A FACILITY FOR RAPID COMPUTER-AIDED GENERATION OF PRECISION GRAPHICS

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I. INTRODUCTION

Computer-aided design has been with us for a long time. One needs only to look over the proceedings of this very workshop to determine the wide-spread use of the many computer-aided design techniques. Where design automation was once an interesting experimental tool, it is now becoming essential. The growing availability of on-line hardware and software with computer graphics capabilities provides the catalyst for developing more powerful design automation systems needed by the fourth generation and beyond.

This paper will describe the design philosophy, implementation, advantages and limitations of a "design facility" which is currently in its initial period of operation at the Hughes Aircraft Company. The term "design facility" is used here to denote an integrated hardware/software system which forms an operational base for the preparation, modification, and production of the design of a particular set of products. In this case, the products will be the various physical elements of a digital system, each of which has precision artwork requirements.

II. PRECISION ARTWORK GENERATION

A. Overview

One of the important areas in the field of design automation is that of precision artwork generation. This is not a new area of concern; machinery and techniques for generating precision artwork patterns have been available and in use for many years. However, there are few well-planned "design facilities" which incorporate these precision artwork machines.

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The need for precision artwork is increasing rapidly. In digital systems, for example, the electrical and logical complexity of the system continues to grow while the overall physical size of the system and its components tends to decrease. Eventually the growth limitations are the physical design and fabrication difficulties for the system components. Automatically generated precision artwork provides a partial solution to the many physical design problems. At this time, the increasing use of large scale integration, especially on a "custom" ship basis, increases the need for rapid, precise generation of artwork patterns. As technology advances, the design, layout, and fabrication of LSI will become so complex that manual methods will be totally insufficient; the use of a "design facility" will be vital.

B. Manual Artwork Generation

The manual generation of precision artwork is a multi-stage, tedious process; nevertheless, it is widely used today and there exist many small and large companies which specialize in this field. Briefly, the manual generation method is this. First, a mechanical drawing of the desired artwork is prepared. Usually the artwork is greatly enlarged, such as ten to twenty times actual size for circuit boards and as much as three to five hundred times actual size for integrated circuits and LSI. The next step is the preparation of a dimensionally stable medium which can be used in the subsequent photographic process to generate the actual size artwork. For circuit boards the commonly used medium is clear mylar, as illustrated in Figure 1. Those areas which represent conductors or conducting paths on the finished artwork are "taped" onto the clear mylar with black tape. The taping process is time-consuming and prone to error; Figure 2 illustrates a circuit board taping operation. For integrated circuits and LSI the commonly used medium is rubylith; the artwork pattern is accurately scribed onto the rubylith with a manually operated precision coordinatograph, and those areas which represent conductors or non-conductors (depending on whether a positive or negative is required) are peeled off of the large rubylith sheet.

The next operation is the photo reduction of the large master sheet and the preparation of 1:1 negatives for the actual photo-etching fabrication process. The photo reduction process is costly and the final accuracy relies on the accuracy of the optical and photographic equipment and the skill of the operator. Often the photo reduction process occurs in several steps, such as a 5:1 reduction followed by a 2:1 reduction for circuit boards, or a 100:1 reduction followed by a 5:1 reduction for rubylith masters. In this manner inaccuracies are often multiplied together, reducing even further the accuracy of the finished product.

The desire to use an automatic system is primarily to avoid those portions of the manual generation process that rely on the human operator's weaknesses. For example, a primary reason for using greatly enlarged master layouts is to permit the human operator to draw, tape, or cut the artwork to the desired accuracy level under the fixed constraints of human eyesight and motor control accuracy. An automatic system which does not require accurate manual skills must produce higher quality artwork. However, the human designer cannot be eliminated, nor should he be eliminated; his strongest attributes, in terms of computing, are pattern recognition and overall process control, and these attributes are important to an automatic generation system.

C. Automatically Generated Artwork

The shortcomings of the manual generation process inevitably lead to the use of automatically generated artwork. There are many independent reasons for the use of automatic methods:

1. Lower Cost Artwork: On a superficial level it might seem that automatically generated is lower in cost than manually generated artwork, this because expensive manual labor has been reduced. However, as will be shown, a modern design facility contains enough computing and plotting equipment to warrant a thorough study of the cost-efficiency of automatic artwork generation. At this point in time, and in the facility under discussion, the economic study has been made and there is a cost advantage to automatic generation. However, even if such a cost advantage did not exist the higher cost for automatic generation might easily be justified on the basis of the remaining advantages.

2. Less Calendar Time Per Job: Since the taping and photo reduction processes are eliminated, the calendar time required for the generation of each pattern decreases significantly.

3. Rapid Execution of Design Changes: Because of the digital nature of the design storage file (punched cards, punched tape, or magnetic tape) design changes are executed simply and rapidly via a straightforward symbolic updating process.

4. Optimization of Product Design: Perhaps for the first time product designers have short enough turn-around to make iterative optimization techniques practical. This is one of the subtle benefits of any short-turn-around-time design system.

5. Improved Documentation: Again due to the digital nature of the design file, the long-term documentation for any piece of artwork is not the artwork itself, but rather a deck of cards or a magnetic tape. Long-term dimensional stability of phorographic media is no longer a problem; specialized storage environments are no longer required.

6. Improved Artwork Quality: The quality of automatically generated artwork is improved over that produced by manual methods. The accuracy and repeatability of the precision plotting table is consistent, whereas manual layout is susceptible to human inconsistencies.

7. Improved Optical Image: Since one or more photographic reduction processes are eliminated, the final optical image has higher resolution and definition. This normally permits a higher pattern density on the artwork.

Figure 3 compares a manually generated pattern against an automatically generated pattern of similar complexity and shape.

What constitutes automatically generated artwork? Important constituents are a large precision plotting table, controlled by a general or special purpose computer, and a device for preparation of the input data to the computer-plotter combination. Figure 4 illustrates a typical system, in fact Phase I of the Hughes Automated Design Facility. A digitizer is used to trace the circuit conductor paths from the mechanical layout drawing. Data from the digitizer is placed on punched cards. The punched cards then contain line end-point digitization information and are coded in a slightly modified EIA numerically controlled machine tool format. The use of punched cards simplifies the corrective process in this basic system. Often a mistake is detected at the digitizer; since the card punch is located adjacent to the digitizer, the operator may easily remove an incorrect card from the output deck.

