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FINAL TECHNICAL REPORT

May 1971

GRAPHICAL MAN/MACHINE COMMUNICATIONS

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PUBLICATION REVIEW

This technical report has been reviewed and is approved.

Murray Kesselman
RADC Project Engineer

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Final Technical Report

1 December 1969 to 30 June 1970

GRAPHICAL MAN/MACHINE COMMUNICATIONS

David C. Evans

University of Utah

This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by Murray Kesselman, RADC (ISCA), GAFB, NY under contract No. AF 30(602)-4277.

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PART I. SUMMARY OF RESEARCH ACTIVITIES

The objective of the graphical man/machine communication effort is the development of computers and computing techniques that people may use interactively in real time to extend their problem-solving capability and to work cooperatively by means of improved communications via computer. This report summarizes the progress made in the four major areas: 1) computer graphics techniques, 2) computing systems, 3) digital waveform processing, and 4) applications.

A brief resume of the overall objective of each major research area is presented, along with highlights of the significant research findings that occurred during the period of 1 December 1969 to 30 June 1970.

A. COMPUTER GRAPHIC TECHNIQUES

The senior investigators in computer graphic techniques are David C. Evans, William M. Newman (Associate Instructor), and Ivan E. Sutherland. There are two aspects of this research: 1) the development of graphics systems that are readily accessible to computer system users and that may be easily used by them for practical applications, e.g., graphic programming languages and the representation of information for graphic systems; and 2) the development of primary graphic techniques for the realistic dynamic display of three-dimensional objects.

Efforts are directed to the solution of computational problems of real-time windowing, perspective transformations, hidden-surface elimination, and the production of shaded color representations of photograph-like quality. Emphasis is placed upon the capability of the user to interact with the structured data representation of the object being viewed by the graphic system, rather than emphasizing the graphic system as a picture generator by itself.

Watkins' Processor

An important milestone was reached during this period when Gary S. Watkins[(1)] completed the development of a new set of algorithms for the production of shaded, illuminated, perspective drawings for three-dimensional systems. Although the new algorithms perform functions similar to algorithms developed previously by Warnock, Erdahl, Evans, Wylie, Romney, etc., (Figure 1), they require much less information storage and significantly fewer computations to create pictures of a given complexity. These algorithms provide the basis for the design of a real-time picture processor capable of producing dynamically changing shaded pictures of complex objects.

Existing algorithms were not compatible with available hardware, so Dr. Watkins created a new algorithm and then developed a program to simulate the hardware processor. He wanted to develop a fast easy way to solve the hidden-line problem in real time.

Current research is being directed toward the development and construction of this special display processor under the supervision of Dr. Gary S. Watkins, research associate. It is an independent, stored-program processor which will operate in conjunction with any general purpose computer system. Current state of the art just now enables the construction of such hardware since it uses semi-conductor memories in the 200 nanosecond cycle range. The processor will have a color scope and the capability to change the shading and color of an object as it is being viewed. Total computation time for generating and displaying pictures is short -- with software it takes one and one-half minutes to process one frame, but the Watkins processor will process 30 frames per second. The algorithm created to augment the processor has been simulated in FORTRAN IV on the University's PDP-10 computer.

Uses for this system are unlimited. Environmental (world, space, flight, molecular, etc.) simulation (see Figure 2) and architectural modeling are only some areas that would benefit from such a display processor.

