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MAN-MACHINE COMMUNICATIONS

Thomas Stockham, Jr., et al

Utah University

Prepared for:

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The objective of the research effort reported herein has the development of computers and computing techniques that aid people in some areas not traditionally subject to the application of computers.

The computer graphics effort has developed computing techniques and original computer components to accomplish the realistic display of mathematically described, three-dimensional objects. Although the primary emphasis was in the display of solid objects (e.g., computer generated television

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) images) some effort was devoted to the more traditional, line-drawing graphics as an interactive aid to the programming and operation of large computer processes---ranging from 3-D display problems to a study in the fluid dynamics of blood.

The waveform processing effort, which has grown and continues under a subsequent contract, has used a digital computer not only for direct results, in the form of processed image and audio waveforms, but also for the simulation of new techniques (e.g., vocoding) which show promise of relatively inexpensive implementation in special purpose hardware.

The symbolic computation effort has produced and is continuing to improve, maintain and distribute a programming language and subsystem, REDUCE, which is of aid in the extremely complicated algebraic manipulation encountered, among other places, in theoretical physics. This subsystem was designed to be minimally machine dependent and has been transferred to a number of different machines, primarily via the ARPA Network.

MAN-MACHINE COMMUNICATIONS

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PUBLICATION REVIEW

This technical report has been reviewed and is approved.

RADC Project Engineer

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SUMMARY

The objective of the research effort reported herein was the development of computers and computing techniques that aid people in some areas not traditionally subject to the application of computers.

The computer graphics effort (Section A) has developed computing techniques and original computer components to accomplish the realistic display of mathematically described three-dimensional objects. This effort has produced not only reports, photographs and motion picture films, but it has also engendered a "spin off" company producing similar devices and techniques. Although the primary emphasis was in the display of solid objects (eg., computer generated television images), some effort was devoted to the more traditional line-drawing graphics as an interactive aid to the programming and operation of large computer processes --- ranging from 3-D display problems to a study in the fluid dynamics of blood.

The waveform processing effort (Section B), which has grown and is continuing under a subsequent contract, has used a digital computer not only for direct results in the form of processed images and audio waveforms, but also for the simulation of new techniques (eg., vocoding) which show promise of relatively inexpensive implementation in special purpose hardware.

The symbolic computation effort (Section C) has produced and is continuing to improve, maintain and distribute a programming language and subsystem, REDUCE, which is of aid in the extremely complicated

algebraic manipulations encountered, among other places, in theoretical physics. This subsystem was designed to be minimally machine dependent and has been transferred to a number of different machines, primarily via the ARPA Network.

SECTION A

COMPUTER GRAPHICS

A.1 Computer Graphics Techniques

Graphics research began at Utah under David C. Evans with the radical notion that one could produce pictures of dynamic three-dimensional computer modeled objects that were:

1. Shaded realistically like photographs rather than mere line drawings.

2. Opaque (i.e. with obscured parts removed).

3. In perspective and color.

4. In real-time motion (i.e. at 30 frames per second).

At the Beginning, these objectives were very far from possible. There were only two known programs for removing hidden lines (Roberts' and Weis'), each of which produced line drawings but consumed 5 to 20 minutes of computing time for each frame produced. The Utah research has realized all of these early notions as well as some others. Furthermore, the achievements of major practical importance have been realized together.

A.1.1 Graphics Algorithms and Shading

The major graphics results have been:

1. The Algorithm of Romney et al. --- This research demonstrated that the incremental computing techniques proposed originally were sound. It dealt only with triangles, but it revealed the basic techniques which have since become better understood. Romney's thesis describes at great length a mechanism for assembling three-dimensional objects out of basic shapes using a semi-interactive environment. Romney's efforts also include a first try at utilizing the notion of "scan-line-coherence" which Watkins later showed to be a key to simple hidden line processing.

2. The Warnock Algorithm --- This research introduced an entirely novel approach to the hidden surface problem, that of using non-deterministic algorithms. Instead of progressing through the picture in a systematic way, Warnock's program progressed from area to area of the picture in a way determined by the picture content. Thus, Warnock's program could quickly develop large areas of the picture that were comparatively simple but would spend considerably more time working out details of the complicated areas of the picture. This was a fascinating computing technique which, at the time, seemed to be highly promising. However, statistics compiled at the Evans and Sutherland Computer Corporation showed typical picture complexity was sufficiently great to warrant near abandonment of Warnock's approach. An example of the Warnock algorithm output is presented in Figure A1.

3. The Watkins Algorithm --- Watkins' algorithm returned to the systematic scan-line by scan-line approach used earlier by Romney, et al, but made full use of "scan line coherence" (the fact that relatively little change occurs between any one scan line and the next). Watkins also made good use of the clipping techniques developed by Sutherland. These techniques, developed earlier at Harvard, quickly perform the depth comparisons required for deciding which of two surfaces obscures the other. Watkins developed extensive statistics showing that his algorithm, if implemented in hardware, could be expected to produce remarkably complicated pictures in real time. The novel components of such hardware have now been assembled and are in regular use at the University of Utah.

4. The Smooth Shading of Gouraud --- Although the surface dimension of objecte may be modeled accurately using plane polygonal modeling elements, computer generated images of these models had flat faces or facets which marred the representation of curved objects. This problem was caused by the shading discontinuities at modeling element edges. Human vision is particularly sensitive to such discontinuities. Gouraud developed and improved shading techniques still employing the simple linear ehading interpolation of Watkins, which greatly reduced this visual problem. Image quality was thus improved without increasing the complexity of computation. Examples of Gouraud ehading are presented in Figures A1 through A3.

5. The Improved Shading and Highlighting of Bui-Tuong Phong --- Through the use of a greatly improved physical model of the scattering and reflection of incident light at a surface, Bui-Tuong Phong developed algorithms which further reduced the shading discontinuities of curved surface models and also provided realistic highlights, the shape of which is not dependent on the details of the local model structure. He also developed a hardware design for realizing the improved shading at a reasonable cost in real time. Pictures made by this technique are the most realistic produced to date. Examples of Phong shading appear in Figures A1, A3 and A4.

6. Real Time Multiple Position Input by Burton --- Techniques for the input of a single position in space have been in existence for some time, some of which have been implemented at the University of Utah. The requirement for measuring the positions of many points, without cumbersome assemblies of levers and wires, led to the development of the "Burton Box". This device is able to measure the positions of 60 light-emitting diodes (LED's) 30 times per second. Uses of the Burton Box include: interactive work with the Head-Mounted Display, the LED's being attached to gloves worn by the user; motion studies where the LED's are attached to the object in motion, e.g., a human being walking; and object recognition research whereby an electromechanically deflected laser is used to scan an object, the position of the moving spot of light on the object being measured by the Burton

Box.

7. The Visual Communication System of Wessler --- Techniques to assist in the production of shaded picture animated movies are the subject of continuing development. This has involved the acquisition of an optical bench with high precision display and computer controlled animation camera. Wessler has developed a software system which greatly facilitates the specification and motion of dynamic scenes. This system removes much of the drudgery associated with animation and allows the user to concentrate on the content and presentation of his production.

8. The New Clipping-Divider of Blanchard --- The real-time line drawing system has been almost completely rebuilt using modern logic and techniques. Difficulties in acquiring a clipping-divider led to the decision to build one in-house. This device, which uses a new algorithm developed by Blanchard and Newell, is expected to be operational early in 1974.

Following the initial successes with algorithms for synthesizing pictures, the continuing research stimulated other research and was in turn influenced by the work of others.

One fundamental influence beginning in 1968 was the work of Thomas G. Stockham, Jr. whose models of visual perception provided insights which were important to understanding the essential qualities of pictures. These were acted upon by Warnock, Gouraud, and Bui-Tuong

Phong to make fundamental improvements in the modeling of curved surfaces, spectral reflection, and color. Further, Stockham's understanding of the photographic medium and his development and operation of a precision image display system was essential to the development of graphics technology.

Other important influencing efforts were the work of Ivan Sutherland in the development of equipment to produce dynamic perspective line drawings, and the work by William Newman on command languages for interactive graphics and the notions of how to program for interactive design.

An interesting ingredient of the Utah research has been the gathering together in Utah of researchers, system builders, and graphics users from other places. In addition to those already mentioned, Ronald D. Resch came from Illinois and has been able to achieve interesting results in computer aided designs through the use of Utah systems. The group has also been joined by Martin Newell of the Computer Aided Design Center in Cambridge, England and by Richard Riesenfeld, who is a leader in the mathematics of surfaces.

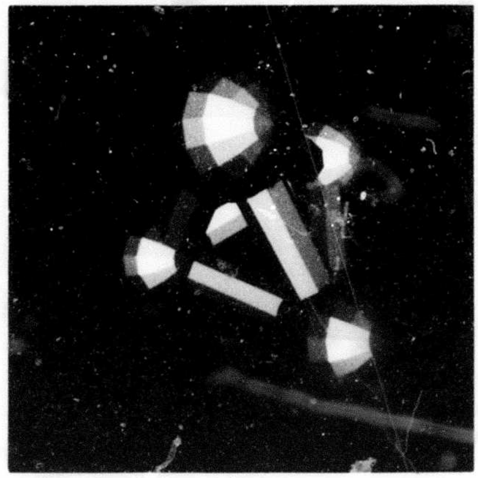
The Evans & Sutherland Computer Corporation has grown up with the Utah research community and has attracted distinguished system builders from industry. One of the functions it serves is the manufacturing of equipment which incorporates the ideas of the Utah research group. Through the efforts of ES, many applications of the newly developed technology have been made. There have already been a number of government and private applications of the research.

Simulation for pilot training is an immediate result of work done at Utah under ARPA sponsorship and the concurrent work sponsored by NASA at General Electric. The Air Force, Navy, and commercial airlines have radically reviewed their pilot training plans to increase the fraction of their training performed in simulators. The Air Force "ASUPT" program and the Navy "2F90" program include major state-of-the-art computer generated image systems. Research systems are installed at the Ames Research Center of NASA, the Air Force Flight Dynamics Laboratory, and the Naval Training Equipment Center. Many commercial airlines have computer generated image systems installed or on order for pilot training. The Maritime Administration has also contracted for a large simulator which includes a computer image generator. At the time the Utah and GE research was initiated there were no plans for any such systems. Such systems reduce the cost of training and increase the quality.

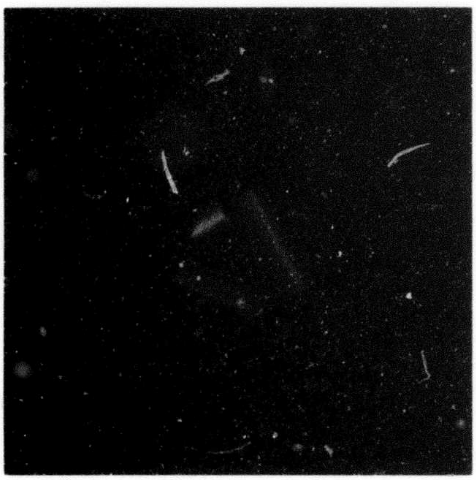
There are many interesting applications for dynamic simulation techniques in mechanical design. Dr. Henry Christiansen, a researcher on the Utah contract, is an expert in the finite element analysis of mechanical structures. During the past year he has used the new graphics technology to make motion pictures of the computed dynamic behavior of sonar transducers, under contract with the Naval Undersea Warfare Laboratory. There are many similar applications including aircraft and automotive design which have been stimulated by the research.

The Utah work has also influenced other activities including the solution of large scale radiation diffusion problems at the Los Alamos Scientific Laboratory, the design of artificial hearts, research in neurophysiology, research in biochemistry and underground mining. Furthermore, the book by Newman and Sproull, "Principles of Interactive Computer Graphics", published by McGraw-Hill in 1973, was based on a graphics course developed by Sutherland and was influenced by ideas developed and used at Utah.

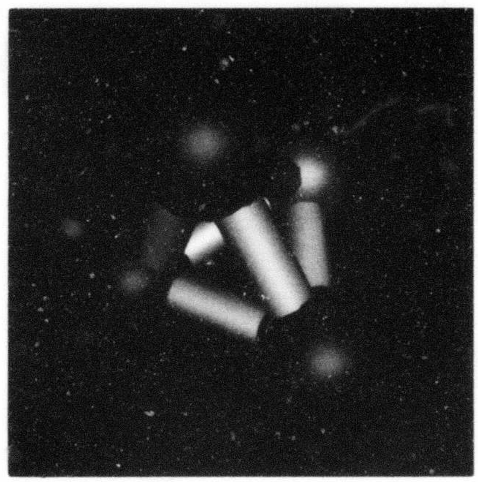
WARNOCK SHADING



WARNOCK SHADING WITH HIGHLIGHTING



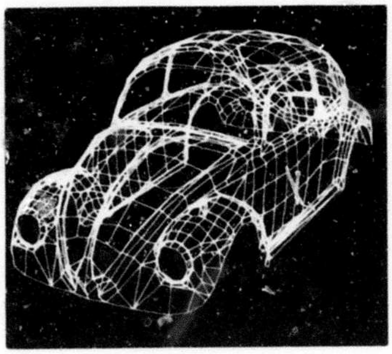
GOURAUD SHADING



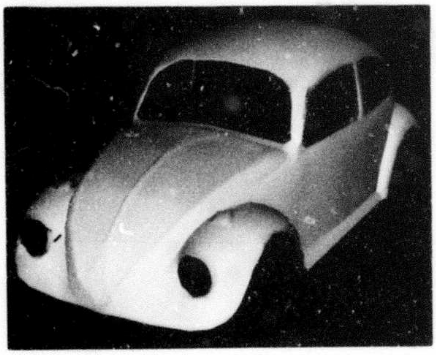
PHONG IMPROVED SHADING

Figure A1

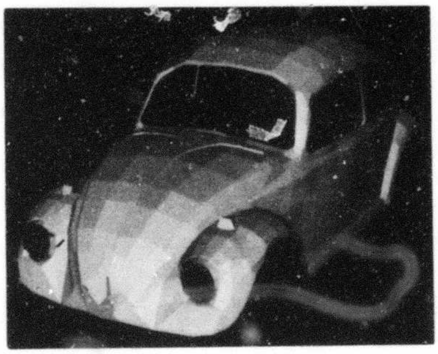
Molecule with Different Shading Techniques



CONVENTIONAL LINE DRAWING



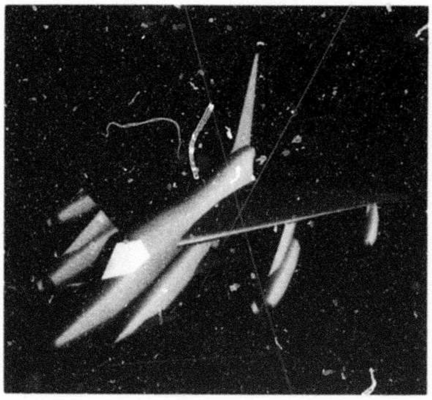
GOURAUD SMOOTH SHADING



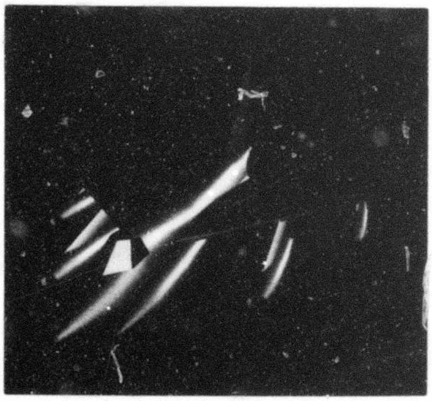
FACETED SHADING

Figure A2

Three Renderings of Same Subject Definition



B-58 WITH GOURAUD SHADING



B-58 WITH PHONG SHADING

Figure A3

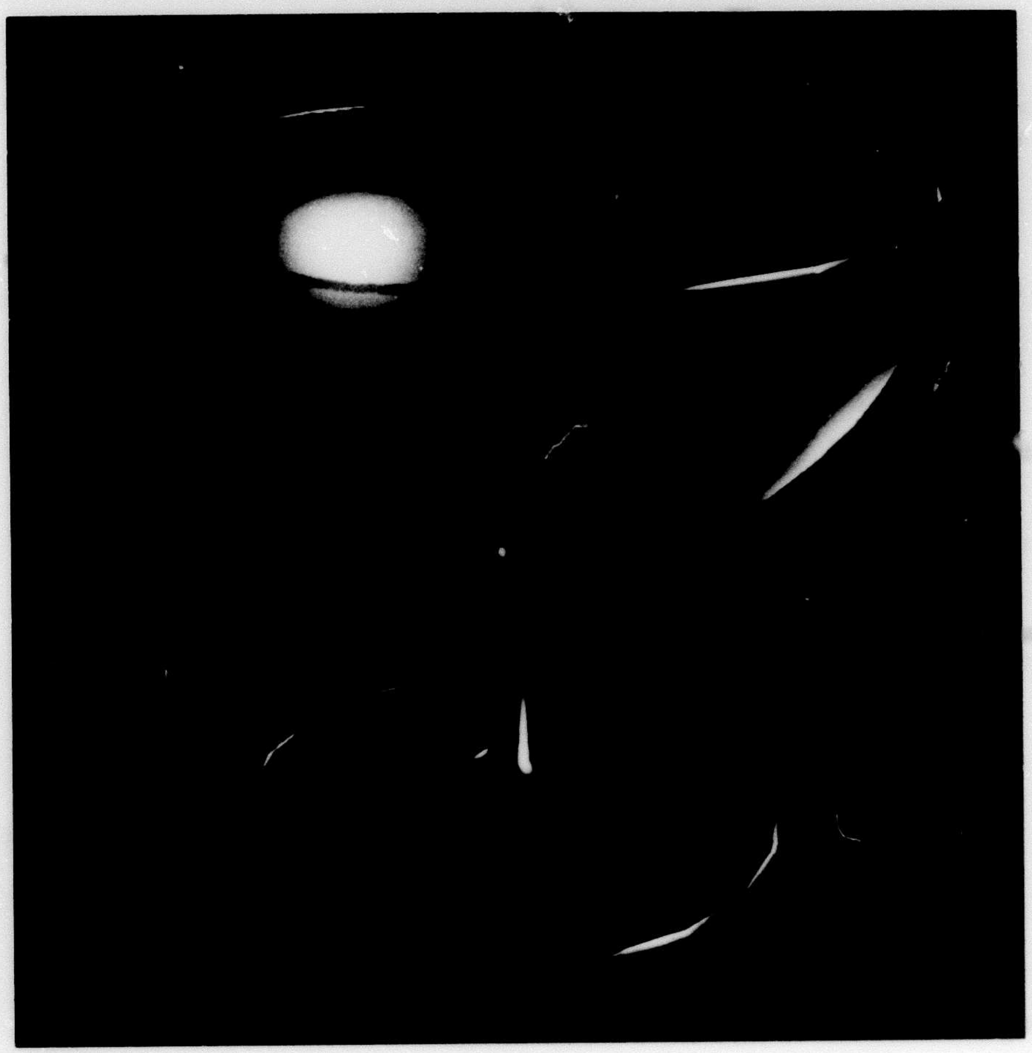


Figure A4

Transparent Cup with Phong Improved Shading

A.1.2 Smooth Edge Contours

This portion of the report is concerned with work done over the past 18-month period. The algorithm for displaying curved surfaces on a raster scan device has been developed as described in the following material. The outstanding feature, which differentiates this work from that of other researchers, is the production of smooth edge contours with cubic functions.