The use of an EIA format should be mentioned. Whereas other forms of coordinate data are more compace than EIA, the growing availability of plotting tables that accept the EIA format provides an interchangeability justification. In addition, most circuit board artwork contains the requirement of drill-through holes; if a numerically-controlled drilling machine is used, the digitizer often can provide an output which is usable directly as input to the drilling machine.

The completed deck of cards from the digitizer is then as input to the general purpose computer. The computer has the main task of providing the drive signals necessary for the operation of the precision plotting table. Maximum plotting speed is achieved through calculation of plotting head acceleration and deceleration rates, as based on a multi-level lookahead procedure. In addition, the computer is used to generate punched tapes for N/C drilling machines when the digitizer output requires code translation.

The initial system is reasonably simple; still it has the many advantages listed above which are common to automatically generated artwork. However, there are also limitations in this system, and these limitations become more significant as the workload and design complexity increase.

III. THE HUGHES AUTOMATED DESIGN FACILITY

A. Design Philosophy

Approximately one year ago the research and development of a design facility was started. The implementation of this facility is now occurring in four well-planned phases. The overall philosophy is to provide a modern production facility, employing accurate plotting and photo finishing equipment, while at the same time providing a facility which is easily expanded and which lends itself readily to an advanced design automation system research environment. As of this date the implementation of the facility, known as the Hughes Automated Design Facility (ADF), is in progress. The various development phases and their status are described below.

B. Phase I

The essential elements of the Phase I system are illustrated in Figure 4. Phase I is an open-loop automatic artwork generation system; data is produced on the digitizer, sent through the computer, and finally plotted on the precision plotting table. The operator may specify to the controlling program any scale factor in the range $000.00000 \leq SF \leq 999.99999$, may request a mirror image plot, or may vary other significant parameters of the artwork. The finished artwork must be visually inspected to verify its correctness.

The Phase I system is a good initial system; it does not require an elaborate software system, nor is the hardware particularly outstanding. The Phase I system forms the core for succeeding variations and extensions, and is always available as a "production-only" system within the research environment mentioned earlier.

C Phase II

In Phase II, an attempt is made to eliminate even more of the manual labor involved in the artwork generation process. Wherever possible, the digitizer is replaced with a computer-generated data file. Figure 5 illustrates the components which comprise the Phase II system. A magnetic tape data file is produced in a centralized data processing facility; optionally the data may be transmitted over voice grade telephone lines.

A large, batch-oriented design automation system resides in the centralized data processing facility. One program in particular, a ROUTER program, provides artwork generation data. The ROUTER, after determining the signal net interconnection paths for an n-layer circuit board, generates a magnetic tape which is used as input to the computer-plotter combination. The ROUTER tape also contains drill-hole information which is available for input to an N/C tape punching program. Since the ROUTER program is often able to replace manual digitizer input, another factor is added to the Lower Artwork Cost argument stated earlier.

The need for a general purpose computer of small but capable size now becomes understandable. Whereas a plotting table can be driven by a hard-wired controller or special purpose computer, the overall flexibility of a general purpose computer, particularly its ability to interface with numerous peripheral devices, is vital. Figure 6 illustrates the complete Phase II hardware configuration. A one million word disc memory is used as rapid-access storage for the Phase II software system, and provides additional capability in the expanding facility.

D. Phase III

Phases III and IV represent a unique and powerful blending of two disciplines: Precision plotting and on-line CRT graphics.

The Phase III system incorporates a CRT graphics terminal into the ADF system, as shown in Figure 7. The graphics terminal consists of a CRT display station, a small general purpose computer which serves as an image buffer memory and device controller, and several man-machine I/O devices, in particular a light pen, function keyboard, and X-Y input tablet. Because the process of generating precision graphics is basically pictorial, a means for interacting with the generation process on a graphical or pictorial basis simplifies the overall control problem and provides a solution to many of the deficiencies inherent in the Phase I and Phase II systems. In addition to precision plotting applications, the graphics terminal provides the capability for future, more advanced on-line design automation processes.

The primary Phase III use for the graphics terminal is the monitoring and correction of the precision plotting table and its input data. The digitizing process is open-loop; without a graphics terminal or other high-speed, low-accuracy plotter, it is necessary to wait until the finished artwork is produced on the precision plotting table before the validity of the digitizing can be evaluated. Often a simple error occurs, such as the omission of a single line or bonding pad. A design facility with a heavy workload cannot take the time to use its precision plotting table as an error-checking device. The graphics terminal, while it has some limitations, provides an excellent means for "previewing" the design file before that data is committed to the plotting table.

It is well known that graphics terminals have certain limitations. Perhaps the most significant limitation is that only a limited amount of information can be displayed on a 10" x 10" screen. For most circuit boards this data limitation is not reached; however, for LSI and other highly complex patterns, a series of "windowing" operators is needed to focus on a meaningful segment of the full artwork. Hardware for this particular type of windowing is not yet commercially available; a special hardware development effort in conjunction with the ADF is currently defining the necessary hardware elements for a future CRT design terminal. Until these hardware elements are available, the software system will work harder and simulate the new hardware on a reduced time scale.

Another important use for the graphics terminal is real-time monitoring of the precision plotting table, Since the plotting table exposes film directly, it must naturally operate in a darkened room. In addition, the maintenance of plotter and film accuracy requires a temperature and humidity controlled clean environment. These environmental requirements mean that human observation of the plotting table is, at best, barely tolerable. The graphics terminal provides a convenient means for observing the real-time progress of a particular plotting operation; the advantages which are gained, in addition to the satisfaction that the input data is properly translated, are the capability to observe the overall motion of the plotting head, thereby detecting the plotting efficiency or inefficiency of a particular input data set, and the ability to suspend or alter the plotter operation at any time depending on the pattern already generated and displayed on the CRT.

