AD/A-000 935

GRAPHICAL MAN/MACHINE COMMUNICATIONS

David C. Evans, et al

Utah University

Prepared for:

Rome Air Development Center
Defense Advanced Research Projects Agency

December 1972

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: RADC-TR-74-207	2. GOVT ACCESSION NO.
	3. RECIPIENT'S CATALOG NUMBER: AD/A-000935
4. TITLE (and Subtitle): Graphic Man/Machine Communications	5. TYPE OF REPORT & PERIOD COVERED: Semi-Annual 1 Jul 72 - 31 Dec 72
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): David C. Evans, Thomas G. Stockham, Jr.	8. CONTRACT OR GRANT NUMBER(s): F30602-70-C-0300
9. PERFORMING ORGANIZATION NAME AND ADDRESS: University of Utah, Salt Lake City UT 84112	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61101D 08290002
11. CONTROLLING OFFICE NAME AND ADDRESS: Defense Advanced Research Projects Agency, 1400 Wilson Blvd, Arlington VA 22209	12. REPORT DATE: December 1972
	13. NUMBER OF PAGES: 61
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Rome Air Development Center (ISCA), ATTN: Murray Kesselman, Griffiss AFB NY 13441	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release. Distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Approved for Public Release. Distribution unlimited.

18. SUPPLEMENTARY NOTES

None

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

image processing, a priori, homomorphic filter, homomorphic vocoder, vocal synthesis, window functions, symbolic and algebraic manipulation, REDUCE, B-splines, head-mounted display system, three-dimensional objects, kinematic and elastic systems

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This document includes a summary of research activities and facilities at the University of Utah under Contract F30602-70-C-0300. Information conveys important research milestones attained during this period by each of the three major research activities:

1. Waveform Processing
2. Symbolic Computation Research
3. Computer Graphic Techniques

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

GRAPHIC MAN/MACHINE COMMUNICATIONS

David C. Evans
Thomas G. Stockham, Jr.

Contractor: University of Utah
Contract Number: F30602-70-C-0300
Effective Date of Contract: 1 July 1970
Contract Expiration Date: 1 June 1973
Amount of Contract: $4,459,016.00
Program Code Number: 6D30

Principal Investigator: David C. Evans
Thomas G. Stockham, Jr.
Phone: 801 322-8224

Project Engineer: Murray Kesselman
Phone: 315 330-2643

This research was supported by the Defense Advanced Research Projects Agency of the Department of Defense and was monitored by Murray Kesselman, RADC (ISCA) GAFB NY 13441 under Contract F30602-70-C-0300, Job Order No. 08290002.

This report has been reviewed by the RADC Information Office (OI), and is releasable to the National Technical Information Service (NTIS).

This technical report has been reviewed and is approved.

RADC Project Engineer
Murray Kesselman

TABLE OF CONTENTS

FIGURES

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 three major areas: 1) waveform processing, 2) symbolic computation, and 3) computer graphic techniques.

A brief résumé 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 July 1972 to 31 December 1972.

A. WAVEFORM PROCESSING

The waveform processing group has completed four major phases of research during this reporting period and has continued its effort on several others. The principal accomplishments are the development of a homomorphic image deblurring method by E. Randolph Cole, the research into human visual modelling by Patrick Baudelair, the impressive demonstrations of background noise elimination by Neil J. Miller, and the innovation of important improved methods for predictive speech coding by Steven Boll.

Image Processing

During this reporting period a major phase of research has been completed producing a homomorphic method for the estimation and removal of unknown image blurs, which are presumed to have been caused by a linear stationary system. Previous methods have required a more or less perfect *a priori* knowledge of the identity of the blur. The method developed by Cole [1] requires only statistical information about the original scene which led to the blurred image, but does presently require that the blur be phaseless for best results.

The estimation method uses a homomorphic mapping to map sections of the blurred image, which is a convolutional combination of the undistorted image and the blur, into a domain (the log spectrum) in which the components corresponding to the undistorted image and blur are added. An averaging method allows the component corresponding to the undistorted image to be estimated and subtracted, leaving an estimate of the component corresponding to the blur. This estimate is then used to generate a homomorphically estimated restoration filter.

Performance characteristics for the homomorphically estimated restoration filter in the presence of additive noise were derived, and they show that the homomorphic filter has noise and resolution properties intermediate between those of the classic Weiner filter and those of a simple inverse filter. The concept of a family of filters with variable noise and resolution properties has been devised. This family is bounded by the simple inverse and Weiner filters and includes the homomorphic filter. Any member of the family of filters can be generated from the homomorphic filter and an estimate of the noise level. A method for treating the case of multiplicative noise has also been developed.

A technical report which describes these accomplishments in detail is currently being prepared. The report also discusses the present limitations of the method with respect to phaseless blurs.

As described above, research at Utah has developed a method for image deblurring which depends on only minor previous knowledge of the nature of the blur for success. This result has potentially great importance, because as a rule the nature of blurs encountered in practice is not known well enough to allow the design of a successful deblurring process. The only constraint placed upon the blur is that it be a convolutional degradation of the signal under consideration and that the Fourier transform of the point spread function have zero phase. A method of averaging logarithms of magnitudes of Fourier transforms of sections of the blurred image yields an estimate of the magnitude of the spatial frequency response of the blur.

An example of the results of the process is shown in Figures 1 and 2. The blurred picture in Figure 1 was processed as described above to produce an estimation of the frequency response blur. By convolving that picture with the inverse Fourier transform of the reciprocal of the estimated frequency response of the blur produced the image in Figure 2.

A second phase of research into this method of image restoration has been initiated based upon the following problem areas. The restoration has some notable imperfections. Some areas of absolute black, which result from negative numbers, were produced in the restoration process. Also, "ringing" (i.e. multiple imaging or echoing) is

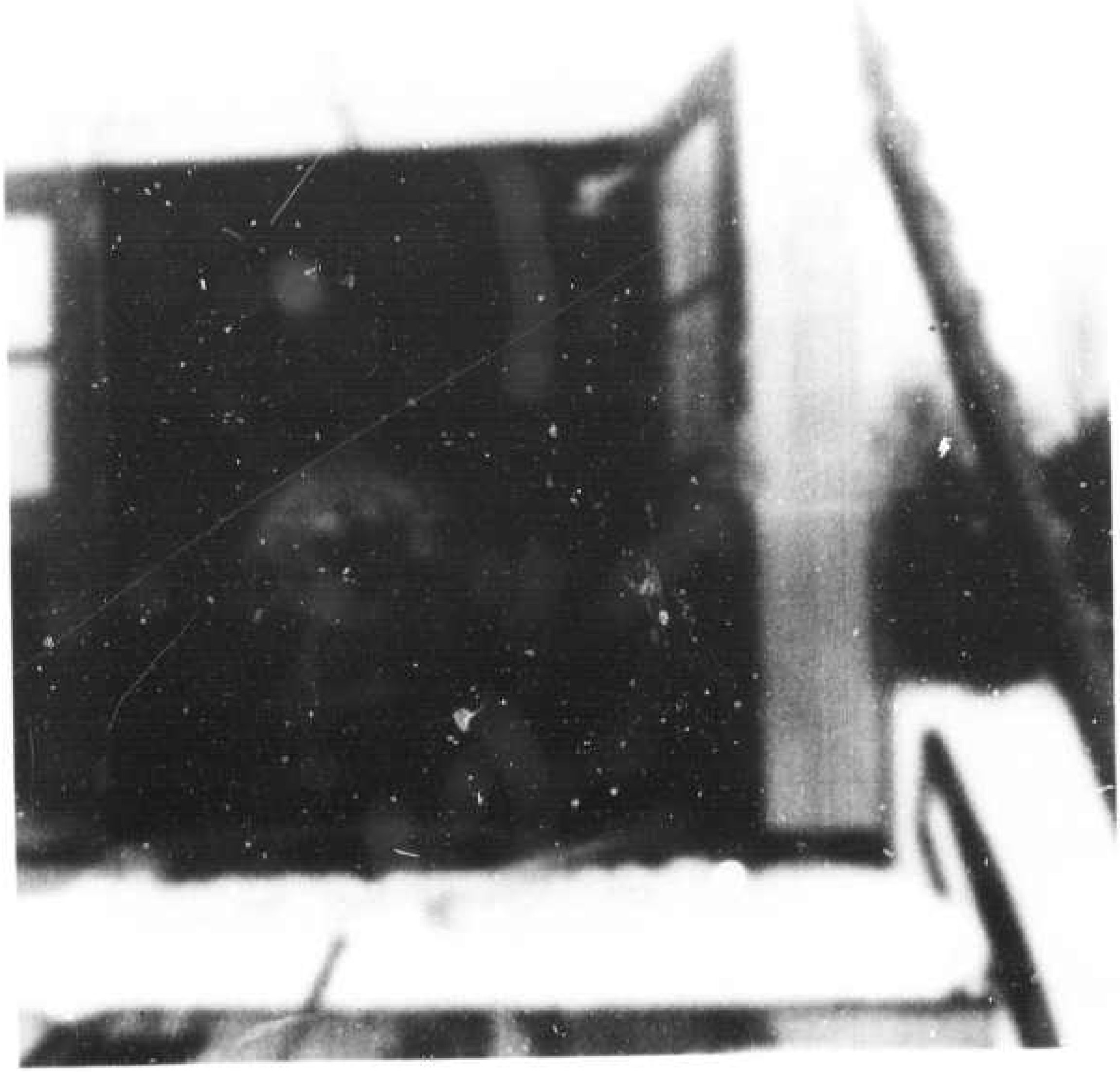


Figure 1. A blurred digital image.