In this technique, the surface to be displayed is approximated by an arbitrary number of bi-variate cubic patches adjoined so that the mathematical description of the two patches is continuous in the first derivative. In other words, the surface is smooth in these locations. A mathematical technique has been developed for mapping the edge of a patch from rectangular three-dimensional real space into perspective three-dimensional screen space. In real space, the patch edge is described as a three-dimensional parametric cubic. In screen space, this edge is described as a difference equation in which x and z are determined functions of y. This latter requirement is necessitated by the fact that the display is on a raster scan device.

In previously developed algorithms for displaying surfaces, the problem of the silhouette edge has been troublesome. Since in these algorithms the surface is assumed to be made up of planar patches, the contour edge of a surface appears to be a series of connected straight line segments. A technique has been developed to provide smooth silhouette edges. The technique consists of identifying points where the patch edge disappears from view. A new patch edge is created, connecting two such disappearing points. This results in a new edge at the contour which is described by a three-dimensional cubic in rectangular space. This in turn, can be approximated by a number of short straight-line segments. The number of straight-line segments can be as large as required to give the desired smoothness.

A fast clipper for curved edges has been devised that takes advantage of Bezier control points. The advantage gained by this technique results from the fact that only rarely does one need to find the roots of a cubic.

These techniques have been incorporated into a program that implements the algorithm to the point that perspective three-dimensional line drawings of objects, with smooth edge silhouettes and correct clipping, can be obtained. The accompanying sample illustrations demonstrate the success of the algorithm. Figure A5 shows a sphere comprised of 6 patches, a sectiof of a right circular cylinder, a torus and a section of a human leg, to include the region from above to below the knee.

These techniques can be applied to current hidden surface algorithms to produce silhouette edges that are smooth. One should be alert to the possibility of frame-to-frame discontinuities when making motion pictures. It can be shown that attempts to smooth only contour edges will result in frame-to-frame discontinuities on the silhouette edges of an object as it changes position. These discontinuities could cause undesirable jitter in the edges of the pictured object. This research introduces the idea of the contour patch as contrasted with the contour edge to correctly solve the problem.

A more detailed description of the above developments will be issued at a later date.

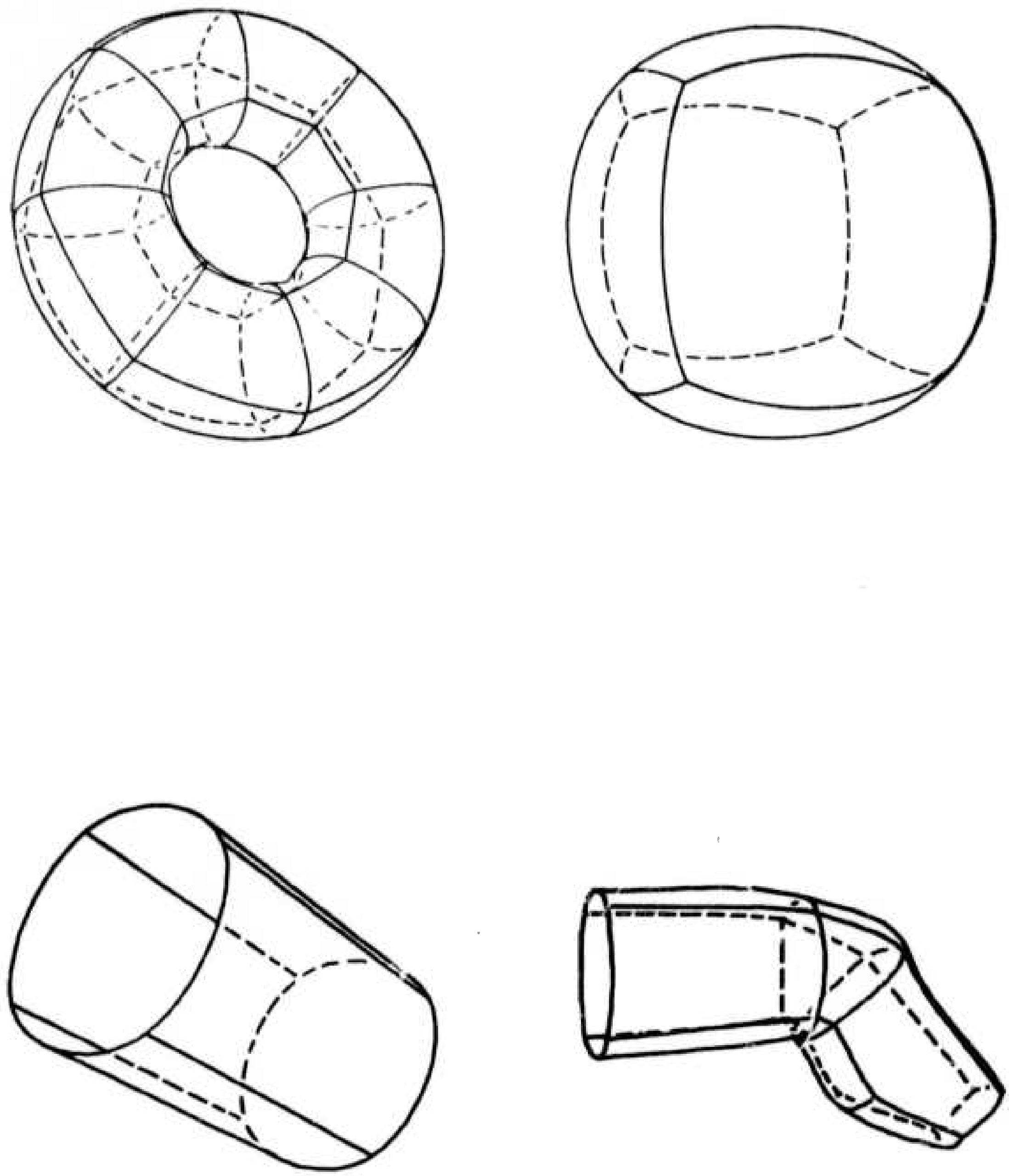


Figure A5

A.2. Computer Graphics Applications

A.2.1 Graphics in Structure Design

We have concentrated on the following applications to computer graphic techniques relative to three dimensional structures:

a. Computer Aided Design Techniques for 3D Structures --- We developed and are using a unique computer controlled 3D model building capability to study folded plate structures and variable geometry for finite element truss definition.

b. Computer Aided Analysis of Structures --- We developed improved techniques for visual presentation of stress analysis data.

c. We made further developments in the theory of Generic Design and numeric controlled manufacturing processes. The specific structures investigated are case studies of generic models.

d. We developed a generalized program for defining a special class of 3D structures which can be created from folded edges and developable surfaces.

Design of Folded Plate Structures. -- Every finite element approximation to a surface which is not developable, will require that the elements are continuously varying in their size and shape. We have been developing techniques which allow an approximation to any surface by a small number of identical modules.

These computer aided design techniques achieve a series of versatile structural systems which are capable of producing an infinite variety of enclosure shapes. These systems make possible the modular production of extremely elegant architectural shell forms.

Initial work in computer simulated structural analysis is complete on these systems. We are able to show, by computer simulated color photographs, the stress distribution throughout the structure. The value of this work is that a generic structural system has been created for use in the design, analysis and fabrication of unique and specific forms, such as domes, warped surfaces, or sculptural free-forms from a single, unified design, analysis, and production system. We have developed these versatile geometric systems by producing drawings, diagrams, and three dimensional models using computer assisted design techniques.

Under computer simulation one can continuously change the plate geometry (Figure A6), make a selection of a specific arrangement of plates and then continuously fold them for study and selection of some desired form of single curvature (Figure A7). The plates may also be folded to achieve an approximation to a doubly curved, or warped surface (Figure A8).

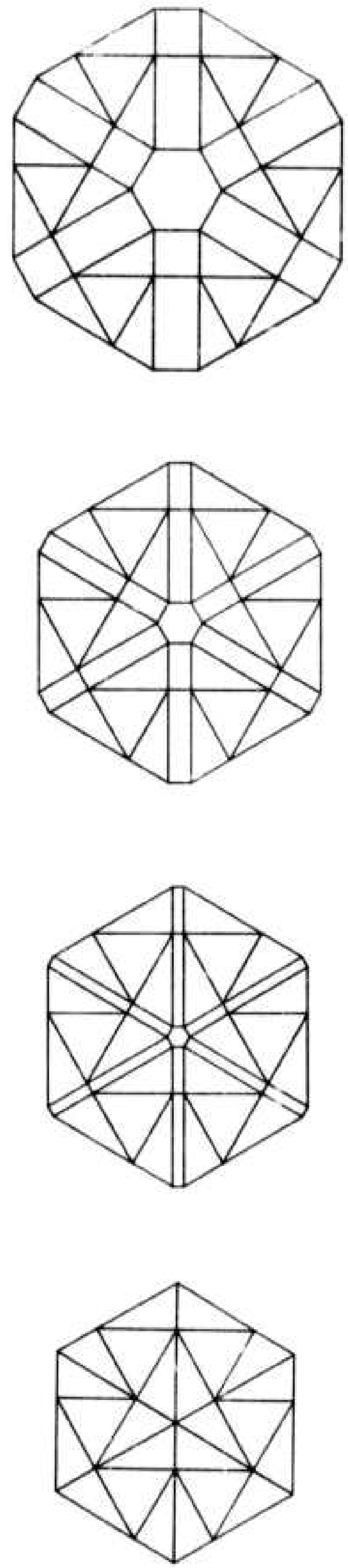


Figure A6

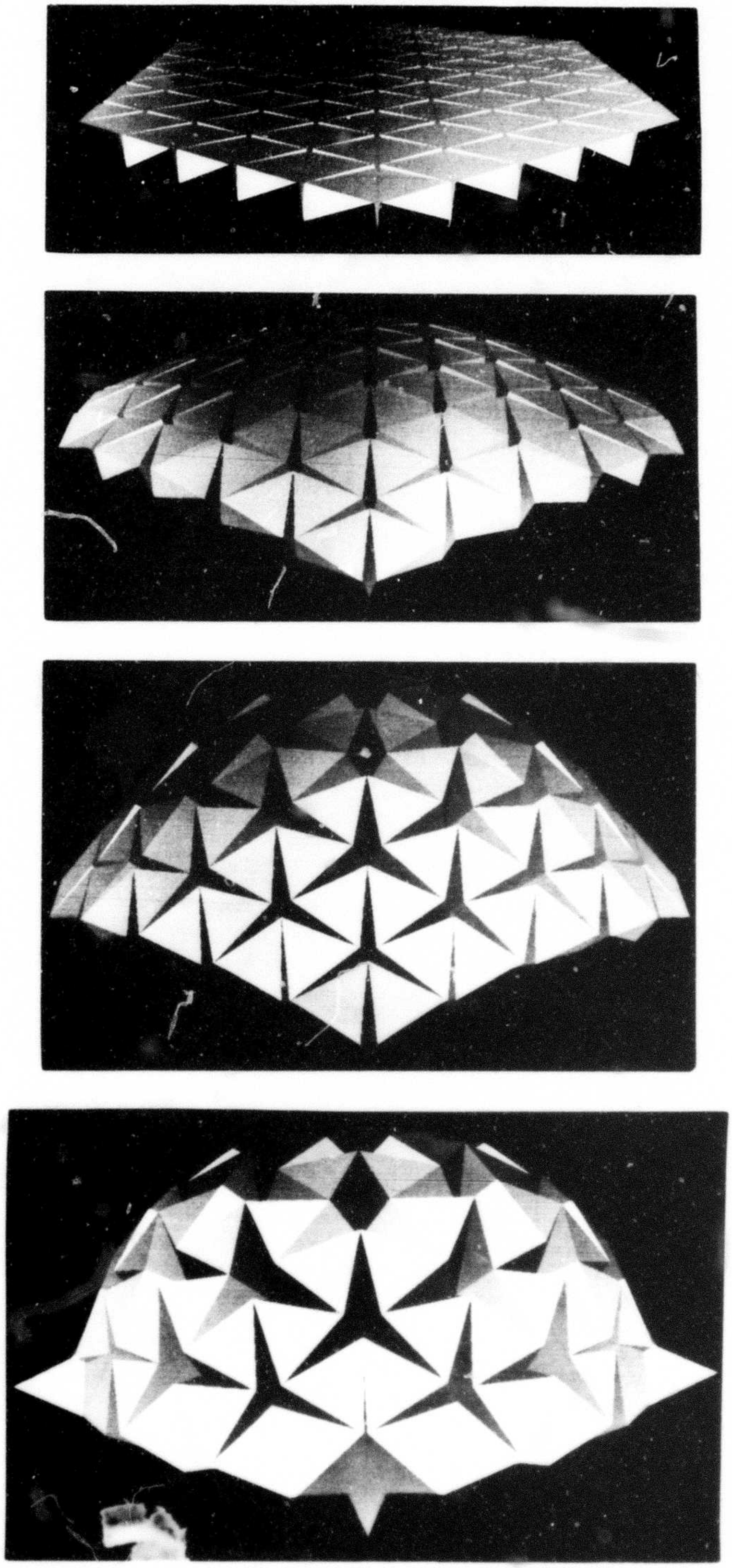


Figure A7

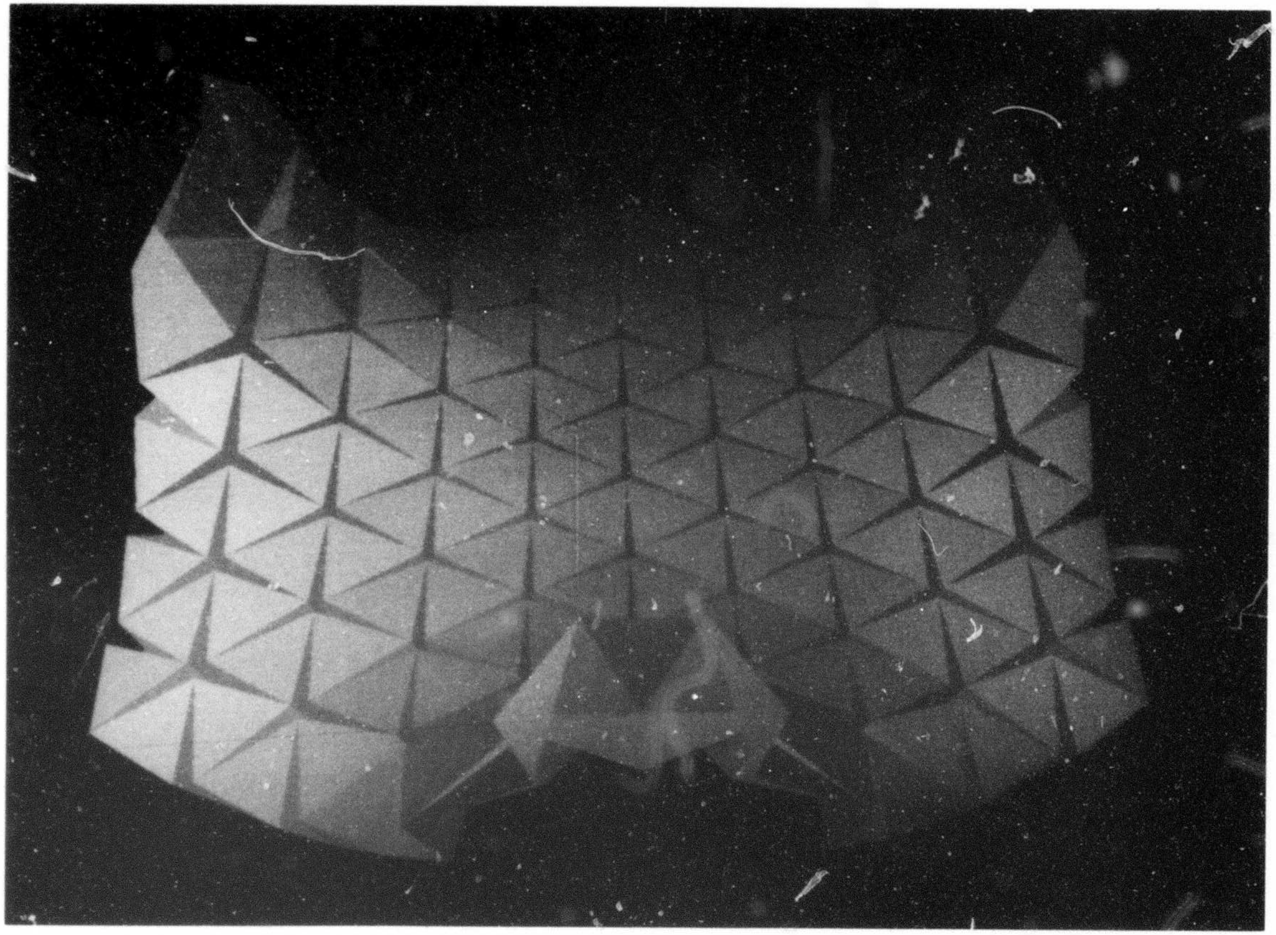


Figure A8

Folded Plate Structures/Analysis. -- We developed, with Dr. Henry Christianssn, a kinematic analysis program to analyze the dynamic behavior of folded plate systems. With the kinematic analysis in hand, the problem of structural analysis of folded plate geometries was considered. These folded plate systems, unlike almost every other, are not prismatic in their analysis.

