INTRODUCTION

With the exponential growth of computer facilities, a great deal of attention has been given to the analytical description of man's decision-making processes. Yet little has been accomplished of general value to automation. We can think of many examples where the human mind can assimilate information and quickly reach a decision where we would be hard pressed to computerize the thought process. Since it will be many years before man's general decision making powers can be channeled into computers, he must be given an optimum remedial problem-solving capability. This means that he must be given the facility to communicate or interact directly with the computer and he must be given adequate tools to accomplish this interaction. In an idealized man-computer system, facilities will exist to yield a homogenous mix of man's decisions with routine computation. With the addition of fast response, it will be possible to shorten span time and to increase the learning and the retention of significant results. To this end the concept of real-time on-line computer graphics will play a major role.

An optimum real-time capability is one in which the man receives a response to an inquiry to the computer or a requested action by the computer as fast as the requested response or action can be assimilated. Our present space program, for example, would not exist, as we know it, without this real-time capability. The closer we get to a true and general real-time environment, the closer we will be to maximum problem solving capability. Only with the most recent advances in computer speed and scope performance has a real-time online computer graphics system become practicable. With a visual display and the ability to interact with the computer through the geometric representations, it is possible to perceive and absorb significant information such as shape, area, proximity, density, and intersection to a degree that may obviate the requirements for special-purpose, complex, and cumbersome computations.

The graphic medium of communication is but one of many media by which man is attempting to maximize computer utilization. It is, however, a very important medium to which considerable research and development is being applied with the promise of rewarding results. The contribution of graphics in the real-time on-line system is manifested in all problems where a visual display and the facility to work with the display is desired.

This can be perceived in a broad spectrum of ap-
lications. For example, the designer wishes to create a small part or perhaps a large section of an aircraft. In either case, the ability to view, to evaluate, and to change the design while maintaining the mathematical definition on the computer will be an invaluable contribution. Then there is the program manager who would like to have an up-to-date review of his program and who would like to consider the effects of his proposed changes. The display of a PERT network and the facility to make direct alterations to observe the effect on the critical path will accomplish this function.

Thus the graphical capability augmented to the real-time on-line system will significantly increase the efficiency of solutions of many problems and will open the horizons to solutions of a new class of problems which have not been tractable in the past.

Research in the area of computer graphics reached a significant milestone when Ivan Sutherland completed his initial "Sketchpad" system in 1961. Using a cathode ray display interfaced to the Lincoln Laboratory TX2 computer, Sutherland showed the feasibility of supplying graphical or geometric information to the computer via the display. Cathode ray output has been around for a long time in the computer age, but two-way geometric communication was a revolutionary concept. Certainly, Sutherland is not the only one to have considered the significance of graphical, on-line I/O. General Motors has had a program in computer graphics which was initiated in 1959 and was, for competitive reasons, veiled in secrecy until the Fall Joint Computer Conference in October 1964. Another program which has considerable bearing on computer graphics is Project MAC (Machine Aided Cognition) under the direction of Professor R. M. Fano at M.I.T. Project MAC is a broad-based program delving into all aspects of man-computer systems. Significant achievements are also being realized under programs directed by Douglas T. Ross and Steven Coons at M.I.T. Mr. Ross is developing Automated Engineering Design (AED) compilers which will aid the user of man-computer systems in formulating and solving his problem with increased facility and versatility. Professor Coons is responsible for the development of programs associated with computer-graphic applications. His work is well known as Computer Aided Design.

The dramatic innovation of man-computer graphics adds a new dimension to computer technology. It is a new link in the chain which leads toward more complete automation, as information communicated by pictures or displays is often many times more effective than the written word.