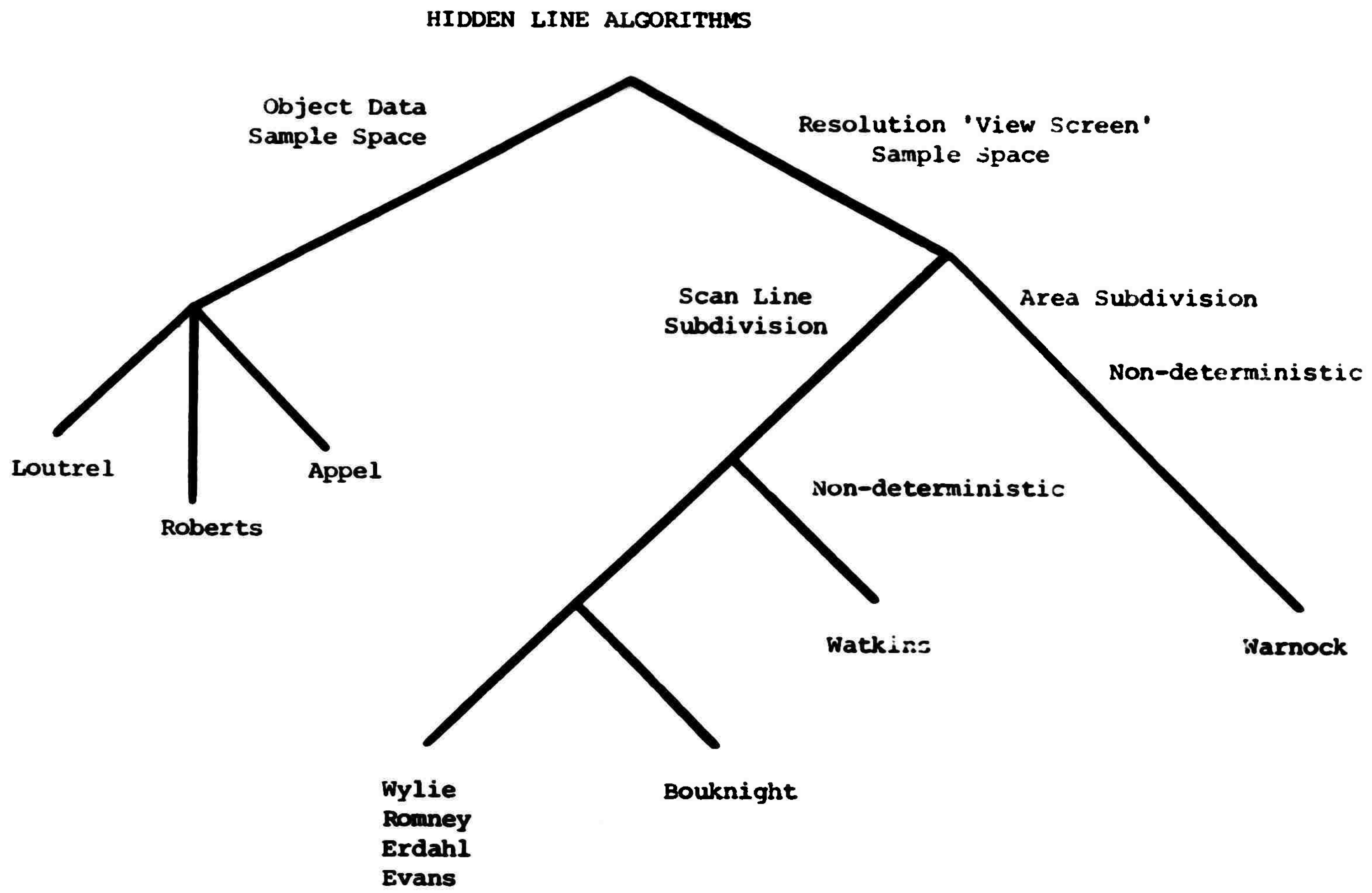


Figure 1

Classification of Algorithms

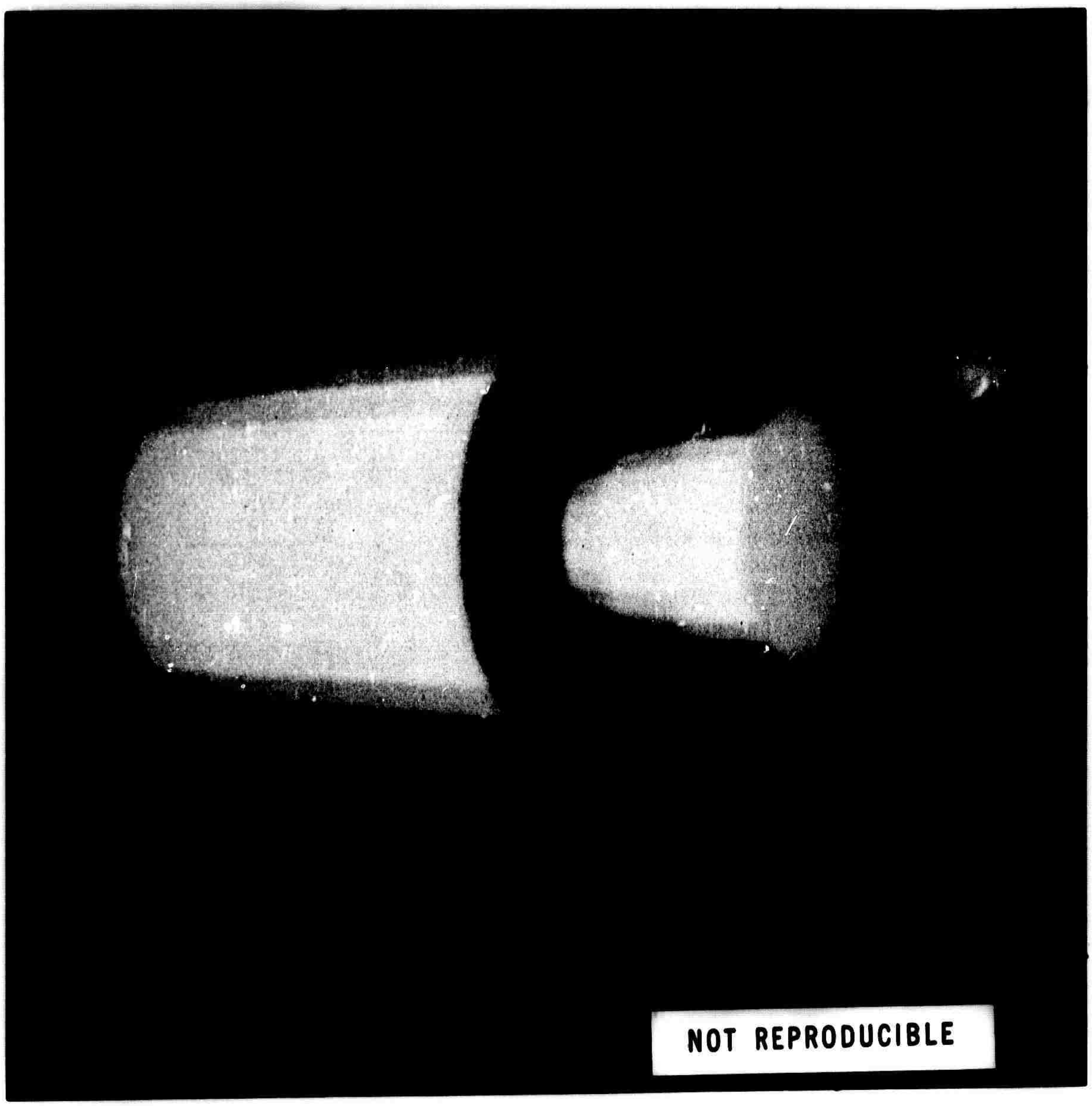


Figure 2: Apollo Command and Service Module.

Watkins' new algorithm allows convex or non-convex polygons of any number of sides to penetrate one another without any preprocessing checks. The algorithm uses a scan line approach, i.e., all visible polygons are determined on one scan line before the processor proceeds to the next scan line. Polygons that are closest to the viewer are assumed visible. Therefore, the processor must do depth comparisons between polygons to find the polygon closest to the viewer at any point on the scan line. A minimum of depth computation will occur if depth comparisons are made only at the points where visible edges cross the scan line. Since these points are not known in advance, the edges that were visible on the previous scan line are used initially for finding the points to make depth comparisons. Since scan coherence exists from scan line to scan line, this is usually a good approximation for finding the sample points. If a visible polygon is not found, the sample span is made smaller until finally a span is found which is covered by a single polygon. Once a visible polygon is found, it is sent to the shader along with its color information to be displayed.

To obtain color photographs, University of Utah researchers use three color filters -- red, blue, green. Then using each of the three filters, they make a triple exposure on film from the black and white cathode ray tube. The researcher is free to specify any color for any polygon. Color is specified by giving a value to each of the additive primary colors from zero to one, i.e., if the color yellow is desired on an object, one would specify green-1, red-1, and blue-0.

By varying mixtures and amounts, any color can be created. (Color values are calculated on floating point numbers which, in this case, divide a given color into 512 different shades between zero and one.) Identical color patterns can also be recreated simply by repeated specification of the object and its proper color mixture.

PDP-10 EULER

A Programmer's Guide to PDP-10 EULER[2] was written by Newman, et al. for implementation on our PDP-10 system at the University of Utah.

EULER is a block-structured language, similar in appearance to Algol but embodying many fresh concepts which make it an easier language to understand and use. The original reason for implementing it on the PDP-10 was to create a language for experimenting with data structures. However, it soon appeared that EULER had many applications as a general-purpose language with good data-handling and debugging facilities.

The first thing that must be said about PDP-10 EULER is that it is different from EULER as proposed by Wirth and Weber[3]. It contains for statements, arrays as well as lists, and omits go to statements. There are also some major differences in the way it has been implemented, but these are probably not of interest to the general user. Persons familiar with Algol 60[4] will have little difficulty in using EULER, once they have understood the basic differences between the two languages.

EULER programs are executed by an interpreter called SEUL. This interpreter operates on Polish-string object code generated by the EULER compiler. The object code is in the form of six-bit bytes, and some care was taken to make it readable for debugging purposes. A number of other debugging aids have been added to the interpreter which probably make this feature redundant.

Other useful features of PDP-10 EULER are string, list and matrix operations, file input-output and a very straightforward library feature.

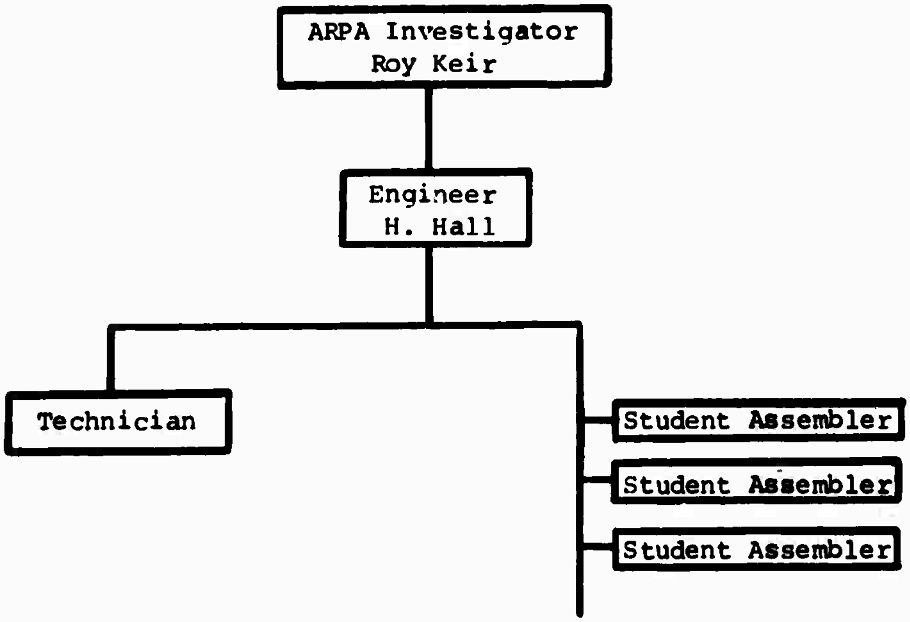
B. COMPUTING SYSTEMS

Computing systems senior investigators are: Robert S. Barton (Faculty), Alan C. Kay (Faculty), Roy A. Keir (Faculty), and Charles L. Seitz (Faculty). This rather diverse set of investigators have as their common interest real computing systems with radically improved characteristics for direct use by people, such as: communication devices, simulation and modeling devices, and computational instruments. Emphasis is not primarily on raw computational capacity, but rather on system problems of the direct use of these machines by people in a natural way so that procedures may be easily described and information may be simply represented.

Experimental Computer Laboratory

The Experimental Computer Laboratory under the direction of Professor Roy Keir is intended to provide a modest selection of components from which a number of interesting computer designs can be assembled for testing on real-world problems at near-real rates. At the end of this reporting period, three projects were under active consideration: first, a computer design embodying some of Professor Keir's ideas on address manipulation for efficient handling of complex data structures; second, application and testing of these ideas on two known problem areas in structured data, programming language translation and motion representation; and third, a computer to be designed under the direction of Dr. Seror according to the principles presented in his thesis[5].

When fully manned, the Experimental Computer Laboratory is expected to have the following cadre:



In addition to the above laboratory employees, there are expected to be from time to time a number of participants from among the research assistants, post-doctoral researchers, and faculty members associated with the ARPA Project. The previously mentioned work of Dr. Seror is an example.

