Graphics and computer-aided design in aerospace

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INTRODUCTION

In 1964, certain hardware developments in graphics equipment were announced by IBM. The interest of management of the Lockheed-California Company was immediately aroused. Possibilities for the development of highly effective programs through the utilization of this equipment were foreseen and action was started to take advantage of this new technology.

A task force was set up to study various applications and make recommendations. Representatives from Structures, Aerodynamics, Loads, Stress, Project Design, and Computer Services participated in this work. This study resulted in the delivery of an IBM 360/40 with one IBM 2250 scope in 1966. This task force also recommended the implementation of certain initial programs. The prime criteria for their recommendation being immediate need and use for the design processes associated with aircraft.

From these early beginnings, we have progressed to a Model 50, 65, 75, and finally the present shared 360/91. On the 360/91, we have fine tuned the system to a high degree of effectiveness. We feel it is our most proficient and cost-effective configuration.

CONFIGURATION

The 360/91 on which we are presently operating graphics has 2 million bytes of high speed core. Those devices dedicated to graphics include a 2314 with 8 disk drives, 2-2301 high speed drums, a 1403 printer, and 4 tape units. One 2250 is located in the computer room and is primarily used for graphic program development, batch program checkout and graphics systems maintenance. Three more 2250s are located in the same building, but in a user environment. Eight scopes are located in an engineering building which is about a mile from the graphics computer. They are connected to the main frame through a 2916 Long Line Adaptor and coaxial cable.

Graphics occupies 528 thousand bytes of the total of 2 million bytes of high speed memory. The rest is used by the system and the batch streams which are sharing the computer with graphics. Normally, at least three batch streams of programs are concurrently being processed. The graphics region is split into four partitions, which in turn drive the twelve scopes. This is done by utilizing a data roll technique for our design package, which allows multiple scopes to be run out of one partition. The design package will be described later.

PROGRAMMING CONSIDERATIONS

Certain programming considerations had a strong influence on the direction taken early in the development of computer graphics. These considerations had their effect not only on the selection of applications, but on how those applications were developed.

The first consideration was to provide a tool that was user oriented. The displays, and the actions taken should not be completely foreign to him. If he is a designer, and the scope is his drafting board, then the methods of construction on the scope should be basically the same as he would use on the drafting board.

The prime reason for placing a user in direct contact with a high speed computer is to be able to achieve a high degree of interactivity. The application should be one where close interaction is essential to the effectiveness of the work to be performed. In addition, the program should use its ability to interact to assist the user in doing his work. This can be done with tutorial messages which always leave the user knowing what he did last, and what his choices are to do next.

Cost had to be kept low in order to make cost effective a wide spectrum of applications. The numerator of the basic cost equation consists of the driving computer, the scopes, and the programming support. The number of scopes becomes the denominator in this equation, and as their number increases, the cost per scope is driven down. Our present need is for 12 scopes, however, the system we have today could be increased to 16 or even a 20 scope system with the only increase in cost due to the scopes themselves and a significant decrease in cost per scope.

The tool that has been given to the user should be responsive. Neither his thought processes nor his actions should be slowed down by the system. Also, the responses should be consistent. Inconsistency in response time, even though fairly fast, can be very frustrating and disrupting to the smooth flow of thought processes.
Another way to reduce costs is to share the equipment with batch processing. This sharing can take place in two ways. The first way is by operating in a time sharing environment where the batch stream is soaking up the CPU time which is left over from graphics. However, graphics tends to be a prime shift capability which sits idle the rest of the time. Therefore, the second way is by scheduling batch processing to fully utilize these off shifts. There are several cost advantages which can accrue. The first is a reduction in the computer cost which is in the numerator of the previously mentioned cost equation. Because graphics does experience peaks and valleys of workload, it would be desirable to be able to increase or decrease without a major impact on cost. Sharing the computer allows a greater flexibility for change.

A tool must be reliable to be effective. This reliability manifests itself in two ways. The tool must not only be available, but it must be continuous. A one minute downtime may have no effect on a batch user (he probably won’t even know about it), but a one minute down time can have a major impact on all graphics users. The system should have quick and complete recovery for the user.

Because the users are usually located at a place other than where the computer is, the scopes should be capable of remoting. High speed transmission equipment had to be used in order to satisfy the volume and response requirements of the equipment.