LOCKHEED-GEORGIA'S COMPUTER GRAPHICS

In its belief in the strong future role of man-computer graphics, Lockheed-Georgia was a pioneer in the aerospace industry when it acquired a system with emphasis on two-way graphic communication as defined above. In December 1964 the UNIVAC 418 Computer connected to the Digital Equipment Corporation's 340 Scope became operational in our Research Laboratory. The system whose graphical section is exhibited in Fig. 1 is dedicated to a research program in the application of man-computer graphic. Our research team consists of experienced personnel in a variety of disciplines including systems programming, mathematical analysis, electronics, information retrieval, design, numerical control and engineering loft. Under the Man-Computer Systems Program of Sys-

Figure 1. Design of an aft fuselage in 3-D.
tems Sciences, there are about 20 team members in all. In addition, regular consultation is carried on in other specialty areas.

Since the UNIVAC 418 had never before been used for graphical operations, development of the systems programming was undertaken by our specialists. The development of “software” is quite involved for computer graphics. Many technical problems are associated with the creation of a drawing or sketch on a cathode ray tube by input from a light sensitive pen or from other sources. In order to perform analyses on or make changes to a display on a scope, it is necessary to program the computer such that the displayed configuration is, at all times, stored in mathematical form in computer memory. Provisions must be made for efficient storage and retrieval of displayed data and the protection of computer memory against careless destruction of vital data. In addition to the light pen input, data such as coordinates may be transferred to the display from input on a standard computer keyboard. Also, certain subroutine functions such as deriving the area, drawing a line, rotating, changing scale, and deleting an entity must be accomplished. These special subroutines are “called up” by the button box, a panel of 28 buttons designed by our engineers and integrated with the computer system. These buttons are under program control; that is, they may have different meanings for different applications programs.

Through the combination of the various input media and the general-purpose software system, it will be possible to develop special-purpose programs to solve particular problems. There is no intent that the presently developing software and general programs are to be the final system. Only those functions of obvious general utility are being incorporated. Then, as specific solutions are sought through the computer-graphic system, need for further extensions to the general package will become apparent. A feedback relationship between solutions to specific problems and extensions to the general program package seems the most reasonable doctrine in a research environment.

The capabilities that exist at the end of August 1965 on the graphic system include the following basic features:

Three-Dimensional Capability

- Four views: three principal projections and a perspective. Drawings are created by working in any combination of the three principal views
- Conversion to single view and return to four views upon request
- Isometric: drawing is created by locating X and Y first, then Z (available as a separate experimental program)
- Definition of points
- Definition of lines
- Definition of circular arcs (elliptic arcs in projection)
- Change of scale
- Rotation about any designated axis perpendicular to any view
- Translation
- Deletion of any element
- Multiple figures can be displayed simultaneously. Proper definition of figures permits alteration of parts of the complete drawing while other parts are held fixed
- Multiple rotation axes: this permits the study of relative motion. Axes may be parallel or orthogonal to each other. Angular rotation rates may differ

Two-Dimensional Capability

The two-dimensional capability includes the definition of points, lines, circular arcs and standard manipulation features using both keyboard and light pen inputs. In addition, a host of special features are planned, or exist, for the numerical control milling application which is explained later. Examples are:

- Construct a circle tangent to a displayed circle and a displayed line with its radius input by keyboard
- Construct a circle tangent to two circles. The radius of the required circle is input by keyboard
- Construct a circle through three displayed points
- Move a point while maintaining connectivity

Features in Other Programs

- Shape or mold a stored geometric shape to fit a preconceived concept or specification
- Freehand sketching
- Alphanumeric display
- Alphanumeric printout of designated text
• Translation of displayed data to hard copy output on an X-Y plotter

A small tracking cross is used as the medium of communication between scope and computer. Its position as directed by the “light pen,” shown in Fig. 1, and the activation of appropriate subroutines by the use of the button panel direct the creation or functioning of the indicated graphical features.