The use of an X-Y input tablet on the graphics terminal simplifies the procedure for specifying coordinate data to the plotter control program. The data tablet may be used to simulate digitizer input, thereby allowing the addition, deletion or modification of any line segment in the design file. Small, low-accuracy patterns can be traced directly on the data tablet; in this manner the graphics terminal becomes a simple input device with immediate, positive, operator feedback.

E. Phase IV

The final operational phase under development is Phase IV. In Phase IV, the hardware and software elements of the first three phases are integrated with a communications channel, and the entire ADF becomes an on-line terminal for a large, centralized computer. Figure 8 illustrates this configuration. The need for such a terminal configuration is this: A useful design automation system in the future must contain provisions for on-line operator interaction; an on-line terminal which centers around a graphics terminal provides the capability for interacting with the design automation system in the manner most comfortable to the designer; namely, pictures, graphs, waveforms, and patterns. In addition, since most design automation systems naturally lead to a final output in graphical form, the use of the same on-line design terminal to control the precision plotting device establishes an integrated, "one-stop" design environment with systematic access to the full design base from system design through final artwork generation.

F. Overview of ADF

Figure 9 illustrates a perspective sketch of the physical plant of the Automated Design Facility. A large Control Room houses the plotting table controller, general purpose computer, magnetic tape transports, disc memory, and graphics terminal. A separate, enclosed room contains the large precision plotting table and other smaller plotting devices. The plotter room is clean to less than 65 particles larger than 5 microns per cubic foot, has temperature control to 69 $\pm$ 2^{o}F, and humidity control to 45 $\pm$ 5%. Also within the ADF is a complete photo dark-room for processing artwork in the same environment as that in which it was exposed. These environmental specifications are necessary for the generation of artwork with $\pm$ 0.0005 inch absolute accuracy, the capability of this equipment. Finally, the digitizer and associated equipment are located in an adjoining room.

IV. LONG RANGE APPLICATIONS

As mentioned earlier, a primary system design goal for ADF is the implementation of a production facility which can also support which research and contains the potential for future growth. Toward this goal the individual hardware and software components within the ADF are "oversized"; that is, they contain built-in expansion potential. The plotting table is large, perhaps larger than needed today. The general purpose computer with its one million word disc is capable of controlling complex design terminal functions. Additional core memory can be added; additional mass storage devices and units can be added. Other peripheral devices, such as a card punch or line printer, can be added easily to the hardware configuration and require no changes to the software system. The most important long range application for the ADF, and the one which is currently receiving primary research emphasis, is the use of the graphics terminal as an on-line interactive device in the full range of design automation activities. Figure 10 illustrates this point. Again referring to digital system design, the ADF terminal can participate in system design, logic design and simulation, circuit design and simulation, partitioning, and routing. In addition, ADF will be used in the design, fabrication, and production of large scale integration (LSI) devices. The problems of discretionary wiring and other chip interconnection techniques may be solved economically through the use of on-line graphics coupled with precision plotting hardware.

V. SOFTWARE SYSTEM

Figure 11 shows a functional schematic of the Phase IV software system. There are three major sections: The centralized data processing facility, the ADF central computer, and the ADF graphics terminal subsystem.

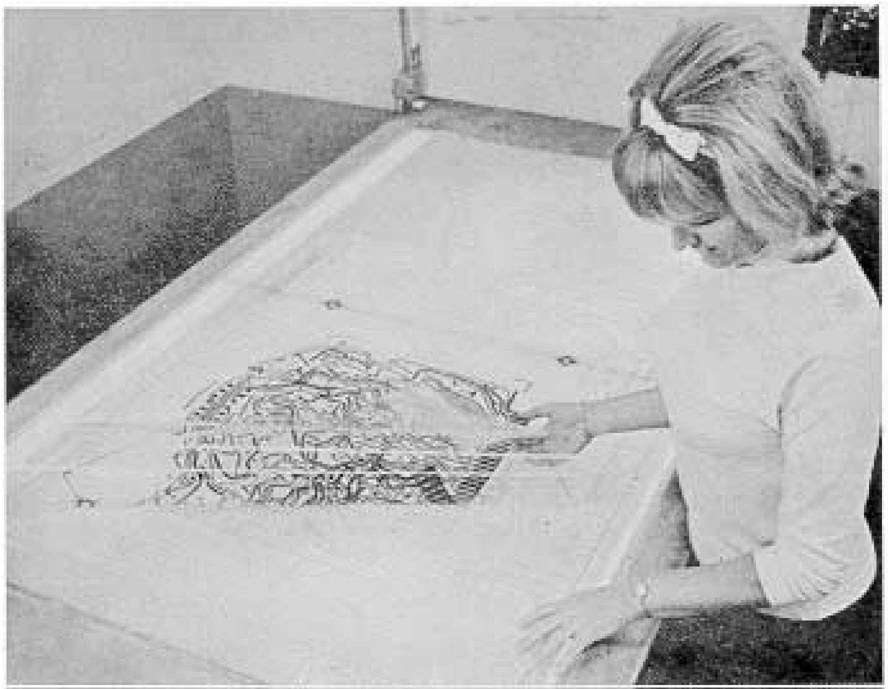
The centralized data processing facility maintains the overall design data base and it provides large computing power and large secondary storage for the various portions of the design automation system. The central facility is assumed to operate in a time-sharing mode so that the ADF is a true on-line terminal to this facility. The design automation system which resides in the central facility is open-ended; it begins with those programs that provide data directly for precision plotting, but many other areas of design can utilize the hardware/software system.

The ADF general purpose computer contains the ADF EXECUTIVE software system. This executive controls the time-sharing communications link with the central facility, controls the data path to the graphic terminal, acts as a monitor for the precision plotter control program, and maintains the local ADF data base. Many utility programs are available for research and development work.

The graphics terminal general purpose computer contains a software system for maintaining the CRT display, controlling the I/O devices, and for communicating with the ADF general purpose computer. An important task for the GRAPHICS TERMINAL EXECUTIVE is the transmission of data to and from the ADF central system in conjunction with operator actions. The GRAPHICS DATA BASE, from which CRT pictures are refreshed, must be related to the current ADF DATA BASE when requests for deletion or modification of CRT image components are initiated by the operator.