USER CONSIDERATIONS

Graphics systems were not developed in a research environment at the Lockheed-California Company. Our present uses are cost effective and have been since the early stages wherever they were applied.

First it was necessary to plan and select the proper graphics applications. These applications were selected on the basis of need, and this activity was participated in by representatives from all potential user areas.

Our new development was confined to programs having broad, immediate day to day use. We did not want to fall into the trap of planning for what we thought might be needed a year or two years down the road. This too often results in finding that the problem has changed and that the program does not now solve the present problem.

We had to assure centralized forecasting of workloads. If we were going to have the equipment available at the proper time, we had to know what the needs were.

Uneven workloads were smoothed out by either planning new work for the valleys, extending scope time available, or modifying the work plan in some cases.

The scope time was in all cases scheduled and coordinated in order to assure a high degree of utilization. If one user is unable to utilize his time, another user is always available to take up the slack.

We utilized a swing shift whenever possible. Not only to take care of peak loads, but to reduce cost. Scope hours go into the denominator of the cost equation.

Adequate training of the proper type of individuals was a requirement. We found that many good, competent engineers did not relate well, did not work well in an interactive environment. Others were extremely effective in their capability of utilizing the equipment. The Lockheed Training Department participates in this extremely important function.

We have developed a comprehensive system for reporting the highly essential statistics generated by Graphics. There are accounting programs that generate the costs of scope time so that it may be charged back against the user. There are programs that generate reports on utilization which may be used by management for measuring past performance and planning schedules and workloads. And there are programs which give information related to performance. What is the response being experienced? How many interrupts per user are being serviced? These help our programmers to improve the performance of the various graphic applications.

ARRANGEMENT OF SCOPE FACILITIES

At present, all of our scopes, except one, are located in the user environment. Proximity to the actual user was deemed necessary so that the engineers and other users would be able to have quick and easy access to the powerful tool. Eight scopes are located in our commercial engineering building and support over fifty engineers on a two shift basis. They not only utilize analytical programs, but prepare drawings for production release in fuselage interior, wiring diagrams, floor beams, and other structural applications. One scope located in another area is manned by engineers doing surface development which is known as lofting. Another is used to prepare tapes for numerically controlled milling machines which cut parts and tools for manufacturing.

APPLICATIONS

We have divided our program development into two general area—design analysis and design drafting. Design drafting includes all work on the Computergraphics Augmented Design and Manufacturing System (CADAM) which is the powerful, general purpose program for design, drafting, numerical control, and lofting. It also includes all of the related system of supporting programs. The design analysis area covers all of the other graphic programs. These include structures analysis, simulation, scrolling, data display, editing, and other programs.

SIMULATION OF AIRCRAFT FLIGHT CHARACTERISTICS

The Interactive Continuous Systems Modeling Program (ICSMP) is a problem oriented program designed to facilitate simulation of continuous processes on a digital computer. The components of the continuous system for
both input and output are represented graphically on the graphic display. It is an adaptation of IBM's CSMP digital simulation language to graphics. Through the use of this language, both static and dynamic simulations are possible. This program has enabled us to simulate closely actual flight conditions. For example, trim, sideslip, wind, ground runs, and take-offs can be simulated for various aircraft configurations. Even feel or touch systems employing friction, detent, spring action or damping such as control column, wheel, or rudder pedal response are possible. The program provides for online editing, correction, display of graphs, and extensive operational interaction through the modification of modeling parameters.

ANALYSIS OF AIRFRAME STRUCTURE

The Two Dimensional Structures Program was developed to complement our larger batch computer programs. The program can analyze any two dimensional structure which can be modeled by assembling axial elements, beam elements and shear panels. It is also capable of analyzing shell supported rings or frames. External loads must be in the plane of the structure. In the case of rectangular panels, the engineer can insert special data on the panel to provide for cutouts, tapered stiffeners, and variations in thickness. Modifications may be made at any time to any of the input data. Some typical modifications are (1) changing geometry, (2) changing external loads, (3) changing the section properties of any member, or (4) changing support conditions. In addition to modifications of the basic structure, new members and supports can be added to the existing configuration.