A major problem in doing the structural analysis was in seeing the resulting data. Most folded plate systems are prismatic and their strains may be viewed as a two dimensional graph. The structural analysis of Resch's folded plate systems would give genuine 3D behavior which could not be represented in this fashion.

Therefore, there was developed an analysis display system which would utilize the Utah picture making capability. Here color and shading should not follow the usual rules of optics and physics, but would represent some analytical property of the structure. Such pictures could give the user an immediate qualitative understanding of the structural behavior from a complex structural analysis.

Octet Truss Program (Curved, Plate Truss Structure). -- Structures which require large, clear spans, such as airport hangers, are usually accommodated by the standard octet space truss. The current method of design and construction of these, however, is limited to a flat truss. There is an obvious need for clear span trusses which have some curvature. To achieve flexibility in the design and construction of such structures, we have developed a system to overcome this flat truss limitation. We have completed the computer program OCTET TRUSS. It allows the specification of any surface of revolution, it will construct the truss on top of that surface the depth of which may also be specified, and it will output a control tape for the creation of all the plates of the given structure.

Figure A9 is a photograph of actual models, showing the standard truss at the bottom, with two trusses of increasing curvature above.

Figure A10 is a photograph of an interior view of a model of the Curved, Plate Truss used as a dome.

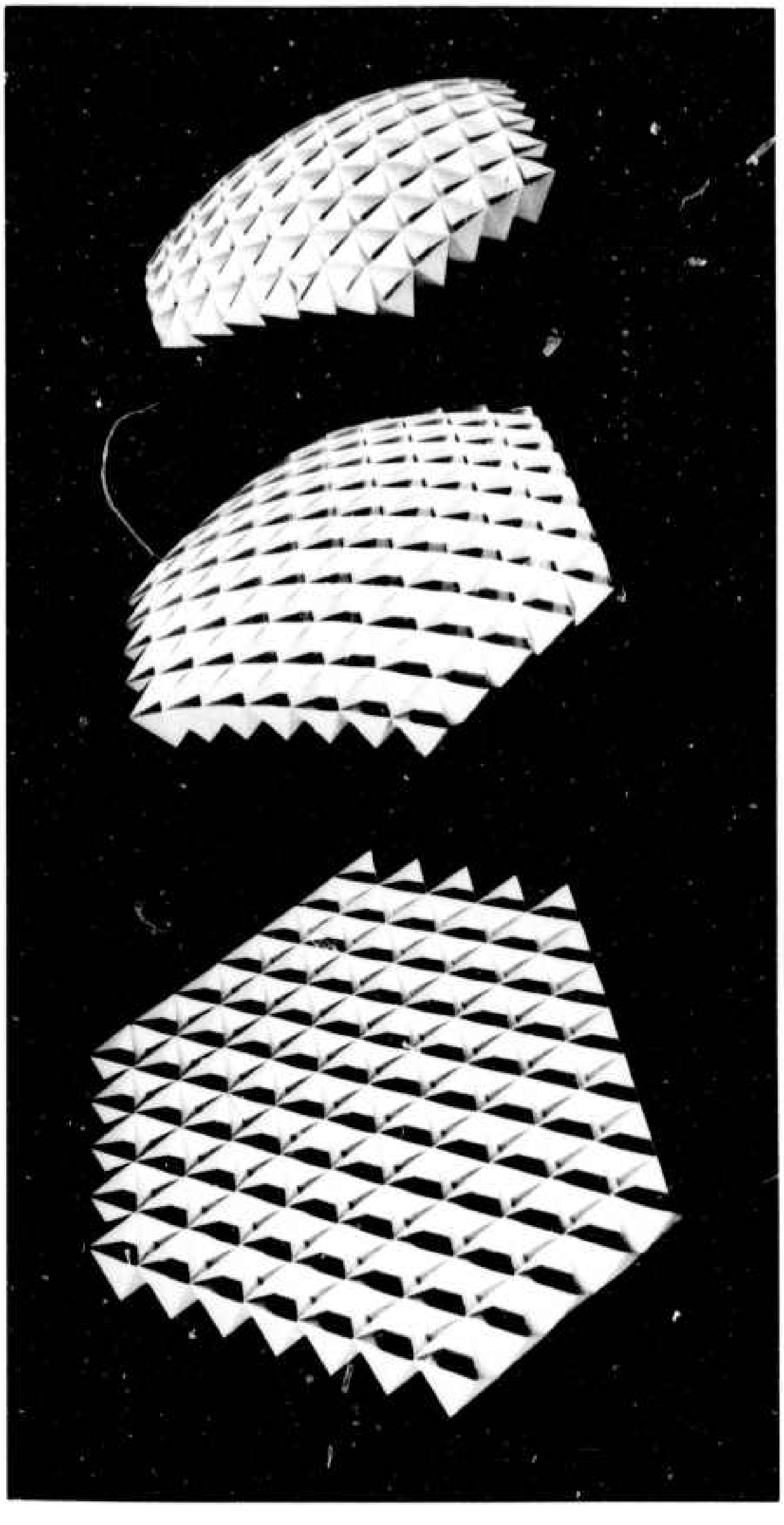


Figure A9

Figure A10

The Developable Surface Program. -- The aerospace industry has brought a growing need for strong, lightweight structures which require complex and precise geometric definition. The usual solution has been by costly numeric controlled milling of solid blocks to achieve these required structures. Our work has attempted to develop alternative inexpensive fabrication techniques to achieve computer defined space forms.

It is well understood that to fold a metal plate along a straight line strengthens it, and that bending it to some radius of curvature will increase its structural stability. We has observed that one can combine these two structural properties by introducing a curved, folded edge to a plate. From this basic structural observation we have created the DEVELOPABLE SURFACE PROGRAM to allow completely general design freedom. It was not at all apparent at the outset, however, that one could generalize a folded edge to any space curve. A thorough mathematical analysis revealed that such a generalization was possible.

The program requires:

1. An analytically defined space curve.

2. A function which describes the dihedral angle of fold at each point along the curve.

3. Functions which describe the width of each developable surface on either side of the curve.

Any of these three may be described explicitly as a function in Polish notation, or the system provides the capability for the user to define a small number of data points through which it will pass a spline curve, which can then be used for any of the above required inputs.

The execution of the program will provide a wide variety of outputs, including orthogonal, (Figure A11, plan), (Figure A12, elevation), perspective, (Figure A13) and stereoscopic (Figure A14) views of the space curve as a folded edge which defines developable surfaces. If the designer chooses to fabricate a model from the defined curve, the system computes the two dimensional score line (Figure A16) which must be traced out by a N.C. tool. The system will also calculate the intersection of a three dimensional model with a plane or other developable surface (Figure A16).

Of the many constructional problems that may be solved by developable surface construction, some applications may require reinforcing of the surface. While simply using a thicker metal plate might solve the problem, we have developed a lightweight solution which is the analog to the corrigated reinforced panel. Here the initial developable surface is transformed into an inner and outer developable surface, having constant separation. Corrigated developable surfaces may be placed between these in such a way that the corrigations contact the inner and outer surfaces along curves which are normal to their generator lines.

Using this concept, one can see that highways of complex bridge interchanges may be constructed. The roadway is a developable surface in space and the bridging under that surface may be considered a corrigation whose folded edges are space curves.

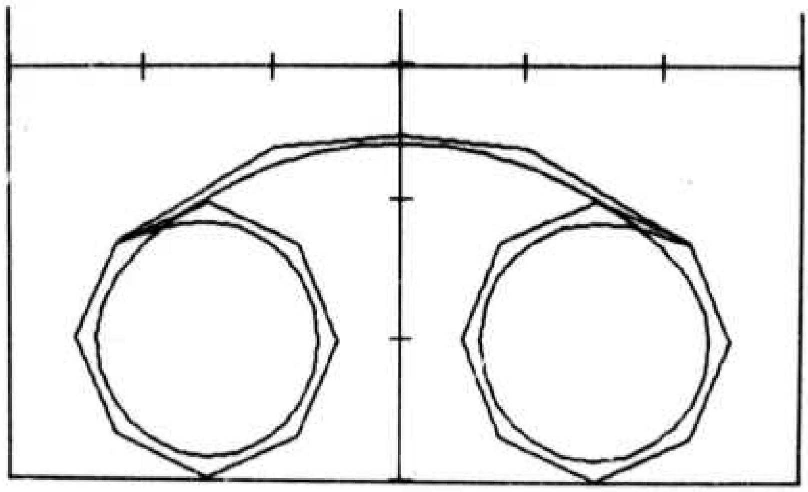


Figure A11

Polygon and Spline Curve XY View

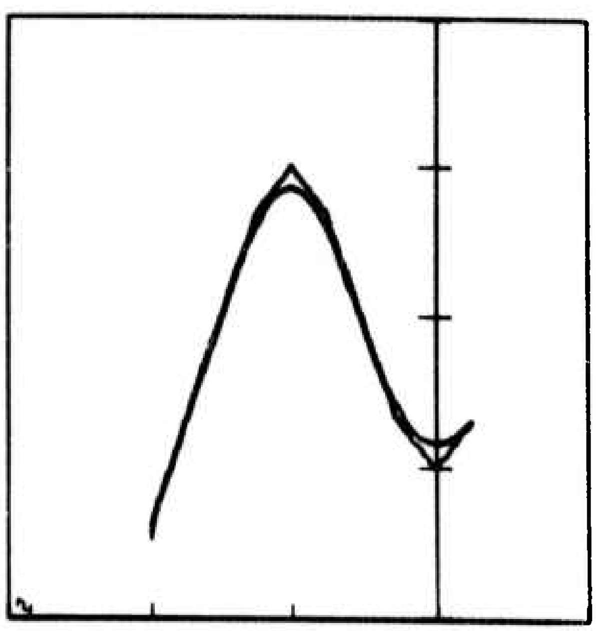


Figure A12

Polygon and Spline Curve XZ View

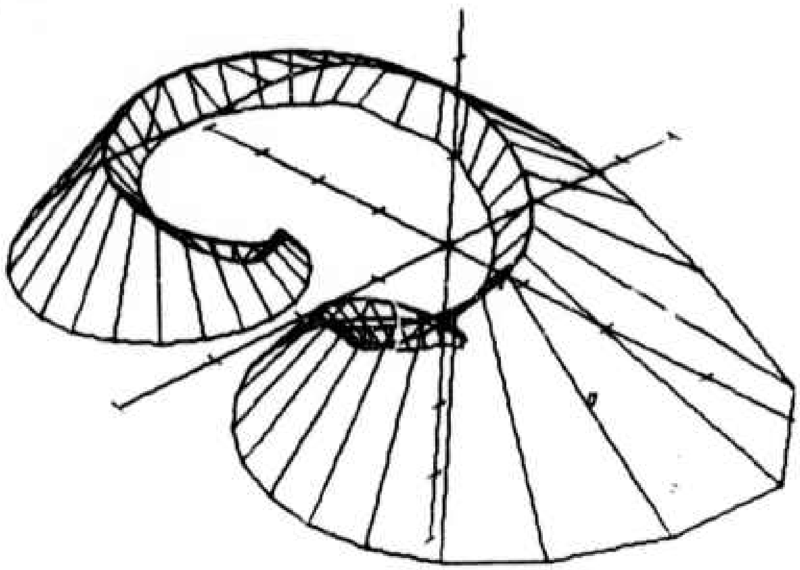


Figure A13

Developable Surface Perspective View

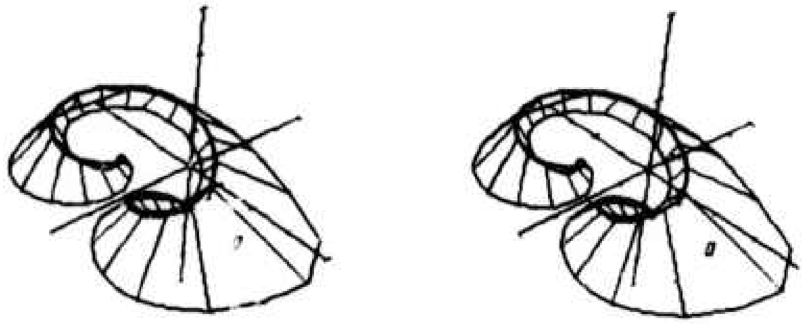


Figure A14

Developable Surface Stereoscopic View

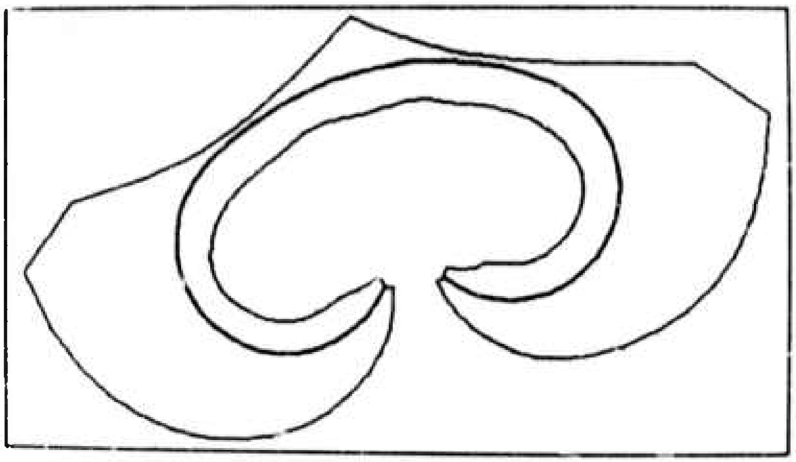


Figure A15

Developable Surface, Flat Plan

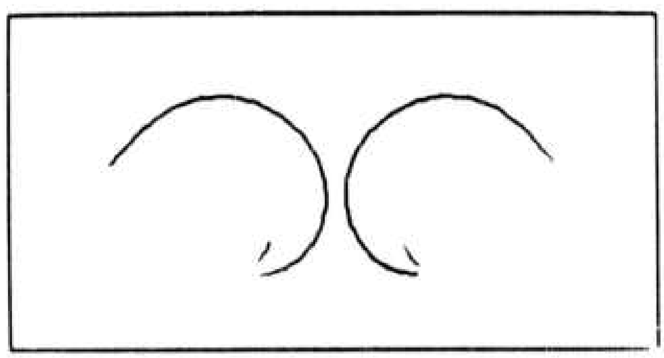


Figure A16

Developable Surface Intersection with Base

From this research we have developed generic and construction techniques which have the following potential applications:

- Dirigible
- Concrete formwork
- Lightweight gas tanks for airplane wings
- Liners for liquid natural gas tankers
- Geodesic torus for space stations
- Lightweight guideways for rapid transit monorails
- Lightweight complex bridge interchanges
- Solar energy reflectors

A controlled, curved surface, or pathway, can be achieved by declaring the space curve to be a folded edge defining two developable surfaces. This program makes the ordinarily difficult task of physical construction of a precise, complex space curve relatively simple and direct, using flat sheet materials and requiring limited joining. The following examples of computer simulated video pictures are typical forms created with the DEVELOPABLE SURFACE PROGRAM:

- Cylindrical helix from the side (Figure A17)
- Cylindrical helix from the bottom (Figure A18)
- Possible architectural application (Figure A19)
- Cylindrical helix
- Possible architectural application (Figure A20)
- Multiple cylindrical helix

An example of 3D spline curve in the construction of an architectural form with 120 degrees symmetry A comparison of Figures A21 and A13 demonstrates that without such shaded pictures the study, development and subsequent communication of unusual and complex architectural shapes would not be possible. It has been noted that one possible reason for the flat and rectangular structures which make up current architecture is a result of the fact that we have not had the tools to study and communicate anything not already known. In other words, "if an architect can't draw it, you can't build it."

