

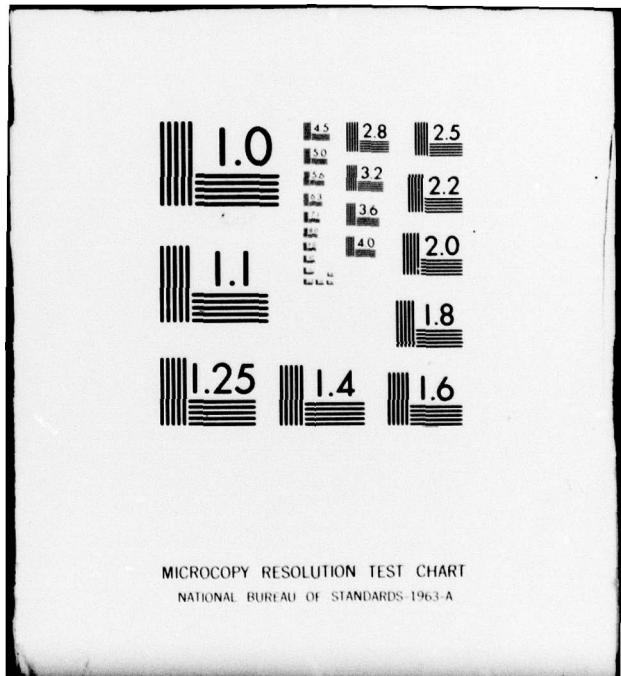
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INTERACTIVE GRAPHIC TECHNIQUES FOR CONCEPTUAL ENGINEERING DESIGN

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ABSTRACT

Conceptual design is the initial and most creative phase of an engineering design project. The effective use of interactive computer graphics to enhance this design phase is dependent upon a highly developed interaction between the designer and the computer. This paper presents an analysis of the environment of conceptual design and proposes techniques for the creation of a successful man-machine interface which fosters the use of interactive computer graphics.

INTRODUCTION

The goal of this applied research topic is to establish a set of techniques which enable the successful application of computer-aided design (CAD) capabilities to the conceptual phase of engineering design. Research in interactive graphics systems, the environment of conceptual design, man-machine interaction, and structured program design was needed to insure all areas affecting the success of a CAD system were considered. The United States Army's need for a sophisticated capability to automate the conceptual design of missile structures provided the test application for the study. This work is being done in cooperation with the United States Army Missile Research and Development Command, Redstone Arsenal, Alabama.

Current Equipment and Software

This research is utilizing a DEC PDP-11/40 computer with 128K of memory, 300-megabyte

disk drive, CALCOMP 1051 drum plotter, and an automated drafting system developed by M&S Computing, Inc. (Figures 1 and 2). Software and procedures written by the author interact with the drafting system software to produce the test conceptual design environment. Evaluation of this missile design package has begun at the United States Military Academy (USMA) at West Point and will be continued at Redstone Arsenal later this year.

USMA Computer Graphics Laboratory

This equipment is part of the United States Military Academy's Computer Graphics Laboratory (CGL). Under the control of the Department of Earth, Space, and Graphic Sciences, it provides a diverse computer facility for use in teaching undergraduate courses in computer science, cartography, and modern graphics. In addition to the above equipment, the laboratory has an LSI-11-based raster scan image processing system, six full microcomputer systems of different

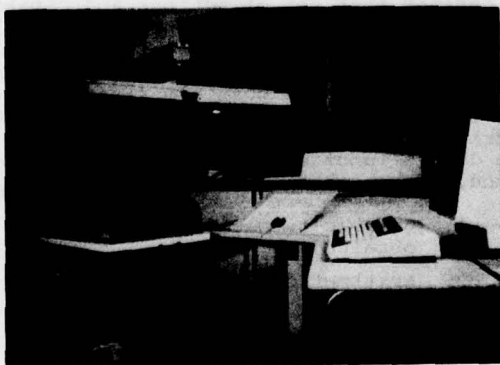


FIGURE 1. Graphics Design Station.