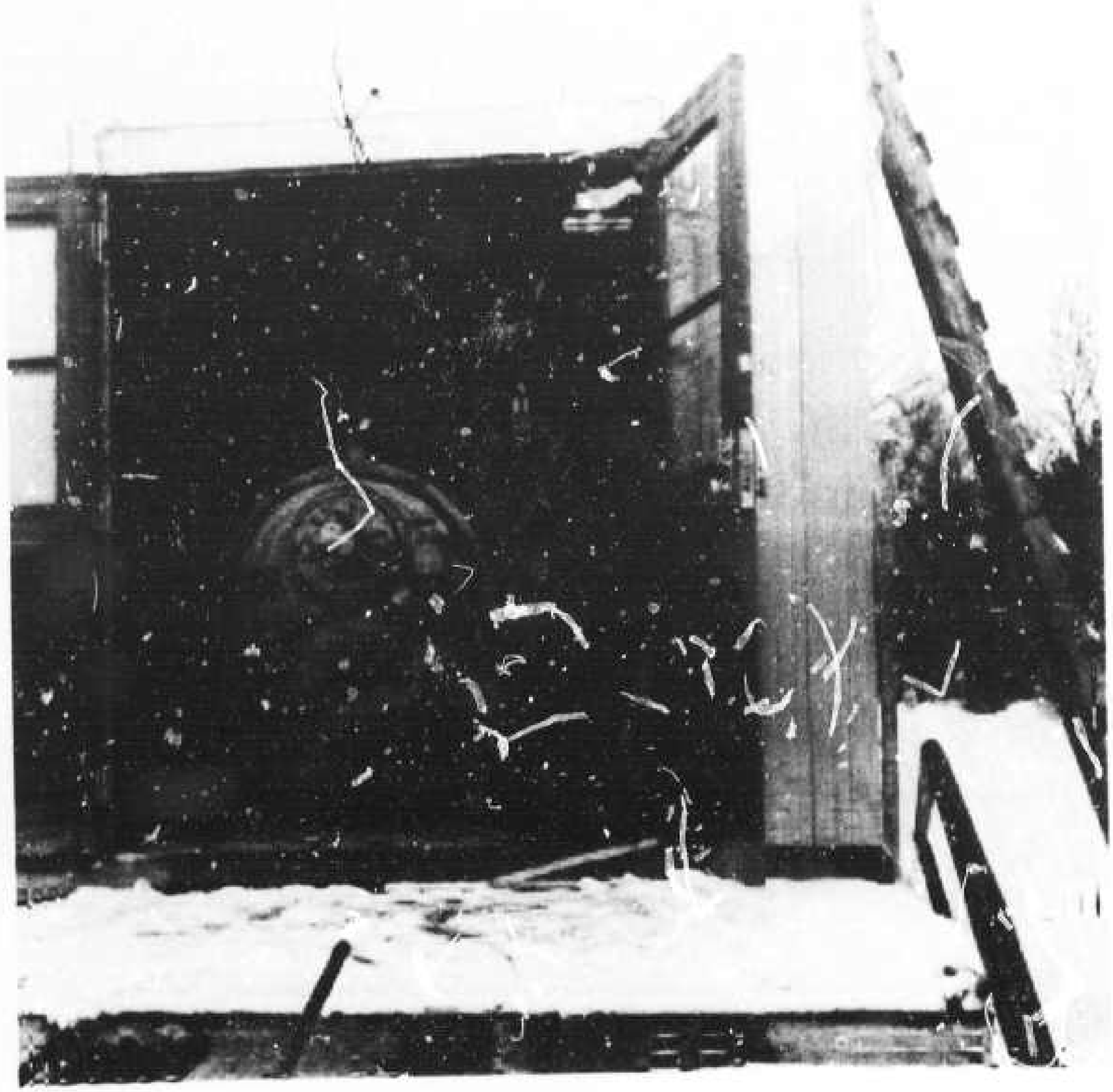


Figure 2. The blurred digital image after restoration by the computer.

especially noticeable near sharp boundaries. The new phase of research centers around the elimination (or optimal suppression) of these phenomena, the relaxation of the zero phase constraint on the blur frequency response, and the modification of the process to handle noise.

Initial avenues of approach include (1) least squares curve fitting of parameterized families of suspected blur frequency response magnitudes which are associated with nonzero phases, (2) using windows for space limiting the restoring point spread function so as to optimize "ringing" (3) using nonlinear intensity mappings to reduce the effect of absolute blacks, (4) giving the restoration process adaptive characteristics to better suppress the noise in images which possess highly non-stationary statistics.

A computer driven display system was used to study brightness contrast phenomena, in a project motivated by research in digital picture processing. The modelling approach was that of Stockham and Davidson[2]. The visual system is modelled as the cascade of a linear system (eye optics) and a multiplicative homomorphic system - that is, a logarithmic transformation (retinal receptors), followed by a linear system (neural interaction) - (Fig. 3).

In order to test the linearity of neural interaction, smooth stimulus patterns were utilized, containing only a few sinusoidal components within the low frequency band, and exhibiting classical brightness contrast effects (mach bands, simultaneous brightness contrast, Hermann grid effect), as illustrated in Figure 4 and 6.

Data were collected from brightness matching experiments with these smooth patterns. The data were verified in preliminary experiments on similar patterns digitally processed by the inverse of the model (Figure 5), in order to obtain cancellation of the brightness contrast effects (Figure 7). The experimental results proved to be in agreement with Davidson's data, obtained by a fundamentally different method. This new experimental approach indicated that the hypothesis of linearity of neural interaction is justified for smooth patterns. Further studies suggested that intensity edges and contours cause strong departure from linearity. Some steps were also taken toward extending the homomorphic model for color contrast phenomena.

Conclusions are drawn about the implications of these experiments in the fields of computer image processing and visual psychophysics. The advantages of computer techniques in visual experiments are presented, the applications of the homomorphic model of brightness perception to digital picture processing are reviewed, and the implications of the experimental findings are discussed in a pending technical report covering these results [3].

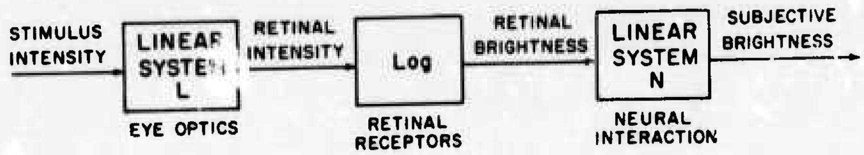


Figure 3. Block diagram of the linear-homomorphic model of brightness perception.

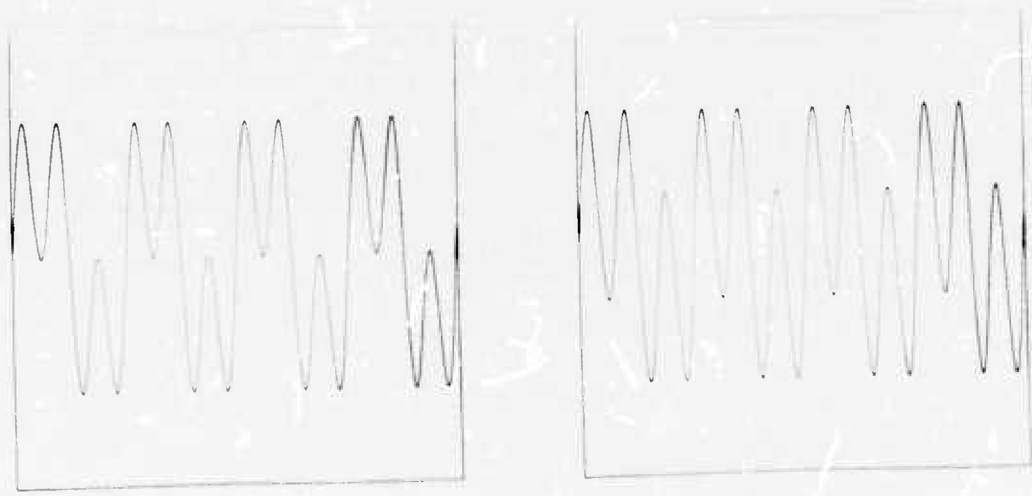


Figure 4. Stimulus density (left): $\sin(2\pi Fx) + \sin(6\pi Fx)$, and corresponding predicted subjective brightness (right). Notice the predicted brightness contrast effect.

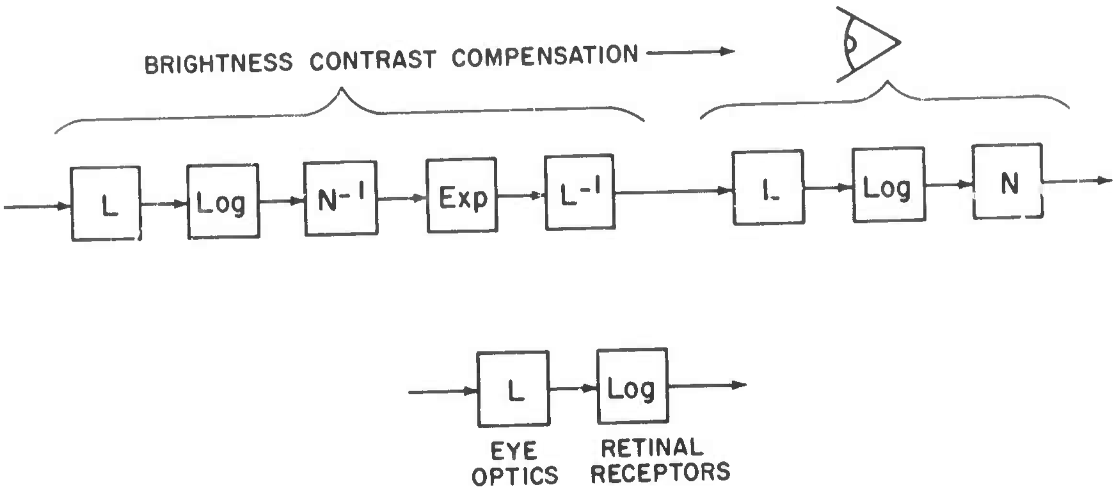


Figure 5. Scheme for brightness contrast compensation according to the homomorphic model for neural interaction.