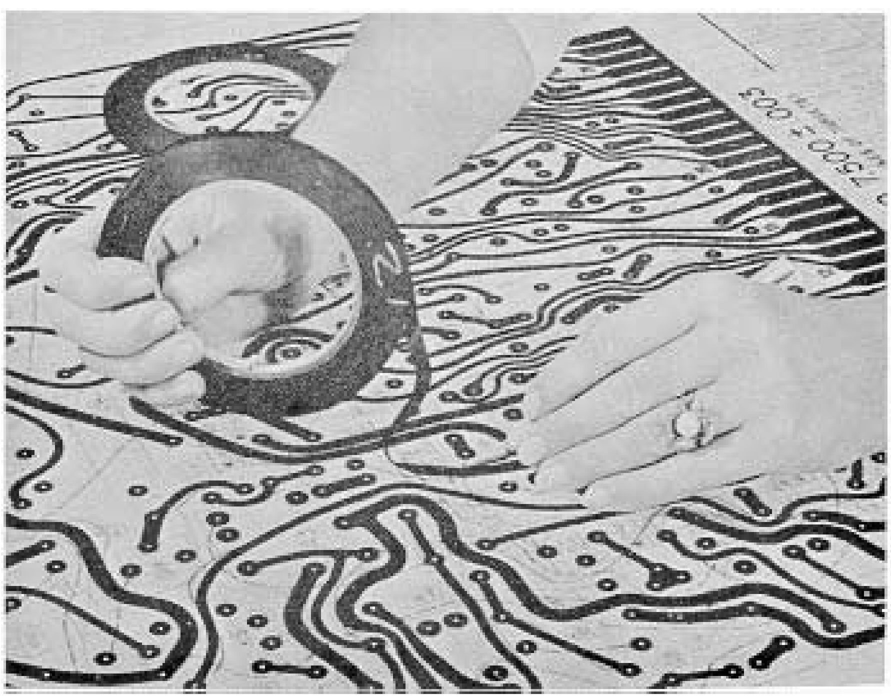
VI. OPERATIONAL STATUS

The operational status of the Automated Design Facility is as follows: Phase I and Phase II hardware components are installed. Software support for Phases I and II is in the final debugging stage. The CRT graphics terminal will be installed and integrated with other equipment during the fourth quarter of this year. Software support for Phase III is currently under development. The communications channel and associated on-line software support for Phase IV are scheduled for completion in late 1969.