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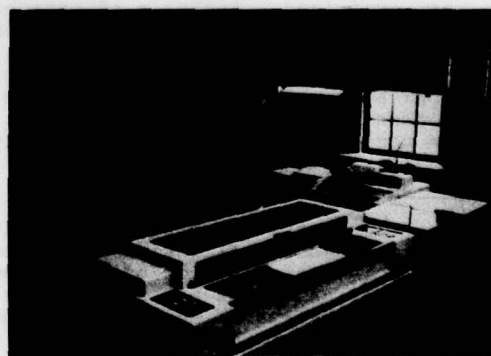


FIGURE 2. CGL's PDP-11/40 System.

manufacture, and several software graphics packages. Faculty research in design automation, microprocessor graphics data bases, battlefield information systems, digital terrain modeling, and uses of computers in education is currently in progress. Because of a significant increase in cadet usage of the laboratory facilities, plans are being made to add a PDP-11/70 or VAX 11/780 system in the near future. This is considered key to accomplishing the laboratory's future goals.

ENGINEERING DESIGN BACKGROUND

The use of computers in engineering design has come about slowly. High costs, long development times, unsophisticated interactive capabilities, few trained specialists, and a lack of proven cost-effective utilization were but some of the reasons computer graphics did not keep up with the spectacular advances experienced by the rest of the computer industry since 1960.

By the mid-70's, however, the evolution and use of computer graphics capabilities in the engineering world had created a great amount of interest. This was primarily caused by significant reductions in hardware costs, an increase in currently available systems, and the documentation of favorable cost/benefit analyses.¹ The growing number of periodicals, conferences, and special interest groups associated with computer graphics and its applications are also explicit indications of its growing relevance.

The Design Process

It is important to have some understanding of the design process before continuing. It begins with the creation of a graphical description of a proposed device and ends with machinists producing the device. Work done at the beginning of the process is highly creative, while work done towards the end is mostly mechanical in nature.² The process can be divided into three phases: conceptual, preliminary, and final.

The conceptual phase is characterized by iterative modification of the initial description until important parameters of the design have been optimized. Analysis of parameters is repeatedly done by qualitative and quantitative methods.

This paper addresses applications of the design process where the resultant product has numerous parts and significant complexity.

Computer Graphics in Design

The use of interactive graphics capabilities in preliminary and final design is now considered a common application of the computation resource. Articles are continually reflecting the benefits of such applications.³ Manufacturers are attracted by the ease of modifying, updating, and documenting designs, which make up a significant part of the effort in these design phases. Also, the

ability to have all the information on a design in one location and to be able to generate any number of up-to-date drawings helps to reduce coordination problems and erroneous usage of other than the latest design version.

The same level of usage is not found in conceptual design. In the last 4-6 years, the trend has been to involve CAD capabilities more in this stage of design. This new thrust, however, has been marked by varying degrees of sophistication and success. With few notable exceptions, new engineering projects are normally put into a computer data format after initial conceptualization is done. This requires a digitization procedure which slows down the entire design process, adds a chance for errors, and does not take advantage of any of the enhancements offered by design automation.⁴ Significant advances in interactive graphic conceptual design have been made by a few large companies who have worked in the area for years. Examples are General Motors' development of the DAC-1 system and Boeing's E/CAD system.^{5,6} A better understanding of the interrelation of a CAD system with the conceptual design process should help change this situation.

INTERACTIVE CONCEPTUAL DESIGN ENVIRONMENT

The fact that CAD techniques are not in widespread use in conceptual design should not be surprising. When one moves from a task of modifying a design to creating a design, a much more unrestricted and interactive mode of work must be supported. Reasons for this are apparent when one analyzes the environment where this activity is done. The fundamental segments of this environment are the virtual graphics machine, the physical arrangement of the work area, and the human designer himself.

The Virtual Graphics Machine

The combination of a computer, its associated graphics input/output hardware, and the software graphics package operating on that computer creates a virtual graphics machine. It defines that set of actions and capabilities available to the designer to accomplish his purpose and the interface through which all man-computer communication will occur. It also defines all possible alternatives for structuring and accessing design data. Overall, it establishes many constraints on the design function which are of significance, such as the:

1. graphic resolution which can be obtained;
2. arithmetic computation accuracy which can be obtained;
3. amount of design data which can be stored;
4. memory size available for computation and transformation;

5. response time for each category of command;
6. sophistication of the man-machine interaction;
7. ability for more than one designer to access the same data structure simultaneously.