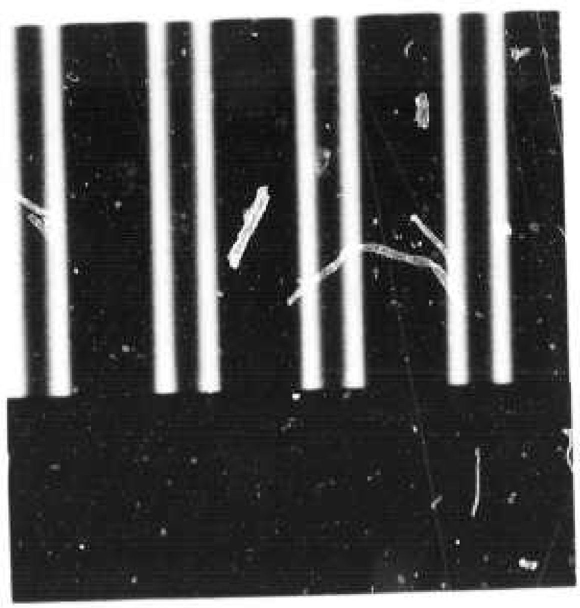


Figure 6. Sinusoidal test pattern corresponding to the density function: $k_1 \sin(2\pi f x) + k_1 \sin(6\pi f x)$, plotted on Figure 4.

Figure 7. Sinusoidal test pattern corresponding to the density function:

$$k_1 \sin(2\pi f x) + 0.5\, k_1 \sin(6\pi f x).$$

Shows the result of compensating for brightness contrast the pattern of Figure 6 according to the average data from the experiment.

A computer aided system for X-Ray Subtraction similar to the commonly used photographic Angeogram Subtraction method is being explored and is illustrated in Figures 8, 9 and 10. Notice that most of the background features, such as details of the bone structure, disappear, leaving visible only the Circulatory System. Any distortions in the Circulatory System structure may indicate damage due to a tumor.

The subtraction was done numerically using the optical scanner described in the previous ARPA Progress Report as an Input Device. Numerical subtraction permits the precise cancellation of background not easily obtainable with photographic methods. It also opens the door to interactive adjustment of the cancellation effect as well as to enhancement techniques such as filtering.

The application of these techniques to difficult materials testing tasks both in manufacturing and field inspection is potentially valuable.

Figure 8. Cranial X-Ray.

Figure 9. Dye added to blood.

Figure 10. Difference between Figures 8 and 9.

An investigation of digital image encoding in the context of a model for the visual system has been started. Block encoding of digital images, based on rate distortion theory has been pursued for some time now. However, the notion of coding density vs intensity images has yet to be fully explored. This seems essential in view of the first order logarithmic behavior of the eye. Also, to this date relatively little work has been done on block encoding using weighted square error distortion measures, and even less work has been done using a visual model to dictate the distortion weightings. This also seems important in view of the models for the visual system which include the notion of spatial filtration i.e., non-equal weightings of different spatial frequency components of an image. It is believed that coding of density images with weighted square error distortion measures dictated by a model for the visual system should lead to better subjective performance for a given compression ratio (or a given % distortion) or lead to equivalent subjective performance for higher compression ratio (or a higher distortion).

Sound and Speech Processing

Research representing the development of a system for the separation of singing voice from musical accompaniment and wide band surface scratch as found on early acoustic disc recordings has been completed [4]. The separation system employs a resynthesis of the singing voice using a mechanism, the homomorphic vocoder, based on the properties of voice signals.

The homomorphic vocoder separately estimates the contributions of vocal tract excitation and vocal tract articulation. When the homomorphic vocoder is applied to voice signals corrupted by noise, the corruptions affect the estimated excitation and articulation components. However, these components have been found to be regular over long time intervals, while the corruptions are not. Therefore, the effect of the corruptions can be attenuated by constraining the synthesized excitation and articulation functions so that they are also regular over long time intervals.

Further improvement in the quality and naturalness of the synthetic voice signal can be made by implementing several additional procedures. The mechanical recording system used to produce the recordings was incapable of responding to high frequencies, therefore, an attempt was made to synthesize artificial high frequencies. The voice signals occurring at the beginnings and endings of singing segments often have much lower energy than the accompanying noise. This makes accurate estimation of the actual vocal tract excitation and articulation functions difficult. This difficulty can be partially overcome by substituting estimations from adjacent, high signal energy sections for the unrecoverable sections. The synthetic signal does not have the benefit of room acoustic dispersion, consequently an attempt has been made to introduce artificial room reverberation.

The major contribution of this research is the presentation and implementation of the notion of filtering a voice signal from noise using an analysis-synthesis system. Although many of the techniques used in this implementation are derived from the literature, several have been developed exclusively for this task. The notion of pitch synchronous reverberation has not been presented elsewhere. This procedure, which interrelates neighboring impulse response estimates, is responsible for much of the success of the filtering process. The heuristic and interactive pitch correction processes, though based on classical notions, have been refined and adapted for this task. Finally, the notion of extrapolating the synthetic signal into intervals with low signal to noise ratios by using information derived from intervals with high signal to noise ratios has been developed successfully in this application. These contributions represent steps not only in the solution of the problem of filtering voice signals from noise, but lead to possible solutions of problems in many other areas.

A successful scheme for extracting a signal from a background of noise has potential for application to a variety of communication problems. The homomorphic vocoder has been successfully used in bandwidth reduction, helium speech correction, and expansion-compression systems [5], [6], [7]. This work explores its utility as a nonlinear filtering mechanism for voice signals and introduces several modifications to further adapt the vocoder to this application. This modified vocoder might be applied to the reconstruction of voice messages recorded in a variety of difficult environments or to any problem where the parameters of resonated quasi-periodic sound need to be estimated and recreated free of other accompanying noises.

A speech analysis-synthesis system has been developed in which the vocal tract is parameterized as a time-varying all-pole filter (predictive coding). The novel aspects of this system are: (1) the predictor coefficients are estimated using a priori least squares and (2) pitch is detected using a modified autocorrelation method.

A priori least squares allows for a narrower window to be used when estimating the predictor coefficients, thus significantly reducing the amount of computation required to determine these parameters. The a priori least squares algorithm requires little additional information compared with standard predictive methods and Robinson's method can still be used to solve for the coefficients because a Toeplitz matrix is still obtained. This method acts similar to a low pass filter when generating coefficients. The coefficients, therefore, exhibit smoother time histories than those generated when a priori methods are not employed.

Pitch is detected using a correlation method which has been modified to take maximum advantage of the predictor coefficients. An a priori estimate of the pitch period is determined by generating the estimation error sequence and detecting the distance between successive maxima. The autocorrelation of the vocal tract excitation function is then determined for only a small neighborhood about the a priori pitch estimate, and the final estimate of the pitch period is determined. By comparing the number of real multiplies, it can be shown that this method of pitch detection requires approximately thirteen times fewer multiplies than cepstral methods and half the number required when the a priori pitch estimate is ignored.

Research during this reporting period has been directed toward finding new approaches to solving the basic problems in separating simultaneous speakers. A new method for estimating pitch is being developed which shows considerable promise for determining two pitches simultaneously. It uses a search for patterns in the positions of peaks in the log frequency domain to make the pitch/no-pitch decision and to estimate the frequency of the pitch. This avoids making the decision on the basis of the height and position of a single peak. A new method for separating two simultaneous speakers also has been tested. This method uses speech synthesis techniques to reconstruct the sound of one voice after the portions of the formant structure (*) belonging to the other voice have been removed. In the tests that have been performed this method has not produced high quality speech but the output of one voice has been perfectly understandable and has contained no trace of the other voice.

The new method for pitch estimation originated with the idea of converting the frequency scale of the spectrum of a voiced sound to a log frequency scale and then convolving that log frequency spectrum

*"Formant Structure" is used here as being synonymous with the envelope of the log magnitude spectrum.

with a "template" consisting of impulses located at the logarithms of integers. The expected result of the convolution was to be a prominent peak at the location of the logarithm of the pitch frequency because at that point the impulses of the template would coincide with the harmonic peaks of the spectrum.

The expected result was produced but along with it came many other prominent peaks occurring where other combinations of integers in the template, such as 2, 4, 6, 8, ... or 3, 6, 9, ... etc., coincided with the harmonic peaks or where the template coincided with similar combinations of harmonic peaks.