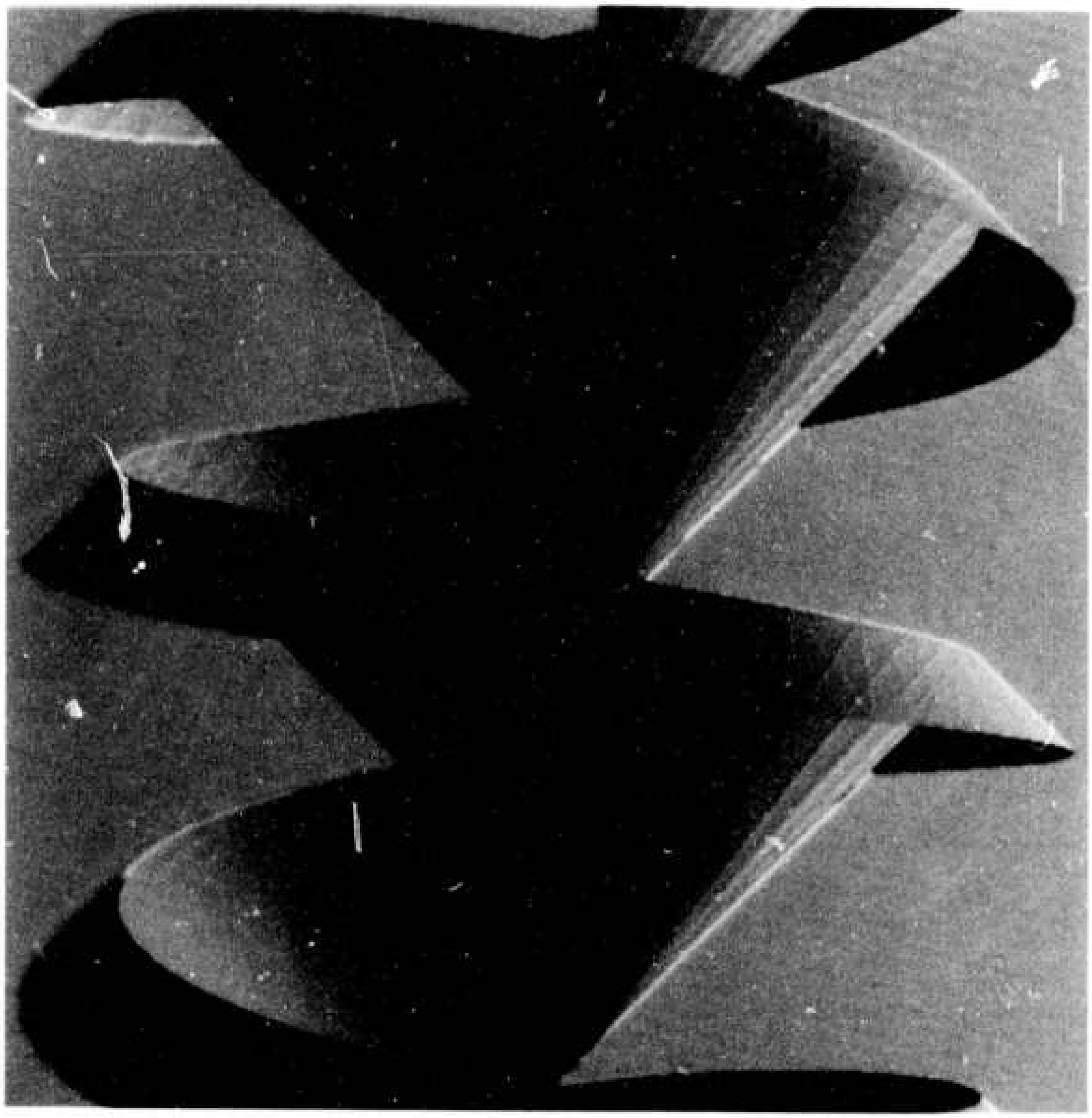


Figure A17

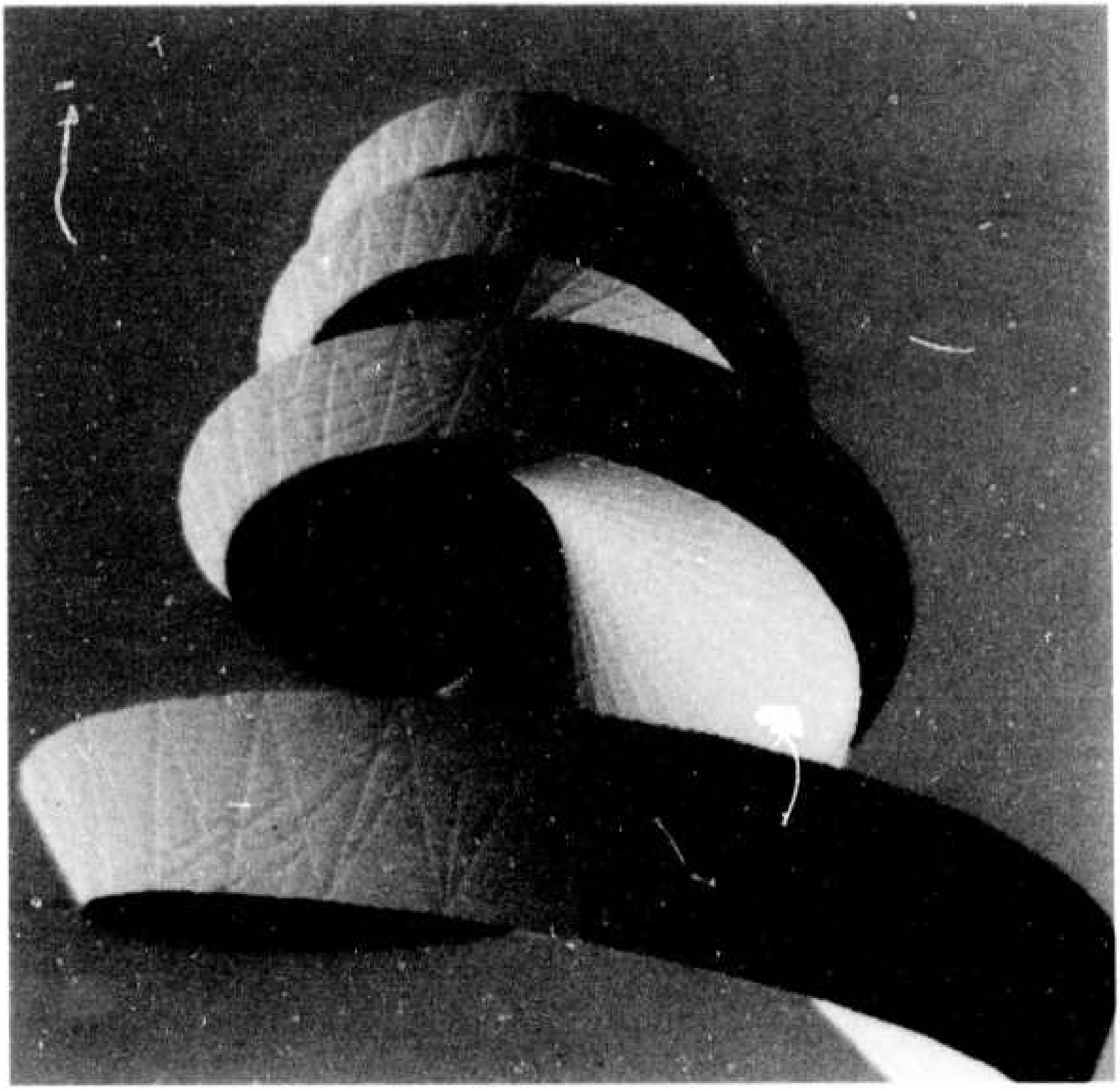


Figure A18

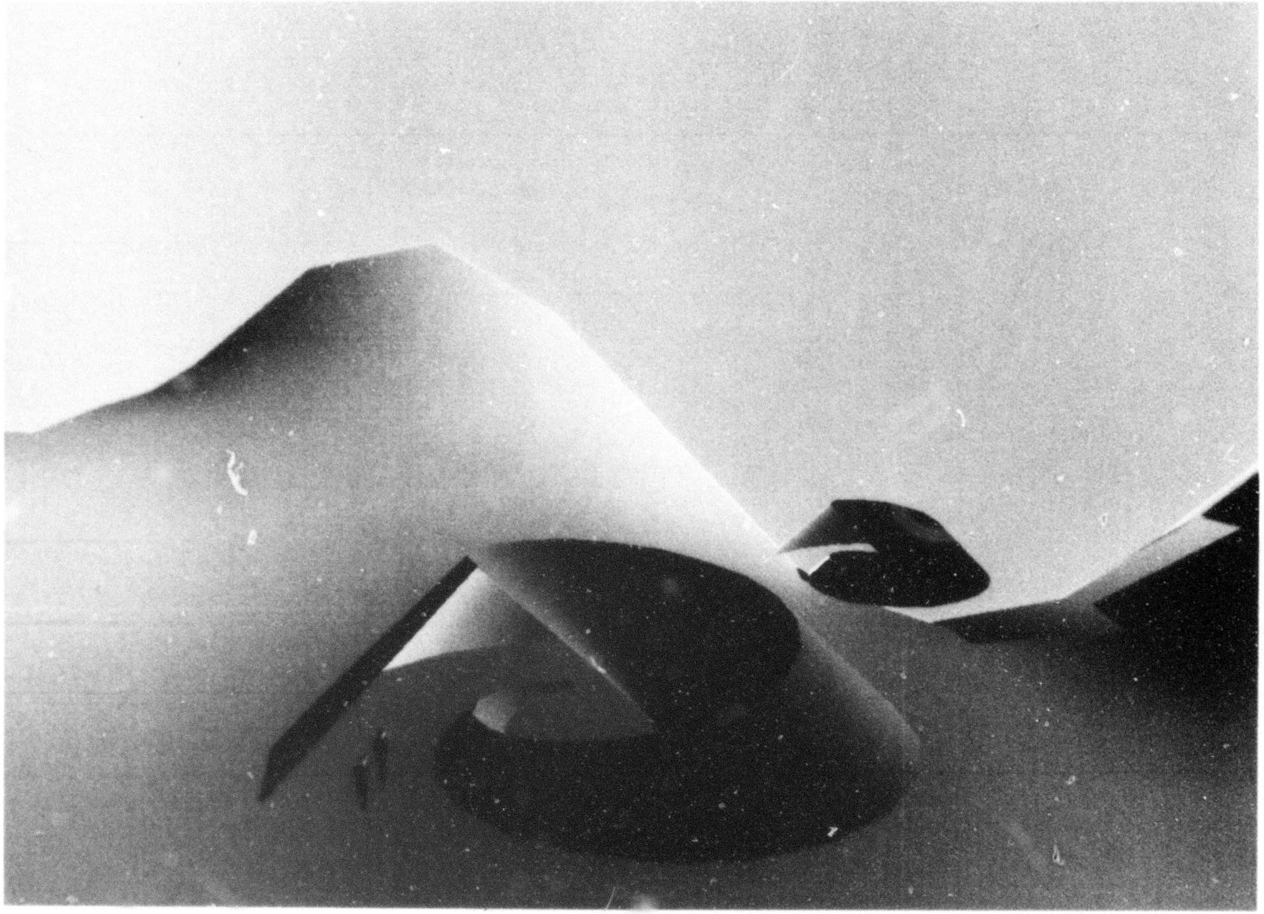


Figure A19

Figure A20

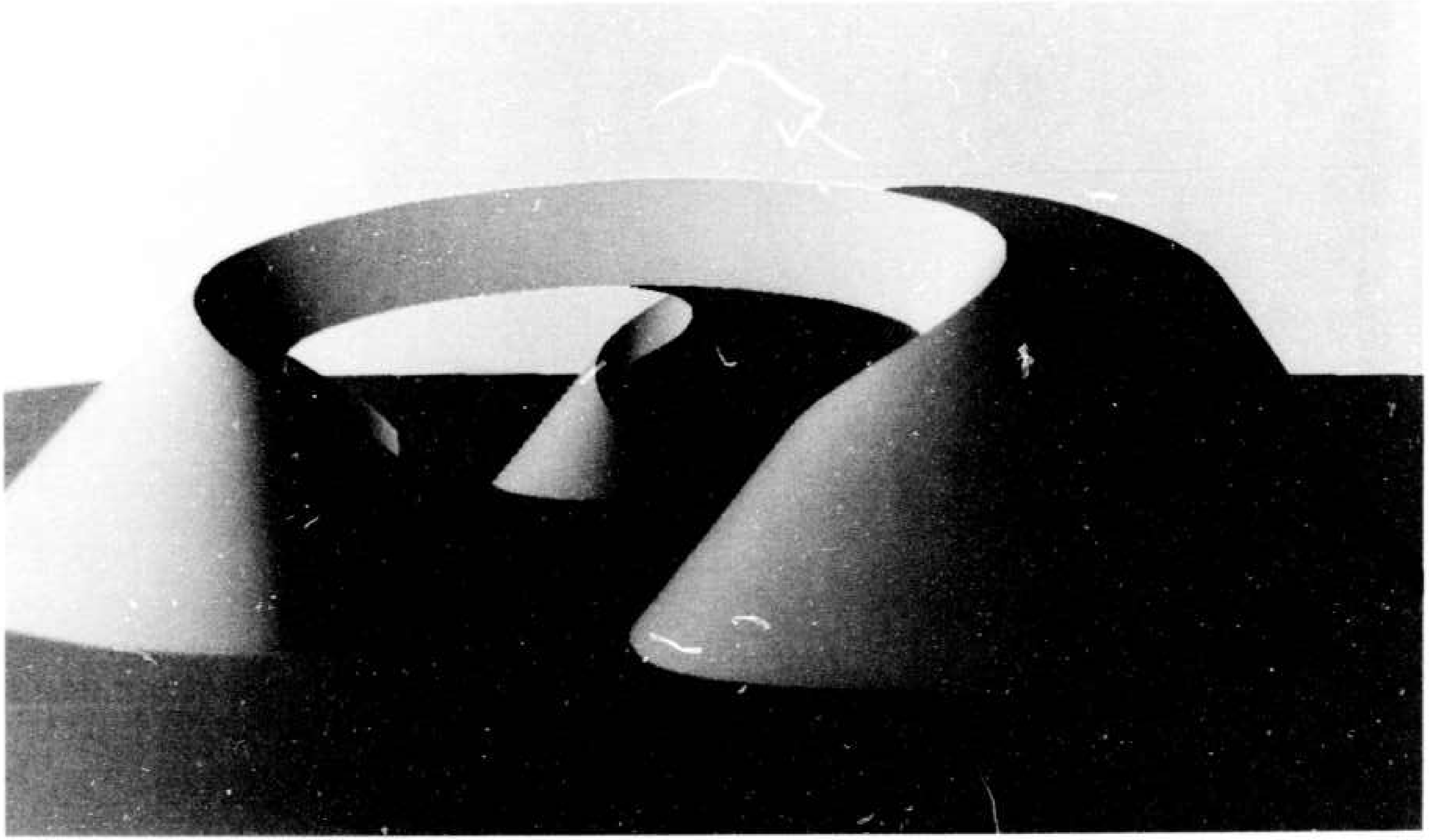


Figure A21

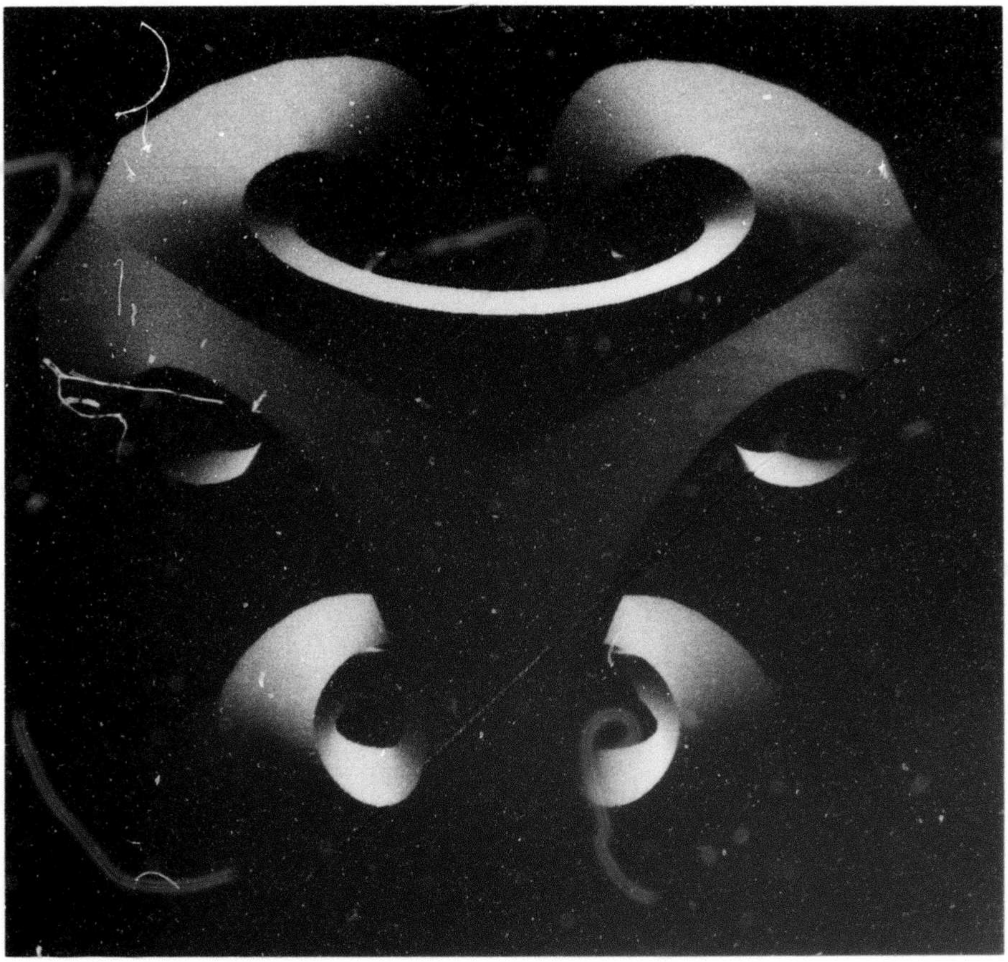


Figure A22

Ruled Surface Program (An Approximation to Warped Surfaces). -- This program constructs a triangular network in a zig-zag manner between the alternate points on two space curves. The curves are definable in the same ways as the curve in the developable surface program. The triangular network may be flattened out to form a flat network. N.C. tapes and pictures of this are available, as well as plots and display pictures of the three dimensional objects. Several networks may also be found and displayed at the same time.