Each of these constraints has the capability of rendering an otherwise well-designed CAD system useless. Since any of these can have such a disastrous effect on system utility, it is hard to call one more important than another. However, this paper will concentrate on the aspects of man-machine interaction.

Arrangement of the Work Area

It may seem insignificant and trivial to include this as a segment of the design environment. However, even the most well-designed system will not be used if it is not located in an area and configured in a fashion conducive to work. Hence, it is of great importance to the success of a CAD project. A survey of graphics installations in industry surprisingly might prove the necessity of this explicit reference to these considerations. The following items should be addressed during the planning of a CAD system:

1. control of distractions, noise, and interruptions (phones, mechanical noise, etc.);
2. comfort in reaching and using all input devices;
3. control of lighting and temperature;
4. sufficient space for layout of documents and references;
5. position of display devices for minimum movement of eyes and head.

These items can be taken care of by applying human engineering principles.

The Human as a Designer

The conceptual designer's goal is to translate a mental picture onto some storage medium and analyze and modify it according to qualitative and quantitative criteria. When it comes to interacting with a computer, he is a tough person to please. But if one is to enhance the conceptual design activity, it is a task that must be accomplished. Hansen puts a prime importance on "knowing the user" of an interactive system.⁷ If he does not see the system as being helpful, then it will be a failure.

The following human traits of a conceptual designer are relevant to the design of a man-computer symbiosis:

1. a creative thinker, involved in new directions and feasibilities; normally of higher intelligence; thinks very rapidly;

2. rapidly iterates through a cycle of creation, calculation, and modification to achieve an optimal design;
3. concerned with the theory of his field; requires involved calculations;
4. exhibits disdain for boring, dull, repetitious work; does not like to waste time; prone to simple errors;
5. well paid.

Licklider and Clark specify an interesting set of responsibilities that a designer fulfills.⁸ He is to select goals and criteria, formulate questions and hypotheses, select approaches, detect relevance, recognize patterns and objects, and handle unforeseen problems. If a designer possessing the above traits is to do all this, it is apparent that the man-machine interface of the CAD system will have to be well planned and implemented.

THE MAN-MACHINE INTERFACE

The man-machine interface of an interactive graphics design system is defined by the virtual graphics machine explained above. Most of the definition affecting the designer's actual work with the system is specified by the software graphics package. Hardware and physical arrangement aspects of the design environment are assumed satisfactory and will not be addressed separately.

Much has been written about the nature of interactive computer work. In a classic paper, Licklider proposed that the aim of a man-computer interaction was to bring the computer into the formulative parts of technical problems and use it effectively to assist thinking processes that must be accomplished in real time. He also felt that the real challenge to the use of CAD was to develop a system which the designer would accept as a replacement for the sketchbook and pencil.⁹

Generally, a man-machine interface must satisfy all information requirements and satisfy the user. In doing this, it must 1) minimize the differences in dialogue and interaction between man and computer, 2) optimally allocate tasks to each of them, and 3) accomplish this without changing man's standard mode of expression to satisfy virtual machine-imposed limitations.¹⁰

Satisfying Information Requirements

A specification of the standard information normal to a graphics system was proposed by Deecker and Penny.¹¹ In addition to those specified in their article (identifying positions, vectors, text, numeric values, objects, and functions to be performed), a designer will have a need to calculate intermediate values of design parameters. From these, the designer will make decisions to modify the design. This should be

considered an additional basic information requirement because of its continuous use and importance to the design process. The application programs to do these calculations should be planned for during CAD system design.

Satisfying the Designer

It is no easy task to match the creativity and speed of the designer's mind to the information processes of storage, retrieval, and modification on a computer data structure. Unless a designer can do this in a somewhat "natural" manner, he will become dissatisfied. A paper on perceptions of the quality of interactive systems suggested seven different "dimensions" of user-perceived quality:¹²

1. self-descriptiveness;
2. user control;
3. ease of learning;
4. problem adequate usability;
5. correspondence with user expectations;
6. flexibility in task handling;
7. fault tolerance.