Considerable effort was expended attempting to manipulate the data and to shape the template to accentuate the desired peak and to attenuate the others. These efforts were abandoned when it was realized that the distances between these peaks are proportional to the logarithms of the ratios of small integers. A program was then written to search the positions of the most prominent peaks for patterns corresponding to the relative locations of the logarithms of small integers. The location of the logarithm of 1 in such a pattern is the position of the log frequency of the pitch estimate even though a prominent peak may not be visible at that location. (The peak which should be there might be merged with a larger peak. This is often the case when two nearly equal pitches are present.)

This method gives fairly good results in estimating the pitches of combined male and female voices although it fails when the female pitch frequency is double that of the male. Likewise, it can separate two male or two female pitches which are not too close together.

Neither of these capabilities is yet a straightforward infallable procedure, however. More experimentation is needed to find the cause of some of the unexpected failures and to adjust the system to handle them. Some of the problems are a result of the fact that pitch frequency is not a smoothly varying, well defined parameter even for a single speaker. Other problems might be traced to the phase interaction of the frequencies in the two voices when they are added together.

When used to estimate the pitch of a single voiced sound this method appears to be more sensitive and definite than the cepstral peak method. Its principal advantage at present is in the dual speaker situation. It is slower than other pitch estimation methods but no attempt has yet been made to improve its speed.

The new method of speaker separation requires the pitches of both speakers whereas the previously tested comb filtering method only used the pitch for one speaker. The new method is quite straightforward but there are areas of the procedure which might be changed to improve the quality of the results.

The basic idea behind the method is to build an approximation to the formant structure of the voice to be passed and to use that formant structure to compute an impulse response for the vocal tract of that speaker. This impulse response is then convolved with an impulse in a time sequence of unit impulses spaced at the pitch periods of the speaker.

The computation of the approximate impulse response is accomplished using the log magnitude spectrum of the same section of data which was used to estimate the pitch. First, the log magnitude is set to zero for all frequencies which "belong" to the voice to be stopped. (We say that a frequency f "belongs" to pitch p if for some integer k, $|kp-f| < p/4$). Next, the log magnitude is set to zero for all frequencies which do not belong to the sound to be passed. This leaves a set of disconnected sections of nonzero points of the log magnitude spectrum. These sections are then reconnected by simple linear interpolation between their end points. The result is a jagged combination of lines and curves which is a rough approximation to the formant structure of the voice to be passed. This rough formant structure is then low-pass filtered to obtain a smooth approximate envelope of the log magnitude spectrum. Exponentiating this smooth envelope and then performing an inverse Fourier transform produces the desired impulse response.

In tests using this method of separation, the best results have been obtained separating a male voice from a combination of male and female voices. The poorest results have come from separating the female voice from that same combination.

The reconstructed voiced sounds also have a rough quality which can probably be improved by temporal filtering at some point in the process.

Theory and Software

Significant progress has been made toward the completion of the catalog of window functions described in the last report. Extensive studies into the quantitative properties of a comprehensive set of windows has been carried out. The windows included are the Fourier window, the Bartlett (Cesaro or Fejer) window, the parabolic window, the Parzen window, the trapezoidal family, the end taper family, the Hanning family (including the Hamming window), the Blackman window, the Kaiser family, the Dolph-Chebyshev window, the Taylor window, and the White family. The quanitative issues investigated are principally concerned with the application of these windows to the following:

(1) the design of finite length impulse response digital filters

(2) the estimation of power spectra

(3) the design of electrically steerable phased arrays.

Poet

Poet is a page oriented text editor designed for TENEX facilities. Poet provides speedy, efficient service making short work of most editing jobs and enabling easy maintenance of large software libraries.

Poet's command language is patterned after QED [8] and the control character functions are similar to those in the TENEX executive; thus, it is easy for a user to learn and remember.

Poet subdivides the body of text into pages which are terminated by formfeeds. This makes it much easier for the user to identify text locations. Also available are options to search the text for some particular string. This addressing scheme is also employed in the executive's type command and in <SUBSYS>SRCCOM. Thus, when teamed together the user has an extremely powerful tool.

B. SYMBOLIC AND ALGEBRAIC MANIPULATION

Symbol Manipulation and Automatic Programming Research

Many of the day to day problems which confront theoretical physicists, applied mathematicians, and engineers involve extensive algebraic or non-numerical calculation. Such problems may range from the evaluation of analytical solutions to complicated differential integral equations on the one hand, to the calculation of increasingly more complicated terms in a perturbative approximation to a physical theory on the other. The difference between these two classes of problems is obvious; in the former case no straightforward algorithm exists which will guarantee a solution, and indeed an analytic form for the answer may not even be possible. On the other hand, algorithms do exist for the solution of problems such as series expansion and differentiation and so a correct answer may always be found provided the researcher possess sufficient time, perserverance and accuracy to carry the calculations through free of error. The appeal of using a computer for the latter class of calculations is obvious. Besides removing the tedium of doing complicated algebra, the result is guaranteed to be error free and can be obtained in a much shorter real time interval. A considerable degree of practical success in this field has now been obtained, and many computer algebraic calculations have been reported in the literature.

The main research of this group is devoted to the development and application of the computer techniques necessary for the solution of such theoretical problems. This research is orientated toward both computer software development and the use of the developed programs involving practical problems. The REDUCE system which we have developed is used as a basis for this work. Originally, this began as a system for solving some particular problems which arise in high energy physics where much tedious repetitive calculation is involved. An account of applications in this area is given in Ref. [9]. However, it has quickly recognized that the simplification processes being used were quite general, and in 1967 REDUCE was announced as a system for general purpose algebraic simplification and released for distribution. Over 60 installations in the USA and Europe now have REDUCE operating and over forty publications acknowledging its use have appeared in the literature.

Work progressed in three main areas of research during this period. They are:

1. System Development - We are planning to make several major improvements in the REDUCE[9] system. In particular, the results of the study we have recently conducted have convinced us that we could gain an increased degree of efficiency by using a different polynomial representation for most of our problems. In order to prepare for this changeover we are presently making as many routines as possible independent of the explicit details of the polynomial algorithms.

2. Language Standardization - The REDUCE language in which the system is written has steadily evolved over the last three or four years. We are presently in the process of defining this in as rigorous manner as possible. In order to facilitate this standardization, a syntax-directed meta-translator was adapted to use REDUCE as a source language. Our experience with this now suggests that we could produce a system within five years which could be implemented quite rapidly on any computer without using the present intermediate language LISP. Such a system will in effect be an automatic programming system to the extent that the user could define his own syntax and semantics for input and output of expressions.

3. Applications Research - We are continuing our emphasis on applying our developed systems to practical problems. In particular, we are studying the possibility of using REDUCE or extensions as the basis of an automatic programming system for a large class of problems in quantum electrodynamics and other fields. We believe, on the basis of our present work, that such programs will become feasible within the next two or three years.

C. COMPUTER GRAPHICS TECHNIQUES

The senior investigators in computer graphics techniques are David C. Evans (faculty), Ivan E. Sutherland (faculty), Ronald D. Resch (faculty), and Robert E. Stephenson (faculty). The primary goal of the research is the development of graphics techniques for the realistic dynamic display of three-dimensional objects.

Two aspects to this research are: (1) the techniques for picture generation from numerical models, and (2) development of languages, input devices, and other tools required to specify and manipulate models and pictures.

Our recent efforts have been concentrated on modeling representation, picture generating algorithms, and machinery. Although much work remains to be done in this area, the art has advanced sufficiently so that the most pressing work now is the graphic input and language problem. 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.

1. GRAPHIC LANGUAGES

Interactive Surface Design

In the last semi-annual report it was mentioned that a new class of functions called B-splines were being developed at Syracuse University. Professor Richard Riesenfeld, whose thesis is an investigation and development of these functions as they apply to interactive computer-aided design, has been continuing research in that area since his arrival at Utah in August. This approach to the design of curves and surfaces appears to be more general and useful than it was originally envisioned. Furthermore, they now emerge as the spline generalization of the Bézier method for designing parametric polynomial curves and parametric bi-polynomial surfaces. This gives the assurance that B-spline curves for surfaces are at least as good as Bézier curves and surfaces, for one always has the option to let the spline degenerate to Bézier polynomials. On the other hand, since B-splines are local approximating functions, they afford the designer the capability of making local perturbations to an existing curve or surface. It also permits the interpolation to linear segments by a curve that is not linear in other regions. Moreover, this can be done with arbitrary continuity of derivatives.

Another consequence of the local nature of the B-spline curves is that they approximate the controlling polygon more faithfully than their Bézier polynomial counterparts. By using B-spline curves, it is possible to increase the flexibility of a curve by adding more knots while keeping the degree of the polynomial components low. B-spline curves then provide an entire family of spline curves ranging from

Bézier polynomial curves to piecewise linear curves that are identical to the controlling polynomial. If one thinks of the mechanical spline rather than the mathematical spline, increasing the degree of the spline has the effect of stiffening the spline. Another aspect of the comparison of B-splines to Bézier curves is that with B-splines it is possible to design periodic curves. That is, closed curves that treat each vertex identically. The method of Bézier as he describes it in his book and as it is implemented at Renault is for the design of open curves only. The initial vertex and the terminal vertex are always distinguished by interpolation. The weighting polynomials that Bézier uses are different for each vertex so, in that regard, each vertex is treated individually. An important advantage of treating each vertex uniformly besides the obvious design advantage is that it makes the computation far less expensive. Essentially one can compute a basis function once and then use a lookup table during the computation. For this reason, B-splines are far more attractive as the mathematical basis of a real-time interactive computer-aided design system for curves and surfaces.

