To the Graduate Council:

I am submitting herewith a thesis written by Supot Charirnwanit entitled "Techniques for Generating Stereoscopic Displays with a Minicomputer." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

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TECHNIQUES FOR GENERATING STEREOSCOPIC DISPLAYS WITH A MINICOMPUTER

A Thesis

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Degree

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ABSTRACT

This thesis presents the techniques for generating stereoscopic displays with a minicomputer. The three techniques are: extracting stereopairs from the known heights, generating random element stereograms and generating stereopairs via perspective transformation. Each technique yields stereopairs of images which are presented to the two eyes separately, using the red-green anaglyph method.

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CHAPTER 1

INTRODUCTION

The visual system of humans has been of great scientific value for many years since it is the primary means by which humans learn about their surroundings. Binocular vision, in particular, has been the subject of much investigation since in some cases it can give rise to the perception of depth that is not possible when viewing an object monocularly. This capacity for binocular depth perception called "stereopsis" has been exploited in the constructing of contour maps from aerial photographs. Furthermore, the principles for stereopsis apply to the viewing of any three-dimensional object, whether it be a building, a mountain or even an automobile. These principles have implications in the theoretical analysis of pattern recognition since retinal image formation must be followed by cortical processing of images provided through stereoscopic viewing.

Since stereopsis has been studied more extensively than any of the other cues to depth, the aim of this research was to develop techniques for creating stereoscopic views using a minicomputer.

Three methods, extracting stereopairs from the known heights, generating random element stereograms and generating stereopairs via perspective transformation, are described in this research.

As a preliminary step to the discussion of stereoscopic display techniques, the main facts and concepts of stereopsis are briefly summarized in Chapter 2. The methods are generated by a mini-computer and are described in Chapter 3. The different techniques are implemented and the results are described and discussed in Chapter 4. The summary of the limitations, capabilities, advantages and disadvantages are described in Chapter 5.

CHAPTER 2

REVIEW OF FUNDAMENTALS OF STEREOPSIS

Binocular vision is very interesting since in spatial localization through vision binocularly, there emerges a new sensation not suggested through monocular vision called "stereopsis." In order that the concepts of stereopsis be more understandable, the structure of the visual pathways will be reviewed briefly in the following section.

2.1 The Visual Pathways

The characteristic of the projection of the retina to the visual cortex is shown in Figure 2-1. The visual field falls on the retina and extends through the optic chiasma and the lateral geniculate nucleus to the visual cortex (Brodmann's area 17). The nerve fibers from the left half of each retina proceed to the left side of the brain, and the nerve fibers from the right half of each retina proceed to the right side of the brain (observe the numbers of the visual field). The fibers from the nasal path of the retina decussate or cross over the chiasm to the opposite (contralateral) lobe, while those from temporal parts of the retina pass to the lobe on the same (ipsilateral) side without crossing. These fibers then extend through the optic tract, the lateral geniculate nucleus and the optic radiation fibers and converge at the occipital cortex (composed of area 17, 18 and 19) [1].

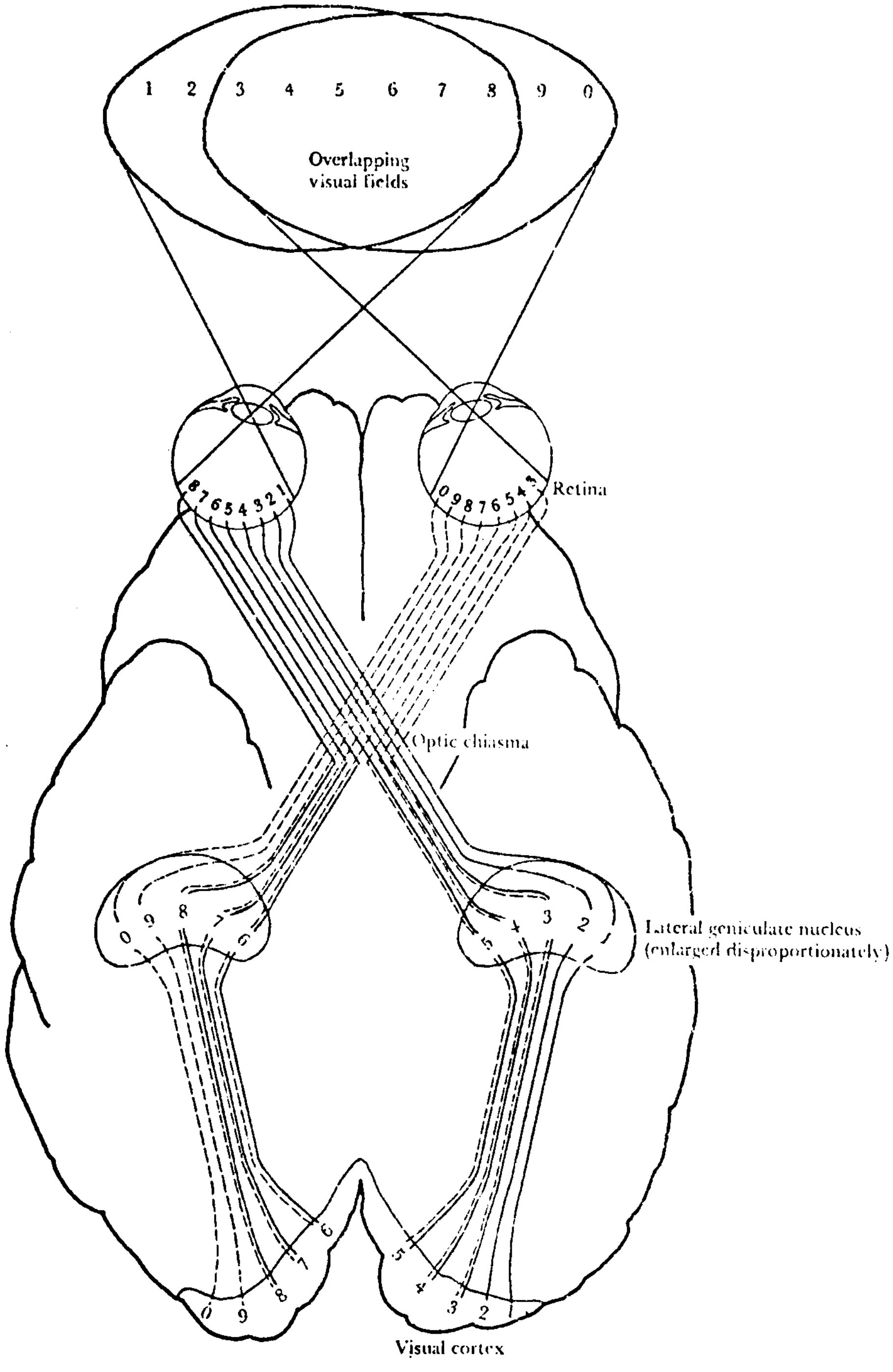


Figure 2-1. The diagram of the optic visual pathway. (From [2]).

2.2 Basic Concepts of Stereopsis

2.2.1 Principle of Stereopsis. Perceiving three-dimensionality of an object binocularly is the basic meaning of stereopsis. Suppose that two vertical rods were placed at different distances as shown in Figure 2-2. But the images of these two rods in one eye will be different from the image in the other eye if the rods are observed by one eye at a time. They are more widely separated in the right eye than in the left eye. When viewed binocularly, the relative depth can be perceived because of this retinal disparity.

The stereoscope invented by Wheatstone (1838) to investigate stereopsis relies on the principle of stereopsis. As shown in Figure 2-3, the instrument is comprised of two mirrors arranged so that the reflected patterns will be presented to each eye separately. It can present a different picture to each eye. The convergence angle can be increased by adjusting the angle between the two mirrors. This increased convergence angle is more consistent with the accommodation needed to view the stimuli.

In this figure, the separations of the lines "a" and "b" of each pattern are different. But the difference in separation must not be too great so that only the vertical lines A and B are perceived binocularly.

From this invention, the viewing of stereograms has been made possible using lenses, a Brewster stereoscope [3] and by using a single

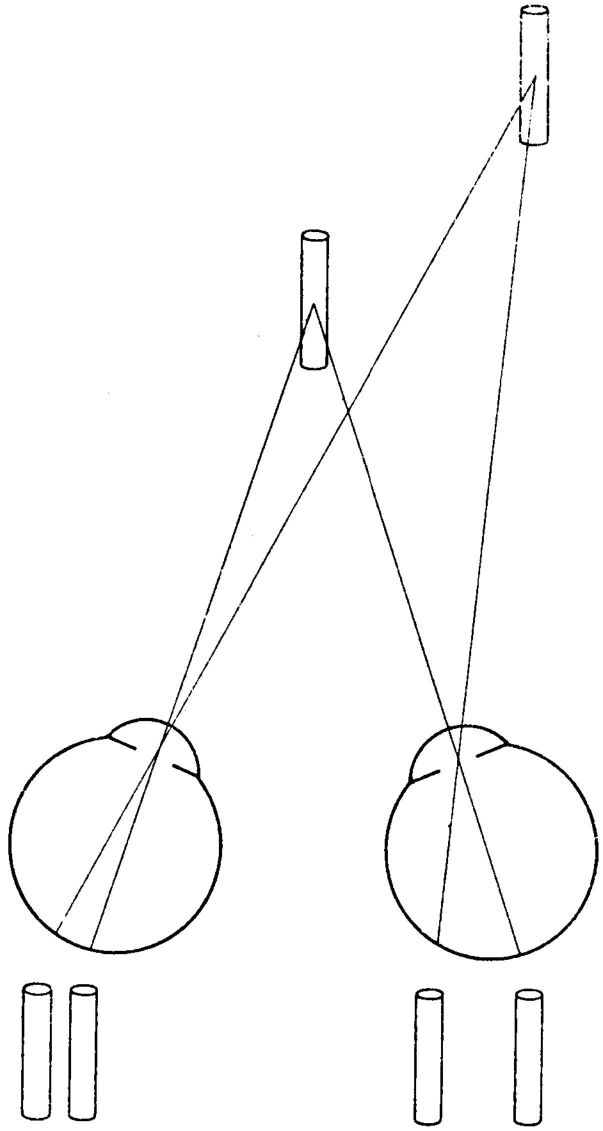


Figure 2-2. The discovery of stereopsis.

The image of the two rods in the left eye are closer together than their images in the right eye. If the pictures of these rods are presented to the two eyes in stereoscope, the observer perceives them in depth. (From [3]).

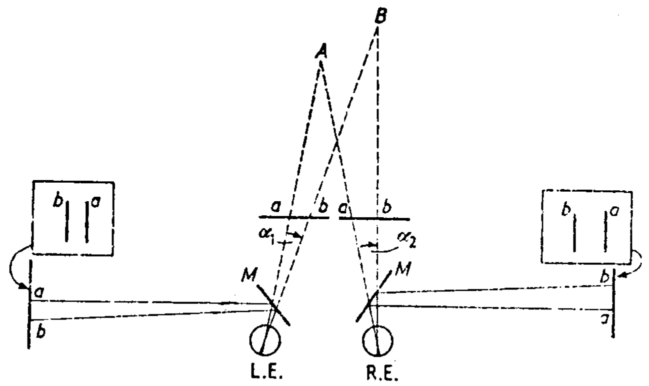


Figure 2-3. Plan of mirror stereoscope. (From [4]).

mirror technique developed by Dr. S. Papert at the Massachusetts Institute of Technology [3]. In addition, there are two common methods for viewing stereograms called anaglyph and polaroid methods [3]. The anaglyph method will be used in this research since it provides adequate separation of the images to the eyes. The following section will describe the anaglyph method.

2.2.2 The Anaglyph Method. As shown in Figure 2-4, the anaglyph is a stereogram in which one pattern is printed in red and another in green fields, which are superimposed. When this anaglyph is viewed through the eyeglasses containing a red filter for one eye and a green filter for another eye, the depth may be perceived.