Since the facility is intended to be adaptable to the implementation of quite diverse computer designs from time to time, a functional block diagram cannot exist except as a snapshot. The experimental facility was envisioned in June of 1970 to become something like that shown in Figure 3.

The facility is intended to be used as outlined previously for the construction of Professor Keir's data-structures-oriented computer and, on a non-interference basis, for the construction of other processors and peripheral equipment.

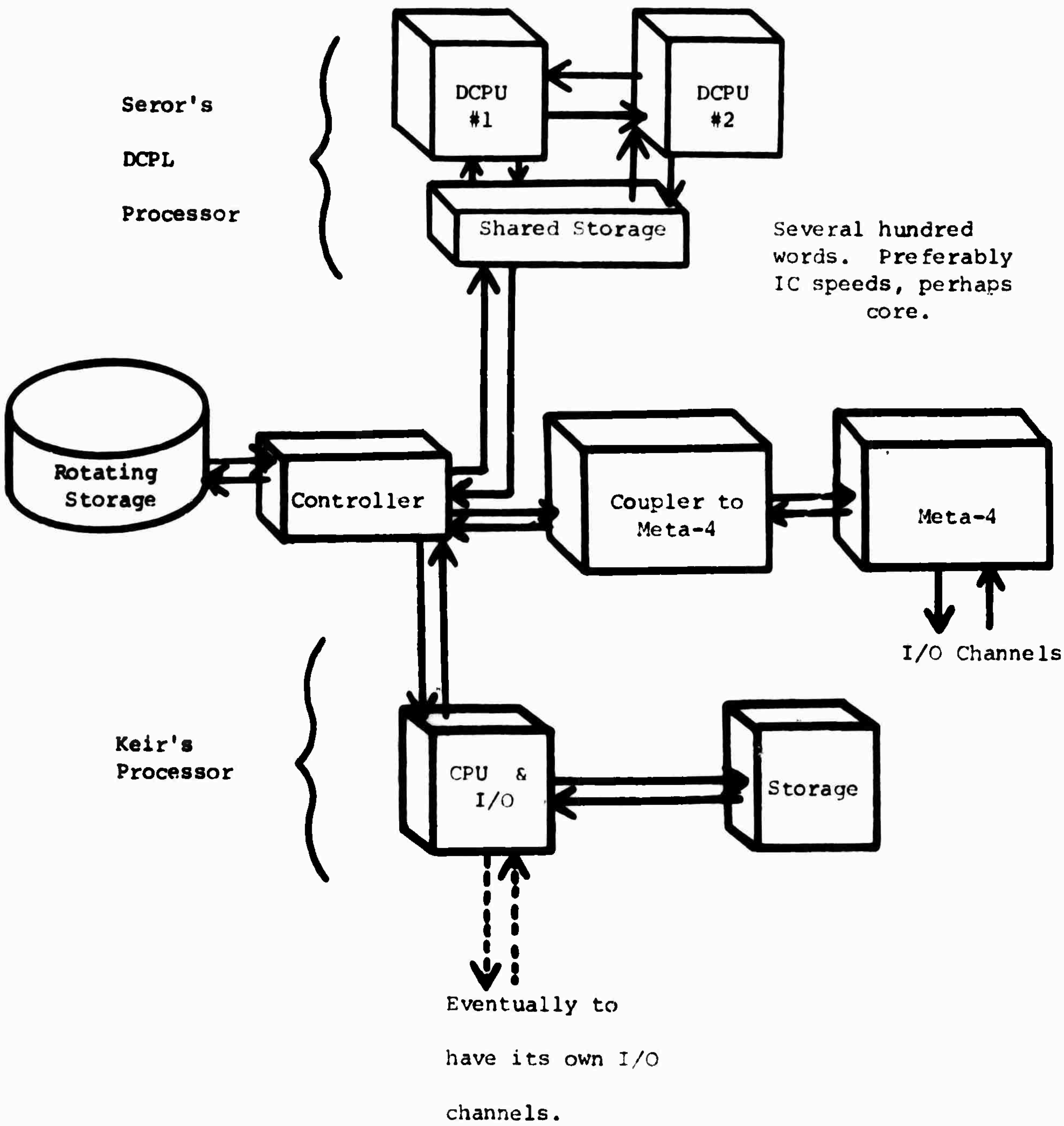


Figure 3: Experimental Computer Laboratory

This facility is not necessarily unique except for the computer design concepts to be implemented. The ability to test certain computer design concepts at near real-time rates on inherently dynamic problems such as rotating storage management and dynamic computer graphics is believed to be important and uncommon if, however, not unique.

Computer-Aided Choreography

The application of the digital computer in the field of dance choreography is a relatively unexplored area, and so was the topic of research by Carol Withrow (Research Associate)[6].

The accumulation of a choreographic literature has been hampered primarily by the existence of two interrelated problems. These are the lack of an adequate movement notation, and the enormous amount of information inherent in the description of even a simple human movement. Dance notation systems do exist, but because they are so time-consuming and difficult, they are seldom used by choreographers.

The prime problems Mrs. Withrow focused upon were: How is a mathematical model of the human body to be manipulated without resort to complex mathematical formulas? How can a dancer model be controlled or driven in a manner sufficiently simple that it not interfere with the creative process or the artist?

In attempting to solve these problems, an interactive program which relates the angular movements of the joints of the display model to hand-drawn curves was created. The picture in this prototype program is a stick figure with two moving joints. Using the coordinates of successive points along the curves, the computer then calculates arrays of angles through which the moving parts of the stick figure will move. The illusion of movement is then created as the computer displays in rapid succession these various positions.

There are four different basic displays that the user sees. These are referred to as "pages." The initial display is Page One, the table of contents, which merely lists the three pages that follow it. Page Two is concerned with determining the movement of the model's right leg about a hip joint. Page Three is similar to Page Two but is concerned with the angle at the knee. As more movable joints are added to the program, similar pages may be added. The program is so structured that it may be extended in this way. Page Four displays a larger stick figure and a set of user options, and also has the usual options for changing the display to other pages. Also associated with Page Four are options to change the positions of the viewpoint, the stage, and to alter the speed of the figure's movement.

As the user sits at the console, he has beside him a one-page manual of instructions for using the program. This manual is intended for use by non-technical persons with no programming experience and is shown in Figure 4.

When fully developed, this type of tool would allow a choreographer to view and control the movements of figures shown on the graphics display. The implementation of a graphics program that would be truly useful to choreographers is a profound undertaking

DYNAMIC MODEL PROGRAM

INSTRUCTIONS FOR THE USER

ALL PAGES:
* DEPRESS PEN ON LEFT OR RIGHT ARROW TO TURN PAGE BACK OR FORWARD.
* DEPRESS PEN ON "TABLE OF CONTENTS" TO RETURN TO PAGE ONE.

PAGE 1
* DEPRESS PEN ON NAME OR NUMBER OF PAGE DESIRED.

PAGE 2
DEPRESS PEN ON DESIRED OPTION:
* "DRAW CURVES"; THEN DRAW CURVES IN BOXES IN ANY ORDER. IT IS NOT NECESSARY TO ERASE BEFORE CHOOSING THIS OPTION. ONE OR MORE CURVES MAY BE RE-DRAWN; THEN CHOOSE "KEEP CURVES."
* "KEEP CURVES" IF CURVES DRAWN ARE ACCEPTABLE.
* "ERASE" REMOVES ANY CURVES DRAWN.
* "SHOW" DISPLAYS LAST CURVES DRAWN. THIS IS USED WHEN RETURNING FROM ANOTHER PAGE OR AFTER ERASURE.
* "RE-USE" THE CURVES KEPT BEFORE WILL BE USED WITH DIFFERENT CURVES DRAWN ON ANOTHER PAGE.

PAGE 3
DEPRESS PEN ON DESIRED OPTION:
* "DRAW CURVES"; THEN DRAW CURVES IN THE BOXES, ANY ORDER.
* "KEEP CURVES" IF CURVES JUST DRAWN ARE ACCEPTABLE.
* "ERASE" REMOVES ANY CURVES DRAWN FROM THE DISPLAY.
* "SHOW" DISPLAYS LAST CURVES DRAWN.
* "RE-USE" THE CURVES KEPT BEFORE WILL BE REPROCESSED AFTER SOME CHANGE MADE ELSEWHERE.