The name B-splines was given to this class functions by the discoverer, I. J. Schoenberg, as a shortening of the two words basis splines. As Schoenberg intended to imply by the name B-spline, these functions do, in fact, form a basis for the linear space of spline functions with fixed knots. In practice, this means that any spline function can be represented as a linear combination of the B-spline. In particular, the more common interpolating spline can be represented as a B-spline. That is, any given spline can be viewed as the B-spline for some appropriate polygon. This is called the inversion problem:

given any arbitrary spline find the appropriate polygon such that it defines a B-spline identical to the given spline. In practice, solving this problem is equivalent to inverting a gram-type matrix. A frequently raised criticism of the Bézier method of curve and surface design is that it requires an intimate familiarity with that type of system in order to guess what the initial approximation that this polygon ought to be. The situation is somewhat improved by the fact that B-splines are much more faithful to the global characteristics of the polygon than are the Bézier curves. But, this by no means illuminates the problem of what the initial guess should be. We propose, rather, a system that uses interpolation as an initial approximation. In such a system, a designer would identify certain points through which he would like a curve to pass. A system would then respond with an ordinary interpolating spline. But, in addition, it would also respond with the accompanying polygon that defines the interpolating spline as the corresponding B-spline. Now the designer is free to perturb the node as the situation and his judgment requires. Much more experimentation and feedback from practice is required to make judgment on this method. However, preliminary reports from the University of Cambridge and Syracuse University, where this has been tried, showed favorable results.

Another application of inversion is to the problem of illuminating undulations and "flats" from interpolating splines. Interpolating splines quite often are satisfactory except for some small modifications, but, since interpolation is a global process that is one in which each part or point of interpolation effects the entire system for a result.

Therefore, attempts to remove undesirable extraneous bumps or undulations or "flats" may have the effect of destroying the interpolation of every point since the interpolating spline is unique. Furthermore, in the process of trying to remove one undesired bump, one may well introduce others. This is one of the long standing problems that accompany interpolation with splines. On the other hand, if we view the interpolation spline as a B-spline, we can make the very obvious appropriate alterations by examining the vertices of the defining polygons and moreover, we can perform these alterations in a completely local way.

This new curve at surface formed several projects related to this development. James Clark, a graduate student in the department, is in the process of bringing together many existing pieces of hardware and modifying other pieces of hardware so that he can develop a real-time three-dimensional interactive design system for curves and surfaces. Some of the computer animation community, notably Barry Wessler, has looked into the use of B-spline curves for delineating trajectories in animated movies. In terms of movies, the smoothness properties of B-spline provides for very smooth looking motion for objects that traverse a B-spline path. The parameter of a curve takes on the meaning of time in this application. Johan Calu is investigating the design of a hardware B-spline generator.

Computer Animation

The mathematics for a curved surface display algorithm have been worked out. The algorithm will work in patches where each patch is defined to be an ordered set of points with a normal associated with each point. An edge connects each point. That edge is perpendicular to the normal of the point at the point. The edge then is a curve and may be described by a cubic equation.

There were three difficult problems that have been solved. The first was to get a simple cubic expression in screen space that closely approximated the correct rational cubic representation of the edge. The second was to find where an edge went from being visible to not being visible, thus creating on the patch an implied edge. The third was to find the difference equation of each edge of x with respect to y from the parametric equations in t.

An algorithm has been proposed and is being coded. There are still some questions about the algorithm that can best be answered by experimenting with the algorithm.

2. OUTPUT DEVICES

Real-Time Three-Dimensional Precision Measurement and Communication System

A hardware-software system is nearing completion which measures the three-dimensional positions of multiple points. The points are light-emitting diodes which may be attached to wands, gloves, clothing, etc. The light-emitting diodes are easily distinguished from one another by flashing them on and off in sequence, under computer control. The position of a light-emitting diode is measured by scanning the environment. Fast, one-dimensional, geometric scans quickly determine planes in which a light-emitting diode lies. The point of interest is at the intersection of these planes. A plane is determined by the position of one of thirty-two narrow, radial slits cut around the edge of a spinning disk. The position of a slit is determined when photons from a light-emitting diode pass through a stationary system of lenses and the slit, and excite a photomultiplier tube positioned behind the slit. Up to eight planes are determined by four scanner boxes mounted in the upper corners of a room. Each scanner box contains a spinning disk and two sensors which determine two nearly orthogonal planes. Transformation matricies which map three-dimensional space into the one-dimensional spaces of each sensor are determined at the outset by a calibration routine. The routine requires each scanner box to make two one-dimensional scans which measure the positions of eight light-emitting diodes at known positions in the room. Equations of scanning planes may subsequently be expressed in terms of linear combinations of the output of the scanner boxes and the elements of the transformation matrices. The three-dimensional coordinates of points in the room are found by a least mean squares approximation to determined scanning planes.

The system operates in two modes. In real-time mode, the rectangular coordinates of a handful of points are determined each second. In nonreal-time mode, the positions of more than nine hundred forty points are measured each second. The data are stored and subsequently reduced to rectangular coordinates.

The system has several advantages. It is unique in its ability to determine the three-dimensional rectangular coordinates of several points in real time. The frequency with which data for storage may be gathered, the ability of the system to generate data which may be rapidly reduced to rectangular coordinates, and the volume of data which may be stored make the method superior to conventional methods. Because the light-emitting diodes, the lightweight connecting wires, and the associated electronics worn by the user weigh less than a pound, the movement of a user is not restricted by the attachment of bulky equipment. No technical skills, interpretation of data, or previous experience is required to achieve satisfactory results. The system is computer interfaced.

The system may be used for interactive surface design, measurement and specification of motion, man-machine gesture communication, and scene analysis.

Head-Mounted Display System

Ever since computers have been used to draw pictures of objects on a cathode-ray tube (CRT), computer scientists have been interested in finding better ways to display, define, and interact with these computer-generated objects, which will hereafter be referred to as "synthetic objects." Initially two-dimensional objects such as squares and circles were represented; soon after, perspective was added making them appear as cubes and spheres. Later, stereoscopic methods[10] of viewing were developed to give the objects a more truly three-dimensional (3-D) appearance. One of the most conceptually advanced 3-D displays[11] puts the observer in a 3-D environment wherein he seems to be surrounded by 3-D synthetic objects.

Even with 2- and 3-D interaction and 3-D viewing capabilities available, some of the more reputable computer graphics institutions still work with 3-D synthetic objects using 1-D interaction and 2-D viewing. At the University of Utah, for example, the system almost exclusively used for defining and interacting with 3-D synthetic objects is a (1-D) teletype and a (2-D) CRT display. Certainly availability of equipment, existing programs and convenience tend to dictate which systems are used. But many two- and three-dimensional systems are simply not very useful because of inadequacies and ambiguities, for example, in trying to "draw" 3-D objects with 2-D devices, trying to visualize 3-D objects on 2-D displays, or trying to coordinate 3-D drawing and 3-D visualizing of objects on present systems.

The problem addressed by researcher Don Vickers, was the development of a system which could be used to display, describe, and interact with 3-D synthetic objects in a realistic 3-D environment.

The Sorcerer's Apprentice system (Fig.11) explored here is a combination of two systems, a head-mounted display[12] and a wand. The display portion of the system was chosen for its availability and novelty. A hand-held 3-D wand was designed for use in interaction. Vickers' major efforts of research centered around this equipment and the programming for it.

For several years the head-mounted display (Fig. 12) has provided the University of Utah with a unique three-dimensional environment for looking at 3-D, computer-generated objects which exist only as data in a computer[13]. The illusion presented to one wearing this display is that he is surrounded by synthetic objects which he sees in addition to the features of his surroundings. These synthetic objects exhibit the size, perspective, and stability characteristics of real objects as the observer freely walks among them. Like real objects they are seen only when the observer is facing them; as he turns or walks past them, they leave his field of view.

A small wand (Fig. 13) with several buttons on it was built to enable an observer to interact with the synthetic objects by reaching out and "touching" them. It was thought that the ability to draw, change, and join 3-D objects in a 3-D environment using natural arm, body, and eye coordination would have many advantages over existing interactive systems. As an aid to reaching and "touching," the wand as seen through the head-mounted display is marked by a spot of light,

