x_2, t_2) as the endpoints co-ordinates.

2. $dx = |x_2 - x_1|$

   $dy = |y_2 - y_1|$

   $P = 2dy - dx$ (P→decision parameter)

3. At each xk, along the line, stating at k>o, ---------- follows test.

   If $P_k < O$, then next point to plot is $(x_k + 1, y_k)$ and

   $P_{k+1} = P_k + 2\ dy$

   Otherwise if b_k next point to plot is $(x_k + 1{,}3\ y_k + 1)$ and

   $P_{k+1} = P_k + 2dy - 2dx$

4. Repeat step 3 dx times.

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5. Stop.

Q. Scan convert the line end points (10, 5) and (15, 9) using Bresenham Algorithm.

$n = y_2 - y_1$ 4

$x_2 - x_1$ 5 <1

$dx = x_2 - x_1 = 15 - 10 = 5$

$dy = y_2 - y_1 = 9 - 5 = 4$ (10, 5)

$P_o = 2dy - dx = 2x4 - 5 = 3$

Since P > O, $x_1 = x_0 + 1$ = 10 + 1 = 11

$Y_1 = x_0 + 1$ = y+1 = 6 (11,6)

P_1 = $P_k + 2dy - 2dx$

= $3 + 2x4 - 2x5$

= 1

Since $P_1 > 0$, $x_2 = 12$ (12, 7)

$Y_2 = 7$

P_2 = $1 + 2 \times 4 - 2 \times 5 = -1$

Since P_2 <O

$X_3 = 13$

$Y_3 = 7$ (13, 7)

P_3 = $-1 + 2 \times 4 = 7$

$P_3 > 0$ (14, 8)

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$X_4 = 14$

$Y_4 = 8$

$P_4 > 0$

$X_5 = 15$ (15, 9)

$Y_5 = 9$

Stop

For slope $|m| \geq |$

1. Read (x_1, y_1) and (x_2, y_2) as the end points co-ordinates.

2. $dx = |x_2 - x_1|$

   $dy = |y_2 - y_1|$ (P = decision percents)

   $P = 2dx - dy$

3. At each x_k along the line, starting at k = 0, portion following test.

   If $P_k < 0$, then next point to plot is (x_k , y_k+1) and

   $P_{k+1} = P_k + 2\ dx$

Otherwise, next point to plot is $(x_k + 1, y_k + 1)$ and

   $P_{k+1} = P_k + 2dx - 2dy$

4. Repeat 'step 3' dy times or $y_1 = y_2$

5. Stop

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