Hyperbolic paraboloids have been extensively used in architecture because they are both elegant and structurally efficient. They suffer, however, from demanding difficult and expensive formwork. The RULED SURFACE PROGRAM allows us to directly build any hyperbolic paraboloid by triangular approximation. Figure A23 is an actual 3D model, not a simulated photograph, of a structure constructed from the output of the program.

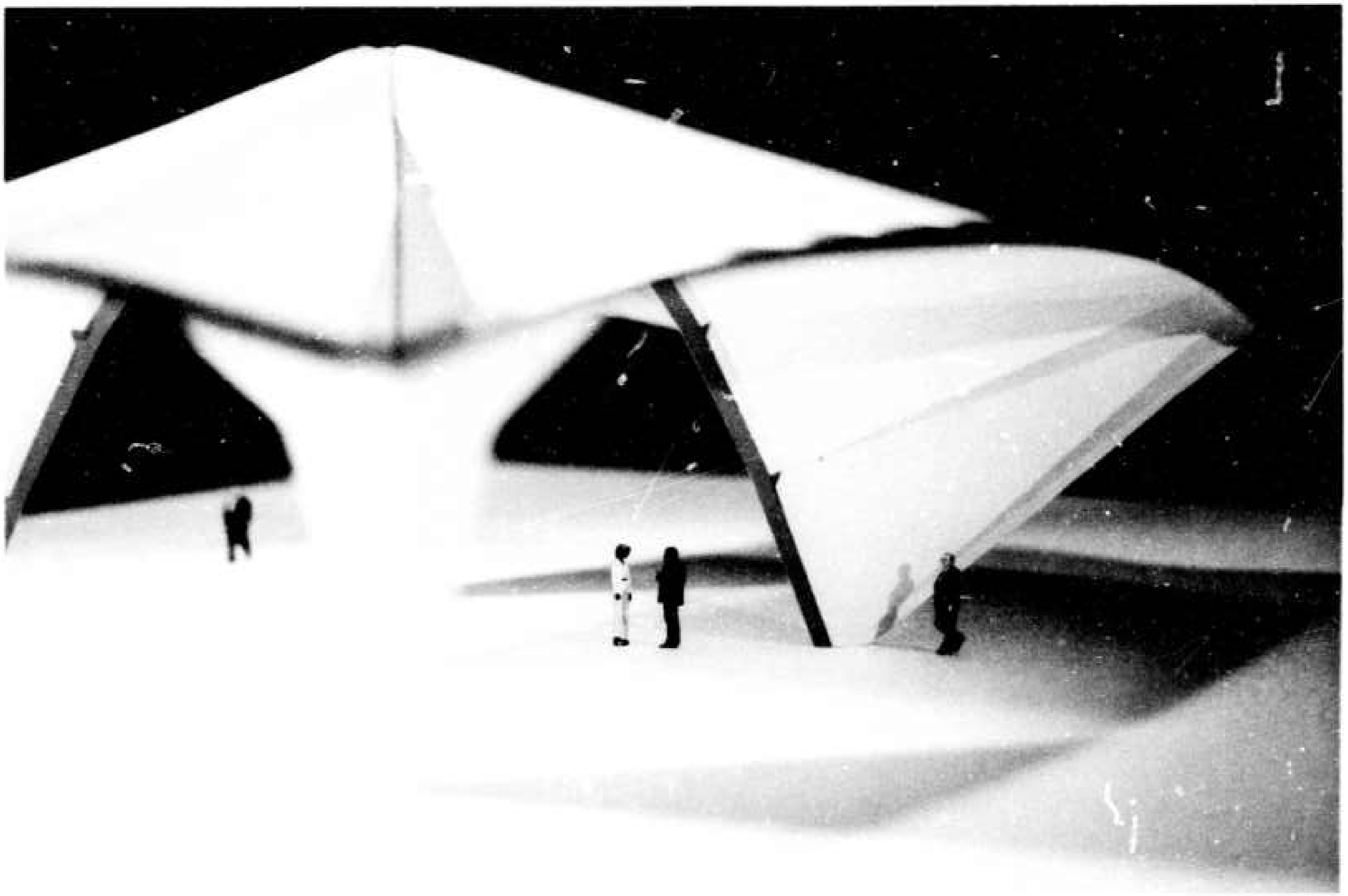


Figure A23

Modified Interpolating Splines. -- We have investigated interpolating splines of the form

$$S(t) = \sum_i X_i C_i(t)$$

where the C_i are piecewise cubic polynomials in t and have found conditions on such splines that allow us to specify that a particular knot be a maximum or minimum of the curve and to adjust the tightness of the curve.

In designing curved lines with splines, interpolating splines have a great conceptual advantage over those that do not interpolate, in that they are guaranteed to pass through their knot points. A designer trying to approximate a curve by a broken line will naturally select some points from the curve as the knots of the broken line, and will therefore want to require that the spline curve of that broken line pass through the knots.

Some well known disadvantages of interpolating splines are that they tend to form loops around knots where none are desired, and to eratically overshoot knots. These characteristics make interpolating splines much more twisted than their knot polygons, and is the major justification for using non-interpolating splines.

The following work is an attempt to alleviate these problems without moving or adding knots. Two basic adjustments are covered. The first is adjustment of the nearness of the spline curve to the knot polygon. This is visually interpretable as the tightness or looseness of the spline. The second is control over the slope of the spline curve at the knots; in particular, being able to make the slope horizontal or vertical. This is useful because, when choosing knots to describe a curve, it is common to select points that are as far up or down, or left or right, as the curve is to go.

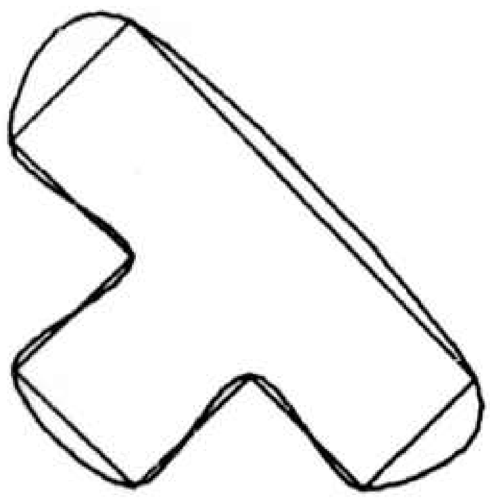
Figure A24 shows:

ALPHA = 1/2

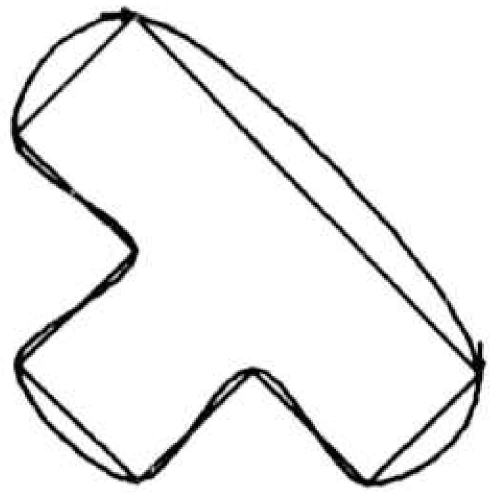
ALPHA = 1/2 Tangents forced to arrows

ALPHA = 1 (looser fit) Tangents forced

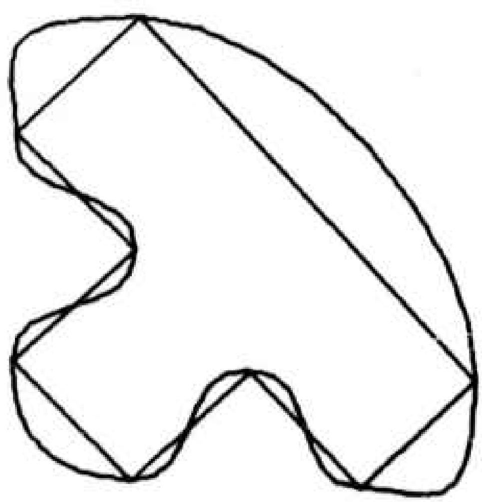
ALPHA = 1/4 (tighter fit) Tangents forced



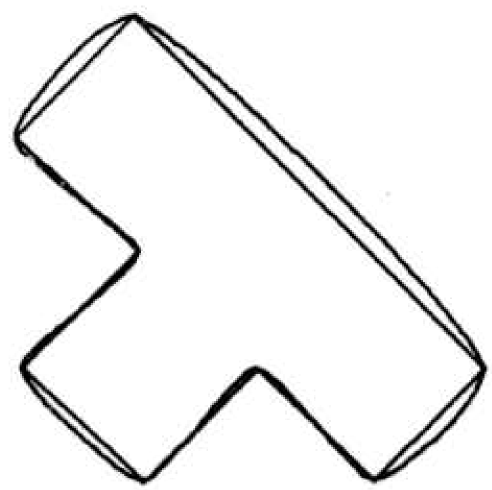
ALPHA = 1/2



ALPHA = 1/2
Tangents forced to arrows



ALPHA = 1 (looser fit)
Tangents forced



ALPHA = 1/4 (tighter fit)
Tangents forced

Figure A24

Animation. -- Our animation program has been developed along the lines of a classic storyboard concept. Each drawing in the storyboard becomes a key frame to our animation program. Each key frame is defined as to its frame number, eye position, "look at" point, (the point the observer is looking at), light source position, and the objects that are included in the data structure. Only the things which have changed at each key frame need be stated. The next program takes this key frame information as input coupled with linear or B spline interpolation and will generate all the intermediate frames for the animated film, which is then recorded on movie film.

The halftone picture display program interprets this command list to produce shaded pictures. Objects to be displayed must be described in terms of polygons and their vertices, and may be either hand calculated or are available as an output of the DEVELOPABLE SURFACE PROGRAM (for displaying developable surfaces). The halftone program also produces line drawings when used on the timesharing system. Figure A25 is an example of a Key Frame from an animated film using the DEVELOPABLE SURFACE PROGRAM.

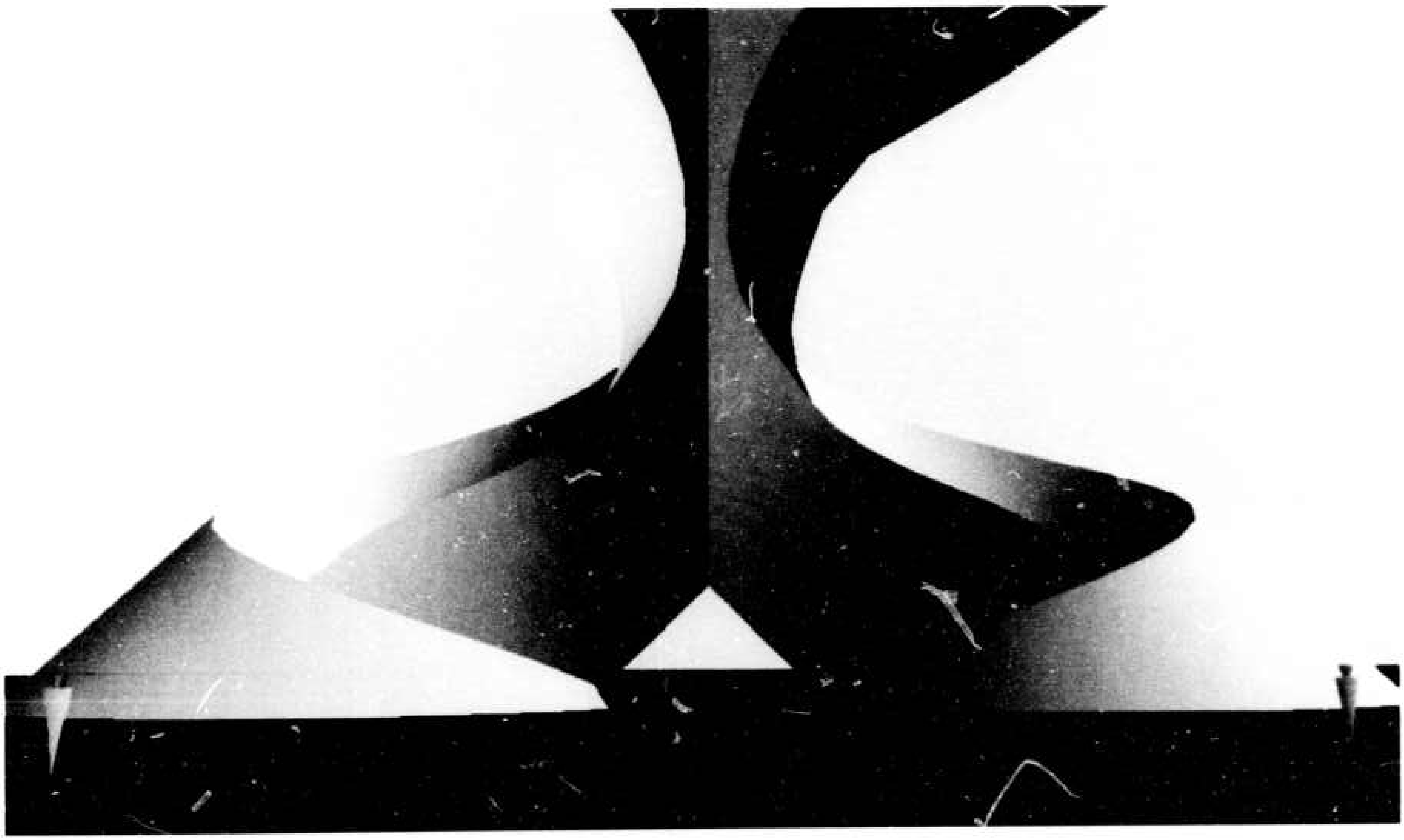


Figure A25

Interactive Line Drawing Editing System. -- Input to the system can be any line drawing generated by the program itself or produced by any other program. The program makes possible the creation of any curve defined by mathematical formula and can also create a spline curve through data points which are either read in or defined on-line.

The need for a line drawing editor is that the output of an existing program might be a small part of a desired drawing, or it may contain errors which are easily seen and corrected with the editing program, but would require major revisions to the generating program. The editor allows reference to points or curves by explicit name or by pointing with the display cursor. The allowable transformations to the referenced objects are: copying, scaling, translating, rotating, reflecting and selective erase. This program can also control the order in which a drawing is executed, a critical feature in a numeric controlled tool. An example of this use of the program may be seen by taking Figure A16 as input, and twice copying and rotating it by 120 degrees to produce Figure A26.

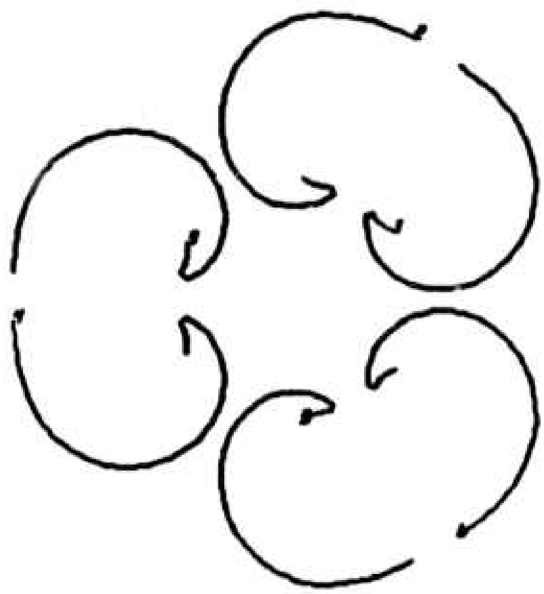


Figure A26

This is an example of the use of the Interactive Line Drawing Editing System

A.2.2 Graphics in the Study of Hemodynamics

An attempt was made to enlarge the usage of computer capabilities in medicine beyond their usually seen tasks. Specifically, the attempt is to understand hemodynamic phenomena with the aid of newly developed computer graphics implements. Applying fluid dynamics principles to blood flow about obstacles, simulation was carried out by the computer and its attached line drawing display systems. Continuoue changes in the blood flow field were pictured and useful eemi-quantitative information unavailable by other methods was obtained. The first year saw preliminary results for application to artificial heart valve and atherosclerosis studies. Comparison of computer reeuits with other investigators' in vitro and in vivo studies were fruitful. The technique applied in the first year was for the two-dimensional, steady flow, rigid wall situations.