Some of the above features are illustrated in the following figures:

- Figure 1 shows the 4-view representation of the design of an aft fuselage
- Figure 2 illustrates drawing in isometric
- Figure 3 is a series of photographs to illustrate multiple axes of rotation
- Figure 4 shows the cross section of a wheel pod. It has been shaped from a starting circle
- Figure 5 shows how connectivity may be maintained when points are moved

PHILOSOPHY OF COMPUTER GRAPHICS RESEARCH

Before discussing our applications activity, I would like to discuss some aspects of the general national interest in man-computer graphics.
At the present time, various degrees of activity are springing up around the country. Some computer manufacturers, in recognition of the future role of computer graphics, have strong programs of their own. They hope to offer a complete system that will give newcomers to the use of computer graphics an up-to-date capability. Actually, it is unlikely that the manufacturers will be able to anticipate all of the problems and demands that will be forthcoming from this new area. Users of the packaged systems may find that their special applications will require additional computer programs that will be difficult to acquire. Though Lockheed-Georgia may use some of the manufacturer's software features when they become available, we believe that the creation of our own program system for our own applications offers the greatest flexibility and, therefore, the greatest success in long term operations.

Because of the tender age of the man-computer graphic concept, we believe that a modest initial effort with freedom to grow with experience is the most feasible course. There are many problems both of a technological and of a human engineering nature which must be dealt with in due time, and
which will influence the growth pattern. Considerable experience and strong familiarization with the MCG concept and its ramifications will be necessary to make accurate judgments to distinguish the primary problems of concern from the secondary problems. In that regard there are many problems that require classification according to priority because any team of modest size can cope with only so many problems in a short time span. Because of this, we tend to prefer that the manufacturer deal with complex hardware problems while we furnish specifications that must be met to allow the system to function properly and to grow. Such problems as time sharing and remoting scopes from the C.P.U. must be given priority attention while the optimum tilt of the drawing surface, the nature of the drawing surfaces, and the number of buttons on the button panel are the type problems that can await attention without jeopardizing the main purposes and payoff of the man-computer graphic system.

APPLICATIONS

Many long-range applications are contemplated for computer graphics, with current emphasis being placed on the design process. Structural analysis, management systems, information processing, electrical circuit layout, process control, and command and control are other areas that are receiving or will receive early attention. The first applications will be fairly specific and of limited technical complexity. In this connection, a “Near-Term” Group has been formed to seek technical contributions to Lockheed-Georgia which can be completed in 1965. This is in addition to the more long-range goals of the computer-graphics team. The “Near-Term” Group is investigating two areas: complete mathematical definition of all surfaces of an aircraft envelope and two-dimensional* numerical control milling procedures with completion dates of September and December 1965 respectively. The problems of mathematical definition of surfaces and of 2-D numerical control are described below.

Mathematical Definition of Surfaces

In regard to the mathematical definition of surfaces, it should be noted that a large percentage of present designs are defined in mathematical terms. However, on some aircraft, there are regions where mathematical definition has not been practical. For example, on the C-141 the wing and fuselage surfaces are mathematically defined but the fillets between these surfaces were created more or less empirically. When complete mathematical definition is attained, the need for “master models” will be greatly reduced. Furthermore, the various activities that must utilize the shape will find that a central source of data in mathematical form will expedite their analyses and will eliminate cumulative errors which accrue when data is used, converted, and passed on to other activities in a serial fashion. Although this “Near-Term” task is not likely to utilize computer graphics per se, follow-on work will see surfaces displayed on the scope to study esthet-

*In the subsequent discussion on 2-D N/C, it should be borne in mind that we are actually working in a 3-D environment, but the 2-D nature of the basic problem should be clear from the context.
ics of design, to permit design alterations, and to perform functional evaluations. Various methods of surface definition have been investigated in depth in preparation for the follow-on work.

By defining surfaces on the display, it will be possible to vary unconstrained parameters and ascertain both the geometric and the analytical effects on the created surfaces. Computations such as surface area and volume will be performed. Parameters may be varied within allowable degrees of freedom to achieve "optimum" results with respect to design specifications.