PAGE 4
DEPRESS PEN ON DESIRED OPTION:
* "SHOW MOVIE" DISPLAYS MOVING FIGURE.
* "ROTATE X" MOVES VIEWPOINT UP OR DOWN ACCORDING TO VALUE TYPED.
* "ROTATE Y" MOVES VIEWPOINT LEFT OR RIGHT ACCORDING TO VALUE TYPED.
* "STOP" TERMINATES PROGRAM.
* "RE-USE" COMPUTES NEW VIEW AFTER SOME CHANGE BELOW.

TELETYPE OPTIONS; AFTER TYPING HIT RETURN KEY
* EYESTG=n CHANGES DISTANCE EYE TO STAGE, WHERE n IS IN FEET. INITIAL SETTING IS 20 FEET.
* EYETUB=n CHANGES DISTANCE EYE TO DISPLAY TUBE. INITIALLY 1.4 SCREEN DIAMETERS.
* LEFT=n, WHERE n IS BETWEEN -.1 and .42 MOVES EYE RIGHT OR LEFT. INITIAL SETTING 0.
* UP=n, WHERE n IS BETWEEN -.32 and .02 MOVES EYE DOWN OR UP. INITIAL SETTING 0.
* NN=n CHANGES SPEED OF MOVEMENT, WHERE n IS BETWEEN 4 and 25, THE LARGER NUMBER BEING SLOWER. INITIALLY 25.

USER'S MANUAL

FIGURE 4

that has not yet been fully achieved. However, the realization of a useful choreography program of the type outlined in [6] may be realistically anticipated.

Computer Systems Scheduling

A major research effort completed in this area was a three part project by Robert Mahl[7] which in the first part examines some aspects of the problem of allocating resources in a multi-programmed computing system. A conflict arises when two or more users simultaneously want to use the same resource. The scheduler has to solve immediate conflicts and minimize the probability of future conflicts; the system should try to run concurrently a balanced set of jobs. However the problem is complicated because of indivisibilities of the users' demands, which do not allow allocation of resources independently from each other, nor independently from previous allocations.

Dr. Mahl next investigates to what extent the users might participate in resource allocation decisions, and he advocates a system that dynamically determines the price of services. A model is studied which yields a balanced set of programs in order to get a good simultaneous usage of the available system's resources. A job has to estimate its needs and state the price it agrees to pay in order to be assured of having a certain progress rate. A macro-scheduler then determines the priority to be given to the job and allocates the non-preemptible resource (for instance, core memory). A micro-scheduler keeps track of the usage of preemptible resources (fast registers and processor(s)) by the allocated resources, assuring that a job which accurately estimated its needs will be served at least as well as promised.

The last area of research documented in Dr. Mahl's report examines how resource utilization figures can affect the choice of equipment to be used at a computer installation and the choice of a swapping algorithm at a system's design time.

C. DIGITAL WAVEFORM PROCESSING

The digital waveform processing activities under the direction of Thomas G. Stockham, Jr. have, during recent years, significantly advanced the understanding and implementation of nonlinear filtering processes. These processes represent an exciting class of computations having particular promise in connection with visual and auditory communication. In connection with visual images, nonlinear filtering techniques have been developed for the enhancement of images and for the reduction of band widths required for the transmission of satisfactory visual images. Recent primary efforts in the area have been directed toward the recovery of musical signals that have been distorted in various ways by the recording and reproduction process. The techniques thus far developed for this process are applicable to the solution of the multipath communication problem, as well as many others, and research investigations are continuing.

The following discloses some recent developments in the processing of images by computer. The principles of two-dimensional digital signal filtering are applied to the problems of image enhancement, dynamic range reduction, and bandwidth compression. The filtering techniques applied make use of the fast linear systems which correspond to the fast Fourier and fast Hadamard transforms, the latter having been the subject of effort during the last reporting period. Strictly speaking, the processing used in these cases is nonlinear, since image density signals (not image energy signals) were used.

This use of the logarithm of image energy is essential to the character of the processes described and the quality of the results obtained. The reasons for these last two statements are described in previously sponsored work[8].

Image Enhancement

A common method for image enhancement is the use of high-frequency emphasis. When used on image energy signals, this method can overcome the deficiencies of optical and electrical image transmission systems by compensating their frequency roll-off characteristics. When used on *density* signals derived from compensated images[8], image enhancement results in the form of increased object visibility and contrast. The same enhancement technique can be and very often is used on already compensated image *energy* signals with fair results. In very precise work especially in images involving large variations in lighting, the inevitable generation of super-black areas rapidly results in unacceptable quality. However, if strong enhancement is used, large dynamic ranges are induced and transmission, display and copying problems arise.

Dynamic Range Reduction

A method for image dynamic range reduction is the use of low-frequency de-emphasis. This method can be applied only to image *density* signals and produces a very convenient and effective solution to the image dynamic range problems especially when they are aggravated by enhancement requirements as described above.

Simultaneous image enhancement and dynamic range reduction can be achieved by applying high-frequency emphasis *and* low-frequency de-emphasis to an image density signal. Figures 5 and 6 show a scene before and after digital processing of this kind was carried out. This process is implemented by applying the principles of high-speed convolution [9,10] using two-dimensional FFT's to a density signal. The impulse response used was designed from frequency domain considerations and was symmetric about its center point so that its effect upon the image would be isotropic. The low-frequency asymptote was one half and the high-frequency asymptote was two[8], corresponding to a dynamic range reduction of two and a contrast enhancement of two.

In the last reporting period, image processing similar to the above has been carried out using fast Hadamard transforms (FHT's) in place of FFT's by rearranging the Hadamard transform coefficients for an image into ordered sequency form and by using emphasis and de-emphasis according to sequencies instead of frequencies. The sequency responses used were similar to those applied in the Fourier case except that the slope of the response curve had to be kept very small near low sequencies in order to avoid the checkerboard distortions which can appear when Hadamard transforms are used in image processing. This problem arises due to the fact that the Walsh functions which form the basis for the Hadamard analysis are square waves. A computational advantage is obtained through the use of the FHT instead of the FFT since the former requires only about 1/6 of the processing time necessary for the latter. The quality of the results are comparable between the two methods, as can be seen in Figures 6 and 7.

Figure 5: Unprocessed Digital Image. 340 x 340 picture elements with 8 bits of linear grayscale are used.

NOT REPRODUCIBLE

Figure 6: Image Enhancement with Dynamic Range Reduction.