The second year saw an improved approach in an attempt to extend the previoue approach to a three-dimensional capacity. Complicated computer algorithms and program subroutines were formed which proved the new approach feasible. A subproject was initiated to allow free eurface boundary conditions in the method so as to eventually allow for a pulsing motion and viscoelastic wall properties. Initiation was also seen of computer graphics usage for studying shear stress analysis of blood-endothelial surfaces. The construction of special photostrese equipment was begun so as to allow experimental verification of computer graphics results. Such verification is unusual.

The third year saw the application in a preliminary fashion of the head-mounted display system. This system uses a helmet in which two small display screens are utilized to form a stereographic image. The system allows one to walk around and into a computer formed simulation. A film was made that showed the observer walking into an idealized artery and a prosthetic heart valve. The simplified Marker and Cell approach was continued and an Arbitrary Marker and Cell concept was initiated to allow finer detailed simulation of the hemodynamic studies.

The fourth year saw a concerted effort in the attempt to include irregular, curved obstacle shapes in the problem. Although such studies allow flow fields of any type to be studied (air, gases, water) about any obstacle in the flow, blood flow was emphasized. The boundary conditions of no-slip and free-slip (the latter of interest in capillary flow) were examined. Stress conditions between an obetacle and a wall were examined for distribution effects. A critical analysis of numerical values for such shear stress distribution was formed. In turn, computer graphics usage for designing optimized flow in heart valves was initiated. Shading and smoothing algorithms were utilized (see Figure A27 wherein a moving toroid allowed one-way, centralized blood flow through a prosthetic heart valve). Some study was also made of the simulation of pulsatile flow motion and comparisons of the amplitude and phase lags between a pressure pulse and resulting flow rate were graphically displayed. Flow in contractions with solutions for non-isothermal flow and non-Newtonian temperature-dependent fluids were solved, placed in algorithmic forms and simulated. The emphasis was placed on the display of a contracting and inflating container (artificial heart ventricle) with resulting shifts in turbulence and stress distributions presented on the display screen. This knowledge, useful for the designing of ncessary reinforcement sites, was then amplified to analyze the stress in natural heart valve leaflets. This stress analysis is continuing via use of the finite element method. Concurrent with these present studies is an experimental program, employing photostress analysis in the attempt to verify results formed by the computer graphics techniques.

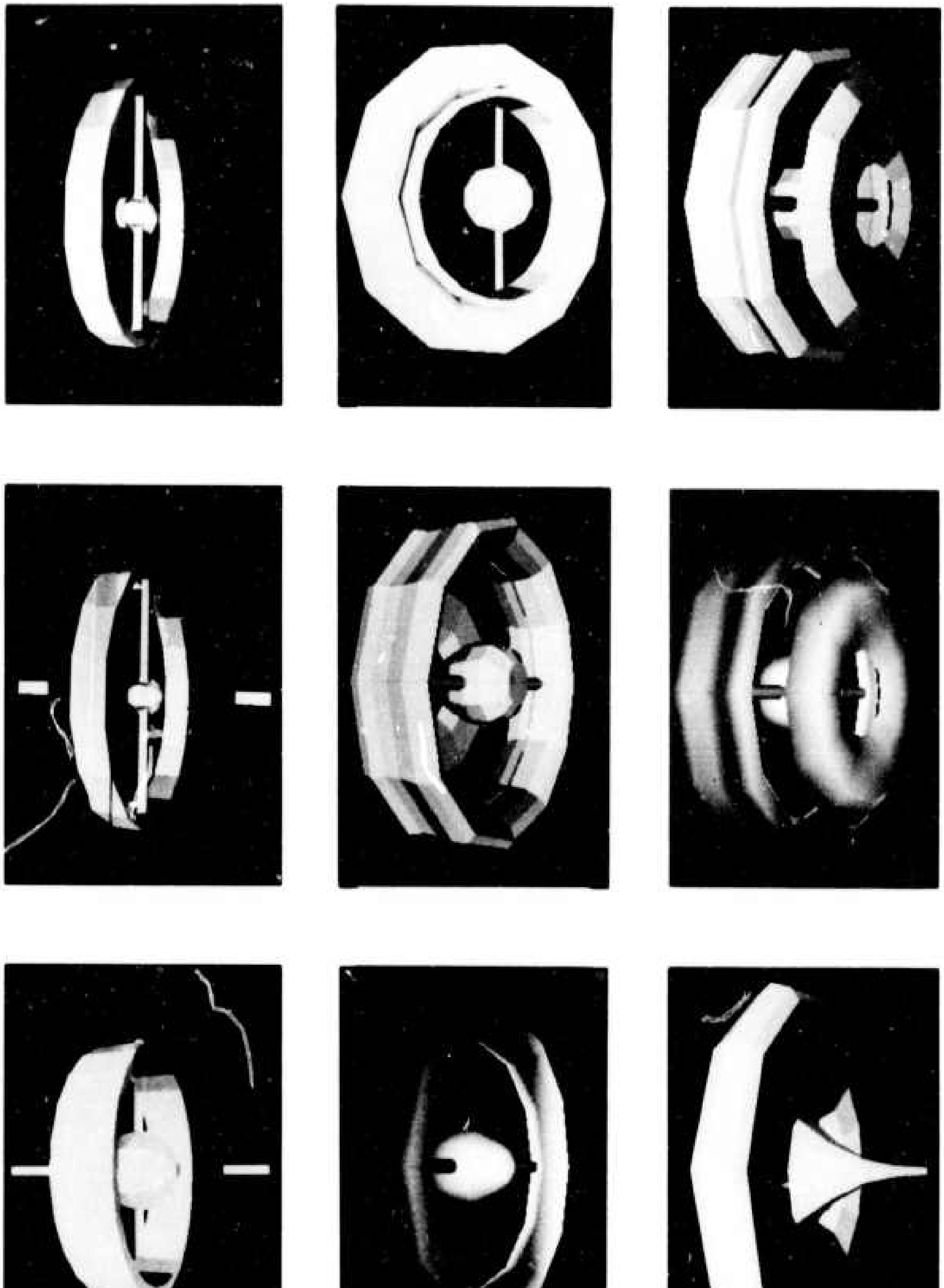


Figure A27

Various Stages in the Design of a Toroidal Heart Valve by Computer Simulation

PUBLICATIONS ON THE HEMODYNAMICS APPLICATION

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SECTION B

WAVEFORM PROCESSING

The principal goal of the Waveform Processing effort over the span of this contract has been to pursue research involving the use of interactive computers in processing signals with particular emphasis on processing images and audio waveforms.

This section summarizes all research in Waveform Processing conducted over the contract period with special emphasis on the unreported research from December 1972 to June 1973. The research embraces a broad spectrum of topics including:

1. modeling of the human visual system
2. homomorphic deconvolution of images, deblurring
3. homomorphic deconvolution of sound, restoration and noise suppression
4. homomorphic deconvolution of seismic signals
5. linear predictive coding, least squares processing of audio data
6. modeling of the human ear, phase sensitivity
7. Hadamard image coding
8. digital window functions

Emphasis has been placed on obtaining very high performance quality, demonstrating the feasibility of processes which represent technological breakthroughs. Particular emphasis has been placed on a high level of interaction between the human observer and the computer. To this end the following hardware and software has been developed:

1. A high fidelity A/D - D/A audio system

2. Image scanning hardware, input/output

3. audio software

4. video file system

5. software for scanning pictures

B.1 Modeling the Human Visual System

A multiplicative visual model was investigated to some extent. The results are summarized in the following text. In addition, current related research is briefly discussed.

The eye is frequently compared to a simple box camera to illustrate how an image may be formed on the retina. If the explanation stops at this point, some very important image processing properties of the human visual system might well go unnoticed. The illusions shown in Figures B1, B2 and B3 illustrate some of these properties.

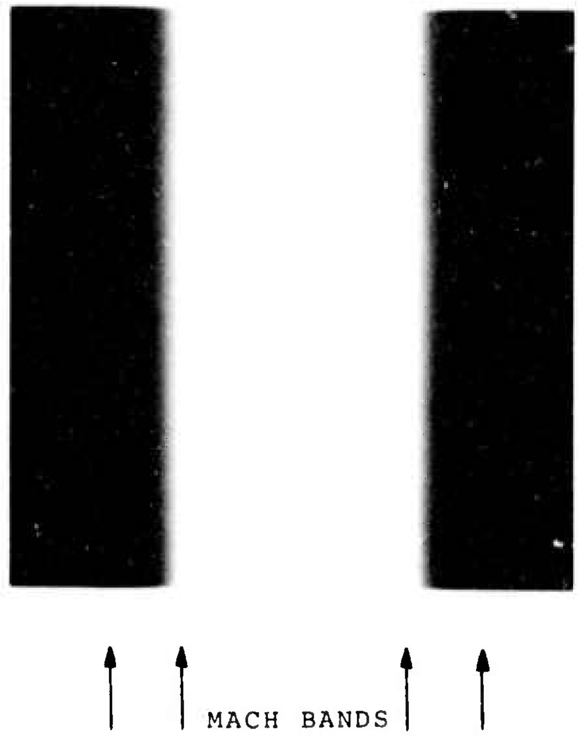

Figure B1
The Mach Band Illusion

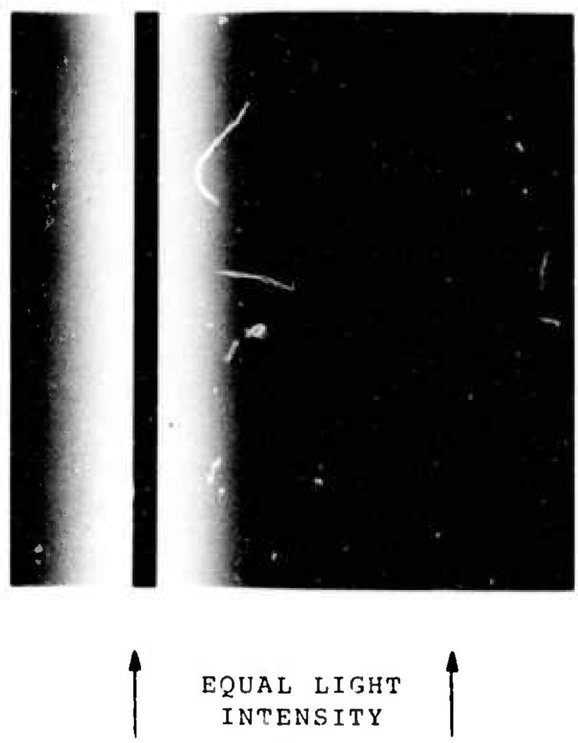

Figure B2
The Simultaneous Contrast Illusion

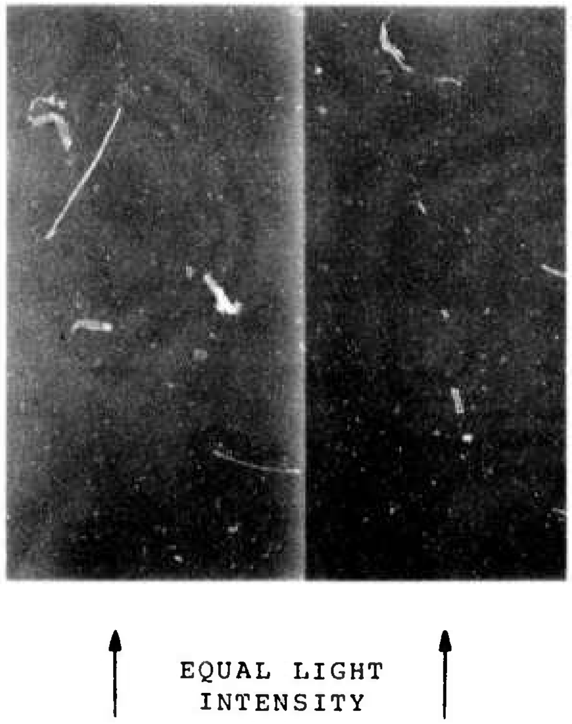

Figure B3
The Cornsweet Illusion
(Left Half Appears Darker)

None of these illusions would occur if the eye were a fidelity copying instrument as implied by the simple camera analogy. Sections of a scene that were equal in intensity would appear to be equal in intensity and the mach bands that appear at the end of an intensity gradient would be absent.

Recent research efforts have been directed toward understanding image processing in the visual pathway and constructing a model that predicts these illusions properly.

A more accurate representation of the visual system is possible if the logarithmic transformation and two dimensional filter are added to the lens system of the eye as shown below.

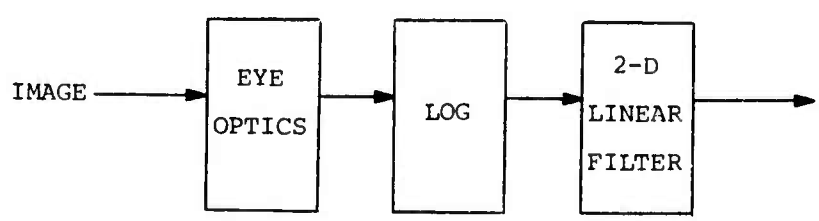

Figure B4

Visual Model

In the context of the three illusions shown, the model performs as follows:

a. Mach bands are predicted correctly

b. Simultaneous contrast is predicted approximately

c. The Cornsweet Illusion is not predicted at all

If the box labeled "eye optics" is approximated by the identity system, the model obeys superposition on multiplication.

Stockham[☆1] showed that an image enhancement scheme, based on the multiplicative model, may be constructed having the following property:

$$I(x,y) \cdot R(x,y) \Rightarrow I'(x,y) \cdot R'(x,y')$$

I represents the illumination component of an image

R represents the reflectance component

This is an important result from a psycological point of view since it points out the fact that detail in an image, due to the reflectance of objects, might be made more pronounced while suppressing the illumination component.

A thorough study by Baudelaire[☆2] demonstrated the following:

a. For smooth patterns containing energy between 0.1 and 8 cycles/degrees, the muliplicative model accurately predicts simultaneous contrast effects.

b. Some local nonlinear mechanism must be incorporated in the model if it is to predict simultaneous contrast correctly on images containing sharp, edge type discontinuities as in Figure B2.

c. Color images exhibit the illusions mentioned above but the present model is applicable only to monochrome images.

An ongoing research effort is being directed toward understanding the eyes behavior near edges. It is currently felt tnat such an understanding would make it possible to extend the multiplicative model to deal correctly with patterns of the type shown in Figure B3.

There hans been some success in doing this using an edge oriented model. Figures B5, B6 and B7 show how this method avoids the large overshoots associated with the multiplicative model while properly predicting the Mach Band effect.

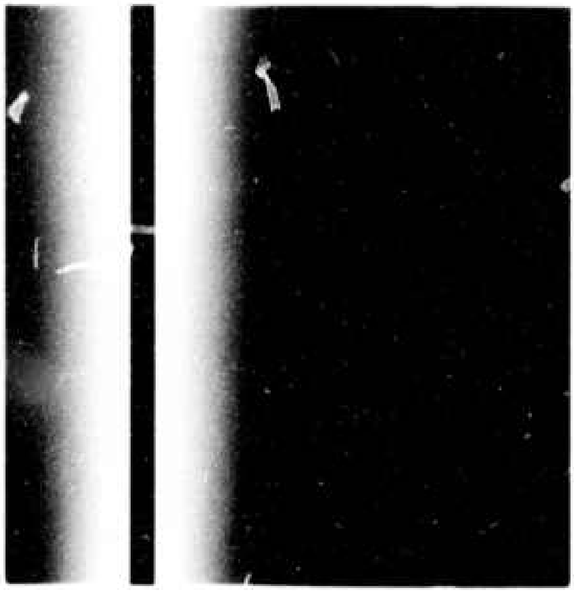

Figure B5

Test Image

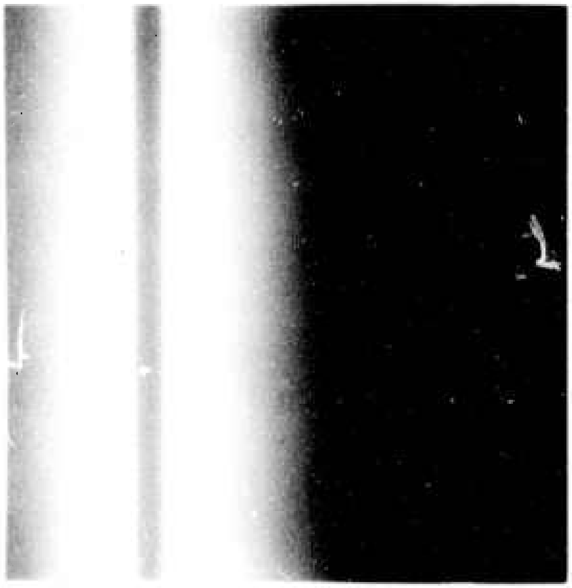

Figure B6

Image of Figure B5 Processed by the Multiplicative Model

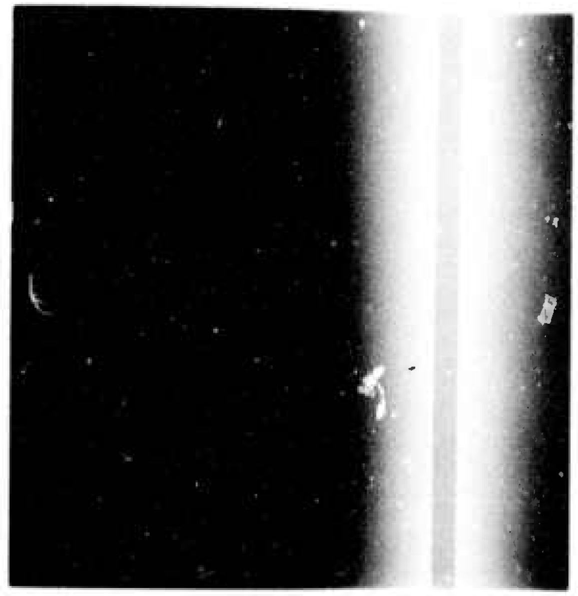

Figure B7
Image of Figure B5 Processed by the
Edge Oriented Model

Efforts are presently underway to understand the local edge oriented mechanism responsible for suppressing large overshoots in the vicinity of edges, as shown in Figures B5, B6 and B7 so that a more accurate model might be constructed.