Manual Artwork Generation

Figure 1



Taping Mylar Master

Figure 2

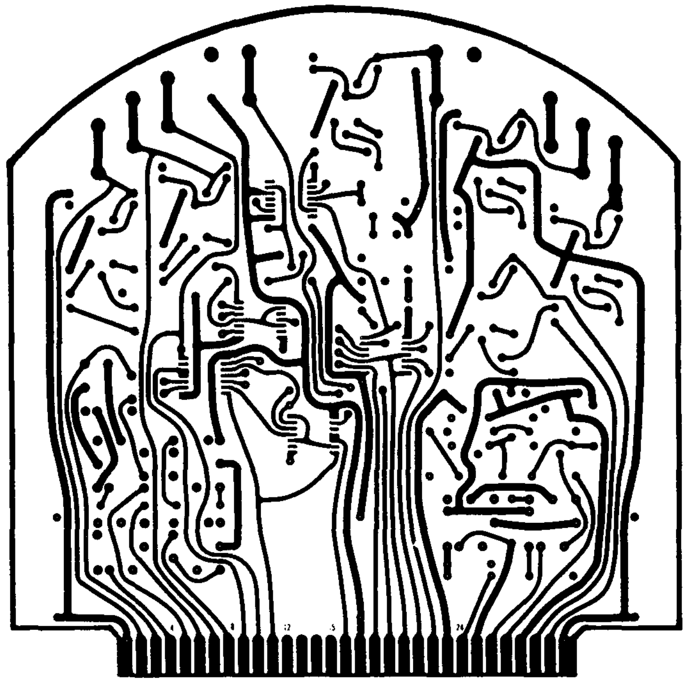


Figure 3a: Manual Artwork

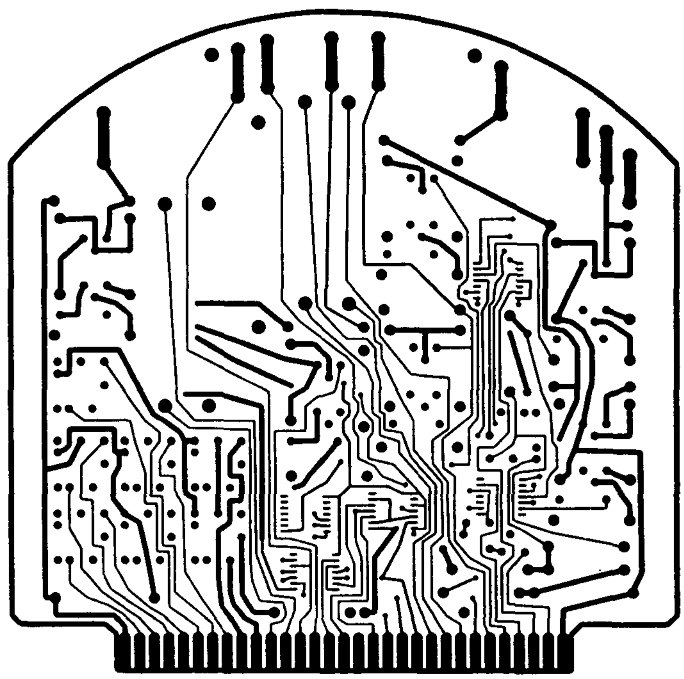
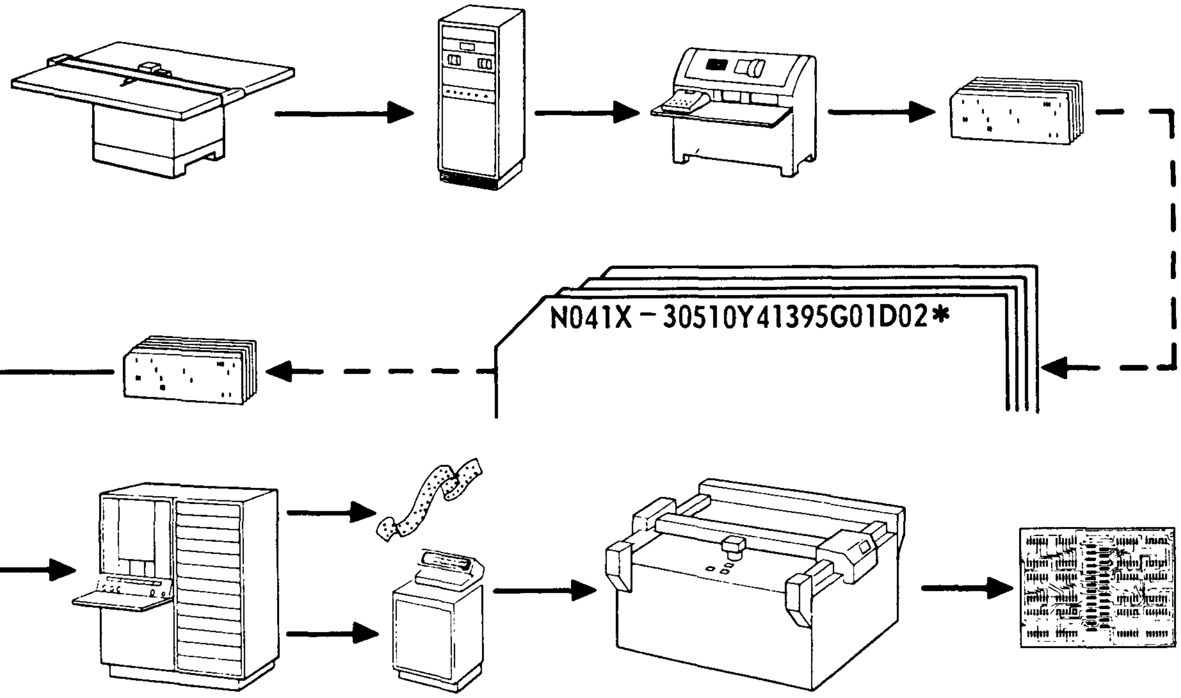


Figure 3b: Automatic Artwork

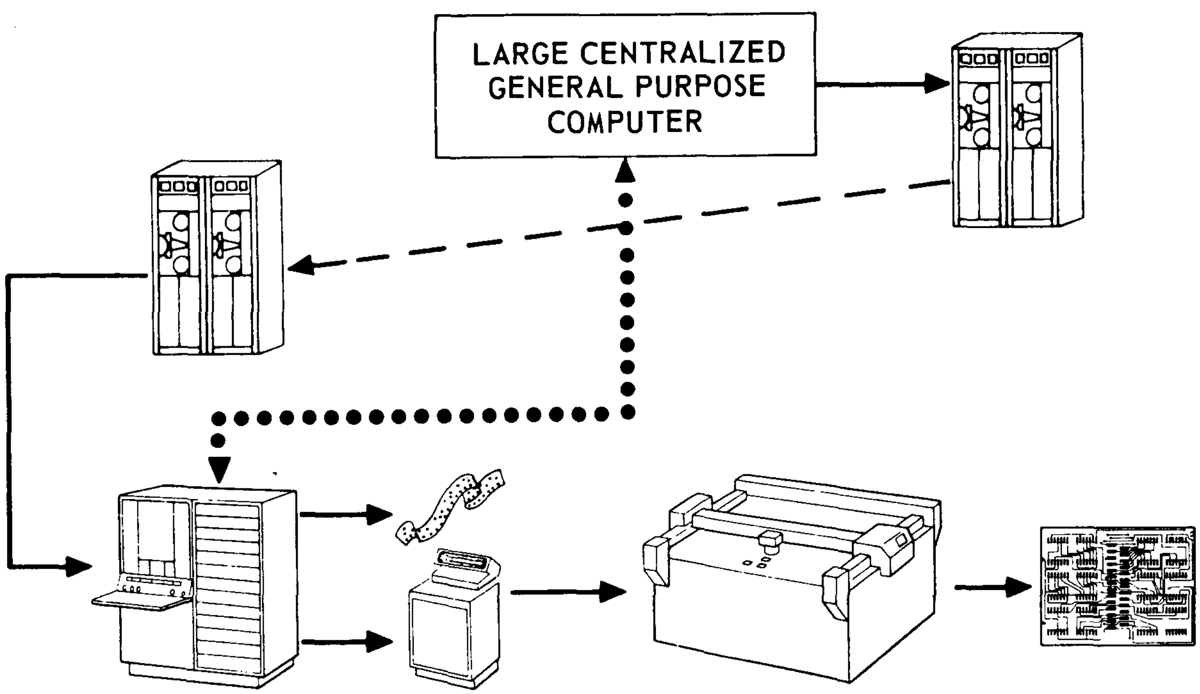
Comparison of Manual and Automatic Artwork