ANALYSIS OF LINKAGE MECHANISMS

The Spacebar program was developed to provide for the analysis of linkage systems in three dimensions. The program provides for the construction, on the graphics scope, of an operable or movable mechanism train made up for one, two, three, or four classic four bar units tied together in tandem and operating in three dimensions. Also provided are means to determine internal loads at any mechanism position, displacements under load and input-output curves resulting from the mechanism motion.

The program constructs a discrete element mathematical model of the composite mechanism and projects it in two views onto the plane of the graphics screen. It is viewed as a series of nodes, joined by elements of fixed length and relative position, all moving on the screen in accordance with the mathematical relationship of the physical mechanism in three dimensions.

The engineer establishes the geometry by describing the plane of motion of the crank arm and giving a line of reference for angular measurements within the plane. He then establishes the relative position of the linkage nodes and their lengths. The mechanism can then be dynamically operated in three dimensions by rotating the bell crank and producing the input-output curve. The program provides the means to determine internal loads at any mechanism position and the displacements under load.

INTERSECTING BEAM PROGRAM

The Intersecting Beam program is another fully operational program available in the Computer Graphics Library. Its primary purpose is to mathematically define a discrete element structural model of two limited series of parallel beams intersecting at mutual right angles, to apply concentrated loads at the points of intersection, and to compute the resulting bending moments and deflections at those intersections. All the beams are straight and lie in a single plane, the plane of the display screen. The loads are applied perpendicular to the grid of beams at the intersection points. Deflections and bending moments are measured in the same direction. Uniform loads must be distributed to the node points as concentrated loads.

The necessary input data includes the applied loads, sufficient information to fully describe the geometry of the grid desired, and the stiffness of each beam segment. All information may be entered at the screen by altering the data of a standard grill called from the data library.

In addition to the necessary minimum geometry and stiffness information, two options of additional data are available. Up to a maximum of fourteen flexible supports may be used to give intermediate support to the grid at the selected beam intersections. The end fixity of the beam may also be provided at the scope to vary the beam ends from full fixity through continuous beam to a condition approaching simple support with no fixity.

This program was used extensively in designing the floor beam structure of the Lockheed L-1011 TriStar.

CADAM

The Computer-graphics Augmented Design And Manufacturing System (CADAM) is a complete system of programs which give design, drafting, lofting, and numerical control capabilities from design concept to manufactured product through computer graphics. It is the result of eight years of development testing and use, and has been effectively applied wherever design input is required. Basically, it is a graphics drawing program, however, its capabilities have been developed to the point where, to my knowledge, I believe it is the most effective and productive graphics program in use.

Let's check some of its capabilities. CADAM is based upon descriptive geometry. Information is stored within the computer in the form of a math model which is retrievable for various uses in the system. Complex shapes are readily constructed. Straight lines, circles, ellipses, splined curves, etc., are readily available by the selection of a function key on the console to enter the proper mode. Design sketches can be translated into precise engineering drawings at considerably higher speeds than by the manual methods.
CADAM provides a common data base for all user disciplines. Design models may be viewed at once by retrieving them from the data base storage and displaying them on scopes in different function areas. Several systems in one model can be developed simultaneously and independently with no loss of time.

With CADAM, views can be stacked, separated, or otherwise located within a drawing perimeter in minutes—the designer sees immediately what he has done. If necessary, he can take immediately any further action required. Batch processing operations would require hours or days for successive adjustments.

Accuracy to at least four decimal places is always obtained with CADAM. The machine plots which it produces are highly accurate and may be produced at any scale.

Interfacing components or details may be shown simultaneously on the scope to assure compatibility. Conversely, an assembly can be broken down into separate details, as may be required in the manufacturing process. It is done accurately, and in a matter of minutes for each detail.

By using CADAM, a detail like a bracket, need be constructed only once and still be positioned and repeated on a drawing wherever needed. One may change sizes and dimensions automatically without distortion.

Provisions in the program permit variations in scale or size to be readily extracted from master drawings to fit individual needs. Changes to drawings can be made accurately, and in minimum time without reconstructing unchanged elements.

A complete library of standards, symbols, and details can be stored in computer memory and then called up by the user as needed.

Error detecting logic within CADAM tends to reduce the incidence of human and construction errors. Interaction with the scope display allows the operator to detect an error in his design without resorting to hardcopy print. If he makes a syntax or geometrically impossible error, a message to that effect will appear on the scope so that immediate, corrective action can be taken.