Other studies consider related user topics. Foley and Wallace promote the importance of protecting against user boredom, panic, frustration, discomfort, and confusion.¹³ Hansen also suggests the interface minimize memorization, optimize frequent operations, and carefully engineer for errors.¹⁴

Techniques for a Successful Interface

More than in any other CAD application, the interface for conceptual design must focus on the user. Its goal is to not restrict the creativity or spontaneity of conceptualization. The identification of a set of general techniques which attempt to support conceptual engineering design will now be specified and discussed. These techniques drive the design of the man-machine interface and allow for the satisfaction of user information requirements in a manner which is pleasing to the designer.

1. Minimize input that does not have a behavioral similarity to drawing.

This is a direct attempt at user satisfaction. Since a large percentage of a designer's work is comprised of "drawing," the man-machine interface should give priority to using an input method which correlates well to sketching with pad and pencil. Some input methods promote this more than others.¹⁵ Keyboard input, for example, is not a natural mode of expression for drawing. It is disliked by most designers. Joy sticks are better, but do not give you the sense of moving across a page as you draw. The use of a mouse on a menu tablet to generate input on a display screen provides the

best drawing correlation for rapid input of design data. However, it requires the user to continually redirect his vision between the tablet and the screen, which is undesirable. This method is being used in the author's missile design system with acceptable success. Drawing with a light pen on a display screen presents what seems to be the optimal solution for the conceptual designer. Using the pen is natural, and seeing the display of the input data at the point of input creates a similarity to drawing unmatched by any other input device. The light pen is, however, an outmoded device. It is driven by interrupts generated by the light of a refresh display. This limits the speed of input below acceptable levels for conceptual design.

2. Maximize the use of video display for interactive input and output.

To keep the designer from redirecting his attention between many input and output devices (tablets with mouse, alphanumeric keyboards and printers, light pens, and storage tube/raster scan display screens), it seems advisable to attempt to collocate as much input and output on as few devices as possible. This will minimize the fatigue of head and eye movement and generally make the system easier for the designer to use.

Since visual stimuli are needed to accomplish most of the designer's work in a graphic environment, this technique recommends high usage of the video display screen. As seen earlier, the graphics hardware used for the author's missile design application uses two screens to get more simultaneous visual display capability (Figure 1). Not only is it possible to split the graphic representation of the design between the screens for clarity, but the screens are used for input of some commands, selection of options, and output of alphanumeric command prompts, status, and feedback. This centralization of input/output has been a successful technique in promoting use of the author's system. The second display screen has proven particularly successful because of the flexibility it provides. It is currently used to simultaneously display command options and design data, two different windows in the design file, and different groupings of design data. Use of two screens is made by some of the following techniques as well.

3. Provide a set of calculation routines which assess interim values of design parameters.

This well-known technique is perhaps the greatest benefit of a CAD system used for conceptual design. Many graphics systems, including the M&S system used by the author, allow for the addition of these routines. However, they should normally be written by a computer specialist.

The primary goal of the technique is to provide for real time analysis of the characteristics of the current design, with output in a form immediately usable for decision-making. To get this information in conventional systems, the person would have to stop designing and either work out the mathematics involved himself or run a separate computer procedure. This is cumbersome and disruptive.

By implementing these calculations with a graphics system menu command and providing output to the designer's display screen, the CAD system can satisfy these important information requirements in a better and faster way. The combination of execution by menu command and use of the design system display for output is very supportive of the iterative nature of conceptual design work. It also minimizes the interruptions of the designer's creative thought and utilizes the computer for the job it does best--doing repetitious work quickly and accurately.