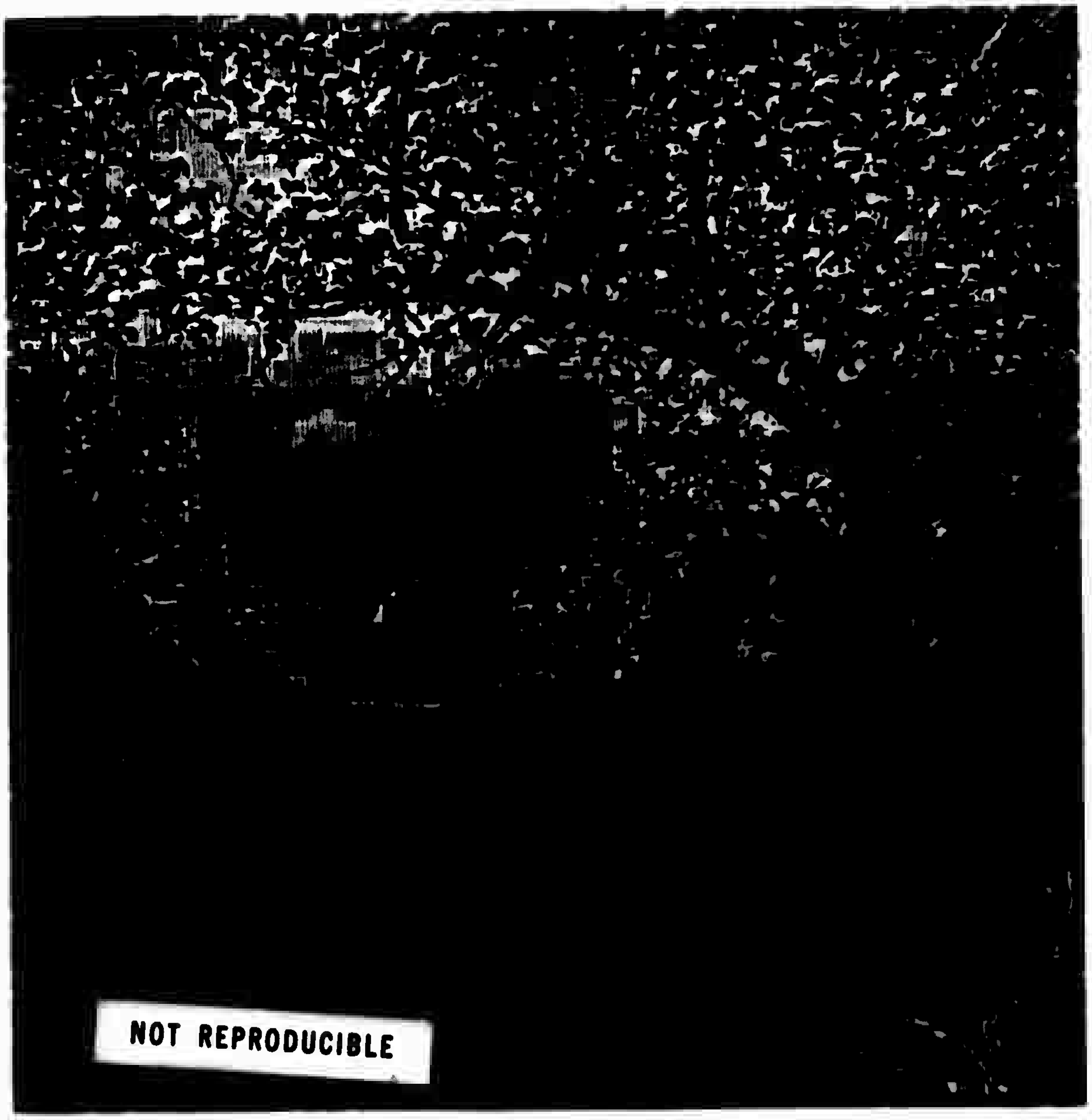


Figure 7: Image Enhancement with Dynamic Range Reduction Using the FHT.

Bandwidth Reduction

The use of Fourier and Hadamard transform techniques in image bandwidth reduction technology is beginning to take hold [11,12,13]. The basic approach has been to alter the transformed image instead of the image itself in order to break down correlation between the distortions induced and the image itself. The results are very encouraging indeed. A different application of the FFT and FHT to bandwidth reduction involves *conditioning an image* by filtering techniques, employing a known reduction technique, and then undoing the conditioning, at least in part. The conditioning process is based upon a model of human vision developed earlier in the contract and still being researched and improved.* Figure 8 shows an image which has been transmitted by applying the Roberts' method [14] to a density signal using only one bit per picture element in the transmission channel. Conditioning of the density signal before application of the reduction process can be achieved by using the visual model described earlier. Using either FFT or FHT schemes, results such as those shown in Figure 9 can be obtained. The improvement in Figure 9 over Figure 8 is indicative of the increase in quality to be expected when other reduction schemes which perform better than, but are not as simple as the Roberts' method are applied to images which have been preconditioned by fast digital signal processing. Figure 9 represents a 9:1 bandwidth reduction over Figure 6 . The higher quality results of Figure 10 used a more complex scheme based upon FHT techniques and represents a bandwidth reduction of 6.5:1 (thesis and report pending).

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*"Natural Image Information Compression with a Quantitative Error Model", by Thomas G. Stockham, Jr., in *Pertinent Concepts in Computer Graphics*, M. Faiman and J. Nievergelt, ed., U. of Ill. Press, 1969.

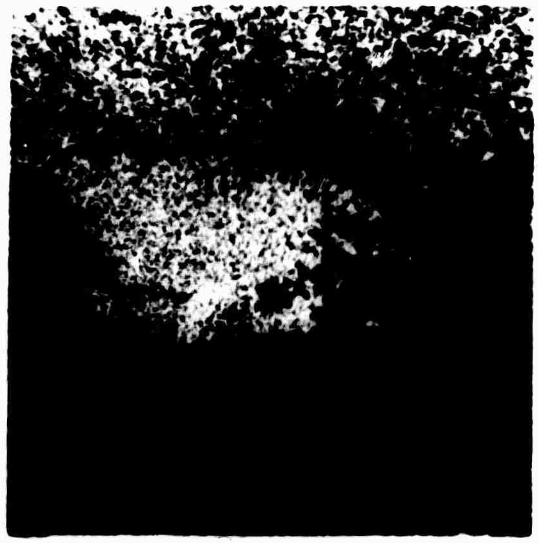

Figure 8: Robert's Bandwidth Reduction Method Using One Bit Per Picture Element in Transmission.

Figure 9: Improved Performance of the Robert's Method Due to Preconditioning with Fast Digital Filtering Techniques.

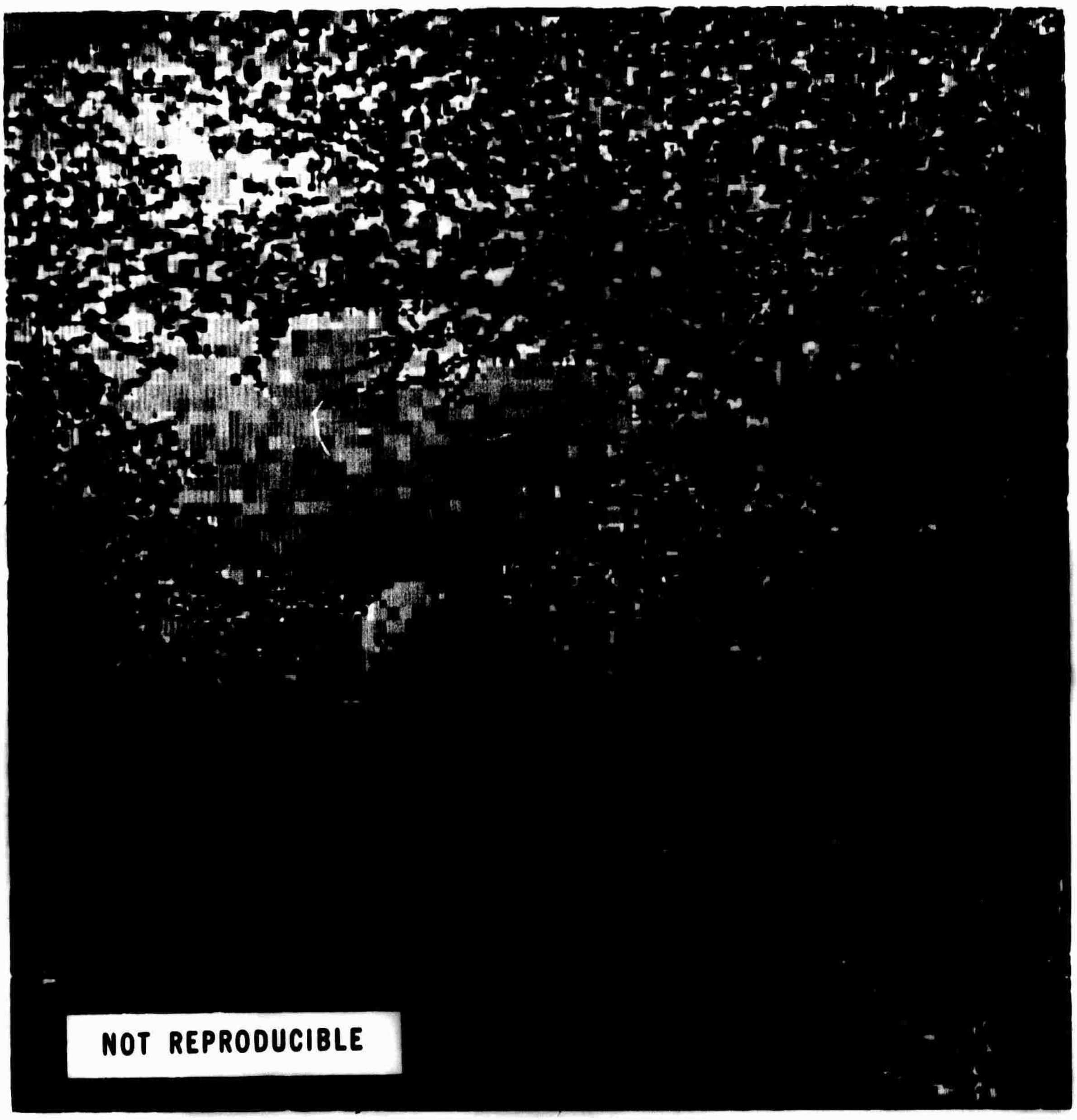

Figure 10: Bandwidth Reduction Using FHT Techniques.

D. APPLICATIONS

The applications area includes a small set of carefully selected problem areas that will provide feedback to the researchers in the first three research categories and will provide a mechanism for publication of newly learned techniques to people outside the relatively closed community of computer science researchers.