Figure 3



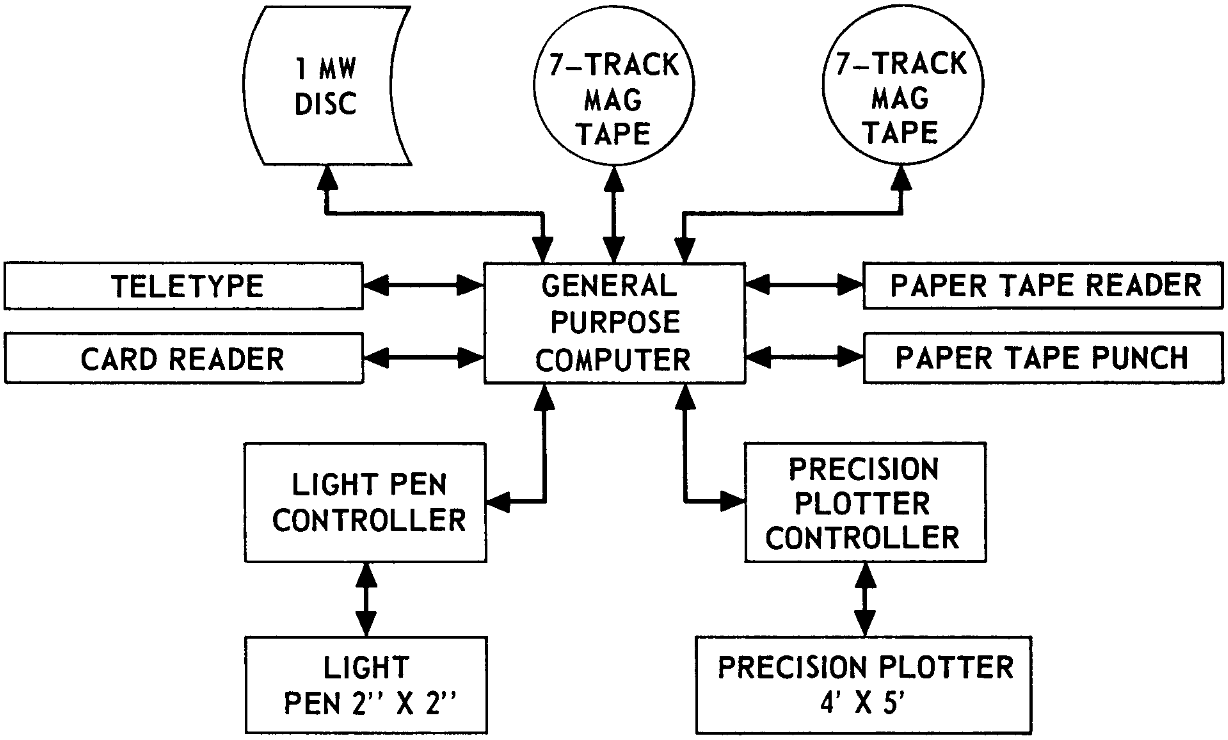
Digitizer Input - Phase I

Figure 4



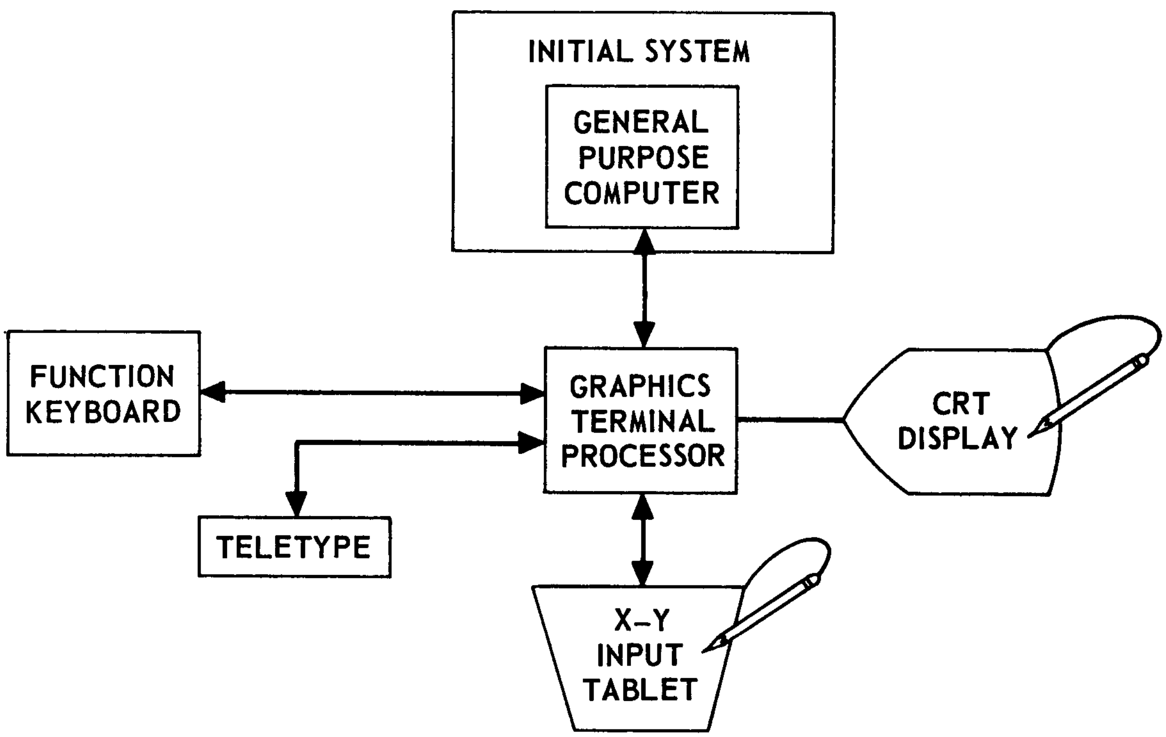
Computer Generated Input - Phase II

Figure 5



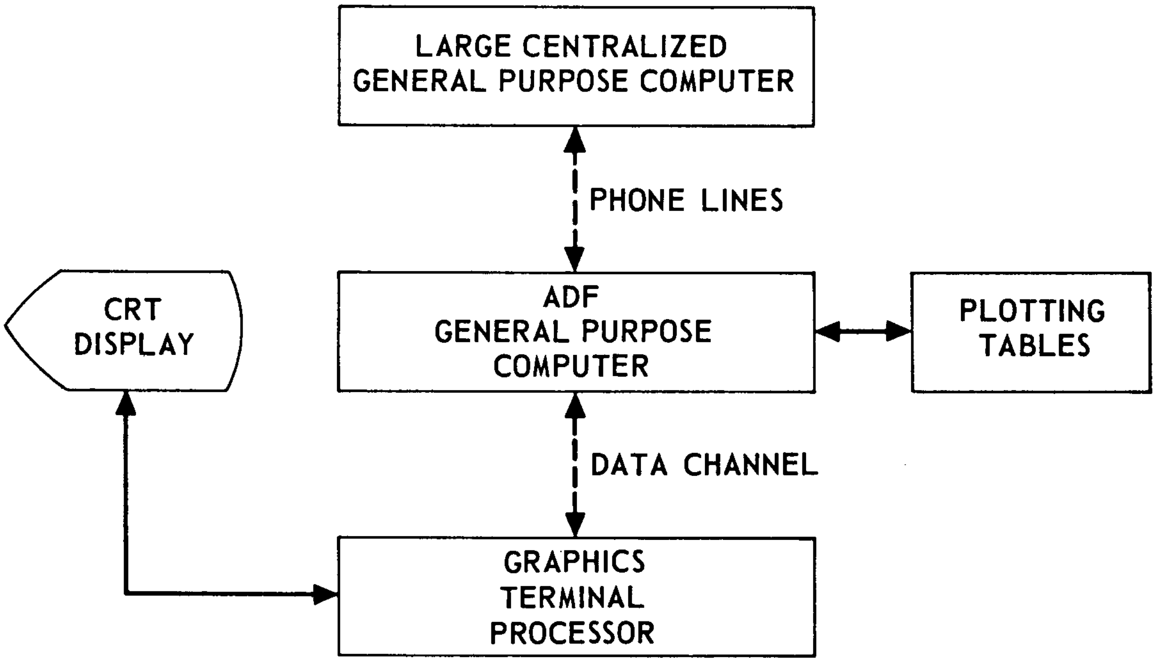