The author has implemented a calculation routine which determines the weight, center of gravity, and pitch and roll moments of inertia of the missile structure held in a specified design file. This information is periodically needed by a missile designer to assess his interim design. An example of the program output which can be sent to a display screen is given (Figure 3).

```

MISSILE DESIGN SYSTEM
MASS CHARACTERISTICS CALCULATION ROUTINE

YOUR MISSILE DESIGN FILE HAS 6 PARTS DEFINED.
THERE WERE NO PART DEFINITION ERRORS.
.....
TOTAL WEIGHT OF THE MISSILE IS 15.000 KGS.
CG POINT: 21.557 M. FROM S STATION.
TOTAL PITCH MOMENT: 69.935 GRAM-CM**2.
TOTAL ROLL MOMENT: 70.000 GR-CM**2.

*****
OBTAIN PRINTER OUTPUT IF INDIVIDUAL
PART CHARACTERISTICS WERE REQUESTED.
*****

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FIGURE 3. Calculation Routine Output.

4. Minimize rigidity in the sequence of design.

If the man-machine interface is to support creative and unrestricted work, the conceptual designer must be in complete control of the system. This implies that he can do what he wants when he wants, interrupt input/output of any command before normal termination, and rapidly switch between designing and receiving design data from calculation routines. This not only promotes great user satisfaction but it minimizes required memorization and makes the system easier to learn.

The implementation of this technique depends on the graphic software command interpreter and the data requirements of the calculation routines. The command interpreter must be very flexible. It should recognize user input at any time and respond to it. Even during the input of a sequence of commands, the command interpreter must allow the designer to change his mind and return him to a state where any other command sequence can be initiated.

Also, in an attempt to simplify the system and reduce memorization requirements, any command which appears to be indivisible to the designer should be executable with the input of one command. This will reduce some amount of memorization and "useless" work as perceived by the designer.

Also, to maintain flexibility in the design sequence, the computer specialist must be careful to write calculation routines that do not force a required sequence of input for design data. This has an undesirable affect on the rigidity of the design sequence.

Most basic graphic systems have a command interpreter which supports this technique. This freedom should also be extended to commands which implement user-defined assistance and calculation routines. A user should not have to constrain the flexibility of the design sequence in order to have user-defined functions.

5. Provide for simultaneous access of the design data base by multiple design stations.
6. Provide aids to coordination among design team members.
7. Establish a procedure to quickly resolve design conflicts controlled at a supervisory level.

Perhaps the greatest constraint to successful use of CAD capabilities is the inability to support a coordinated group design effort. Design projects of the size and complexity assumed for this research can only be cost-effectively accomplished when the project is modularized among individual members of a design team. These techniques provide that capability.

Multiple access alone is not enough to establish a work environment for a design team. Their method of operation requires a means for coordination and conflict resolution.

Coordination among members of the design team can be accomplished by using a text message facility initiated as a graphic system command. A prompt to the addresser's design station would alert him that he should check his message file. This could be displayed on the graphic screens.

A more appealing method would be to communicate simultaneously by audio and visual means between design stations. This could be implemented with 1) an intercom system between design stations and 2) an ability for the designer initiating communication to transfer a graphic image to the slave screen of the designer being contacted. If he then had the ability to direct a cursor on the receiver's display screen, he would have a complete audio and visual capability to explain his thoughts to another designer. These methods can also be used to bring a design conflict to the appropriate person for resolution, although personal coordination will certainly be needed as well.