B.2 Homomorphic Digital Image Processing

Previous phases of this area of research have led to the development of a reliable method of homomorphically estimating the magnitude of the frequency response of a linear system through which an image has been passed and blurred. The method consists of estimating the log power spectrum of the blurred image and subtracting from that a prototype power spectrum of a statistically similar but undistorted image. In so doing, the convolutional combination of blur and image has been mapped into one of addition. The difference between the two power spectra is the sought after estimate of the blurring system. From this a restoration filter is generated, which, as was shown by Cole[*4], has restoration and noise handling properties intermediate to those of the Wiener and simple inverse filters.

Current research efforts have resulted in a means of calculating the phase associated with the system estimates of two common blurs, namely, out-of-focus and motion blurs. The frequency response for each is a well defined mathematical function, i.e., a Bessell function for the former and a trigonometric function for the latter. Characteristic defining parameters can be obtained for each from the corresponding system estimate and from these the correct phase is readily induced. These parameters are obtained from the zero crossings of the estimated system frequency response; they are quite accurate as they are sought in the low frequency region of the estimate, a region relatively unaffected by noise. Restoring a distorted image with the phase, as well as the magnitude of the blur, produces very satisfactory results.

Problems with negative numbers ("superblacks") in the restoration have been overcome by restoring the density version (logarithm) of the blurred image and exponentiating the result. The process not only insures a positive definite result but also allows for simultaneous contrast enhancement as described by Stockham, Oppenheim, and Shafer [W5].

The above-described estimation and deblurring process is of great interest because it not only produces pleasing results but also requires very little a priori knowledge concerning the picture or the blur. The only constraint placed upon the blur is that it be convolutional in nature; only a general statistical knowledge of the image is necessary.

An example of an out-of-focus image is shown in Figure B8. The magnitude and phase of the blurring system were estimated as described above. Figure B9 shows the result of having passed the logarithm of the image through the convolutional inverse of this system and exponentiating the result. Figures B10 and B11 illustrate the same method applied to a horizontal motion blur; non-axial motion blurs are handled equally well. It should be noted that the appearance of Figure B9 was much improved by simultaneously enhancing the image as it was deblurred.

The appearance of many restored images has been greatly improved by the implementation of the so-called "resistive" filtering scheme first proposed by Tuckey earlier this year. The method is very effective in removing anamolous noise spikes from the initial data while leaving actual image information unchanged. Such spikes can have deleterious effects on the restoration of the blurred image and are the cause of the many "teardrop" distortions seen in Figure B9. The method consists of setting the value of each picture element equal to the value of the median of its neighbors. Figure B11 shows the result of applying resistive filtering to the data before deblurring.

A third type of blur, namely that of atmospheric turbulence, has also been recently investigated. The acquisition of a Questar telescope allowed us to photograph several scenes at long distance on hot summer days. The variations in atmospheric temperature (and resulting changes in refractive index) are modeled by a linear system which has a phaseless Gaussian frequency response. The resulting blurs are quite severe and restorations, unless properly filtered, are dominated by noise. Figures B13 and B14 illustrate the case of a sign in a small-town business district photographed from a distance of 3 miles. Although the restoration is not striking, it is indeed possible to deduce the meaning of the sign.

Immediate areas of research include improved methods to obtain the phase information of the blur that are relatively insensitive to the choice of prototype power spectrum. A second promising area is to generate mathematically the frequency response of the blurring system (as well as its phase). This can be done from the same parameters that define the phase, and leads to a deblurring process that bypasses the need for a prototype power spectrum.

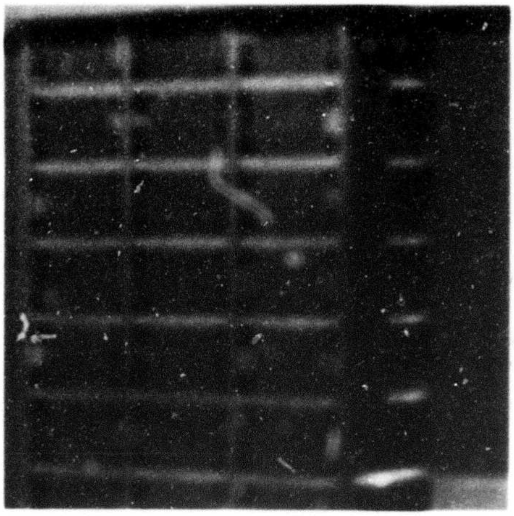

Figure B8

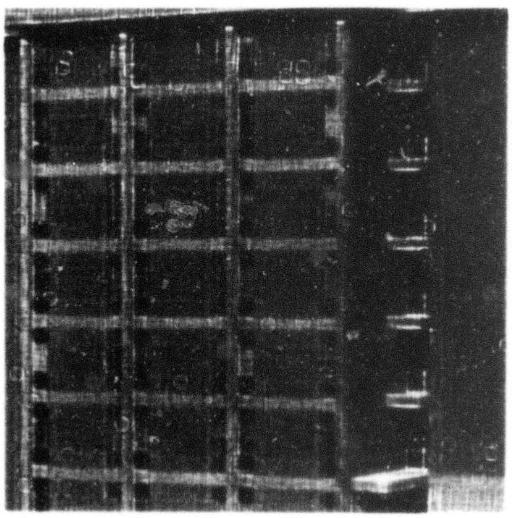

Figure B9

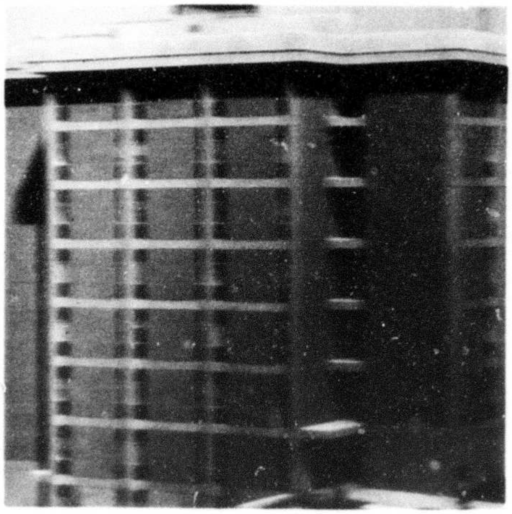

Figure B10

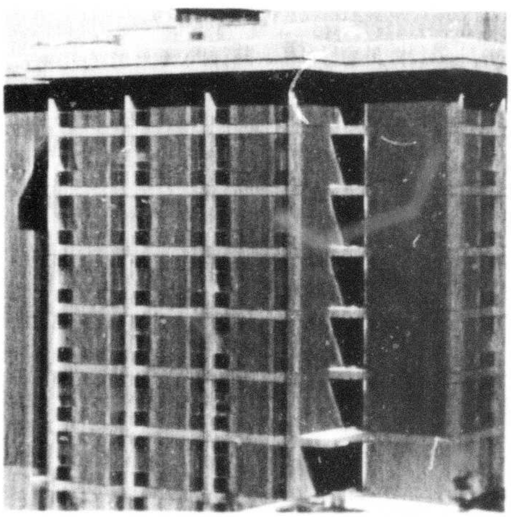

Figure B11

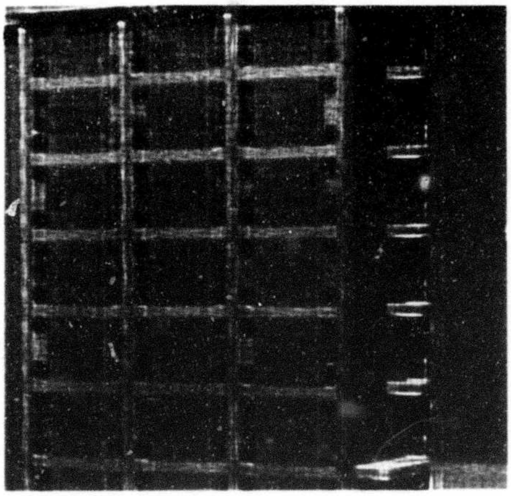

Figure B12

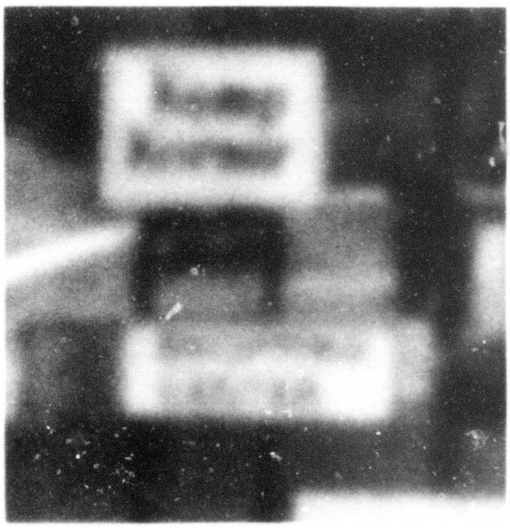

Figure B13

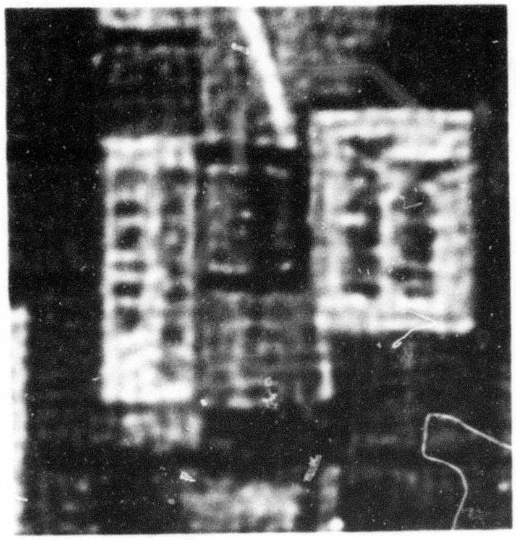

Figure B14

B.3 Homomorphic Deconvolution of Sound

Restoration and Noise Suppression

Research into the problem of eliminating reverberations from audio digital signals has led to the invention of statistical deconvolution based upon the theory of homomorphic filtering[☆6]. The method can also be applied to image deblurring as described in the previous section. The method was applied to the removal of recording horn resonances from old acoustic discs[☆7].

The homomorphic method of deconvolution is based upon averaging the log magnitude spectrum of many stationary segments of the recording. The log magnitude is the sum of the log spectra of the reverberation distortion and the natural acoustical source. The natural acoustical source nearly averages to zero, leaving essentially the spectrum of the reverberations. That spectrum can then be subtracted from all spectra of the stationary segments, producing an excellent approximation to the natural acoustical source.

A noise suppression method in speech signals was developed based upon homomorphic vocoder methods[☆8,☆9]. Broadband noise, whose frequency spectrum overlaps the speech spectrum to a great extent, can be suppressed. The basic idea is to extract only those signals that correspond to signals that can be generated by the human vocal apparatus, namely voiced speech waveforms in which pitch information can be derived. The noisy speech signal is analyzed in the cepstrum to find pitch. The impulse response of the speaker is estimated by short pass filtering the cepstrum. Pitched speech is then synthesized by convolving the impulse response with the estimated sequence of pitch pulses.

B.4 Homomorphic Deconvolution in Reflection Seismology

Homomorphic deconvolution can be used to recover the source wavelet from a reverberating wave train. This source wavelet can then be used to design a more effective predictive deconvolution filter than has been used before. No assumption of the phase spectrum of the source is necessary. Studies show that in the complex cepstrum, the principal contribution of the source wavelet is concentrated at short periods. Hence, the reverberatory contributions are located at long complex cepstrum periods.

We have just begun this investigation and have only developed a basic homomorphic deconvolution package for the PDP-10 for use on model and single trace seismic data. Work completed under this contract, but reported earlier, includes the following.

Interactive computer graphics has been applied to geophysical modeling, seismic data procesing, and two- and three- dimensional data representation. Gravity, magnetic, resistivity, and induced-polarization data have been modeled in two dimensions using the interactive console for data and variable manipulation. Cathode-ray tubes were used to display line drawings of observed and theoretical responses and earth models. These techniques are shown to be an effective new tool in geophysical interpretation with time savings of hours versus days over general batch mode processing.

Seismic data have been processed utilizing the interactive system to design and implement filters and deconvolution operators. Seismic profiles have been displayed in black-to-white halftone variable density plots on CRT's.

Two-dimensional representations of three-dimensional surfaces have been displayed in color-shaded perspective views. These included gravity, aeromagnetic, topographic, and correlative data. Furthermore, these views can be translated and rotated to any viewing position, allowing the interpreter to visualize several variables of data at any scale and apparent viewing location. In addition, stereographic views of these data can be obtained, allowing a true four-variable representation of geophysical data.

In conclusion, the application of computer graphics in geophysics has shown a dramatic decrease in time required for problem solutions and data display. The rapid solutions and simultaneous graphic view of data lead to quicker and better solutions because the geophysicist can make judgments based upon immediate displays of solutions. He can devote full concentration to display solutions without having to wait for long turn-around time in normal batch processing and digital data plotting. These techniques have shown that interactive computer graphics in geophysics can produce meaningful and efficient problem-solving methods in the future.

B.5 Linear Predictive Coding

The primary goal of this research was to investigate the various aspects and advantages of linear predictive coding of speech in order to design a complete analysis-synthesis system which generates high quality synthetic speech while minimizing both the channel bandwidth as well as the amount of arithmetic computations.

The research was focused on two principle areas: (1) improved efficient estimation of vocal tract parameters using a priori and recursive least squares; and (2) improved efficient estimation of pitch, voicing, and silence detection using modified auto correlation methods.

Vocal Tract Parameter Estimation --- The vocal tract is parameterized as a time-varying all-pole filter. The vocal tract parameters (either predictor coefficients or reflection coefficients) are estimated using either the auto correlation method or the covariance method. These basic techniques can be modified to incorporate a priori information in which case the parameters are estimated using either a priori or recursive least squares. With these modifications made to the basic algorithms, it was determined that the analysis window size could be further reduced in addition to increasing the smoothness of the coefficient time histories and the stability of the vocal tract transfer function.

Additional methods for estimating the coefficients were investigated which minimized the dynamic range (peak to peak values) of the coefficients. This resulted in fewer bits per coefficients when quantizing for channel transmission. A 20% reduction in channel bandwidth was realized when this "minimum norm" estimation method was used.

Additional Fortran subroutines have been written to transform predictor coefficients to parcor coefficients and back again; to compute pole locations from predictor coefficients; and, to compute frequency spectra from either predictor coefficients or pole locations. These programs have been used to measure the sensitivity of the vocal tract spectrum to coefficient quantization.

Efficient Detection of Pitch, Voicing and Silence --- The goal of this research effort was to develop automatic, single-pass algorithms for detecting pitch, voicing and silence which could be used to generate synthetic speech which was free of intrusions. That is, pitch doubling and halving errors and incorrect voicing decisions, but which could be implemented in real time with special purpose hardware. A fairly sophisticated pitch detection algorithm was implemented using a modified autocorrelation method. This method used the all-pole model to remove the effect of the vocal tract from the speech waveform, leaving only the effect of the glottal excitation. The removal was effective enough that secondary checks for pitch doubling and halving errors were unnecessary.

Voicing was detected by both comparing the normalized magnitude of the correlation error sequence at a delay equal to the pitch period against a prescribed threshold and examing the ratio of the signal energy divided by the estimation error energy.

The algorithms were then streamlined to reduce the amount of computation by down sampling the input speech sequence and performing the analysis using only a fourth the number of data points and therefore taking approximately a fourth the time. This required an implementation design of a digital filter to low pass the data in order to prevent aliasing as well as an interpolation routine to resolve the pitch estimate to sufficient accuracy.

Channel Bandwidth Simulation --- Fortran programs have been written to simulate channel bandwidths of 9600, 4800, 3600, and 2400 bits/sec, using the methods described above for analysis and synthesis. Variable input data sampling rates of 16khz, 10khz, 8khz, or 6.4khz can be used for the simulation.