Two-Dimensional Numerical Control

In our manufacturing process, many items are milled automatically by numerical tape-controlled milling machines. The creation of this tape is a laborious task. To produce the numerical control tape for a part or tool, an accurate drawing of the item must first be produced. Then a part programmer must painstakingly go through the drawing and define the points, each distinct line, curves, and other significant features. A series of computer instructions is then written to represent the path that the cutting tool must follow to mill the item according to the design specifications. The language and computer program for writing, for compiling, and for interpreting the instructions is called APT (Automatically Programmed Tools). The resultant output is a magnetic tape. With additional post processing, a paper tape for directing a particular milling machine is created. The APT system has been developing for many years, and the task of producing it has been a formidable one.

Still, the various steps leading to the production of a numerical control tape require many man hours. It was recognized that the application of new techniques in automation could significantly reduce the manual effort. It is estimated that about 80 percent of the items produced by means of numerical control at Lockheed-Georgia are of a two-dimensional line and circle geometry. Therefore, the desirability of using the early computer-graphic capability to assist the 2-D N/C problem became apparent. First the item would be defined directly on the scope using the various input media—light pen, buttons, keyboard, etc. The geometry of the item would be stored in computer memory on a permanent file. This geometry, which would be represented mathematically in the computer, would serve as the basis for the description of the cutter path.

Figure 6 shows a typical part that has been created on the scope. The two views show the circular top of the cutting tool at the beginning and near the finish of its path around the periphery of the part. Each line or circular arc of the figure is a surface since the part is viewed from the top.

To create the part, the part programmer must describe a path, composed of linear elements, for the cutting tool. In general, there is no way to determine the optimum path. The part programmer only knows that he must consider each of the detailed elements and their dimensions. The computer-graphics program to assist him is called PATH, and its operation is summarized in the sequel.

![Figure 6. Top view of a typical part with cutter path description.](From the collection of the Computer History Museum (www.computerhistory.org))
When the part of concern has been displayed as in Fig. 6, the mathematical description will exist in the computer. Then the process of defining the cutter path can begin.

The initial position of the cutter is, in general, not on the part. The starting position in the X-Y plane is input as is the depth coordinate Z. The cutting tool will cut to the indicated depth and the Z value will be automatically associated with each (X, Y) of the succeeding path until a change in Z is requested and keyed in. The cutter radius must also be input at the beginning of a sequence of steps to enable the computer to automatically create appropriate offsets. Now, a point on a line (surface) of the part is designated as the first (X,Y) to which the cutting tool will move. Before the movement, however, it must be ascertained to which side of the line the cutting tool will be tangent or if the center of the cutter is to be positioned directly on the line. This is accomplished by moving the tracking cross to one of three approximate positions with respect to the line. That is, the cross is moved by the "light pen" distinctly to one side, "near" to, or distinctly on the other side of the line of interest. When the appropriate button is pushed, the circle representing the diameter of the cutter will be automatically positioned on the display and the center coordinates will be automatically recorded. The next step in the process of cutting out a part profile is to indicate the second surface of interest. Tangency or direct centering must be established as before. The cutter center will then move on the display and in the computer to the (X,Y) location of the intersection of the two surfaces. Where tangency is sought, appropriate offsets will be automatically allowed. Cutter path definition for succeeding surfaces is derived similarly.

In many cases, an automatic mode for defining many steps of the cutter path may be employed. With respect to the geometry, the path will be continuously defined in this mode until the operator sees an error and stops the process or until the cutter arrives at a position where the next move is insufficiently defined. In the former case, the console operator may delete the erroneous portion of the path and correct it by stepping through the questionable region as previously described. In the latter case, the operator may resolve the ambiguity which the computer had indicated and restart the automatic process or continue step by step. In all cases the cutter path for several preceding steps is displayed for the perusal of the console operator.