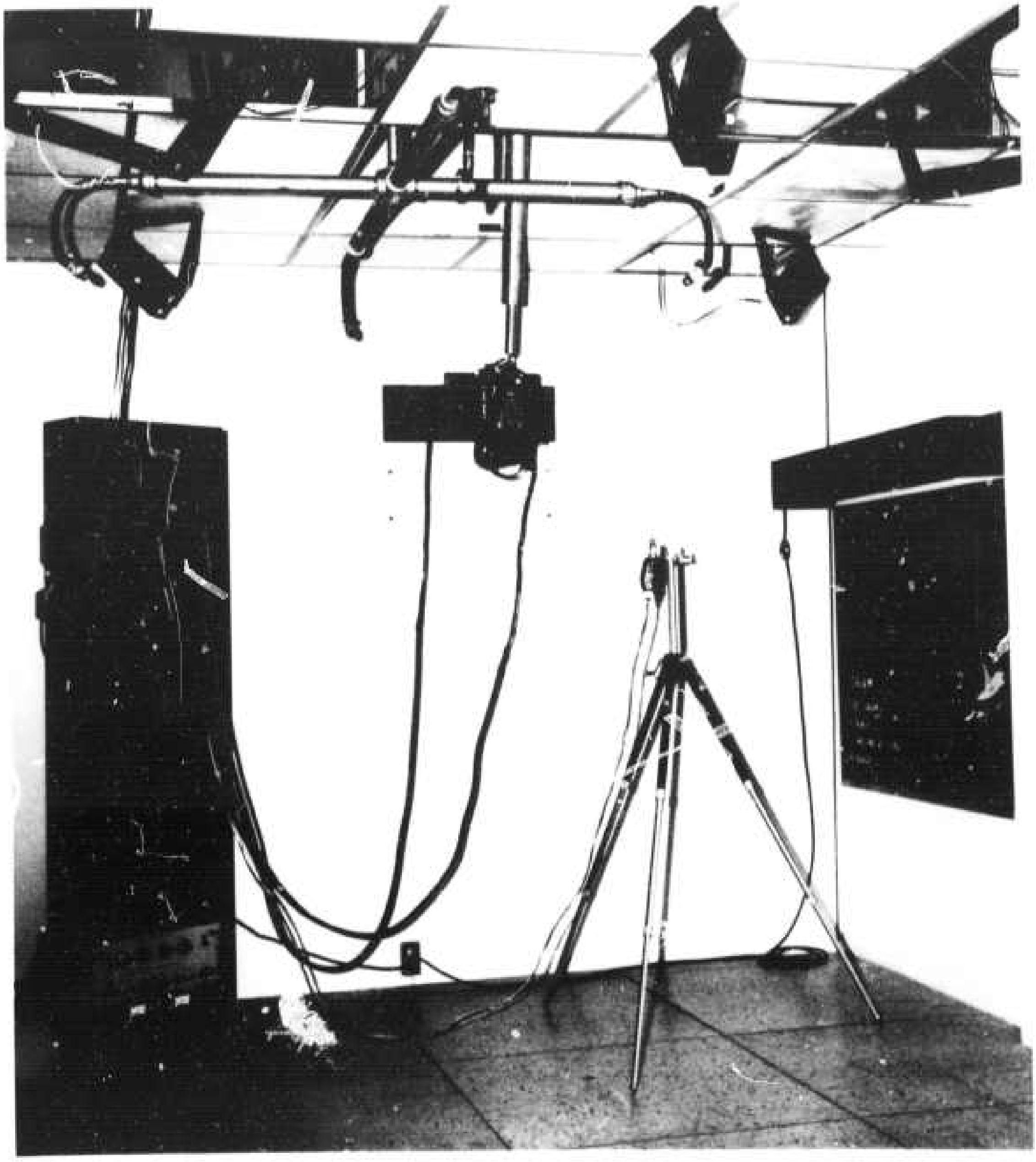
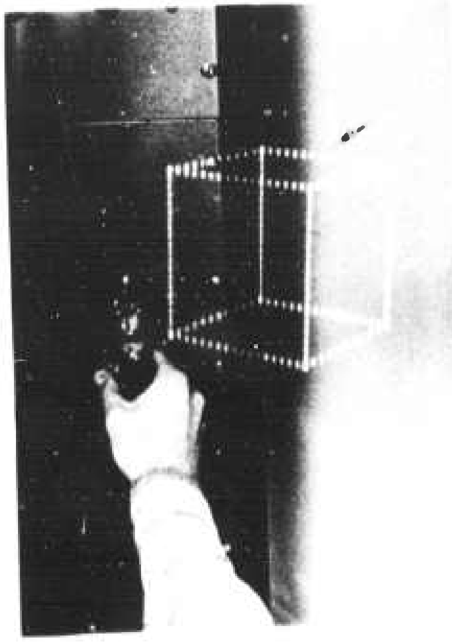
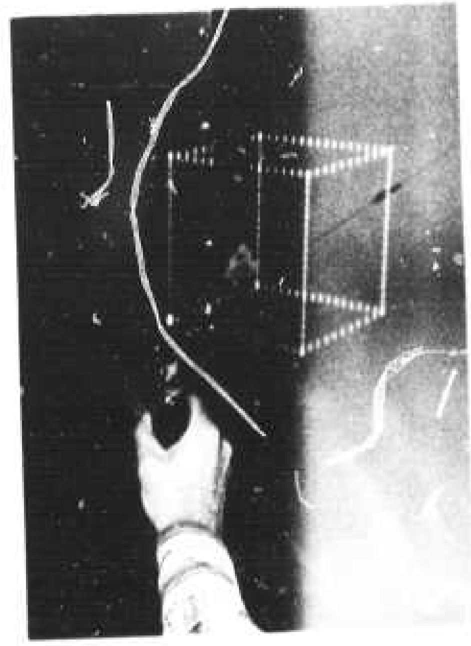


Figure 11. Sorcerer's Apprentice.

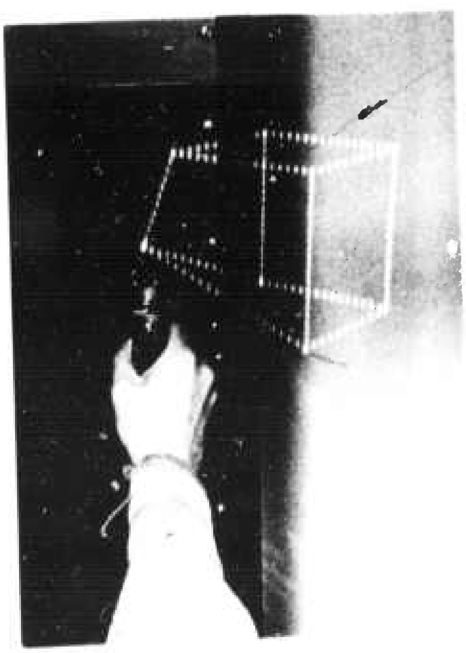
Figure 12. Head-Mounted Display.



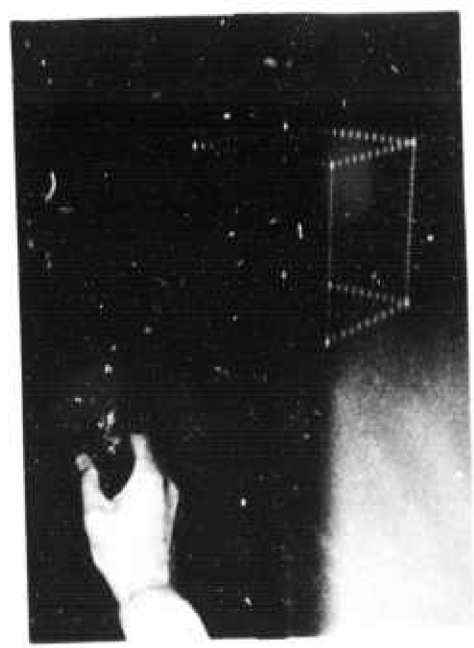
(a)



(b)



(c)



(d)

Figure 13. Photographs taken through the head set showing effects of the DEFORM command. The observer is: (a) approaching the cube, (b) "touching" a vertex of the cube, (c,d) DEFORMing the cube.

a cursor, which normally moves as though attached to the wand. Lines drawn using the wand appear as glowing wires and form "wire-frame" drawings. These lines do not fade in time but appear to be stationary in space. With the wand the lines can be joined to form objects which can then be moved, modified, and stored in magnetic tape from which they can be re-entered at a later date for further modification.

The system is fairly simple to use. Available commands are few and uncomplicated. Some can use it well the first time, but most require several sessions on the system to pass the "tolerance limit"--that point when the system becomes useful instead of merely tolerable.

Many minor problems still distract one while using the Sorcerer's Apprentice system, yet the ability to observe and modify three-dimensional objects in real time and in natural manner is very striking and very realistic.

3. GRAPHICAL APPLICATIONS

Kinematic and Elastic Systems

This report period has seen modifications to three display programs to utilize the "hardware" version of the hidden surface problem and to allow color. One routine has also been modified to allow the production of computer generated continuous tone movies.

Displays of Distorted Panel Systems

This routine was subject to each of the modifications mentioned above. Color is utilized to a) indicate separate parts in a complex object, b) to improve the simulation of real objects, and c) to indicate displacement levels in specified directions. Coloring the elements to indicate displacement levels proceeds according to

$$C_{ijk} = A_{ik} \cos^2\alpha + B_{ik} \sin^2\alpha$$

where: C_{ijk} is the intensity of the ith color component at node j for surface k.

A_{ik} is the intensity of the ith color component specified (by the user) for surface k and displacement level δ_A.

B_{ik} is the intensity of the ith color component specified for surface k and displacement level δ_B.

$$\delta = \frac{\pi}{2} \frac{(\delta - \delta_A)}{(\delta_B \quad \delta_A)}$$

$$\delta = \vec{U}_o \cdot \vec{U}_j$$

$\vec{U}_o$ is a unit vector which indicates the specified direction for measuring displacements, and

$\vec{U}_j$ is the displacement vector for node j. These intensitites are also modified by multiplication with the cosine squared of the angle between the local normal and the direction to the light source.

Animation capability was introduced to allow the specification of vibration amplitude and frequency as well as smoothly accelerated motion of objects in translation, rotation, "explosion", and to peel back surfaces (exposing hidden parts).

Figure 14 shows a color display, which closely simulates the actual structure, of an unclassified U.S. Navy sonar transducer. Figure 15 shows the color stress fringe capability applied to a "Free Flooded Cylinder" (another unclassified U.S. Navy sonar transducer).

Display of Distorted Frameworks

A "hardware" version with color was finished for this routine. Figure 16 shows a color display of a structural framework. Work was started on a modification to allow the display of shear and bending moment diagrams by use of a spectrum of colors.