Current Program Configuration --- The analysis-synthesis methods described have all been programmed in Fortran IV. The various routines are in subroutine form and can be interchanged. The programs can be run on either the time-sharing PDP-10 or the single-user PDP-10 by interchanging the input-output routines. The programs run at approximately 28 times real time using 8khz sampled input speech and 22 times real time using 6.4khz sampled input speech.

B.6 Sensitivity of the Ear to Monaural Phase Effects

The fact that the ear may effect frequency analysis after the manner of Fourier was first stated by Ohm in 1843. Helmholtz (1854) verified the law and, as a result of his own work, added the dictum that the musical quality of an acoustic signal was phase independent. Since the time of Helmholtz, there has been a great deal of work done to test the validity of his phase law.

The experimental work performed to test the phase rule falls into four general areas of classification, which depend on two parameters of the testing stimuli, the intensity and phase function. The intensity may or may not be great enough to produce aural harmonics, and the phase function may be linear or nonlinear. The four areas of experimental work may be classified as illustrated in Figure B15.

INTENSITY	PHASE	
	LINEAR	NONLINEAR
NO AURAL DISTORTION	I	II
AURAL DISTORTION	III	IV

Figure B15

Monaural Phase Effect Research Areas

Results of research in Area I have both supported and refuted the phase rule. It is in this area that Helmholtz conducted his own work, and in fairness to Helmholtz it is not unreasonable to assume that he meant his assertions to apply only to this area. Schouten's (1939) work supported Helmholtz' rule while the work of Beasley (1930), Mathes and Miller (1947), Licklider (1957), Schroeder (1959), and Craig and Jeffress (1962) did not. All of these investigators were able to demonstrate discriminable monaural phase effects.

Research in Area II has been conducted by Flanagan (1951) with all-pass systems capable of advancing or delaying one frequency band relative to the rest of the spectrum. Flanagan determined that speech intelligibility was impaired with advances or delays of approximately one-quarter second when the advanced or delayed band was near the center of the spectrum. Mathes and Miller (1947) have noted that nonlinear phase distortion have long been recognized as causing noticeable transient distortions which are coloquially known as "tweets" and "birdies."

Work in Areas III and IV include the work of Chapin and Firestone (1934), and Trimmer and Firestone (1937). Obviously, when the ear is forced into a nonlinear region of operation by test stimuli of excessive intensity, the discriminable stimulus quality will vary with the onset, growth, and phase relations of the distortion products. Although work in this area will likely lead to further understanding of the auditory system and further revision of the theories of hearing, it is not clear that positive results refute Helmholtz' phase rule any more then the properties of a material stretched beyond given limits violate Young's elasticity rule. It may also be argued that the data gathered from experiments in which the ear is operating in an abnormal mode relate to secondary characteristics of the ear. The area of research covered by this report is that of Area II.

The sensitivity of the ear to phase modifications within complex acoustic stimuli is well established. It is not clear, however, what the thresholde of phase sensitivity are for various types of phase modification, and in what domain the phase relations are to be meaningfully modified to adequately test the sensitivity. Preliminary research has been undertaken in an attempt to tabulate the sensitivity of the ear to phase modifications and to determine the domain in which the phase functions are to be modified.

Initial thrust nto research Area II has been made with a set of all-pass, non-recursive digital filters with parabolic phase. Each filter of the set varies parametrically in the extent of the phase advance or delay at the Nyquist frequency. The word "IT" was sampled at 10 kHz, digitized to 16-bit resolution, and stored on disk. This digitized epeech sample was the standard in the following comparison teets. The standard was in turn convolved with each filter and the results were stored on disk. A signal comparison program was written which presented N-pairings of the standard stimulus (S1) and one of the phase modified stimuli (S2). The program was of such generality that signals of any resonable length could be paired for comparison. The signal comparison test program presented N-pairings of S1 and S2 with rectangular distribution, i.e., S1-S1, S1-S2, S2-S1, and S2-S2 pairs occurred with equal probability. With each presentation of a pairing, the listener was required to respond either by depressing a "same" key or a "different" key depending on whether or not the signals sounded the same or different. A separate test was conducted for each phase modified condition and the results plotted as illustrated in Figure B16.

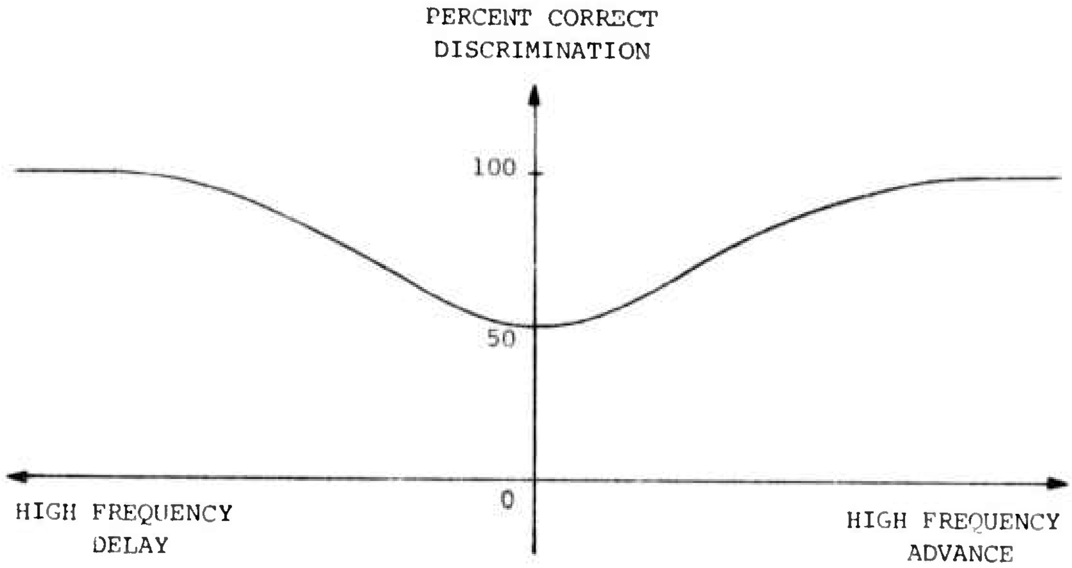

Figure B16

Correct Discrimination as a Function of High Frequency Shift

Early results indicate that there may be slight differences in the discrimination function between phase advances and delays. Phase advances and delays could be made roughly ten times longer before greater than chance discrimination if the pair was presented over a loudspeaker rather than earphones.

Research is continuing to determine the thresholds more accurately for various phase conditions and stimulus intensity levels, and an attempt will be made to relate the results to modern auditory theories.

B.7 Hadamard Image Coding

The Fast Hadamard Transformation which parallels the Fast Fourier Transformation was applied to image coding. Three results were demonstrated:

(1) Computational time is proportional to Nlog N (N = number of data points. Although the proportional computation time for Fourier Transform is the same instruction, the proportionality constant is only about 2 to 3 times smaller for the Hadamard Transform.

(2) Bandwidth reductions of less than one bit per picture element were studied.

(3) The images which result from Hadamard processing appear much less natural than those resulting from Fourier processing.

Processed images and discussions of the above topics are presented in reference [☆10].

B.8 Digital Window Functions

A catalogue of thirteen digital window functions and various variations was compiled and reported by Han-Yun Huang [☆11]. Various studies comparing many of the windows were completed and reported. The windows studied were:

Fourier
Bartlett
Parabolic
Parzen
Trapezoid
End Taper
Hanning
Hamming

Blackman
Kaiser
Dolph-Chebyshev
Taylor
White

B.9 Waveform Processing Technical Support

Image Scanning, Hardware Input/Output.--High quality images are routinely scanned in and out of the PDP-10 computer using specialized I/O equipment designed and built at Utah.

Image input is done by mounting a reflection print on a reflectance scanner and digitizing, with 14 bit A/D, its video output for storage on disk. Image resolution of 1024 x 1024 requires about 10 minutes for the complete input scanning process. Color images may be input by scanning the red, green and blue components individually.

Output is done in a similar manner except that a precision CRT is used in place of the reflectance scanner for the display device. Color images may be made by displaying the red, green and blue data files through appropriate color separation filters on color photographic film.

A/D and D/A Fidelity.-- A method has been developed for evaluating the fidelity of A/D and D/A equipment for maintenance purposes [☆12,☆13]. The method involves a digital computer program which provides a simple method for completing the test that can be made on a routine maintenance basis.

The computer generates a precise digital sinusoidal wave that is passed through the D/A, then reconverted to a digital signal by passing the analog wave through the A/D. The digital computer then analyzes the reconstructed digital wave relative to the initial digital sinusoidal wave in terms of quantization noise, additive random noise, and aperture noise.

Computer Interface Hardware.-- The following significant hardware systems have been designed, tested, and implemented to enhance the audio and video signal processing activities.

(1) Audio 16 Bit DAC System...This system consists of two precision 16 bit digital to analog converters with the necessary control and interface logic to match it to the I/O buss of the PDP-10 computer. The system greatly enhances the audio waveform generation capability of the computer system.

(2) Precision Programmable Clock...This system allows highly stable clock pulses of any desired frequency to be generated under program control. The stable output of this unit may be used to drive any of the three precision D/A converter systems available. A stable clock of this type is an absolute necessity for the precise generation of audio waveforms.

(3) Storage Scope Interface System...This system provides graphics capabilities of various kinds to users of the single-user

PDP-10 computer.

(4) Sweep Failure Protect System...This system provides protection for the expensive CRT used in the precision display equipment. It senses the derivative of the x axis deflection signal and blanks the CRT if that derivative ever falls below a preset value.

(5) Pulse Tripler System...This is a small logic circuit which allows precise setting of the settling time and intensity time of the individual points of a disply on the precision display system.

(6) General Purpose Interface System...This system makes the I/O buss interface of the single user PDP-10 computer available for connecting miscellaneous temporary peripherals of many kinds.

The following hardware systems have been finished and implemented since the last semi-annual report.

(1) Audio Counsel System...This system provides a compact portable unit providing, in modular form, the amplifiers, filters, attenuators and various other audio interfaces necessary to fully process computer generated audio waveforms. The modular amplifiers, filters, etc. are designed to be of the highest quality with total noise and distortion -88 DB below the maximum signal level. They are designed to be stand-alone units which are compatible with each other and with other standard audio equipment. Each unit is modular in construction and may be interchanged with any other module in

other positions in the system. Since the modules are plugable and interchangeable, the system may be expanded without limit by the design of new modules.

(2) I/O Buss Simulator...This system was designed to allow off line testing and debugging of computer dependent peripherals. It is a logic system capable of transmitting an I/O buss command repeatedly or singly with exactly the same timing and logic levels as the computer would send. It is useful in the checkout of equipment that requires an I/O buss interface for operation.

(3) Audio Equipment Cabinet and Control...This unit combines all of the audio reproduction and recording equipment in one cabinet with a master control panel that controls all internal signal paths at the touch of a finger.

(4) Display Test System...This system is a complicated off line precision tester for high resolution display systems. It generates three internal video patterns for testing; (1) a flat field at any desired intensity level, (2) a step wedge for intensity calibration and, (3) a shaded field. In addition, it may also receive and display any desired video pattern from an external source. Any of the video patterns can be painted in one of four resolutions; 9 bit, 10 bit, 11 bit, or 12 bit resolution. All other necessary controls for complete testing of any raster scan or line drawing system are available as front or back panel controls. The system is small, portable, light weight and easy to use. It has already

contributed greatly to the reduction of unwanted noise in our precision display system.

Software for Waveform Plotting.-- The development of sensory information group software at Utah has been channeled into four basic areas. First, routines to service the various specialized input/output devices, many in real time, have been developed. This also includes graphics utilities for convenient plotting of waveforms.

Audio Software Support.-- Second, a program that allows users to interactively record, playback and graphically examine digital audio recordings has been created. At present, this program also allows some user specified processing of these audio segments. Based on considerable experience, this program is being augmented to provide more flexible graphical interactive examination of large digital audio recordings for specific features of auditory interest.

Video File System Software.-- Third, a substantial effort has been expended in the development of a Video Storage And Retrieval System (VSARS). VSARS has allowed the various researchers involved in image processing at Utah to easily share data with a common flexible data format imposed by VSARS. Primarily VSARS was designed to treat a disk pack as a series of named images with provisions for the storage of the digital image and data of an important but auxilliary nature. This, along with protection against accidental overwrite or deletion, has proved especially valuable. A body of shareable software, contibuted by the researchers, has been a significant byproduct of VSARS' standardization of digital image format. It should be stressed that the specific format imposed by VSARS is not proposed as superior; the important fact is that a common format has been adopted.

POET --- Page Oriented Editor for TENEX.-- Fourth and finally, during the development and maintainence of this substantial body of software, it was found that no editor with sufficient power and ease of use was available for TENEX. Prior to POET's creation, users were forced to operate with a triply interpreted editor, QED, and suffered sufficient delays to encourage them not to edit --- thus slowing research progress. POET was developed to resemble QED (and surpass it) but to take advantage of the full power of TENEX, making it easy to manipulate large bodies of text. This editor, coupled with representation of text as formfeed delimited pages, has permited easy manipulation of large software libraries.

Software for Image Scanning.-- Digital image processing requires the facility of initially making digital versions of a scene and eventually making a viewable version of the processed digital image. Generally, both processes employ photographic media which introduces nonlinear distortion. At Utah, a rotating drum mechanical input scanner, imploying a photomultiplier tube, is used to digitize reflection prints and a Z axis modulated precision cathode ray tube display is used to produce photographic representations of digital images for human examination. In both cases, the major effort beyond servicing I/O devices is devoted to compensating for the photographic nonlinearities. The approach in both cases has been to measure samples of the nonlinear characteristics of the photographic medium and fit a smooth curve through the samples. Then the functional inverse of the estimated nonlinearity characteristic may be used to estimate the original scene intensity on input or achieve the desired reflection from a photographic print of a digital image. Only with this careful compensation, and control of the photographic process to avoid saturation, can photographic media accurately be used to transfer images to or from a digital representation. In essence, the photographic material is only an imperfect measuring tool that may adequately be compensated by the use of appropriate models of the imperfection.

This technique is applicable to color and black and white. A further set of problems is involved in the crosstalk between colors in color photography. The color filters used to separate the colors for an image are not sharp enough to eliminate crosstalk between colors and the problem is compounded by the crosstalk in the photographic emulsions. Preliminary results of work to matrix the digital image colors based on crosstalk measurement has provided better color rendition and kindled increased interest in a parallel investigation of color correction for input.

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SECTION C

SYMBOLIC COMPUTATION

During the tenure of this contract a new research effort was initiated which was concerned with the development of effective techniques for the solution of a wide range of symbolic algebraic problems by computer. This research is oriented towards both computer software development and the use of the developed programs in solving practical problems. Most of the work of this project has been concerned with the development and extension of the REDUCE system for algebraic simplification and its use in solving practical problems. One major achievement during the contract period was the release of the whole REDUCE program in its own language. As we are committed to the goal of making REDUCE as portable as possible, we believe that the successful implementation of this step will enable a much larger class of users to understand how the program works. Previous distributions were made in the LISP programming language.

In addition to this major step in improving the exportability of REDUCE, several significant improvements and extensions of the program were completed during the contract period. In particular the following specific tasks were accomplished:

1. The matrix handling facilities were completely revised and the new routines proved to be an order of magnitude faster.

2. Extensive work on the problems associated with the calculation of the greatest common divisor of two polynomials has led to improved algorithms and significantly better computation times for all rational function operations.

3. Further work on the standardization of the REDUCE language has necessitated extensive modifications of the syntax analysis part of the program and as a result, significant improvements have been made.

A number of applications problems were solved using REDUCE during this period. In particular, solutions to the first three problems posed in the problem section of the SIGSAM Bulletin were published. SIGSAM is the Special Interest Group on Symbolic and Algebraic Computation of the Association for Computing Machinery. In addition, a program designed for the analytic computation of a large class of definite integrals which occur in quantum electrodynamics was developed. We expect to extend this program to a wider range of integrals in the future.

With the advent of the ARPANET, it has been possible for us to make our programs available to a much wider audience by implementing them on a wide range of machines throughout the NET. Our insistence on a standard language for programming has allowed us to provide users with access to a variety of different machines throughout the NET. In particular, a user can choose that machine which is best suited for his programs at the time of running without having to take this fact into account during the writing of the program. For example, for very large calculations the user may run his program in batch mode on the UCLA 360/91. However, the program may have been developed and tested on several of the PDP-10's within the NET. As part of the general ARPA presentation, a demonstration of some of these resource sharing concepts was given at the ICCC meeting in Washington, D.C. in October 1972.

Use of the NET and the development of programs utilizing its facilities was impeded on many occasions by the fact that all NET access had to be made through the Utah PDP-10. Now that a TIP has been installed, we expect to have a much more flexible procedure for NET utilization.

Much of our work during the last twelve months has been done on the USC-ISI PDP-10. Again, the complete interchangability of our software meant that researchers saw no significant difference in the running of their programs on the two machines except of course that the larger core on the ISI machine meant that programs ran more quickly, and in fact more efficiently, as a result. The small core size of the Utah machine has been a constant impediment to our work in the local environment and we hope that the acquisition of more core to be installed during the next contract period will alleviate this problem.

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