When the outer profile has been described, the operator may choose to change Z and move to another section of the part for profiling or for swathing a flat top. When the cutting tool is placed tangent to a circle and when it is necessary to circumnavigate the circle, it is required that the operator key in the allowable error tolerance. The successive coordinates are then defined automatically by the computer such that the cutter may move linearly from point to point around the circle without exceeding the indicated tolerances.

When the path has been derived, it can be redisplayed step by step or continuously for operator approval. From an operator’s point of view, the system is reasonably simple because there are relatively few operations of buttons, keyboard, and tracking cross which need to be learned.

With successive coordinates thus described, an output tape can be generated that describes the necessary cutter motion and completely bypasses the APT system requirement.

It is estimated that the average part programming time for approximately 1500 parts amenable to this graphic representation was 60 hours per part for the C-141. The estimate for the same requirement using the computer-graphic PATH program is 10 hours. Considerable savings will also be manifested in tooling and template manufacture. In addition to the great reduction in manhours, the decrease in span time will be even greater because the graphical system should inherently reduce program errors and because batch processing is replaced by real-time operation.

As of this writing, an evaluation of competitive bids for a three-scope system is being completed. The system will be dedicated to the single but important numerical control application. Delivery is expected early in 1966. The system will be separate from the continuing computer-graphic Research facility.

MAN-COMPUTER GRAPHICS IMPLICATIONS

The specific areas of application which have been alluded to are relatively simple in many respects. Until computer graphics reaches a somewhat more advanced level of sophistication, even the seemingly simple problems offer a considerable
challenge. It is one thing to solve specific problems but quite another thing to solve large classes of problems and to integrate newly developed problem solutions into systems of somewhat greater breadth. An optimum solution to a particular problem may not be optimum when a solution to a more all-encompassing problem is sought. Thus the successful introduction of computer graphics into our technological “bag of tricks” will necessitate our investigation of new methods and techniques for computer graphics. For example, current design practices require a sequence of relatively autonomous operations. The layout is created. Drawings are distributed to the various specialty areas. Information is extracted and forwarded to the central computer facility for the analyses that characterize each specialty area. Results of the computer runs are interpreted and, perhaps, design changes are requested. Among the many conflicting design requirements, compromises must be made and the cycle from designer to specialists to computer and back again is repeated.

With computer-aided design, the team concept may be altered considerably. Specialists may actually take part in the early design process. Some of their evaluations might be accomplished directly as the design develops and this may cause almost immediate modifications before extensive time is lost by the creation of unacceptable designs. As another approach, the various specialty areas may have their own display systems which are linked to a common central computer. Design specifications and alterations may be perceived at each station when information is called up. This capability will compress the time expended for the entire design process.

The types of future computer-display systems that will best suit Lockheed-Georgia or any other company will depend on many factors, including the number of departments which will utilize the system, the interdependence of the encompassed activities and, of considerable importance, the direction of growth in computer facilities which will be made available by computer manufacturers.

SELECTION OF AN “OPTIMUM” SYSTEM

The evaluation of equipment for our follow-on man-computer research facility is now in process. This evaluation involves many subjective decisions which are characteristic of the selection of any major computer system. Timing is most important because a good system for today may lack flexibility to grow into tomorrow’s requirements. Once we are committed to a computer system and the development of the associated software, it takes considerable time to justify and implement a change. It is therefore incumbent upon us to plan for the solution of tomorrow’s problems though they are not totally defined today.

The computer-graphics research facility at Lockheed-Georgia has provided a rare opportunity for gaining insight and experience in the vast area of man-computer systems. Familiarization with the problems and the general capability of computer-graphics will equip our personnel with the background and training to adjust quickly to new and uncharted areas. Indeed, analogous to the portion of an iceberg that lies beneath the water’s surface, there are many more as yet undiscerned applications which lie just beneath the surface of current comprehension.

ACKNOWLEDGEMENTS

I would like to express my appreciation for the encouragement and support that the Man-Computer Graphics Program has received from many people in the Engineering, Computing, and Manufacturing Branches of the Lockheed-Georgia Company.

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REFERENCES