Involved in the applications activity are C. Stephen Carr (Faculty), Winfred O. Carter (Faculty), Henry N. Christiansen (Faculty), Harvey S. Greenfield (Faculty), Nelson S. Logan, Edward R. Perl (Physiology Faculty), Ronald D. Resch (Faculty), Louis A. Schmittroth (Adjunct Professor), Robert E. Stephenson (Faculty), and Homer R. Warner. Applications are in the field of computer-aided design, the modeling of complex geometrical structures, the modeling of a collection of fluid-flow problems (including the flow of blood in the human circulatory system), the use of computers in education, and certain information-processing problems in physiology. There are a large number of senior investigators listed in connection with these application problems, but these problems are in the main supported jointly by the University of Utah and other agencies including the National Institutes of Health; hence this work does not represent an unreasonable fraction of the total resources.

Computer Aided Design

One year ago completion of a computer-aided design (CAD) system was reported by C. Stephen Carr. It was then decided to give the system a one-year trial venture to test effectively its feasibility and use in a real-world environment. Since that time the design system has been transferred from the Computer Center's 1108 to our PDP-10 computing system where its interactive use is more reliable, cheaper, quicker, etc. Furthermore, the goals of the system were broadened from architecture to all three-dimensional design including mechanical design, electrical packaging, etc. The academic year 1969-70 was spent enhancing the overall system and adding subsystems for structural design and numerical control of machine tools. The system utilizes an exotic set of building blocks or "spaceforms" which can be manipulated into any number of desired shapes. These spaceforms are the cube, sphere, cylinder, and the hexagonal rod and triangular rod. On command, any of these can be squeezed, stretched, or manipulated into creative designs as seen in Figure 11. The CAD system is also capable of hidden-line perspective drawings that can be rotated, changed, and manipulated with only a second or two delay between command and execution on the screen.

A demanding set of experiments was established to test the system's use primarily in architectural design and structural analysis. The most notable successes resulting from the experiments were: truss and frame (structural) analysis, performed by Winfred O. Carter; and the designing and machining of parts on numerically controlled machines, conducted by William Hughes. These projects were completed as experimental uses of the system and will be reported subsequently. To visually document the project, a 16 mm., 20 minute film, "Low Cost, Graphical Computer-aided Design", was produced and is available for loan upon request.

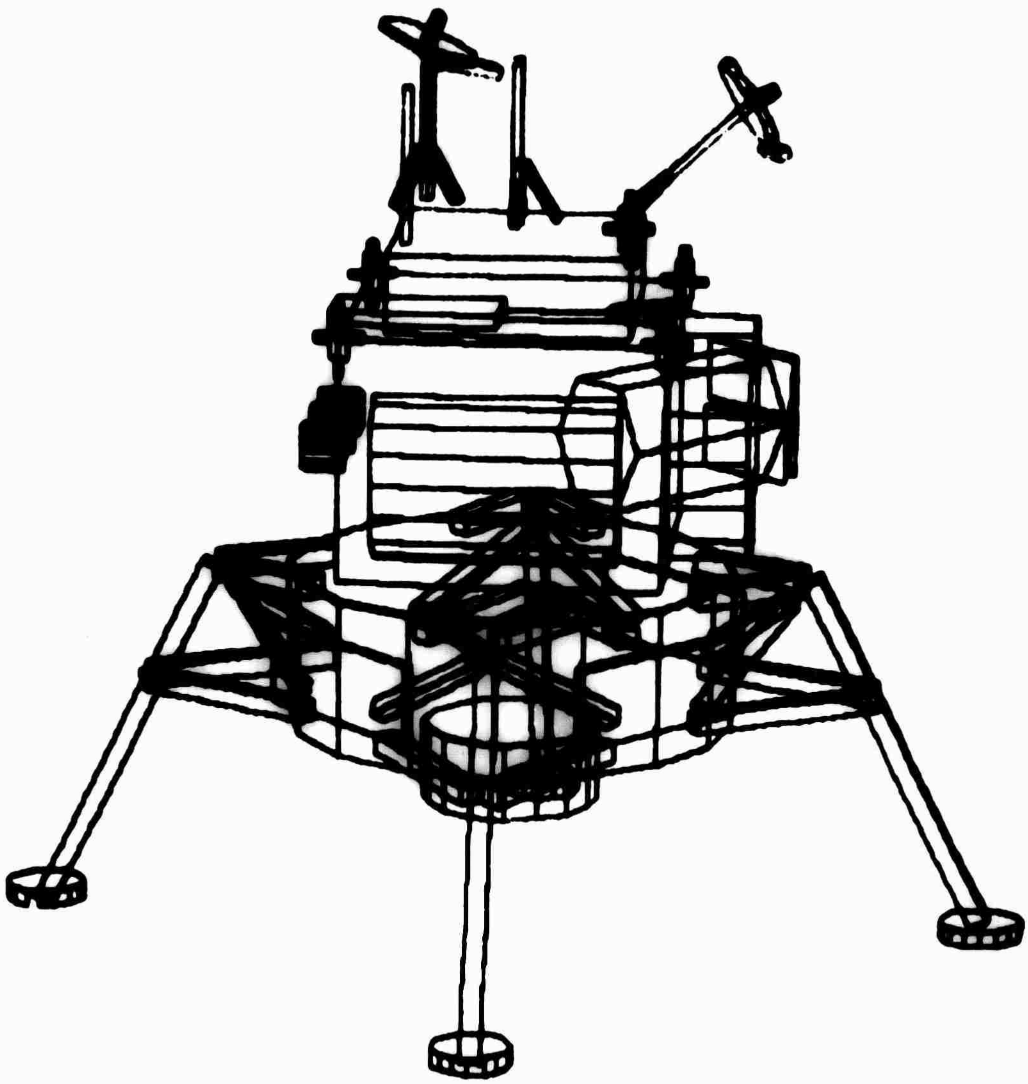

Figure 11: Lunar Module.

Kinematic Folded-Plate Systems

The exploration of dynamically defined geometries and their potential applications is under the direction of R. D. Resch.

Kinematic folded-plate systems are initially geometry generating systems for the creation of folded-plate shells. Their defining procedure is shape independent, which makes them unique from most geometry systems (such as Geodesic Domes) for buildings. Kinematic structures are systems which enable motion; their concept is dynamic, allowing for continual change in total form, and the motion of the system is not necessarily limited, as in the case of mechanical machines, to a single path, or in the case of buildings, to a single shape.

The dynamic study of kinematic folded-plate systems for architectural designers (authored by Resch) has recently been realized through computer simulation programs (authored by Christiansen). This investigation of the combination of the design system and the computer simulation could possibly eliminate monotonous serial production in favor of mass production of non-identical shell forms. Key developments include the theory by which the elastic forces are generated for the large displacement problem (Fig. 12a) and a fold element which is utilized for structural stability (Fig. 12b). Kinematic solutions are obtained by the repeated application of a process involving an elastic analysis, an updating of the nodal coordinates, and a relaxation of the fold elements (Fig. 13a,b).

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*Ronald Resch, "Experimental Structures" in *Emerging Concepts in Computer Graphics*, D. Secrest, J. Nievergelt, eds., 1967 University of Illinois Conference, published by W.A. Benjamin, Inc., 1968.

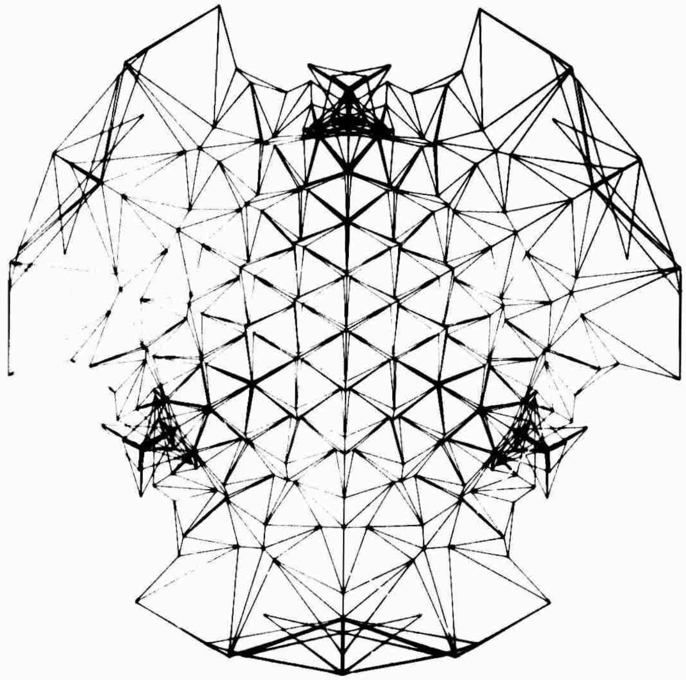

Figure 12 a: Elastic deformation computed by the analysis routine.