The red filter reduces the intensity of the green pattern so that the eye covered by this filter sees high-contrast black lines of the green pattern. The green filter reduces the intensity of the red pattern so that the eye covered by this filter sees the red pattern as

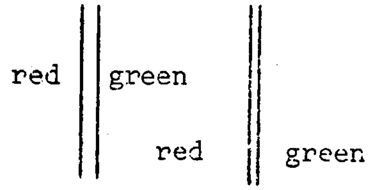


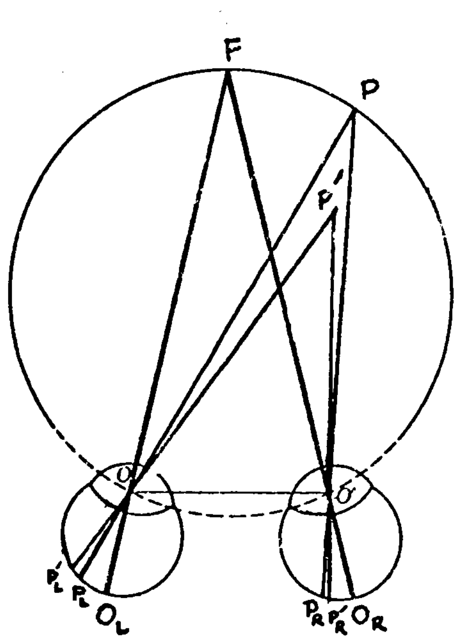
Figure 2-4. A typical anaglyph.

If the left lines are red and the right lines are green, stereopsis may be obtained when a red filter is placed over one eye and a green filter over the other eye.

black. The advantage of this method is that it provides spectral separation of the images to the eyes. Though the best result of the anaglyph method occurs when the images of the left and right eye are totally separated geometrically from each other, these images may be superimposed.

2.2.3 The Geometry of Stereopsis. If one views the different objects, he will perceive the different directions of the field of views with respect to his body. The ability to distinguish the differences of directions is attributed to the discrete character and arrangements of the receptor elements in the retina. When the eye is directed to a given fixation point, the image of that point falls on the fovea, and the subjective direction associated with the retinal elements of this fixation point is called "principle vision direction" [1]. All other visual directions are said to be relative to the principle visual direction corresponding to the point of fixation. If one binocularly looks at a fixation point in space, there will be an overlapping of the visual field of each eye. If the left eye and right eye images of an object are located at the same distance and in the same direction from their respective fovea, the two images are said to fall on the "corresponding retinal points." In other words, the corresponding points are the points that give rise to identical visual directions when they are stimulated.

As shown in Figure 2-5, 0 and 0' are the center of rotation of the two eyes. The point of fixation, F, has the same visual direction for both eyes and is seen as a single point. The two views of the eyes are said to "fuse" into one. O_L and O_R are the visual central points on



L.E. R.E.

Figure 2-5. The definition of corresponding points and their associated visual directions. (From [5]).

each retina, which have the visual direction F. P_L and P_R are corresponding points on the two retinas, with the visual direction P. The points F, P, 0 and 0' all lie on the so-called "Vieth-Müller horopter-circle." The Vieth-Müller horopter-circle is based on the notion that corresponding points occur at equal distances along a radius rotated about the origin through equal angles from the horizontal ([4] and [5]). The locus of points giving rise to single vision for a given attitude of the two eyes is called the "horopter." So the Vieth-Müller circle is a special case of the horopter. For each state of covergence, there is a different Vieth-Müller circle, because it is defined in terms of the points 0 and 0' and F. P' is a point off circle which stimulates non-corresponding points. According to Müller, P' will be seen as "double" if the disparity between points is great enough, or if the disparity is not great, the object will be seen as single but as nearer or farther away than a fixated object. F and P will be seen as single since their images fall on the corresponding points on the two retinas. Regions within which single binocular vision can be perceived are called "Panum's fusional areas." Whether the image will be seen as single and as nearer or farther away than a fixated point (or reference plane) depends on the disparity, which is determined by the location of P'. The perception of the depth in terms of disparities of the pattern elements is called "stereoscopic depth perception" or "stereopsis."

Since the discrimination of differences in visual directions is attributed to the discrete character of the receptor elements of the retina, one can assume that for each of the receptor elements (or group of elements associated with a single neural fiber) there is a corresponding type of functional "local sign" ([1] and [4]).

Hering (1864) expressed the theory of local sign that the depth value of a point on a retina is proportional to the horizontal distance of the point from the center of the fovea. The direction of the depth, nearer or farther than the fixation point, depends on the direction of the displacement from the fovea.

As shown in Figure 2-6, F_L, F_R, A_L and A_R are the images of the points F (fixation point) and the point A. According to the theory of local sign, the local sign of F_R and F_L are zero. A_L is imaged temporally relative to F_L, and the local sign of A_L is positive. A_R is imaged nasally relative to F_R and has the negative local sign. The depth effects of A_L and A_R have opposite directions. The total local signs of the points associated with A_L and A_R add algebraically, and in this case, the depth direction of A will be rearward relative to fixation point F since it has negative depth value. If A has a positive depth value, it will be seen as nearer than F.

There is another way to determine stereoscopic depth which will be called "the derivation of depth in terms of angular disparity." One must know the value of angular disparity first.

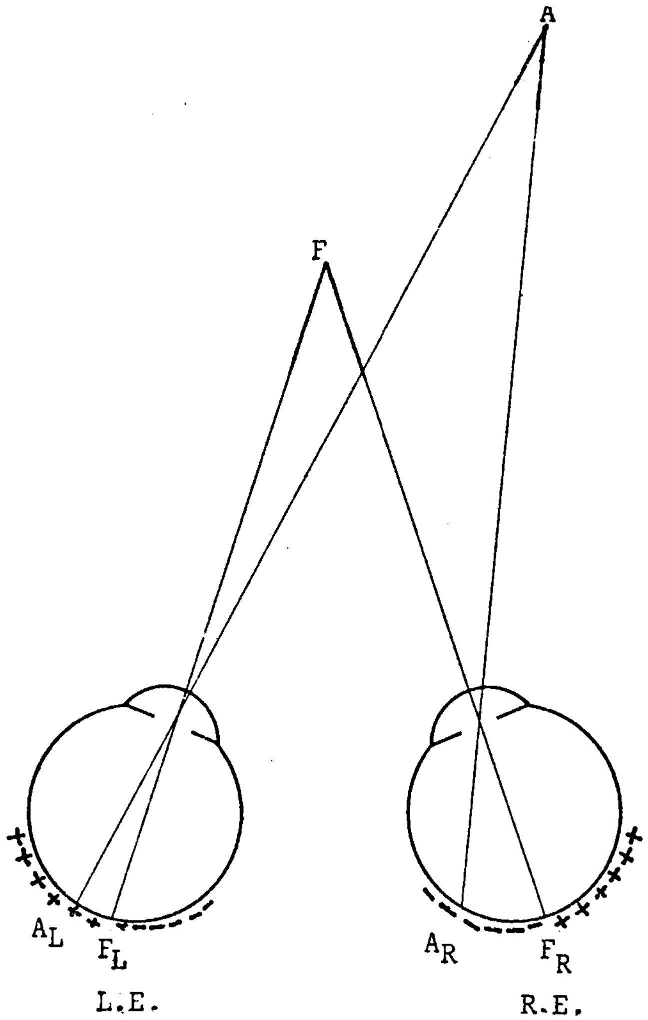


Figure 2-6. Illustration of concepts of local signs.

As shown in Figure 2-7, F is a fixation point, and 2a is the interpupillary distance (about 6.4 cm.). F' represents the point that does not lie on the same horopter as F. The letter "b" is the distance to F along a perpendicular to the interpupillary axis, and Δb is the distance along this perpendicular between F and F'.

In general, "b" is much greater than 2a or Δb and F' is not too far from the perpendicular to 2a on which F lies [5], we have

$$\alpha_2 = \frac{2a}{b}$$

$$\alpha_1 = \frac{2a}{b \pm \Delta b}$$

in radians.

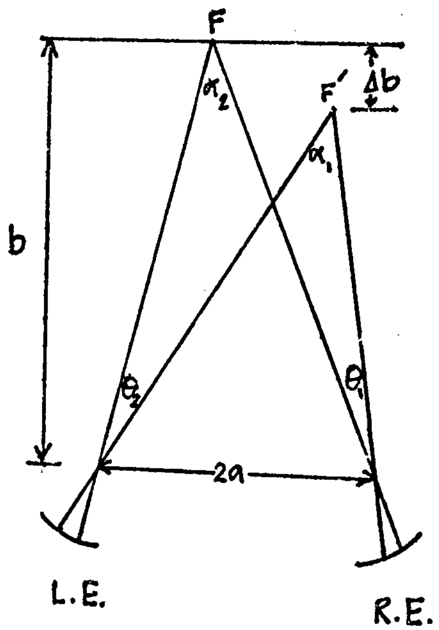


Figure 2-7. Figure used in derivation of linear depth in terms of angular disparity. (From [5]).

Since the difference in visual angles is the difference in convergences, we obtain:

$$\alpha_2 - \alpha_1 = \Theta_1 - \Theta_2 = \eta$$

$$\eta = \frac{2a}{b} - \frac{2a}{b \pm \Delta b}$$

$$= \frac{(2a)b \pm (\Delta b)(2a) - (2a)b}{b^2 \pm (\Delta b)b}$$

$$\eta b^2 \pm (\Delta b)b\eta = \pm(\Delta b)(2a)$$

$$\Delta b = \frac{\eta b^2}{(\pm 2a \mp \eta b)}$$

So if F' is distal to the fixation point, the disparity is said to be "uncrossed," the distal stereoscopic depth is given by

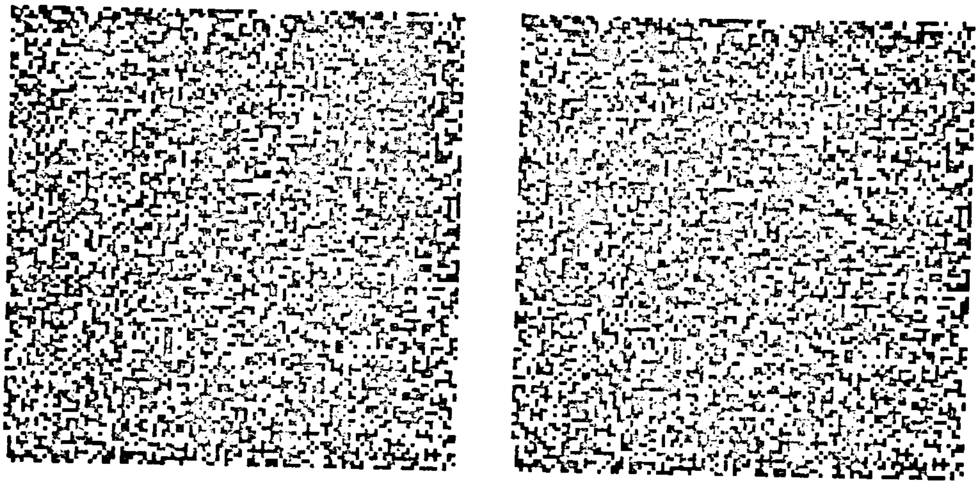
$$\Delta b = \frac{\eta b^2}{(2a-b\eta)}$$

2.3 Random Element Stereograms

After the development of the geometry of stereopsis had been researched, stereopsis was analyzed in many areas. One of these interesting areas, called random element stereogram, will be discussed in the following material.

Random element stereograms were invented by Julesz (1960). The basic idea to generate the kind of stereogram is depicted in Figure 2-8 (A-B).