A key code in CADAM makes it possible to automatically control the release of drawings and prevent unauthorized changes. This makes the data available only to authorized individuals.

Multi-axis numerical control programming is available through CADAM. The interactive computer programs are designed to help the user develop a sequence of operations on a punched tape which in turn will be used to direct a specific machine tool to produce a part swiftly, accurately, and with a minimum of tool tries. It is now possible to produce a machined part straight through from the design on the scope to the cutting of the part on the numerical control machine.

CADAM makes available to the user the ability to dynamically display the cutter centerline path and the part geometry in both the plan and elevation views simultaneously. An image of the cutter actually moves along the cutter path on the screen. This permits ready and easy editing of the cutter path. If the programmer notes an error, he can go backward or forward at any time to check the sequence of cutter motions. Errors of small magnitude are eliminated at an earlier stage by analysis verification of part geometry. In actual use, we have found 30 percent of the control tapes required no change to be put in production. The total number of tool tries was reduced by 50 percent.

CADAM allows the complete definition of the surface geometry of a vehicle such as an airplane. This process is known as lofting. Its use falls mainly in three general areas. First is the building of contours and the smoothing of these contours from raw data. Next comes the interrogation as required of these previously defined contours. Finally, there is the assembly of related contours into layouts suitable for plotting as undimensioned loft drawings.

At present, work is proceeding on developing a system to generate parametric surfaces. This program is needed to enhance our capabilities in the generation of surfaces for compound curvature areas of an aircraft such as fillets, nacelle leading edges, and other difficult surfaces.

**CADAM SYSTEM**

One of the particularly unique features of CADAM is the ability to operate multiple scopes from a single region of memory in the computer. Up to seven scopes can be operated from a single region with no noticeable degradation in response time. As many as ten scopes have been operated from a single region, but certain action on the part of the users can cause lengthy and somewhat unacceptable response times. Each of the multiple scopes operating in this data roll mode is working on a different drawing, but to each user it appears that he is the only one using the computer.

The interactive graphics program requires only 126,000 bytes of high speed memory. Of that memory, 84,000 bytes are rolled to and from high speed drum storage. The

![Figure 1](image-url)
remaining 42,000 bytes contain the input-output buffers, the control monitor, the attention queue and the other fixed parts of memory.

A comprehensive system of saving the drawing files has been implemented. Even though the drawing is released in its normal hardcopy form, we safeguard the drawing while it is being constructed and after it is released. Both drawings and programs are saved on a daily basis, a weekly basis, and finally on a monthly basis at a remote site.

If the computer or the system goes down during the day, a “warm start” can be made to recover the drawing. The drawing will be in the same condition as it was the last time it was rolled to the drum storage. Within seconds after the computer is up again, the user can again be working on his drawing. Occasionally it happens that the drawing cannot be recovered, and the user has to go back to the drawing file or start over. For this he uses what is called a “cold start.”

The drawing files are managed by the user (i.e., the engineer, numerical control programmer, or loftsman). He may purge a drawing or file a drawing as his needs dictate. Normally, only one man in an area is assigned the task of data management. The user area is therefore responsible for and does all the work in maintaining their drawing files.

The interactive graphics program of CADAM consists of 60 percent FORTRAN programs and 40 percent Assembly Language. The assembly language programs are those which are most frequently used and require very fast execution. It is in this way we achieve the high effectiveness and the fast response time of the system. Common response time is less than a half a second. System up time is greater than 96 percent where the system up time is defined as what the user sees. The down time may be due to hardware, the operating system, the program, the computer operator, or the user himself. Occasionally, down time is generated by the transition time necessary to change allocations of memory or scopes.

SUMMARY

The Lockheed-California Company has developed a strong and effective computer graphics capability. It has grown from an idea based on new equipment announcements in 1964 to many scopes used on multiple shifts in 1973. Adherence to sound considerations relating to both the programming and the user were important factors in this successful development. Computer Graphics need not be restricted to a research environment, but can contribute profitably to all phases of work. At Lockheed, it is a growing computer-aided design tool with contributions ranging from design concept to manufactured product. Its potential for growth to meet future needs is unlimited.