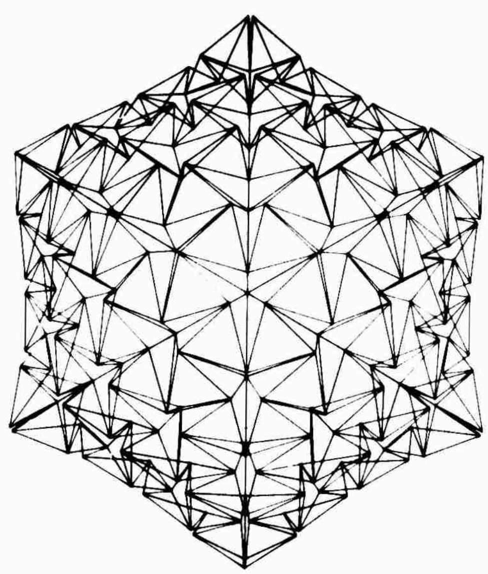

Figure 12 b: Kinematic analysis of the folded plate system in which only a folding behavior occurs.

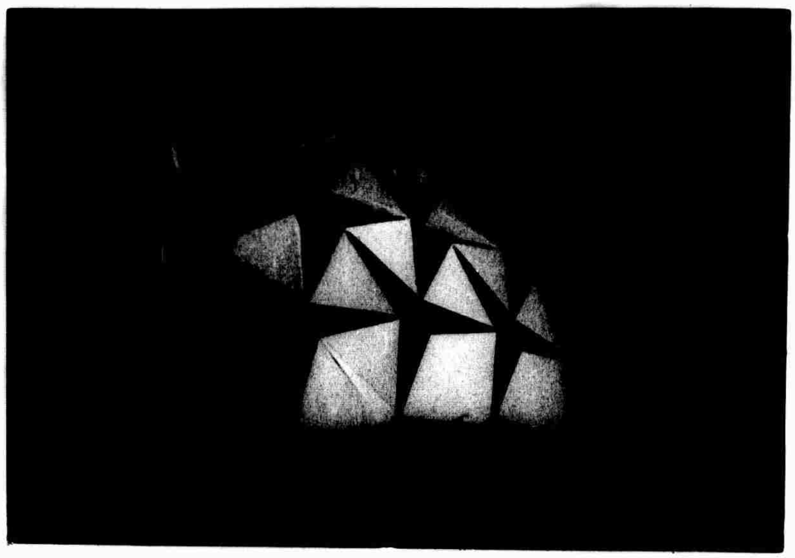

Figure 13 a: Real world Kinematic Folded Plate system.

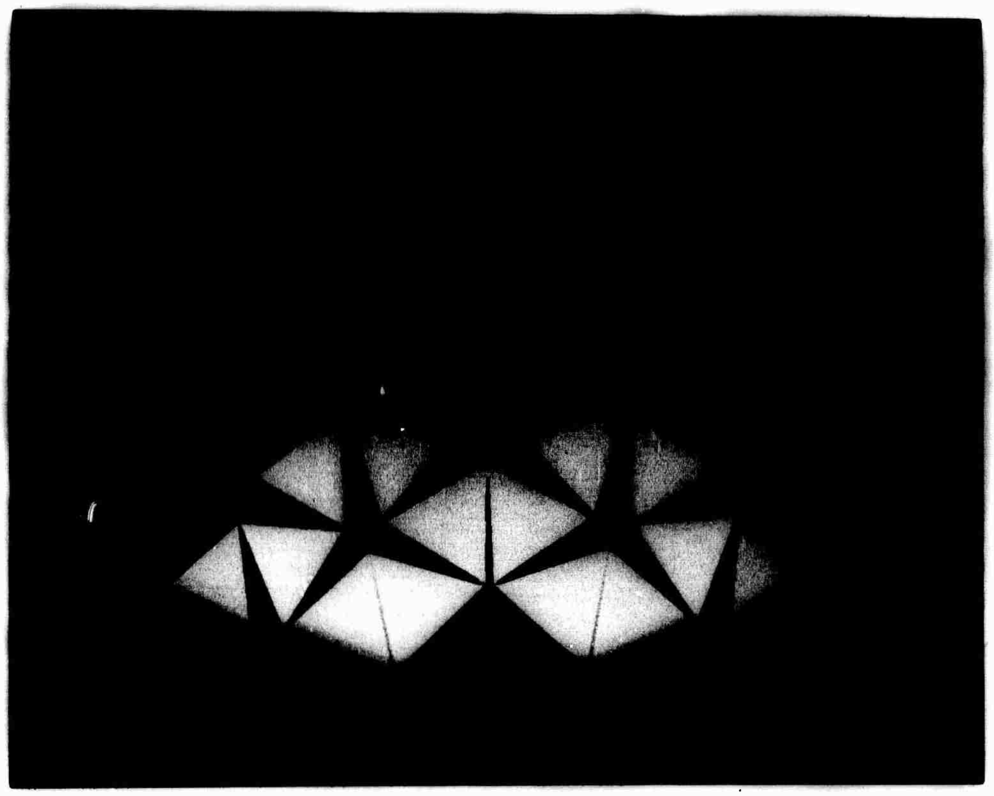

Figure 13 b: Computer simulated video pictures
of a Kinematic Folded Plate System.

An Experiment in Using Interactive Computer Graphics in Teaching Transmission-line Theory

One important objective in teaching a course (which is often difficult to reach), is that of helping the student to obtain a qualitative understanding of basic phenomena rather than just an acquaintance with a mathematical expression that he can manipulate to get some numerical answers. The use of a computer graphics routine appeared to be a valuable tool in reaching this objective in an experiment conducted in teaching EE 553, Electromagnetic Fields, at the University of Utah by Professor Carl H. Durney[15].

The computer graphics routine was an interactive routine which displayed the propagation of the transient voltage wave on a two-conductor transmission line excited by a step function. The student could enter a value of inductance, capacitance, or resistance for the element at the end of the transmission line, and then observe the resulting waveforms. In this way, the student quite quickly obtains a qualitative feel for the effect on the waveform of the load impedance at the end of the line. He could visually observe the reflected wave produced by a capacitor and compare it with that produced by an inductor or resistor. He could also see how the reflected waveform changed when the capacitance at the end of the line was increased or decreased. In addition, he could specify the internal resistance of the step-function generator exciting the line and see what effect this had.

Before the students used the system, they were given a set of questions to answer which were designed to get them to think about what happens on the transmission line and why. Included in the set of questions were some to be answered by using this system. This was to insure that the student was actively seeking understanding during his use of the system. Two key points used in designing and using the system were that the student must be active and that the system must be interactive. If a student is not active, he is not learning. If the computer graphics system is not interactive, it might as well be replaced by a movie.

Although no attempt was made to measure formally whether the students learned faster using the interactive computer graphics system than they could have without it, both the instructor and the students felt they did learn faster, and that an interactive computer graphics system can be an extremely useful learning tool. The experiment was felt to be an indication that the possibilities of exciting uses for interactive computer graphics in our education system are endless.

A Computer Graphics Method for Solving Transcendental Equations

In the solution of many physical problems, a kind of equation called a transcendental equation is encountered. A transcendental equation is one which contains transcendental functions; transcendental functions are functions like sia x, tan x, e^x, log x, etc., which are not algebraic functions. An important characteristic of a transcendental equation is that it cannot be solved like an algebraic equation. For example, consider the transcendental equation:

$$\tan x = x$$

There is no way to solve the equation to obtain an expression for the values of x which satisfy the equation. There are two commonly used methods for solving this kind of equation. One is to try values of x until one or more values are found which satisfy the equation. The other method is to plot the left-hand side of the equation versus x; then plot the right-hand side versus x, and then find the values of x which make the two sides of the equation equal. These methods work very well for simple transcendental equations like the one above, but for the much more complicated transcendental equations encountered in many physical problems, either method becomes very laborious and time consuming, and it is difficult to find all the roots of the equation, or even to know how many there are.

For these difficult equations, many numerical computer methods have been developed which amount to trying values of x until the right ones are found. These methods are called search methods. One of the problems with a search method is that it becomes very expensive sometimes unless something is known about the approximate location of the roots. This is especially true if x is a complex variable. The computer graphics method developed during this study by Professor Carl H. Durney[16] is designed to provide information about the root pattern, that is, the location of the roots in the complex x plane.