Phase II Hardware Configuration

Figure 6



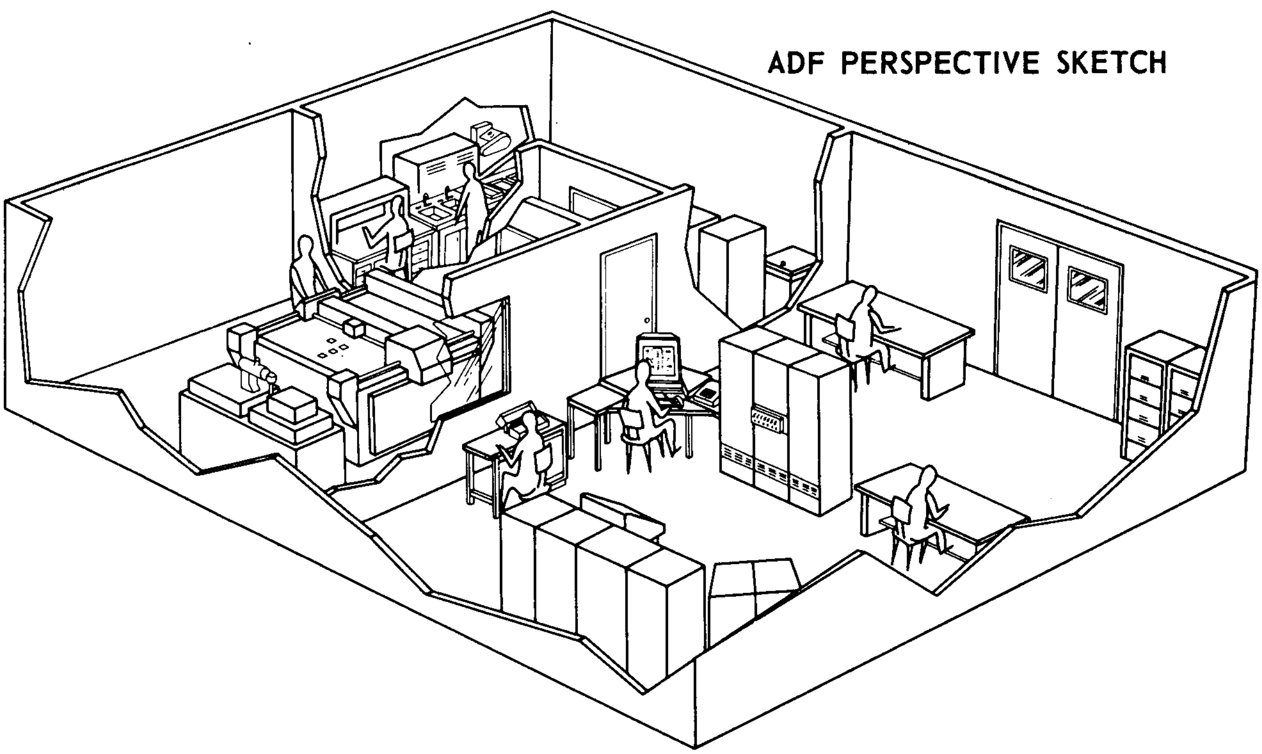
CRT Graphics Terminal - Phase III

Figure 7



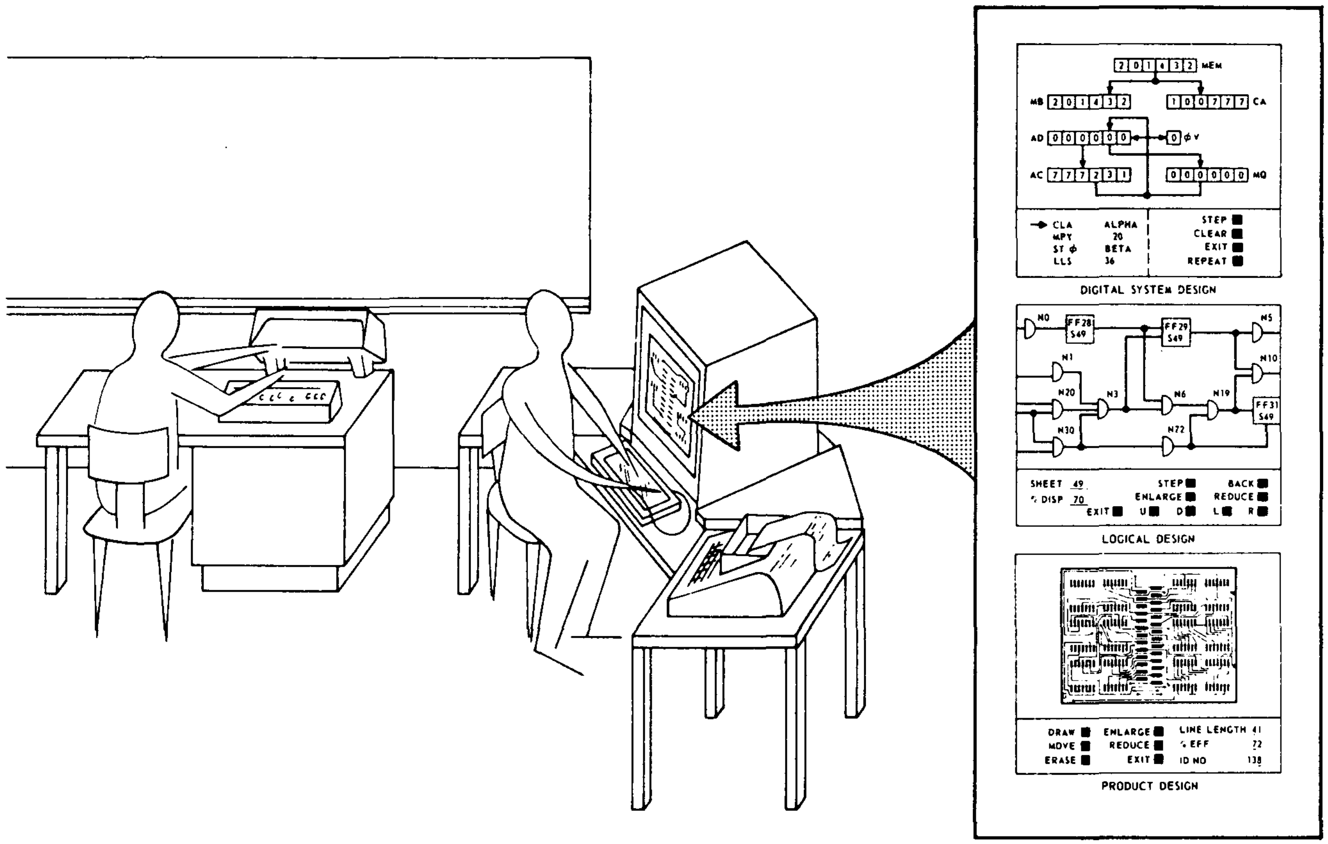