Julesz generated random element stereograms by using a computer as shown in Figure 2-8A. In Figure 2-8B, each side of a stereopair of the pattern comprises a matrix of random dots. The matrices are identical except for the certain areas that are identical but shifted horizontally. The shifted area (denoted by A and B dots) covers certain areas of the background (denoted by 1 and 0 dots). The certain areas uncovered (denoted by X and Y cells), because of shifting of the shifted area, are filled with an independent set of random dots. The result of horizontal shifting causes binocular parallax when the stereopair of pattern is viewed in a stereoscope, the area where the disparity exists stands out from the reference plane. The direction of stereopsis depends on



A. Random dot stereogram of Julesz

1	0	1	0	1	0	0	1	0	1
1	0	0	1	0	1	0	1	0	0
0	0	1	1	0	1	1	0	1	0
0	1	0	Y	A	A	B	B	0	1
1	1	1	X	B	A	B	A	0	1
0	0	1	X	A	A	B	A	1	0
1	1	1	Y	B	B	A	B	0	1
1	0	0	1	1	0	1	1	0	1
1	1	0	0	1	1	0	1	1	1
0	1	0	0	0	1	1	1	1	0

1	0	1	0	1	0	0	1	0	1
1	0	0	1	0	1	0	1	0	0
0	0	1	1	0	1	1	0	1	0
0	1	0	A	A	B	B	X	0	1
1	1	1	B	A	B	A	Y	0	1
0	0	1	A	A	B	A	Y	1	0
1	1	1	B	B	A	B	X	0	1
1	0	0	1	1	0	1	1	0	1
1	1	0	0	1	1	0	1	1	1
0	1	0	0	0	1	1	1	1	0

B. The principles of construction

Figure 2-8. Random dot stereogram and the principles of construction. (From [7]).

whether the displacement in the central region is nasal or temporal (nasal displacements are associated with points farther than the fixation plane, and temporal displacements are associated with the points nearer than the fixation plane).

The importance of this technique originates from the fact that monocular pattern recognition cannot occur in the sense that neither half of the stereogram alone contains cues to the binocular stereoscopic pattern that emerges. Though the direction of stereopsis obtained from this technique follows the geometry of stereopsis, the fact that depth occurs in this stereogram is still inconsistent.

There is a question in Julesz's random dot stereograms, as to why the subject sees the planes of depth, and why the dots in the disparate regions do not fuse with all of the other nearby disparate dots, thereby producing uncertain depth.

From the stereogram in Figure 2-9, there exists the possible fusional possibilities, lines a and b, a and F', F and F' and F and b. But only lines a and b, F and F' actually occur in perception. Yet, there is no fusional theory to describe this fact. Julesz (1971) pointed out that multiple fusional possibilities or "ghosts" may exist. He proposed a model of stereoscopic depth perception called "difference field model" ([7] and [8]), modified from fusion theory, which he believed capable of eliminating ghost images in his stereograms. However, the difference field model is unable to eliminate ghosts in line stereograms. The next question in the random element stereogram is how false localization of targets (ghosts) occurs in binocular vision, and how the eyes perceive only the true targets. As shown in Figure 2-10, there are four points in both the right eye view and the left eye view. There are

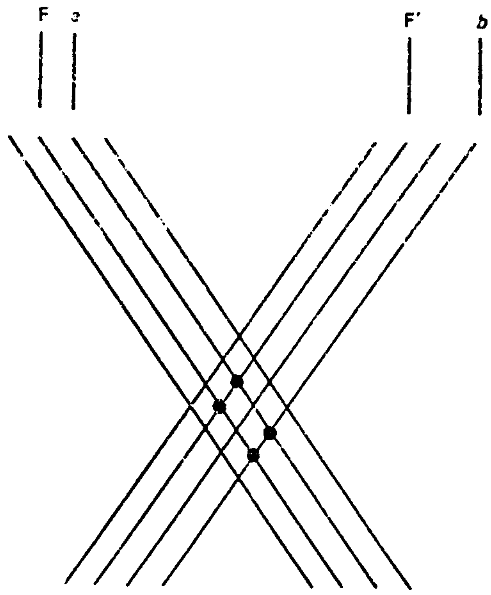


Figure 2-9. "Ghost" images occur when F combines with b and F' combines with a. (From [3]).

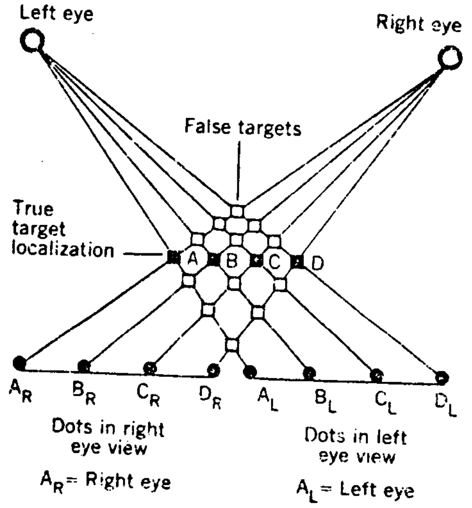


Figure 2-10. Illustration of true targets on false targets localization. (From [7]).

sixteen different fusional possibilities. This means that there are twelve false targets (ghosts) since only four true targets (A, B, C, D) actually occur. It has been illustrated ([7]) that no matter how many point targets there are, the ratio of the number of false targets to all targets is $(N^2-N)/N^2$. So the number of false targets is much more than the number of the whole targets in one situation. The visual system, however, resolves the ambiguities of the locally fused corresponding points in the two retinal projections so that only the true targets are perceived.

CHAPTER 3

DESIGN CONSIDERATIONS OF STEREOSCOPIC DISPLAY

One can see the three-dimensional objects obtained by looking at photographed double images through double viewers. Two types of these are: those that use the separate pictures, each eye seeing only one of the pictures and those in which the two pictures are superimposed but are in different colors and are viewed through the colored viewers. The concept of both cases is the same: one eye sees one picture, the other eye sees the other picture and the depth can appear. The diagram of how two projections of an object give rise to a three-dimensional sensation is shown in Figure 3-1.

Stereograms can be generated from various types of data. For example, as shown in Figure 3-2B, the waveform of EEG's are recorded by conventional electrodes. An example of those waveforms is shown by analyzing a single waveform shown in Figure 3-2A. The power spectra are generated by obtaining the Fast Fourier Transform and the components are subjected to smoothing and displayed with override suppression. Then, the smooth curves are digitized and the data file will be obtained. Figure 3-2B shows a hidden line display of this data. Since some portion of the lines are hidden, the information of those data must be lost. This problem can be eliminated by viewing the top view

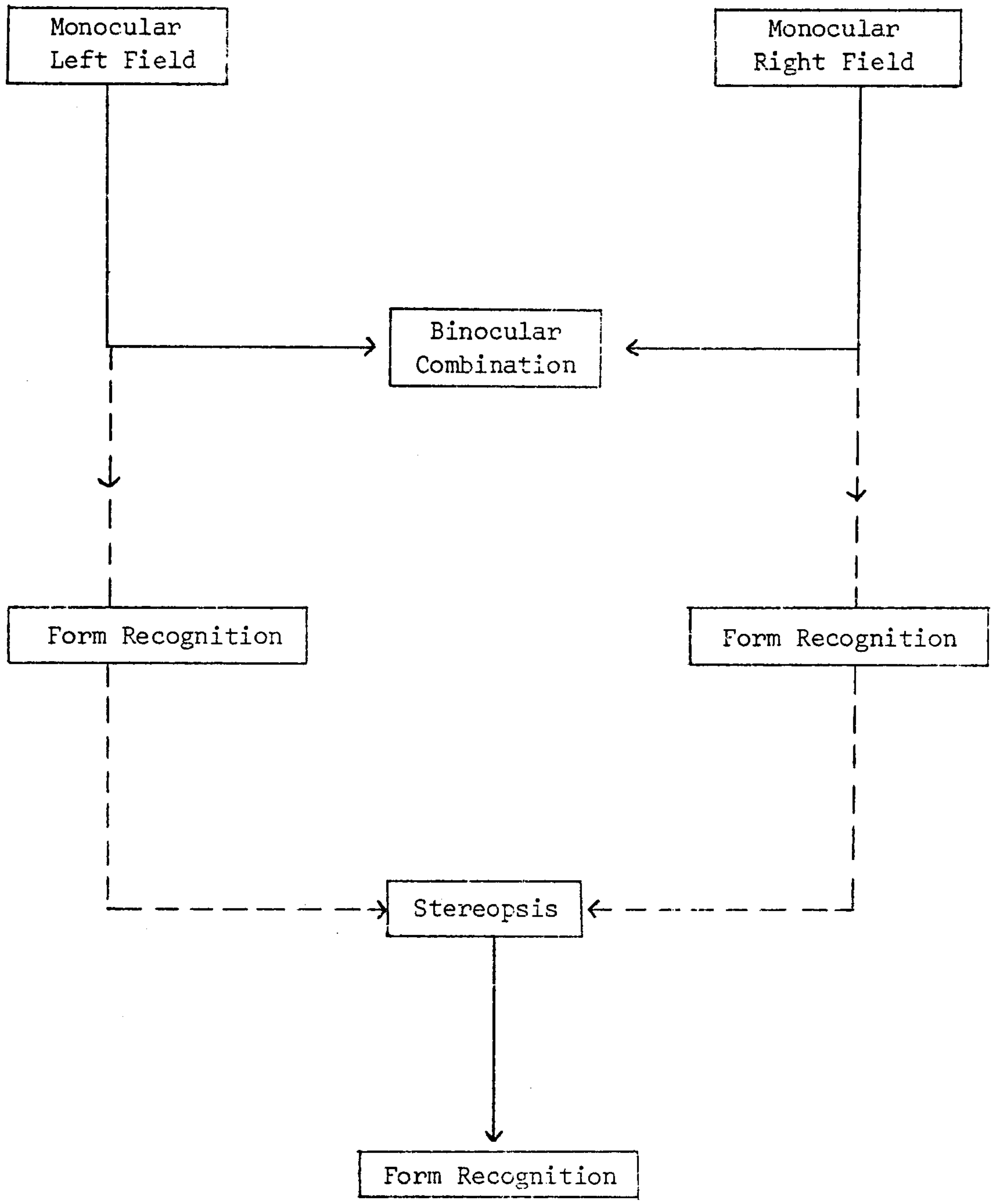
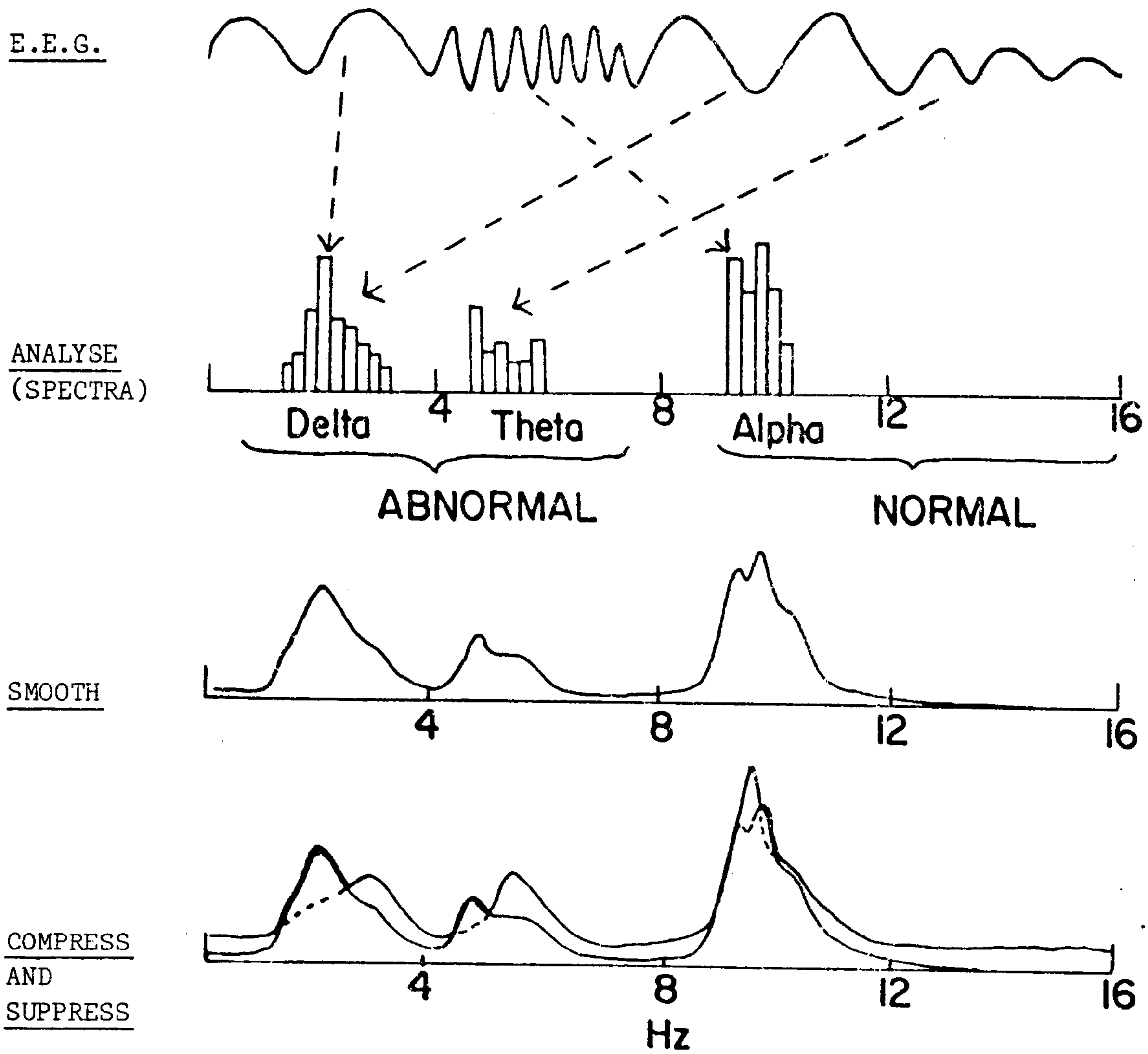
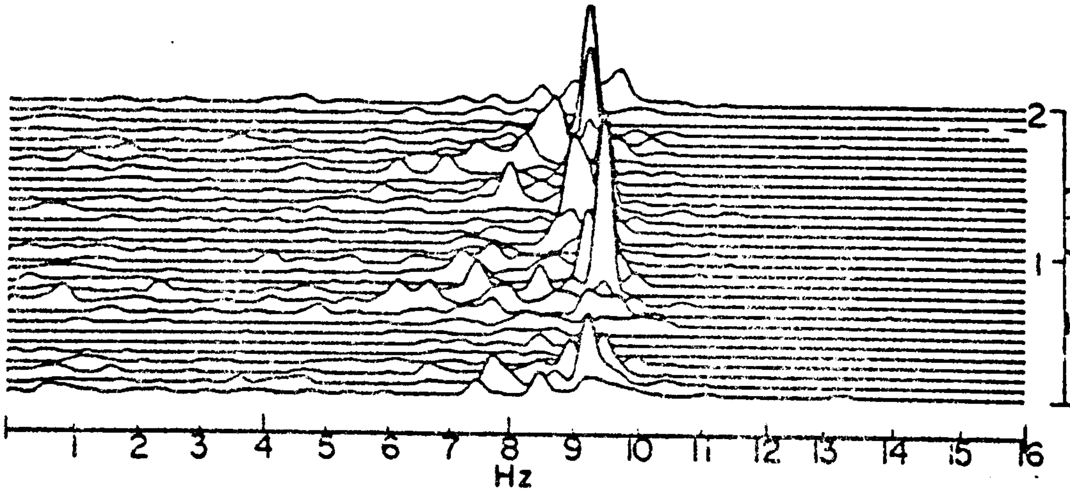