Display of Two-Dimensional Elasticity Results

Color was introduced in this routine so as to allow the production of color stress fringe pictures. Figure 17 shows an example of this work applied to the display of the results of a finite element analysis of a flat plate with a circular hole. Color is used (magenta, red, yellow, green, turquoise, blue) to indicate descending levels of maximum normal stress.

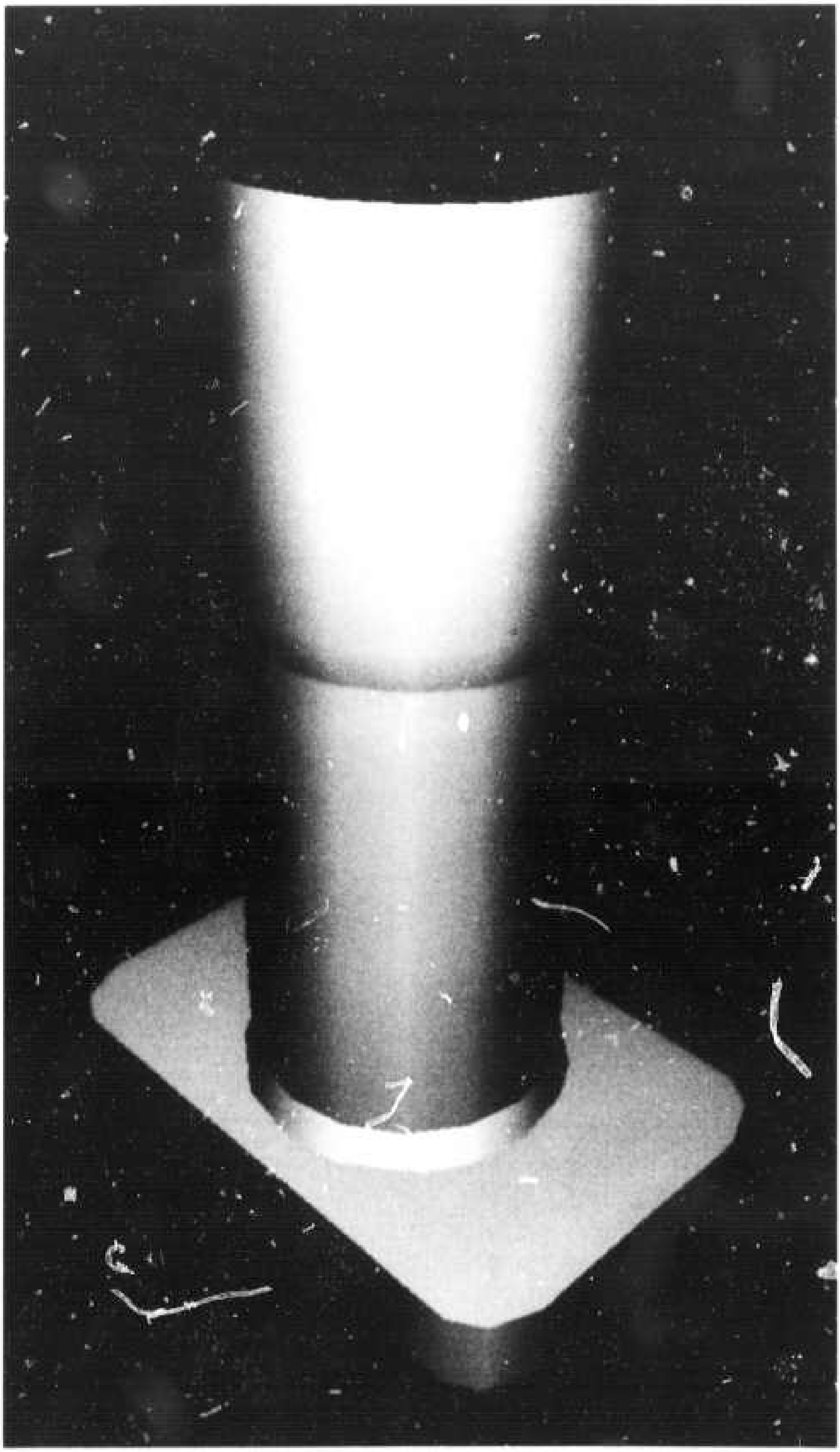


Figure 14. Simulated U.S. Navy Sonar Transducer.

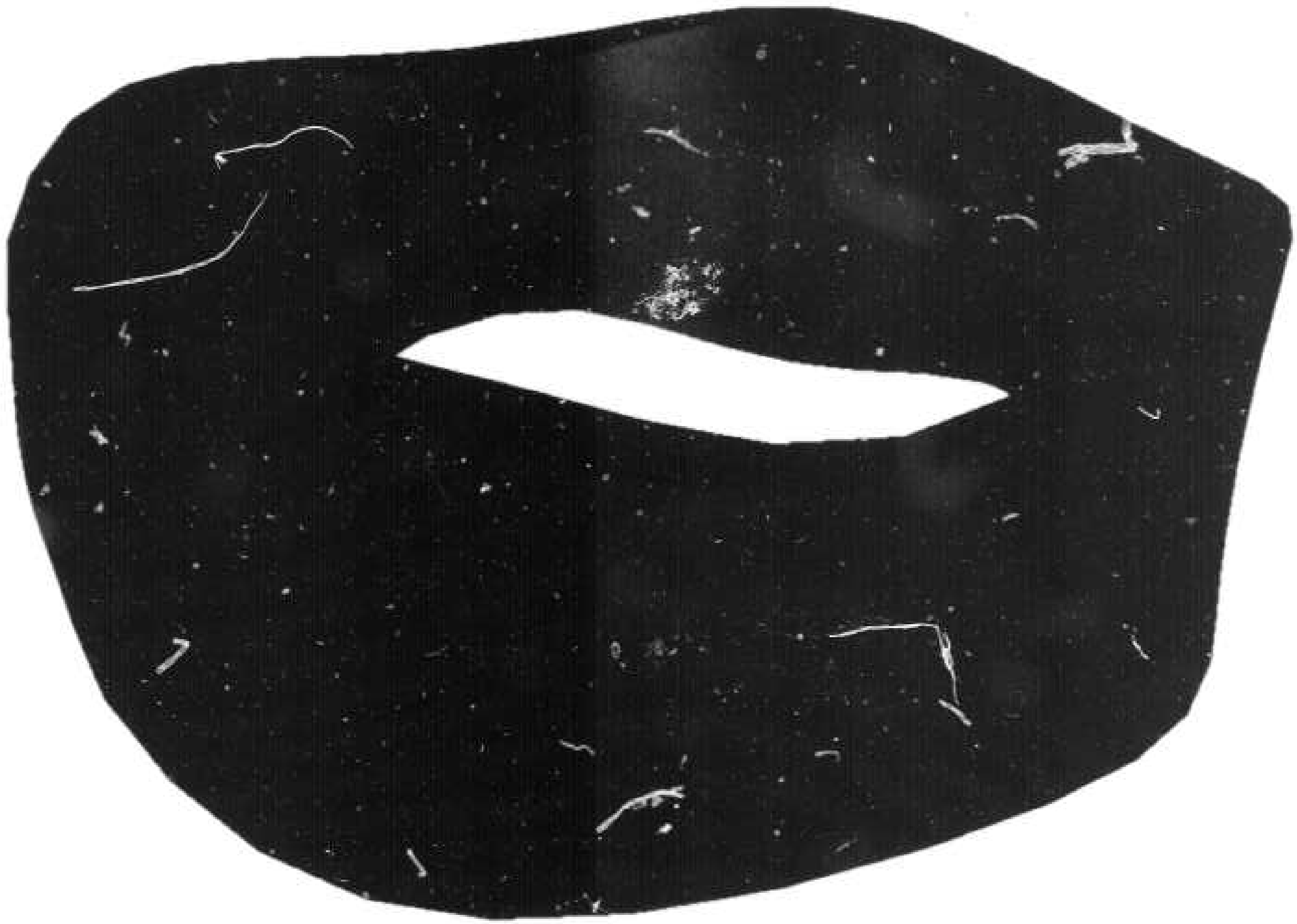


Figure 15. Color stress fringe capability applied to a "Free Flooded Cylinder."

Figure 16. Color display of a structural framework.

Figure 17. Color stress applied to the display of the results of a finite element analysis of a flat plate with a circular hole.

PART II. FACILITIES

Hardware

The PDP-11 which is to drive the Xerox Graphics Processor arrived during this period and was brought up rapidly. The interface between the PDP-9 and PDP-11, which was designed and built locally, was brought up and tested and is now lacking only a permanent cable for connection to the PDP-11.

Drawings of the 10-10-1108 and IMP interfaces have been brought up to date. Most of the indicator lamps in the computer room have been replaced with Led's. All of the data sets have been brought into working condition, and spares have been ordered to allow local repair in the future.

Our IMP interface was modified to allow total re-initialization under software control. At the same time, we were finally able to prove that a half-duplex IMP interface will be guaranteed to produce a "deadly embrace", operating with the current (and planned) IMP software.

Software

We modified the TENEX scheduler to implement our new scheduling procedure. The procedure's description will be ready shortly for publication. In short, we are now able to guarantee arbitrary relative shares of computing resources to the various members of the user community, and to dynamically vary the relative "costs" of each resource according to supply and demand. As a side-effect of this modification, our average lost time has dropped from around 40% to around 20%.

A new loader, designed to take advantage of TENEX's full virtual address space and file system, was written and can now load anything except Fortran files.