The addition of these techniques is to be included in the next version of the author's missile design system. Their need and importance to successful engineering design were highlighted by their absence in the original version.

8. Provide a simple method to associate all elements defining an individual part in the design.

Designs considered in this paper are made up of many parts. Each is comprised

of some number of lines, arcs, curves, and nodes of textual information. The primary benefit of this technique is that all the elements of one part can be identified by calculation routines. Without this, many calculations based on results from individual parts would be impossible.

This can best be accomplished by using advanced techniques in structuring graphic data bases. Additional cells of data can be added to the structure indicating part and even part group associations. This extra data is even more important when there are requirements for a three-dimensional representation of the design. Here, hidden line and surface algorithms need complex tree structures to store design data in order to execute efficiently.

An example of a simple missile structure drawn on the author's design system shows that there is no requirement for the designer to waste time marking each element with a part number (Figure 4). This data can be automatically stored in the design data base. Now the mass characteristics calculation routine can associate any number of lines for a part and calculate the required inertial moments.

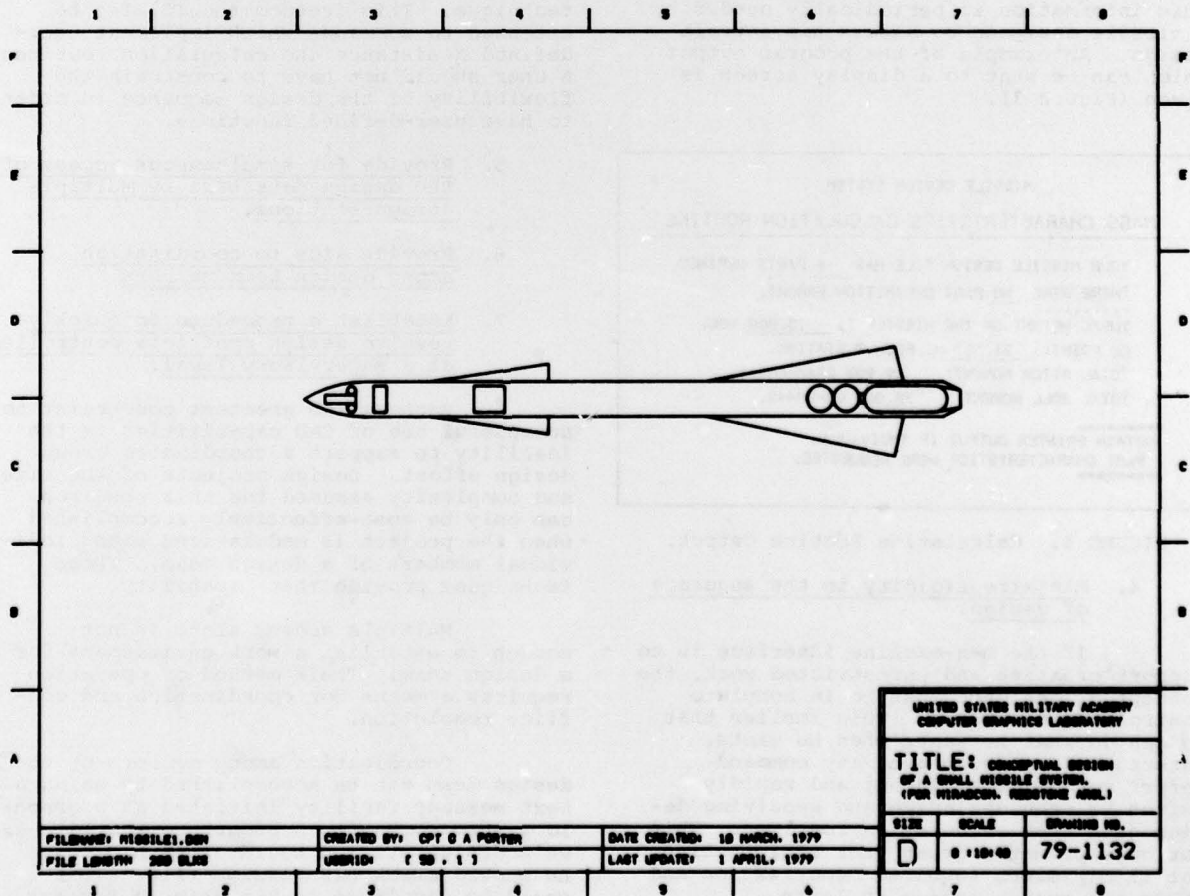


FIGURE 4. Sample Conceptual Design.

9. Maximize use of libraries of common symbols and features.

The use of this technique eliminates some repetitious work for the designer. If there is extensive use of this technique, the time to accomplish the conceptual design phase can be significantly reduced. It also appeals to a user's expectations of a well-designed system.

The ability to produce a more standardized and consistent design is also enhanced by these libraries. They should be available to all members of a design team to insure conformity throughout the design.

Most available CAD systems have the capability to use graphic libraries. It is normally a feature of the graphics software, but it can be written as an application program executable from the menu tablet. This is a worthwhile technique to promote successful conceptual design.

The author's system makes extensive use of libraries for architectural features, electrical symbols, computer flow chart symbols, and similar items from many disciplines.

10. Minimize the designer's input of dimensional quantities.

The goal of this technique is to free the designer of simple work that can be done by the computer. This, in turn, will allow the designer to concentrate more on his design.

This technique can be implemented in software by allowing the user to associate a scale to his graphic design plane. This association allows the location and dimension of an element (even though stored in terms of addressible points in X-Y) to be interpreted in a meaningful way by application programs with no additional input from the designer. For example, the volume of a missile nose cone in terms of addressible points has no immediately usable meaning. If the calculation routine can automatically convert this into cubic centimeters, the designer can gain immediate value from these data. Again, the designer's creative process is not interrupted by the required input of location or dimension data on each element.

The use of this technique will also give the designer information on the accuracy obtained with the specified scale. If he specifies a scale which has four addressible points for an inch of scale distance, the best accuracy obtainable is to the nearest .25 inches. This would be used early in the design process to insure the design will achieve the desired accuracy.