Figure 3-1. Flow diagram of a stereopsis. (From [7]).



A. Diagram of Method

Figure 3-2. The example of the EEG data. (From [9]).



B. Spectral Display of the EEG of a Normal Subject

Figure 3-2. (Continued)

obtained from techniques for generating stereoscopic displays. Also, contours obtained from processed maps can be the data in stereo generation. Once data has been obtained, the method of stereogram generation using a minicomputer can be employed. It will be explained next.

3.1 Extracting Stereopairs from the Known Heights

The analog data shown in Figure 3-3 can be used to generate stereoscopic stimuli after first being digitized. (In this research, the data is digitized into 128 points for each waveform.) The point P(x, y) generates a pair of points, $P_L((x-d),y)$ and $P_R((x+d),y)$, d is the disparity.

The height, h, at P(x,y) is rescaled to be the gray level at this particular point. The two halves of a stereopair, the red one and the green one, are generated by assigning the gray level h to the brightness of the particular color. But a problem can occur if the brightness is

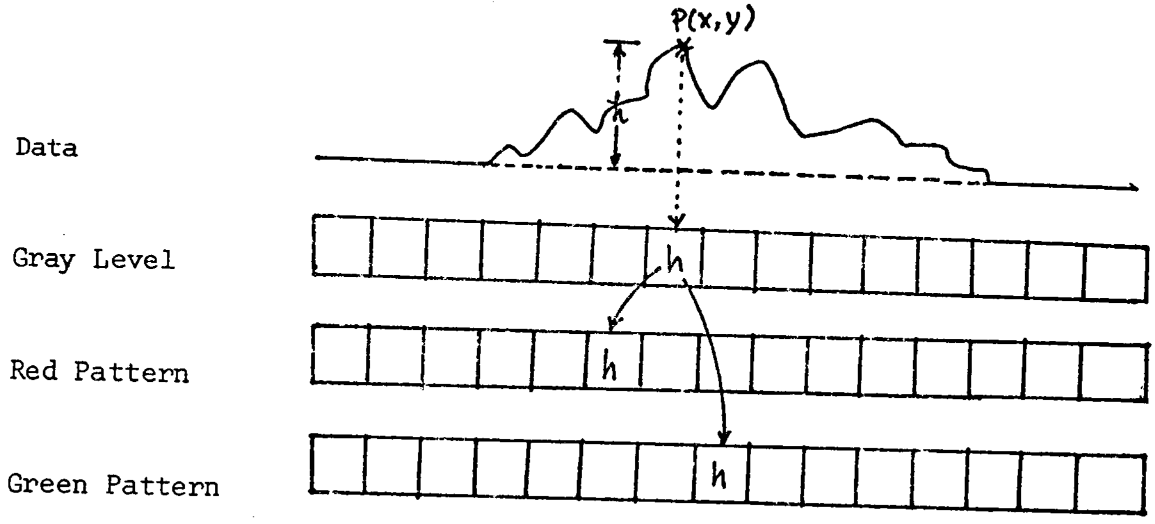


Figure 3-3. An algorithm of extracting stereopairs processing approach.

filled in the same point many times, since the disparities generated from different points do not have to be the same value. In this case, one should keep the highest value of brightness at each point. This means that when one looks at the pattern from the top view, the higher portion should be seen rather than the lower one.

When the stereoscopic stimuli are generated, one pattern must be superimposed by the other one. This superimposed pattern is the anaglyph mentioned in Section 2.2.2. The stereoscopic depth will be perceived if one views the anaglyph through the red-green filter. The flowchart for the method of extracting stereopairs is shown in Figure 3-4.

This method can be modified to make strong stereoscopic stimuli with great detail by repeating the number of rows of each pattern to make it clearer. Interpolation between the curves may be useful since it makes the pattern look smoother. Finally, one might repeat the columns of each one so that the depth may be perceived. In case of disparity, it can be produced and manipulated from Figure 3-5.

As shown in Figure 3-5, we obtain

$$\Delta ABC \sim \Delta\ ADE$$

$$\frac{h}{(H-h)} = \frac{d}{L}$$

$$d = \frac{hL}{(H-h)}$$

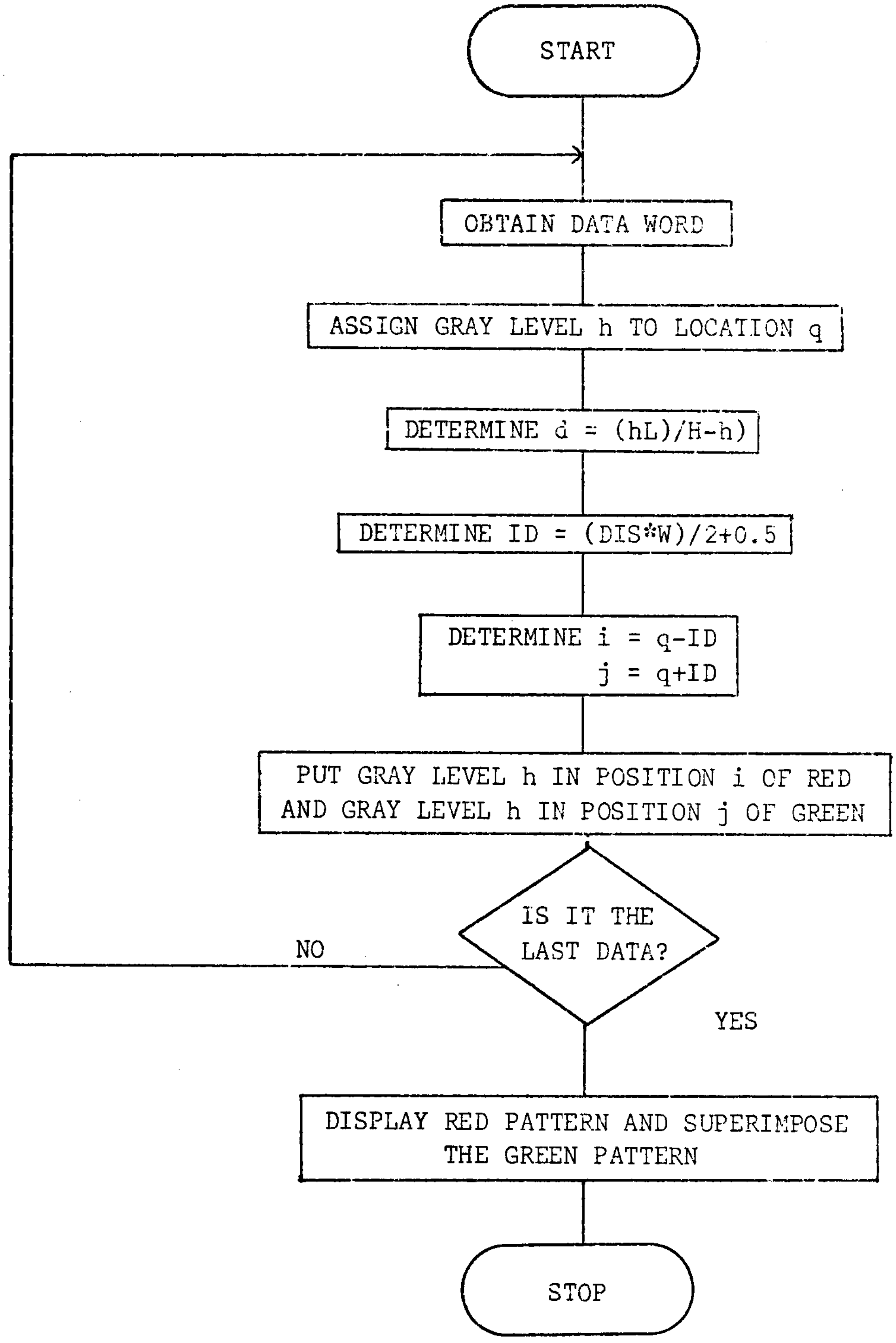


Figure 3-4. The flowchart for the solution of extracting stereo-pairs.