A new machine diagnostic was written and is being used. This diagnostic, unlike those previously available, uses our full machine configuration .... both processors, the "Watkins Box", the swapping disk, etc. Although this program will probably continue to grow for a long time, it will shortly be able to exercise our machines as well as the worst combination of real users.

The necessary "handles" for TENEX inter-process communication (Send-Receive of the DEC 1050 system) have been created, and TENEX IPC will be available very shortly.

The appropriate Fortran subroutines have finally been made generally available, allowing bi-directional communication between the 1108 and a normal TENEX user program.

Waveform Processing Laboratory

During the last quarter of 1972 a high percision 16 bit Digital to Analog converter system was added as a peripheral device on the Single User PDP-10 computer. The system is designed to be used in audio waveform research giving a precision which has never before been achievable at this facility. Extensive testing of the system indicates total harmonic distortion is less than -88 db below the maximum signal level and system noise is approximately -93 to -95 db. This is an improvement of 24 db over the 12 bit DAC's previously used.

PART III. PUBLICATIONS AND PRESENTATIONS

1 June 1972 to 31 December 1972

The 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.

Catmull, E., "A System for Computer Generated Movies" paper published in the Proceedings of the ACM Conference held at Boston, Massachusetts, August, 1972.

Christiansen, E.B. and Kelsey, S.J., "Nonisothermal Laminar Contracted Flow" paper published in the AICHE Journal, 713-720, July, 1972.

Christiansen, H., "Computer Graphics Application and Instructional Mechanics" talk given at the Naval Civil Engineering Laboratory at Port Hueneme, California, July 21, 1972.

Christiansen, H., "Computer Graphics Application and Instructional Mechanics" talk given at the Naval Undersea Center at San Diego, California, July 24, 1972.

Christiansen, H., "Computer Graphics Application and Instructional Mechanics" talk given at the Naval Undersea Center at Pasadena, California, July 25, 1972.

_______________, "Computer Graphics Application and Instructional Mechanics" talk given at Ford Motor Company, Dearborn, Michigan, August 21, 1972.

_______________, "Computer Graphics Application and Instructional Mechanics" talk given at Lawrence Livermore Lab, Livermore, California, October 20, 1972.

DeBry, R. and Greenfield, H.S., "Treatment of Arbitrarily Curved Surfaces in Nemodynamic Studies by Computer Graphics" Proceedings of the 1st USA-Japan Computer Conference, Hitachi Press, Tokyo, Japan, 597-604, 1972.

Greenfield, H.S., "Use of Graphic Terminal Device for Distributed System Simulation Studies in Hemodynamics" Chapter 7 in Computer Techniques in Biomedical Engineering, Automedica Publishers, 1972.

_______________, and DeBry, R., "Interactive Graphic Representation of Hemodynamic Phenomena" published in the Proceedings of the International Conference on On Line Interactive Computers (edited by R.D. Parslow and R.E. Green), 1972.

_______________, "Simulation of Prosthesis Components" special lecture at the University of Strathclyde, Glasgow, Scotland, August 26, 1972.

_______________, "Simulation of the Human Heart and Its Sub-System, the Heart Valve" speech at the International Congress, Cybernetics, Queens College, Oxford University, August 29, 1972.

_______________, "Interactive Graphic Representation of Hemodynamic Phenomena" two lectures given at Brunel University, Uxbridge, England, September 5-6, 1972.

_______________, "PDP-9 and PDP-10 Usage for Special Medical Simulations" talk given at the Royal College of Surgeons, London, England, September 9, 1972.

_______________, Interview on BBC Radio for program "Science in Action", London, England, September 10, 1972.

_______________, Interview on BBC-1 Television for program "Science and Technology", London, England, September 10, 1972.

_______________, "Blood Flow Simulation" lecture presented at the ACM Computer Graphics Workshop, Anaheim, California, December 5, 1972.

Greenfield, H.S., Participant in Round Table discussion "The Computer's Use in Medicine", Science and Society, KUED Television, Salt Lake City, Utah, November 1972.

Hearn, A.C., "An Improved Non-modular Polynomial GCD Algorithm" published in the SIGSAM Bulletin, ACM, New York, 23, 10-15, 1972.

__________, "Use of REDUCE via the ARPANET" demonstration at the ACM National Meeting, Boston, Massachusetts, August 13-17, 1972.

__________, "Use of REDUCE via the ARPANET" demonstration at the ICCC Meeting, Washington, D.C., October 19-26, 1972.

Hicks, G., "Measurement and Post Costs for Transmitting Network Data" paper for the Network Information Center (NIC), #11584, October 12, 1972.

__________, "Utah's File Transfer Program" project shown to the ICCC Conference, Washington, D.C., November 1972.

__________, "User FTP Documentation" paper for the Network Information Center (NIC), #12404, December 14, 1972.

Kay, K.R., "The PLEX Facilitators" (Internal document, not for further publication).

Kelsey, S.J., "The Application of Quasilinearization to Nonlinear Systems" presented at the 73rd National Meeting of AICHE, Minneapolis, Minnesota, paper S4a, August 1972.

Loos, R., "Analytic Treatment of Three Similar Fredholm Integral Equations" published in the SIGSAM Bulletin, ACM, New York, 21 32-40, 1972.

__________, "Algebraic Algorithm Descriptions As Programs" published in the SIGSAM Bulletin, ACM, New York, 23, 10-15, 1972.

Parke, F., "Computer Generated Animation of Faces" paper published in the Proceedings of the ACM held at Boston, Massachusetts, August, 1972.

__________, "Computer Generated Animation of Faces" presentation to the National ACM Conference held at Boston, Massachusetts, August, 1972.

Stockham, T.G., Jr., "Image Processing in the Context of a Visual Model" published in the Proceedings of the IEEE, July, 1972. (Digital Signal Processing).

__________, "Image Processing in the Context of a Visual Model" talk at a short course entitled Computer Processing and Recognition of Two Dimensional Images, University of Southern California, Los Angeles, California, July 1972.

Stockham, T.G., Jr., "Enrico Caruso Revisited -- Digitally" talk at the Center for Advanced Computation, NASA Ames Research Center, San Francisco, California, August 1972.

Sutherland, I. "Computer Graphics" talk given at Yale University, New Haven, Connecticut, October 31, 1972.

Ting, D. and Greenfield, H.S., "Spline Function Interpolation in Interactive Hemodynamic Simulation" published in the International Journal of Man-Machine Studies, 4:256-269, 1972.

Vickers, D., "Sorcerer's Apprentice: Head-Mounted Display and Wand" a paper presented at the First National Conference on Remotely Manned Systems, California Institute of Technology, Pasadena, California, September 13-15, 1972.

__________, "Interaction Using Sorcerer's Apprentice" a movie presented at the First National Conference on Remotely Manned Systems, California Institute of Technology, Pasadena, California, September 13-15, 1972.

__________, "Sorcerer's Apprentice: Head-Mounted Display and Wand" Ph.D. dissertation presented at the University of Utah, Salt Lake City, Utah, November 3, 1972.

__________, "Sorcerer's Apprentice: Head-Mounted Display and Wand" a paper presented at the Symposium on Visually Coupled Systems, sponsored by AFSC, Brooks Air Force Base, San Antonio, Texas, November 9, 1972.

BIBLIOGRAPHY

1. Cole, Edwin Randolph, "The Removal Of Unknown Image Blurs by Homomorphic Filtering," Technical Report pending.

2. Davidson, M.L., "Perturbation Approach to Spatial Brightness Interaction In Human Vision," Journal of the Optical Society of America, Vol. 58, pp. 1300-1308, September 1968.

2. Stockham, T.G., Jr., "Image Processing In The Context Of A Visual Model," Proceedings of IEEE, July 1972.

3. Baudelaire, Patrick, "Digital Picture Processing And Psychophysics: A Study of Brightness Perception," Ph.D. Thesis, Technical Report pending.

4. Miller, Neil J., "Filtering Of Singing Voice Signal From Noise By Synthesis," Technical Report pending.

5. Oppenheim, A.V., and Schafer, R.W., "Homomorphic Analysis Of Speech," IEEE Trans. Audio and Electroacoustics, Vol. AU-16, pp. 221-226, June 1968.

6. Zue, V., "Translation of Divers' Speech Using Digital Frequency Warping, "Research Lab. of Electronics, M.I.T., Cambridge, Mass., Quart. Progr. Rept. 101, pp. 175-182, April 15, 1971.

7. Stockham, T.G., Jr., "The Application Of Generalized Linearity To Automatic Gain Control," IEEE Trans. Audio and Electroacoustics, Vol. AU-16, pp. 267-270, June 1968.

8. Call, Duane B., Reference Manual PDP-10 QED, University of Utah, March 16, 1969.

9. Hearn, Anthony C., "Application Of Symbol Manipulation In Theoretical Physics," CACM 14 (1971), pp. 511-516.

10. Riley, Wallace B., "Through A Glass, Lightly," Electronics, Vol. 42, No. 25, p. 174, 1969.

11. Sutherland, Ivan E., "A Head-Mounted Three-Dimensional Display," Proceedings of the Fall Joint Computer Conference, Vol. 33, pp. 757-764, 1968.

12. Sutherland, Ivan E., "A Head-Mounted Three-Dimensional Display," Proceedings of the Fall Joint Computer Conference, Vol. 33, pp. 757-764, 1968.

13. Vickers, D.L., "Head-Mounted Display Terminal," Proceedings of the IEEE 1970 International Computer Group Conference, Washington, D.C., pp. 270-277, June 1070.