Centralized Computer Tie-In - Phase IV

Figure 8



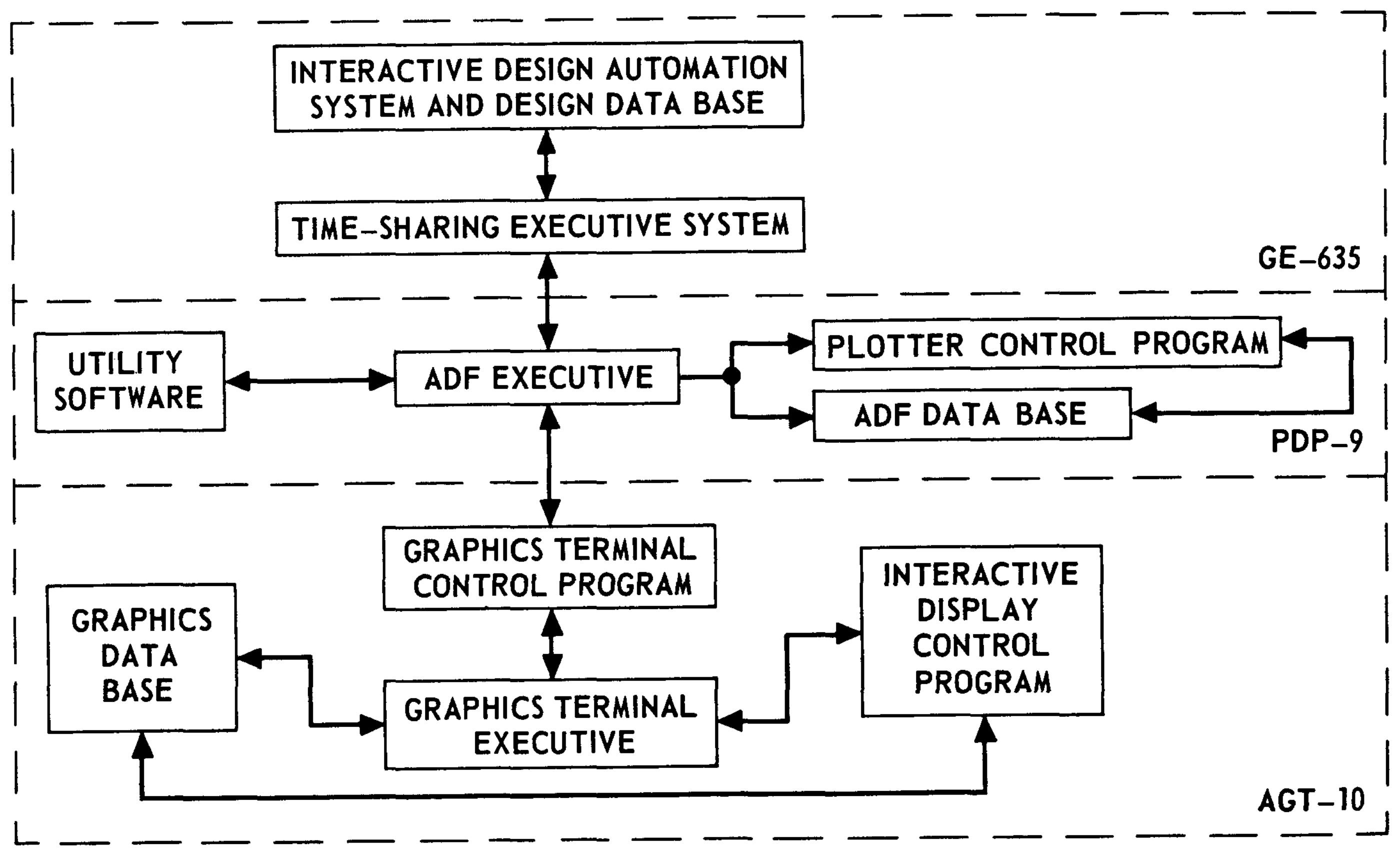
Hughes Automated Design Facility

Figure 9



On-Line CRT Graphics In Design

Figure 10



Software Structure

Figure 11