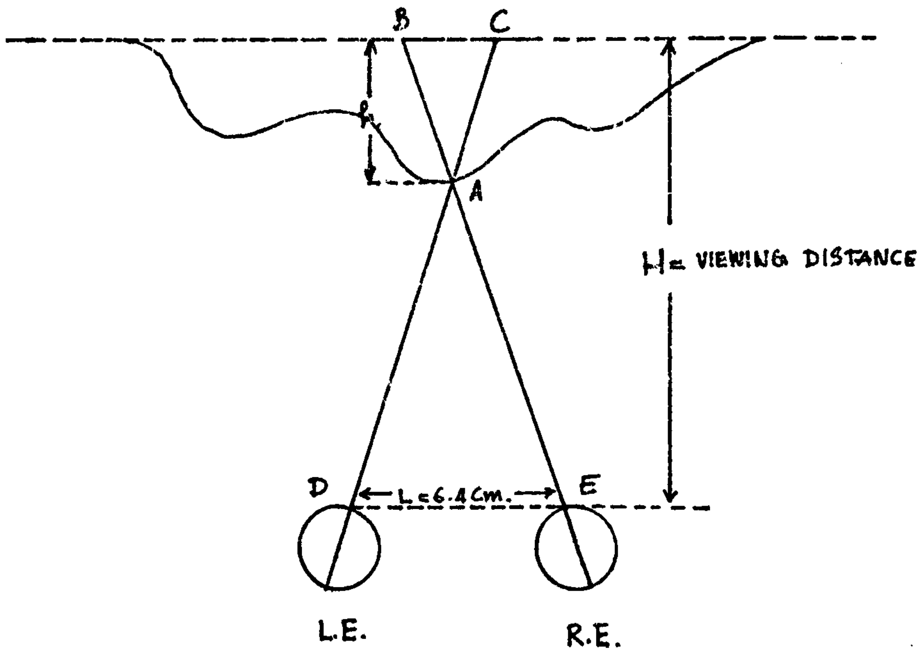


Figure 3-5. The image A arises in the projection field when the half-images B and C, on the plane of fixation, are fused.

where d is the disparity (in unit of length) of the two half-images, h is depth, H is the viewing distance, and L is the interocular distance (about 6.4 cm). To determine the number of pixels to be shifted to the left side and right side, one has to change the value of d to be the number of pixels. This can be arrived at by multiplying the length d by the number of pixels per centimeter, W.

3.2 Generating Random Element Stereograms

The basic idea of random element stereograms has been described in Section 2.3. A stereopair of the pattern is assigned a brightness value at random. The number of brightness levels are not important to affect stereopsis. The horizontal displacement causes binocular parallax and the direction of stereopsis. Stereopsis, however, is obtained from emergence of the matching point domains.

The stimuli used in this research are simple figures, such as a square, T-shape and ring-shape in three dimensions. These figures are not difficult to create and one does not have to have a pictorial input facility. The minicomputer uses a subroutine to generate the psuedo-random numbers, 1's and 0's, to fill in both matrices. When the input data of the arrays for the left eye and right eye have to be filled in, the disparity must be assigned which, in turn, determine the displacement. The uncovered area must be filled in with another set of random 1's and 0's. If two disparities overlap, the computer must keep the one with greater height. When a cell that has been filled in randomly must be assigned a value, then the computer uses the value.

The images of the left eye and the right eyes are displayed in red and green, respectively. The stereoscopic depth will be obtained by looking through the red-green filters.

The flowchart of this method is shown in Figure 3-6.

3.3 Generating Stereopairs Via Perspective Transformation

The three-dimensional object can be displayed by the technique mentioned in Sections 3.1 and 3.2. Since a discrete image is represented by the matrix consisting of cells or pixels, another technique to create stereopairs is the transformation of matrices, called perspective transformations.

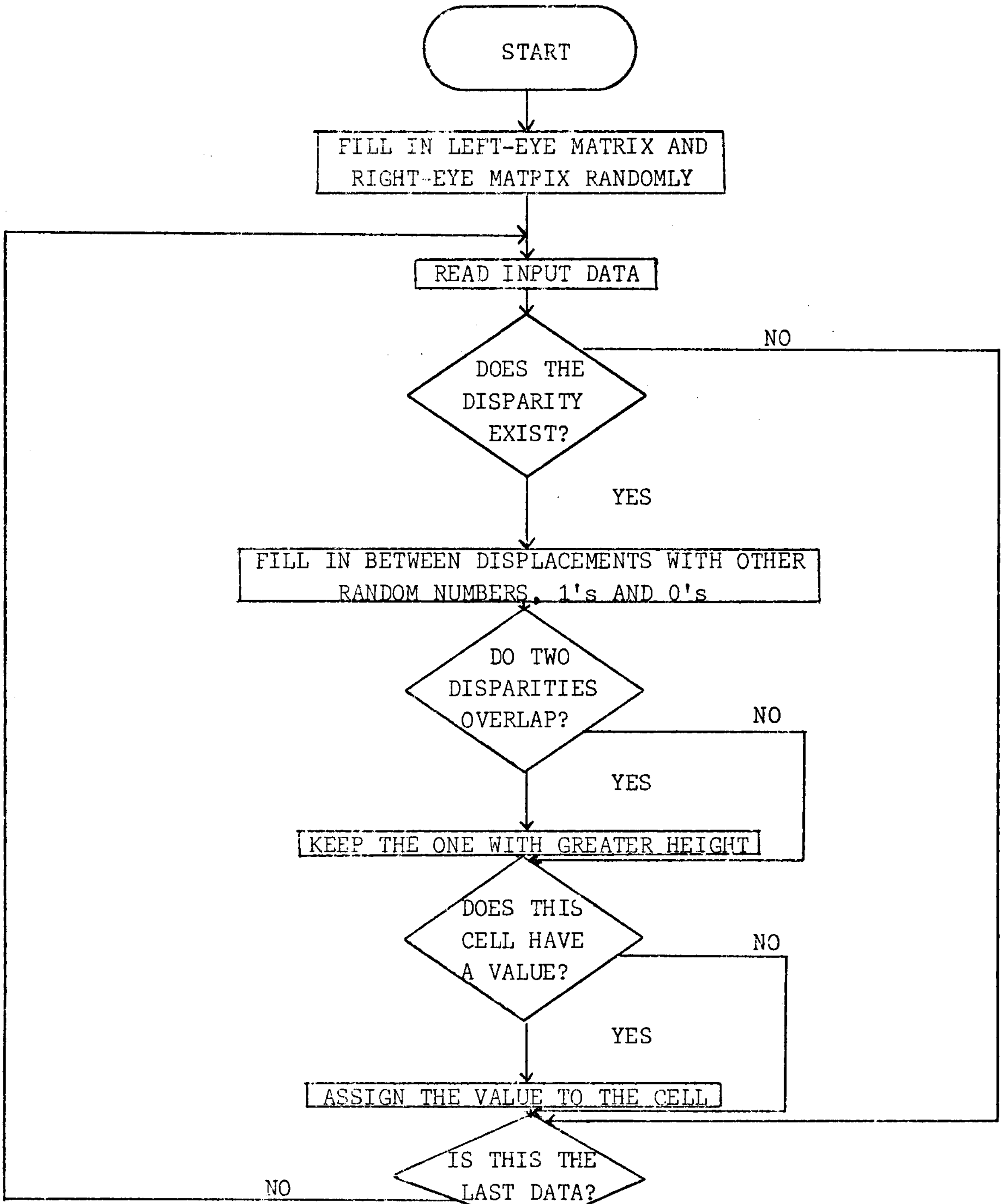


Figure 3-6. The flowchart of generating random element stereograms.

Suppose a three-dimensional point in homogeneous coordinates $(x_1,y_1,z_1, 1)$ is transformed to the point $(x_2, y_2, z_2, 1)$, we have

$$[x_1,y_1,z_1,1]\ [T] = [x,\ y,\ z,\ h]$$

$$\text{and } [x_2,y_2,z_2,1] = [\tfrac{x}{h}\ \tfrac{y}{h}\ \tfrac{z}{h},\ 1]$$

where T is a transformation matrix (from [9] and [10]). The matrix T is represented by

$$[T] = \begin{bmatrix} T_{11} & T_{12} & T_{13} & T_{14} \\ T_{21} & T_{22} & T_{23} & T_{24} \\ T_{31} & T_{32} & T_{33} & T_{34} \\ T_{41} & T_{42} & T_{43} & T_{44} \end{bmatrix}$$

This transformation shows that the points or pixels of one image can be transformed to the corresponding points of another one. The effect of the elements of matrix T are shearing, scaling, rotation, translation, perspective and overall scaling. T_{41}, T_{42} and T_{43} produce translation along x, y and z axes, respectively. T_{14}, T_{24} and T_{34} produce perspective transformation. T_{12}, T_{13}, T_{21}, T_{23}, T_{31} and T_{32} produce rotation and shearing. T_{11}, T_{22} and T_{33} produce scaling in each axis. T_{44} produces the overall scaling. This transformation matrix is very useful to transform the image to the desired positions. In this research, the perspective transformation and translation will be discussed since it is used for creating stereopairs.

Suppose the point $[x_1, y_1, z_1, 1]$ in one image is perspectively transformed to the corresponding point $[x_2, y_2, z_2, 1]$ of the second image, we have

$$[x_1, y_1, z_1, 1] \begin{bmatrix} 1 & 0 & 0 & p \\ 0 & 1 & 0 & q \\ 0 & 0 & 1 & r \\ 0 & 0 & 0 & 1 \end{bmatrix} = [x_1, y_1, z_1, (px_1+qy_1+rz_1+1)]$$

then we have

$$x_2 = \frac{x_1}{H} = \frac{x_1}{(px_1+qy_1+yz_1+1)}$$

$$y_2 = \frac{y_1}{H} = \frac{y_1}{(px_1+qy_1+rz_1+1)}$$

$$z_2 = \frac{z_1}{H} = \frac{z_1}{(px_1+qy_1+rz_1+1)}$$

which will yield three vanishing points, at $[\frac{1}{p}, 0, 0, 1]$ on x-axis, at $[0, \frac{1}{q}, 0, 1]$ on y-axis, and at $[0, 0, \frac{1}{r}, 1]$ on z-axis. This is called three-point perspective transformation. If one or two of these elements (p, q and r) of the transformation matrix are zero, the transformations are called single-point or parallel perspective transformation and two-point or angular perspective transformation respectively. The single-point transformation yields one vanishing point, and the two-point transformation yields two vanishing points.

If p=0 and q=0, the transformation matrix is

$$[T] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & r \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The three-dimensional point can be perspectively projected to the z=0 plane by the transformation below.

$$[x_1, y_1, z_1, 1] \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & r \\ 0 & 0 & 0 & 1 \end{bmatrix} = [x_1, y_1, 0, (rz_1+1)],$$

and if $r = \frac{1}{k}$

$$x_2 = \frac{x_1}{rz_1+1} = \frac{x_1}{\frac{z_1}{k}+1}$$

$$y_2 = \frac{y_1}{rz_1+1} = \frac{y_1}{\frac{z_1}{k}+1}$$

$$z_2 = \frac{0}{rz_1+1} = 0$$

This transformation yields the center of projection located at [0, 0, -k, 1] on the z-axis.

To generate stereographic projection, the single-point perspective transformation with the vanishing point on the z-axis can be used to create the perspective projection to the image plane. The stereopairs have to be shifted horizontally. To meet the requirements previously mentioned, the transformation matrices for the left-eye image and right-eye images are:

$$T_L = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{k} \\ d & 0 & 0 & 1 \end{bmatrix} \quad \text{and} \quad T_R = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{k} \\ -d & 0 & 0 & 1 \end{bmatrix}$$

respectively.

The element d is the number of pixels to be shifted to the right or left of the original image. But there might be a problem that there may be many points in the original image transformed to the same point in the two-dimensional image. This case causes the hidden points condition that may yield holes in the transformed images. To eliminate the holes, one may use the nearest neighbor criterion to assign values to these holes to make the images smooth.