The technical report[16] documenting this research describes two techniques. The first is a method of displaying the root pattern in the complex x plane in a computer-generated photograph. This technique is a relatively simple computer graphics technique because the desired information is displayed in one black-and-white photograph, while some other graphics methods use more complicated color photographs. The second technique described in the report is a method for displaying the root pattern in the complex plane in an ordinary computer printout requiring no computer graphics system at all. With this method, the same information about the roots that was displayed in the computer-generated photograph can be displayed in the printout, although the photograph is prettier. However, the display of the root pattern in the computer printout should be very valuable because it can be used with any digital computer, requires no graphics system, involves a very simple program, and yet provides the powerful advantages of computer graphics methods.

Both methods described are important because they provide a practical method for getting a "feel" for the transcendental equation to be solved. These graphics techniques allow one to visualize the nature of the root patterns and thus to obtain valuable intuition about the equation and what it means in a physical system. It is this intuition, which is so sorely needed in solving physical systems but is so difficult to obtain from ordinary computer outputs, that computer graphics techniques can provide.

PART II. FACILITIES

During this period the PDP-10 computing facilities have stabilized and become a very reliable and usable computing facility for support of research.

The UNIVAC displays, though initially unreliable, are being reworked by the manufacturer and some are now operating quite satisfactorily. Units are installed and operating at Montana State University, the University of Utah Medical Center, and in our Computer Science research area. Special input devices being used with the displays include mice and a Sylvania Tablet.

The ARPA Network IMP/PDP-10 interface is completed and working. Primary use of the net has been with SRI.

With the installation of a precision XY display, notable photographic improvements have been realized particularly by the waveform processing and graphics techniques groups.

All research has moved from the 1108 facility of the University's Computer Center to the Computer Science dual PDP-10 system which, with the addition of six disk drives, is able to adequately support all current research requirements.

PART III. PUBLICATIONS AND PRESENTATIONS

1 December 1969 to 30 June 1970

Following is a listing of presentations and publications made by Computer Science Department personnel during the reporting period related to ARPA sponsored projects and/or activities. This listing is included merely to indicate the scope of exposure our work has had during this period and not as a means of announcing new research discoveries made under the contract. All significant information contained in either the presentations or written articles has been previously reported on an individual basis.

Barton, R. S., "Ideas for Computer Systems Organization; A Personal Survey," talk given at the Third International Symposium on Computer Information Sciences (COINS-69), Miami Beach, Florida, December 1969.

Carr, C. S., "HOST-HOST Communication Protocol in the ARPA Network," *AFIPS Spring Joint Computer Conference* 1970, pp. 589-597.

Carr, C. S. and W. Hughes, et al., "Low Cost, Graphical Computer Aided Design," 20 minute, 16-mm color motion picture demonstration of the system, June 1970.

Greenfield, H., "Artificial Heart Valve Studies with Computer Aid," Lecture at the University of Michigan Summer Course, *Computer Graphics for Designers*, Ann Arbor, Michigan, 15-26 June 1970.

Greenfield, H., "Artificial Heart Studies with the Aid of Computer Graphics," Lister Lecture Hall Series, Glasgow Royal Infirmary Glasgow, Scotland, 18 April 1970.

Greenfield, H. and K. Reemtsma, "Preliminary Analysis of Blood Flow Characteristics in the Abdominal Aorta by Computer Interpretation," International Symposium on Computer Graphics, Brunel University, Uxbridge, England, 14-16 April 1970.

Greenfield, H., K. Reemtsma, and L. B. Sandbery, "Some Theoretic Aspects of Vascular Degeneration," *American Journal of Surgery,* Vol. 119, May 1970, p. 548.

Hankley, W. J., "Contour Analysis and Applications in Pattern Recognition," Seminar presented at Technological Institute, Northwestern University, Evanston Illinois, 10 June 1970.

Hankley, W. J. and F. E. Templeton, "Dynamic Optimal Control of a Process with Discrete and Continuous Decision Variables," talk presented at Ninth International Symposium on Techniques for Decision Making in the Mineral Industry, Montreal, Quebec, Canada, 16 June 1970.

Knowlton, P., "On the Extensibility of Fortran," talk given at the Third International Symposium on Computer and Information Sciences, Miami Beach, Florida, 20 December 1969.

Lee, R. M., "Selecting Storage Devices for Large, Random-Access, Data Storage Systems," *Computer Design,* Vol. 9, No. 2, February 1970, pp. 59-63.

Newman, W. M., "An Experimental Display Programming Language for the PDP-10 Computer," University of Utah Computer Science Technical Report, UTEC-CSc-70-104, June 1970.

Resch, R. D., "Kinematic Folded Plate Systems," *Utechnic: University of Utah Engineering Magazine,* May 1970, pp. 8-11.

Stockham, T. G., Jr., "Digital Processing of Image Signals," International Seminar on Digital Processing of Analog Signals, Zurich, Switzerland, March 1970.

Stockham, T. G., Jr., "Digital Processing of Images and Sound", Communication Sciences Seminar, Watson Research Center, I.B.M., Yorktown Heights, New York, April 1970.

Stockham, T. G., Jr., "Initial Efforts in Acoustical Restoration," presented at the IEEE Arden House Workshop on Digital Filtering, Harriman, New York, January 1970.

Stockham, T. G., Jr., "Techniques for Processing Images and Sound," presented at a special meeting involving personnel of the Burroughs Corporation, Catalina Island, April 1970.

Stockham, T. G., Jr., "Dereverberation of Acoustic Recordings," Guest lecturer for the course *Digital Signal Processing*, in the Department of Electrical Engineering, Massachusetts Institute of Technology, Cambridge, Mass. April 1970.

Sutherland, I. E., "A Method for Solving Arbitrary-Wall Mazes by Computer," *IEEE Transactions on Computers*, Vol. C-18, No. 12, December 1969, pp. 1092-1097.

Sutherland, I. E., "Computer Displays," *Scientific American*, June 1970.

Taylor, R. W., "Interactive Multiple Access Computer Networks," talk given at the University of Texas Mitre Corporation Conference, Austin, Texas, 10 April 1970.

Viavant, W., "Computer Science--Business or Profession?", North Dakota Small Computer Symposium, April 1970.

Vickers, D. L., "Head-Mounted Display," *Utechnic: University of Utah Engineering Magazine*, May 1970, pp. 14-17.

Vickers, D. L., "Head-Mounted Display Terminal," *Proceedings of the IEEE Computer Group Conference*, Washington, D.C., June 1970.

Vickers, D. L, "Looking through the Head-Mounted Display," 16 mm film, 9 minutes, University of Utah, 11 June 1970.

Wehrli, R., M. J. Smith and E. F. Smith, "ARCAID: The ARChitect's Computer Graphics AID," University of Utah Computer Science Technical Report, UTEC-CSc-70-102, June 1970.

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7. Mahl, Robert, *An Analytical Approach to Computer Systems Scheduling*, University of Utah Computer Science Technical Report, UTEC-CSc-70-100, June 1970.

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13. Woods, J. W. and T. S. Huang, "Picture Bandwidth Compression by Linear Transformation and Block Quantization," Proceedings of the Symposium on Picture Bandwidth Compression, to be published.

14. Roberts, L. G., "Picture-Coding Using Pseudo-Random Noise," *IRE Transactions on Information Theory*, Vol. IT-8, No. 2, February 1962, pp. 145-154.

15. Durney, Carl H., *An Experiment in Using Interactive Computer Graphics in Teaching Transient Transmission-Line Theory*, University of Utah Computer Science Technical Report, UTEC-CSc-70-110, Publication Pending.

16. Durney, Carl H., *A Computer Graphics Method for Solving Transcendental Equations*, University of Utah Computer Science Technical Report, UTEC-CSc-70-109, Publication Pending.

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13. ABSTRACT

This document includes a summary of research activities and facilities at the University of Utah during the final reporting period under Contract AF30(602)-4277. Report abstracts convey important research milestones attained during this period by each of the four major research activities:

1- Computer Graphics Techniques

2- Computing Systems

3- Digital Waveform Processing

4- Applications.

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elastic analysis						
EULER						
fluid- flow						
geometrical structures						
graphics techniques						
head-mounted display						
image enhancement						
kinematic folded-plate systems						
nonlinear filtering						
perspective						
picture processor						
real-time windowing						
scheduling						
shaded						
structural analysis						
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three-dimensional						
transcendental equations						
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