11. Provide interim status (reassurance) on commands that require longer than 3 seconds to execute.

The purpose of this technique is to reduce confusion and uncertainty in the mind of the designer. If a command is executed and no visible indication is given to tell the designer "all is well," he will very quickly become unnerved and assume something went wrong. Any actions taken at that point are based on frustration and will create a complete interruption of his train of thought (a panic situation). If the designer is reassured that the computer is processing each command satisfactorily, this situation can be prevented. The technique is especially important with long calculation routines.

A visual method can be used to accomplish this reassurance. Reassurance messages should appear in the display area normally reserved for command and input prompts. Continuous feedback by the system can be indicated by flashing the message or providing a countdown clock. Both of these methods help focus the user's attention to that message as well.

The flashing message was used by the author's design system because the graphic hardware supported this technique. It was of considerable value in relieving the uncertainty in the designer's mind in situations of extended system response time.

12. Provide the ability to store different categories of design data on different virtual drawing surfaces.

For a complex design, the amount of information stored in the design file can quickly make the displayed output impossible to read. Not only that, the designer normally does not need to see all the data all the time.

By segregating logical groups of information in such a way that they can be selectively displayed, the designer is able to avoid clutter and confusion. This becomes even more important when more than one designer can work on the same design file. Normally one member would not need nor want to see another designer's working data, even though both sets of data may be in the same area of the drawing. For example, one missile designer may be working on exterior detail at the tail of the missile while another is working on propulsion system design in the same area. Display of either designer's data to the other can only create confusion and error. Also, security requirements may dictate mandatory restrictions to parts of the design file.

The author uses this technique, as was provided by the graphics system software, to segregate design data according to function parts of the missile design (Figure 5). It has contributed a great deal to the success of the design environment.

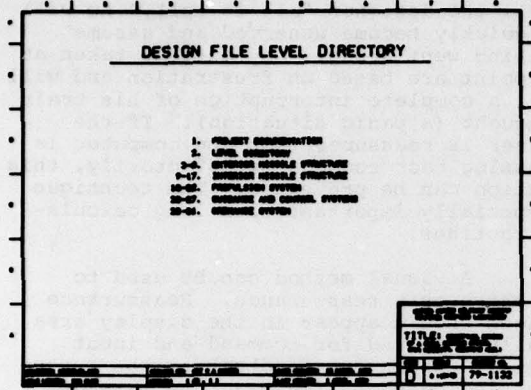


FIGURE 5. Directory of Data by Level.

CONCLUSION

In this paper I have presented a set of techniques to implement when designing a man-machine interface for conceptual engineering design. Preliminary results obtained from using the author's missile design system indicate that each technique has a positive effect on the successful utilization of a CAD system for conceptual design.

Throughout any specification and implementation of a man-machine interface, it must be acknowledged that the key to its success is the satisfaction of the user and his information requirements. It should be the computer specialist's goal to change the nature of the computing resource to accommodate the natural environment of the designer, not vice versa. Therefore, a sound relationship between computer scientist and designer is essential in the design of the system.

It should also be noted that the underlying ability to implement these techniques was based on the capabilities of the graphics system hardware and software. A generally sophisticated computer graphics system is required to create a sufficiently powerful and flexible man-machine interface.

Associated topics which are appropriate for further research include a study of the relative importance of these techniques, the trade-off between flexibility and execution speed of graphics software, and an in-depth study of the restrictions to CAD in a design team environment.

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