Suppose there is a hole at (x, y, 0, 1) in the transformed image and the neighbors are as shown:

12	12	14
12	0	15
14	15	15

12	12	14
12	13.5	15
14	15	15

one can assign the value 13.5 to this hole. There are other methods used for interpolating ([11] and [12]) the images, but these are more difficult and are outside the scope of this research.

Thus, one can create stereopairs by using the perspective transformation method. Then, the stereopairs may be displayed in red and green. The stereoscopic depth will be perceived by viewing through the red-green filters.

Up to this point, three techniques for generating stereograms have been presented. The specific conditions and examples of the results of each technique will be discussed in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSION

The three techniques have been explained in Chapter 3. The methods for each technique have different conditions, limitations and results. The discussion of the methods will be discussed next.

4.1 Method 1. Extracting Stereopairs from the Known Heights

As mentioned in Section 3.1, the disparity d can be calculated from the formula $d = (hL/(H-h))$. Then the disparity is changed to the number of pixels, $d*w$, where w is the number of pixels per centimeter. Finally, the relationship between the disparities and the heights are shown in Table 4-1.

The viewing distance will be varied in some ranges. For a human with average eyesight, the strongest stereo-effect occurs at a viewing distance of about 50 cm [11]. The disparity should not be greater than 7 pixels in order that the points can be fused into one. The maximum height perceived will not be more than 9 centimeters. The computer programs used in this technique have the same concepts:

1. In the event that more than one gray level is assigned to the same pixel, keep the highest value and

2. Perform truncation of the pixel locations to integer values as a last step to maintain as much precision as possible.

TABLE 4-1

THE DISPARITY (IN PIXELS) AND THE HEIGHTS (IN cm)

Disparity (in Pixels)	The Heights, h
0	$0.00 \leq h < 0.74$
1	$0.74 \leq h < 2.17$
2	$2.17 \leq h < 3.49$
3	$3.49 \leq h < 4.80$
4	$4.80 \leq h < 5.97$
5	$5.97 \leq h < 7.10$
6	$7.10 \leq h < 8.19$
7	$8.19 \leq h < 9.22$

4.1.1 Results. The examples of the results of Method 1 are illustrated in Figures 4-1, 4-2, 4-3 and 4-5. Figure 4-4 is an example of the hidden line technique. In Figures 4-1 and 4-2, the squares have the disparities of 4 and 8 pixels, respectively. When these images are viewed through the red-green viewer, the square pattern in Figure 4-1 is apparently in front of the background. The image in Figure 4-2 is seen as double images. Figure 4-3 shows the result of various repetitions of lines. Figure 4-5 is the stereoscopic image of Figure 4-4. Both of

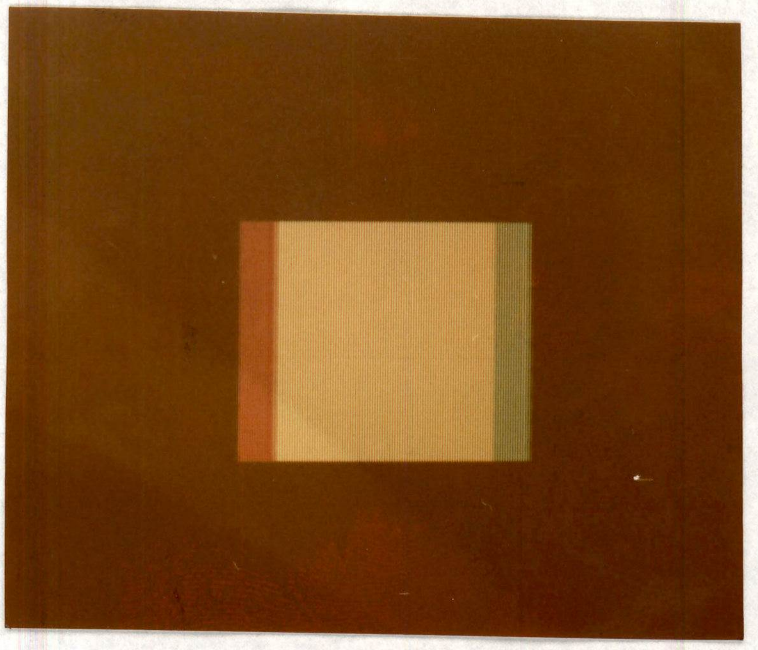


Figure 4-1. The square pattern obtained from Method 1 with 4 pixels of disparity.

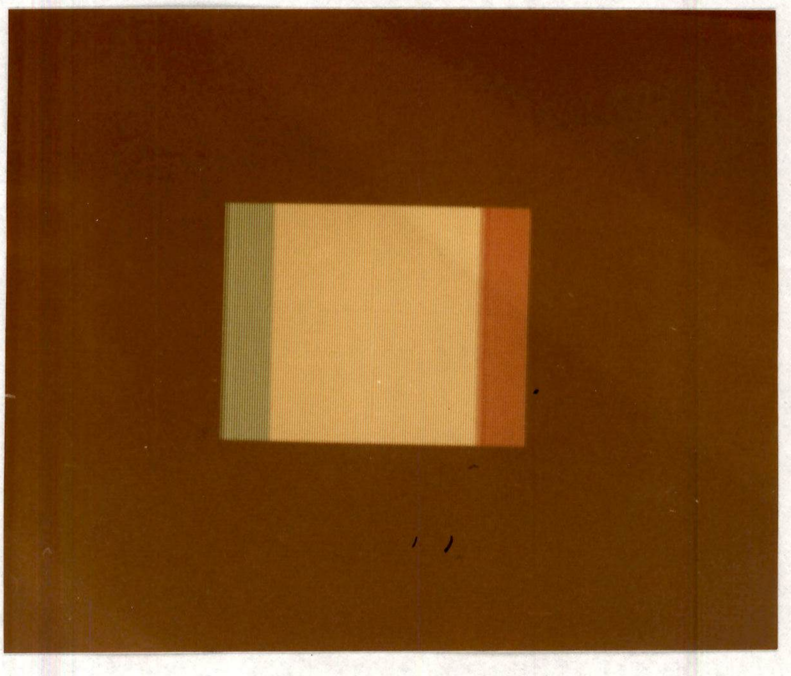


Figure 4-2. The square pattern with 8 pixels of disparity.

Figure 4-3. The curves with different repetition of lines.

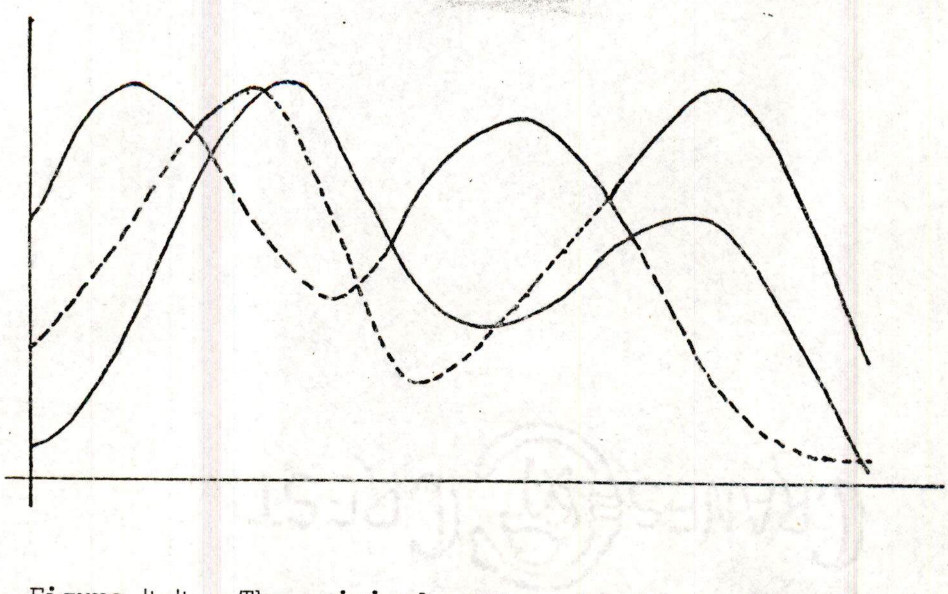


Figure 4-4. The original pattern of three lines with hidden lines.

The dashed lines are the hidden parts of the lines.

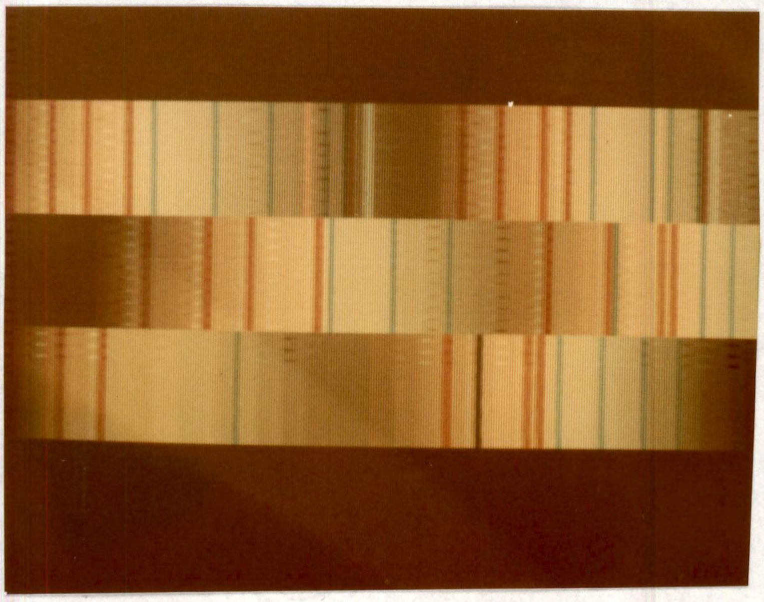


Figure 4-5. The stereoscopic image of Figure 4-4, obtained from Method 1.

those two images are not completely fused to obtain stereopsis no matter what the number of repeated lines are.

4.1.2 Discussion. The square pattern in Figure 4-1 is seen as a single fused image, but the one in Figure 4-2 is seen as the double images because the disparity is too great. This agrees with the theory that if the disparity is not too great, the object will be seen as nearer or farther than the fixed objects (reference plane). The stereopsis of Figures 4-3 and 4-5 are not perceived because the pairs of the heights cannot be fused. Perhaps fusion does not occur because the visual system cannot consistently resolve the cues of intensity and disparity which may sometimes be in conflict.

4.2 Method 2. Generating Random Element Stereograms

The objective of this method is to create the stereograms of the patterns. This technique is approached by the use of Julesz's method described in Chapter 3. One has to remember that stereopsis occurs from the fusion of the cluster of dots. The horizontal displacement of those dots causes binocular parallax. The number of brightness levels is not important ([13] and [14]). The program RANDOM. FOR used to generate random element stereograms is given in the Appendix.

4.2.1 Results. The example results of Method 2 are illustrated in Figures 4-6 through 4-12. Figures 4-6 through 408 show the example results of the distribution of black elements to be used. The one with

50% black elements is the superior. Figures 4-9 through 4-11 are the patterns of a square, double squares and a ring, respectively. For the double squares, the inner one is higher than the outer one. Figure 4-12 is the stereoscopic image of the hidden lines in Figure 4-4.

4.2.2 <u>Discussion</u>. As shown in Figures 4-6 through 4-8, the letter "T" is well perceived when the percentage of the black elements is 50%. In Figures 4-9 and 4-11, the square and ring are perceived very well. The inner square is higher than the outer one in Figure 4-1 because their disparities are 5 and 3, respectively. This means that the greater disparity yields the higher height. In Figure 4-12, the three lines are the stair patterns. Those lines can be perceived stereoscopically, but the boundaries are not sharp. This is because the patterns are discrete and need to have clusters to be perceived.

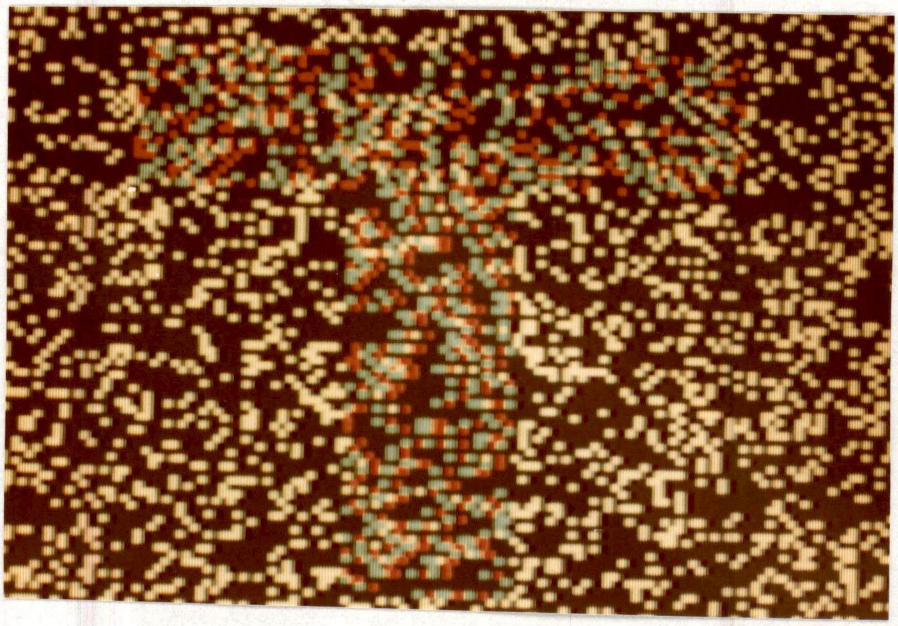


Figure 4-6. The "T" pattern with 80% of elements.

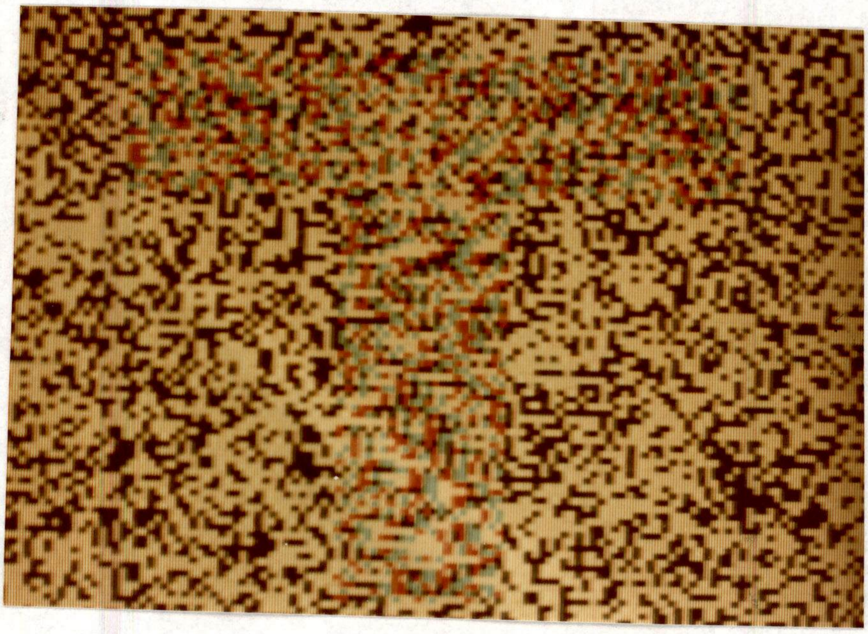


Figure 4-7. The "T" pattern with 50% of elements.

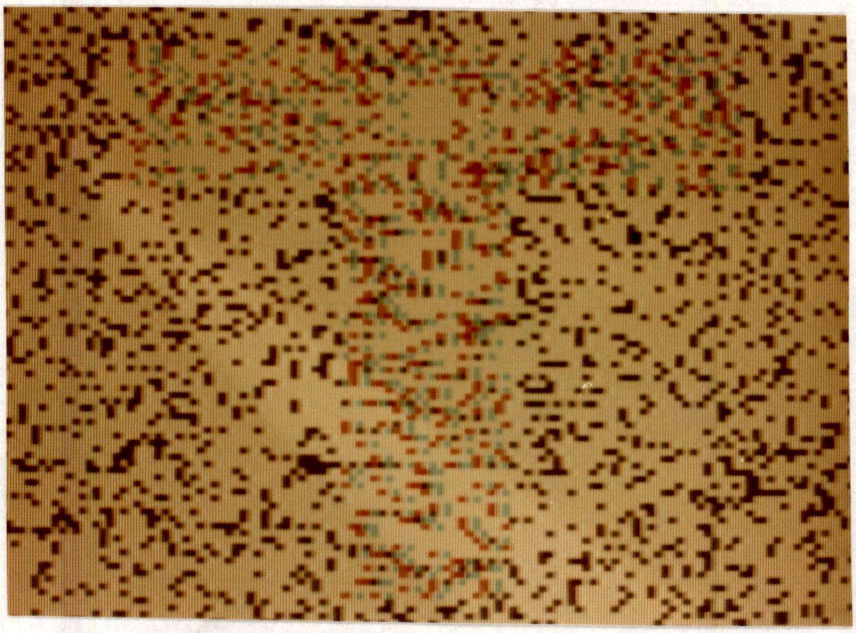


Figure 4-8. The "T" pattern with 20% of elements.

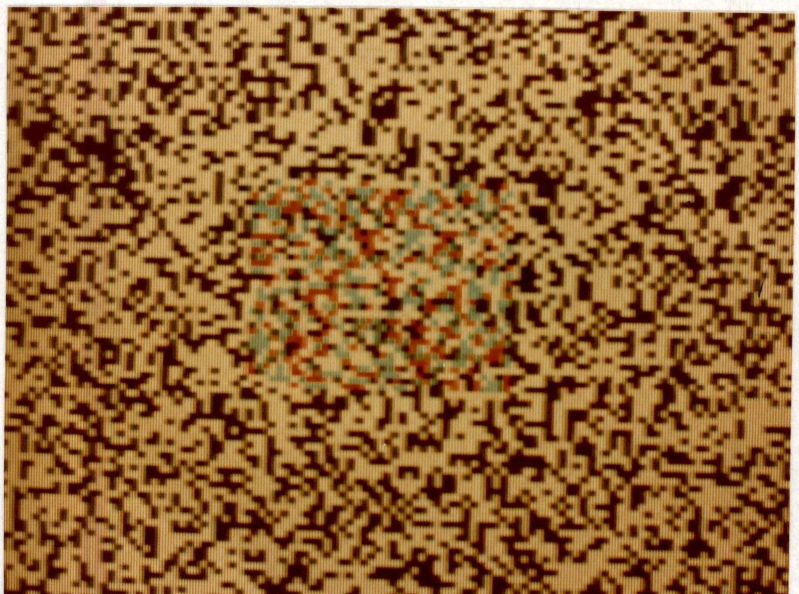


Figure 4-9. The square pattern with 4 pixels of disparity.

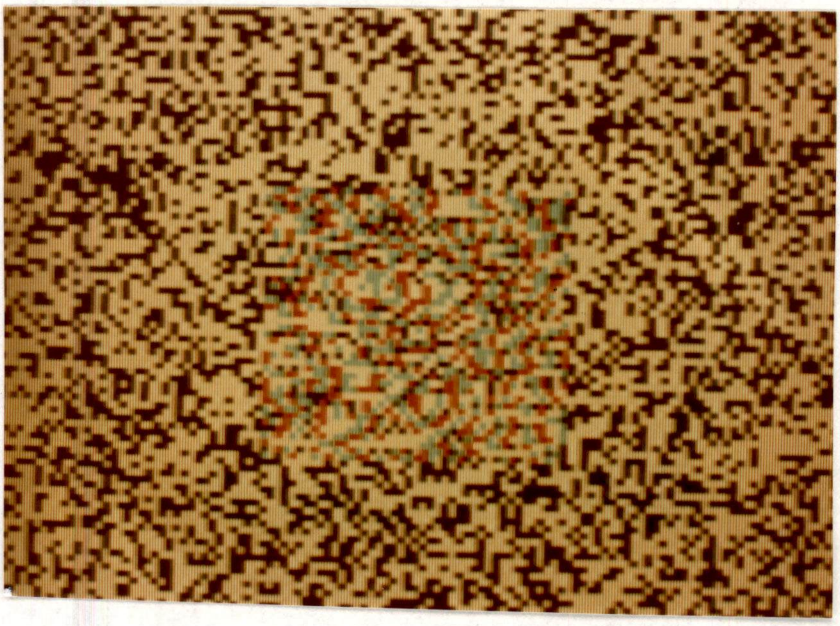


Figure 4-10. The double square patterns.

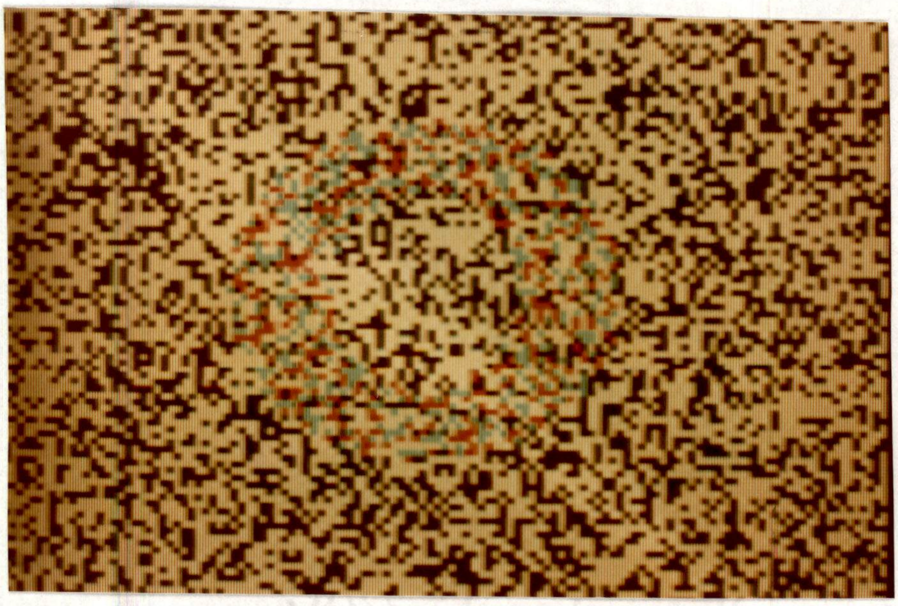


Figure 4-11. The ring pattern.

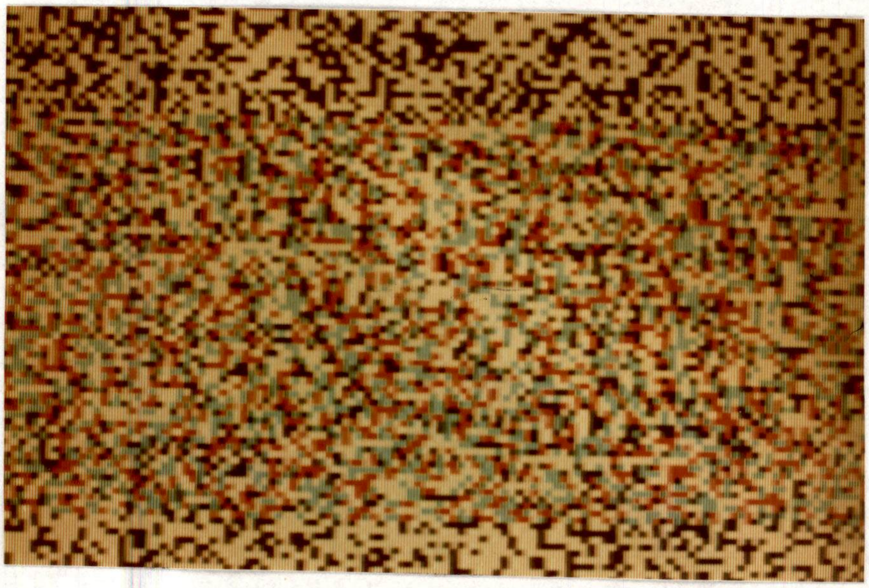


Figure 4-12. The stereoscopic image of Figure 4-4, obtained from Method 2.

4.3 Method 3. Generating Stereopairs Via Perspective Transformation

As mentioned in Section 3.3, the stereopairs created from the perspective transformation have the transformation matrices for the left-eye image and right-eye image as shown below.

$$[T_L] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{k} \\ d & 0 & 0 & 1 \end{bmatrix}; \quad [T_R] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{k} \\ -d & 0 & 0 & 1 \end{bmatrix}$$

The element d will perform the horizontal displacement, and k is the distance from the center of projection to the image plane (x-y plane). From the transformation from one image to the second image with the above transformation matrices, we obtain

$$x_2 = \frac{x_{1 \pm d}}{\frac{-z_1}{k} + 1}, \quad y_2 = \frac{y_1}{\frac{-z_1}{k} + 1}$$

Since x_1, y_1, x_2 and y_2 are always positive, we obtain

$$\frac{-z_1}{k} > -1$$

or

$$\frac{z_1}{k} < k$$

or

$$\boxed{z_1 < k}$$

i.e. the gray level, z_1, of one image must be smaller than the distance, k, from the center of projection to the image plane.

4.3.1 Results. The example results of this method are shown in Figures 4-13 through 4-17. Figure 4-12 in the stereoscopic image of the hidden lines shown in Figure 4-4. The lines are perceived well. Figure 4-14 is a segmented image with the range of gray levels from -128 to +127. The left-eye image and the right-eye image are shown in Figures 4-15 and 4-16, respectively. The holes can be seen in the figures. The stereoscopic image is shown in Figure 4-17.

4.3.2 Discussion. The lines in Figure 4-13 are perceived better than the lines in Figure 4-5. The holes in Figures 4-15 and 4-16 occur because there are some points in the original image that are mapped to the same point in the transformed image. However, stereopsis is perceived in Figure 4-17.

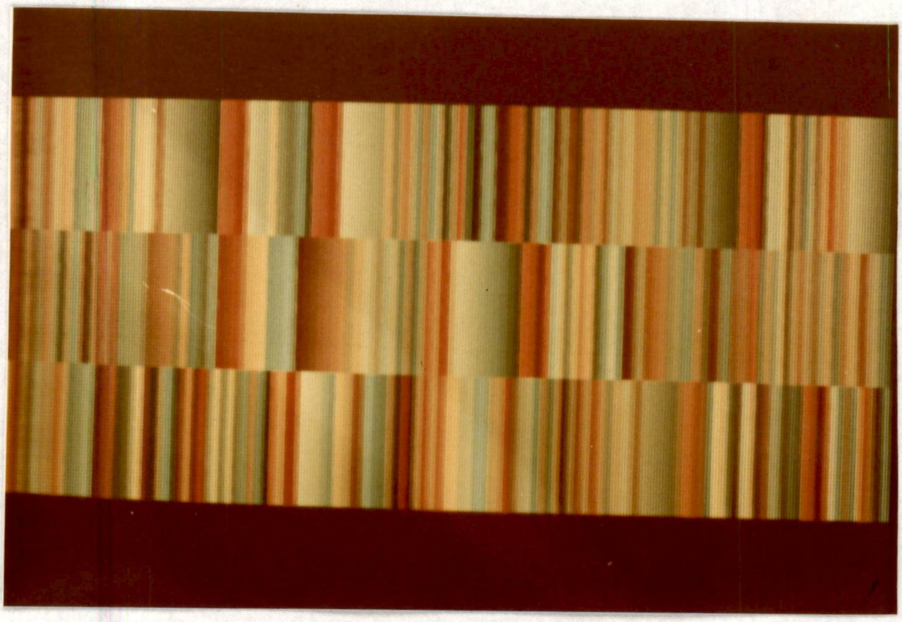


Figure 4-13. The stereoscopic image of Figure 4-4, obtained from Method 3.

Figure 4-14. The original image.

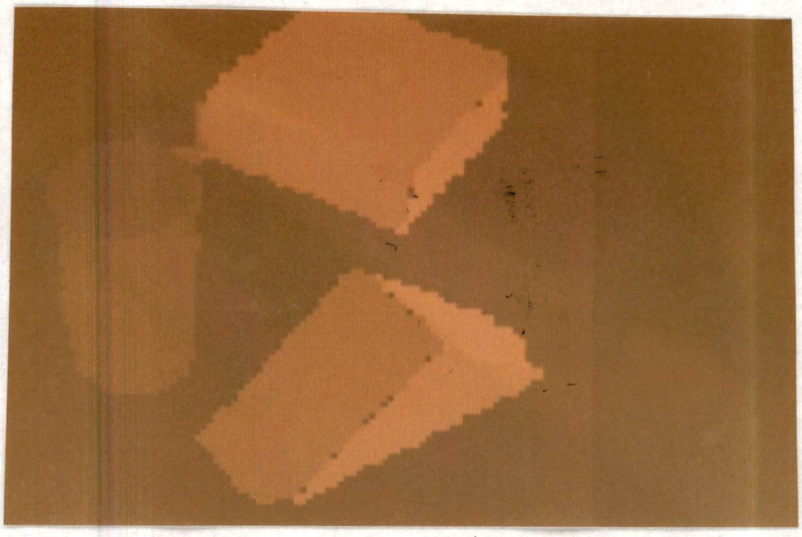


Figure 4-15. The left-eye image of Figure 4-14.

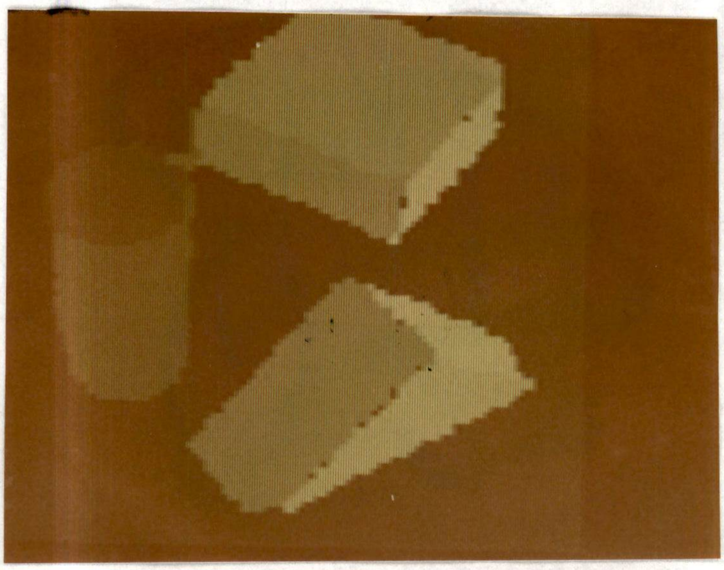


Figure 4-16. The right-eye image of Figure 4-14.

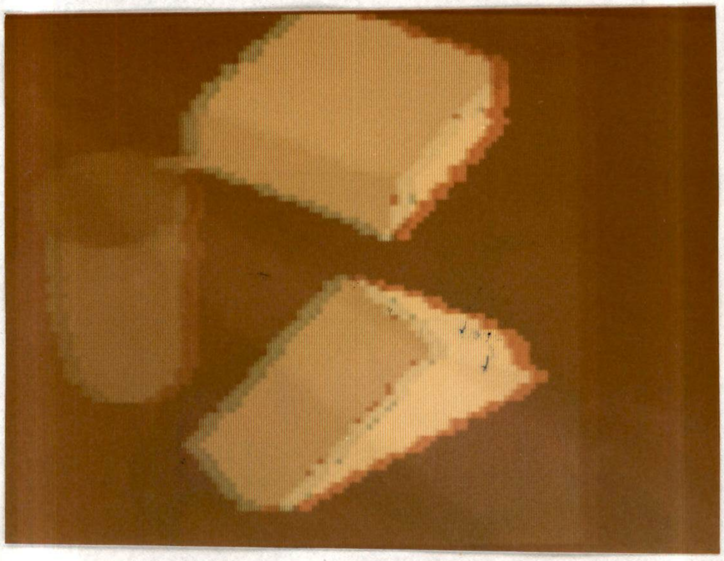


Figure 4-17. The stereoscopic image of Figure 4-14.

CHAPTER 5

SUMMARY

Three techniques for generating stereoscopic displays with a minicomputer have been illustrated. Though one does not obtain stereopsis from extracting stereopairs from the known heights, the random element stereograms and the stereopairs via perspective transformation work very well. At least, the results of these techniques make more understandable conditions of stereopsis with the use of a minicomputer. The second technique is suitable for obtaining the depth of only simple patterns since it does not show the boundaries of the different patterns clearly.

Therefore, this research has demonstrated the techniques and conditions of obtaining stereoscopic displays. Furthermore, it is hoped that it will be useful to future research about stereopsis and its applications.

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REFERENCES

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APPENDICES

APPENDIX A

The computer programs used in this research are written in higher language, FORTRAN. They are used with the Digital Equipment Corporation PDP-11/40 minicomputer and RT-11 system. The use and descriptions of those programs are explained below.

RANDOM.FOR

This program generates the random element stereograms. It can read the input data from any integer data file. The output images are the displaced random element images. Then, those images have to be displayed superimposedly to perceive stereopsis when one views through the red-green viewers.

MAT1.FOR

This program performs the general image transformations. The transformation matrix T can be changed to be associated with the particular type of transformation. The gray levels of the first output image are changed to be suitable for the machine to display the final image in colors (red, green or blue).

Any gray level N of a pixel of the image can be changed to the gray level M of the primary colors (red, green and blue) by the formulas below.

$$M = (N-8)*16 \qquad \text{where } 0 \leq N \leq 15$$

or

$$M = N*16 \quad \text{where } -8 \leq N \leq 7$$

This program also can be used to check the gray levels of any picture by using the transformation matrix, T, below.

$$T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

SUBROUTINE PICTUR (128)

This is a very useful subroutine since it can write any array of small (128 x 128) and medium (256 x 256) size to the disk file. It is very convenient to use this subroutine to store the arrays of the images onto the disk.

APPENDIX B

RANDOM.FOR

```
THIS IS THE PROGRAM USED FOR GENERATING RANDOM DOT
STEREOGRAM
H=VEIWING DISTANCE
AL=THE INTEROCULAR DISTANCE
W=PIXELS/CM.
A=ANY NUMBER BETWEEN 0. AND 1.
.......................................................................
INTEGER*2 IHI(128,128)
LOGICAL*1 IARRAY(128,128)
COMMON IARRAY
H=50.0
AL=6.4
W=5.182
A=0.4
GO TO 115
TYPE 111
FORMAT(' ENTER THE VALUE OF "A" ')
ACCEPT 112,A
FORMAT(F)
TYPE 120,A
FORMAT(' THE VALUE OF "A" IS',F)
TYPE 130
FORMAT(' DO YOU WANT TO CHANGE THE VALUE OF "A"?1 IS YES')
ACCEPT 140,IA
FORMAT(I)
IF(IA .EQ. 1) GO TO 1

CHOOSE THE TYPES OF DATA

TYPE 12
FORMAT(' WHICH PATTERN WOULD YOU LIKE?
1 1 SQUARE,
1 2 DOUBLE SQUARE,
1 3 T-SHAPE,
1 4 RING-SHAPE,
1 5 STAIR')
TYPE 13
FORMAT(' ENTER THE NUMBERS 1,2,3,.....OF THE DESIRED PATTERN')
ACCEPT 15,INP
FORMAT(I)
```

```
GO TO (21,22,23,24,25) INP
CALL SQR(IHI)
GO TO 28
CALL DSQ(IHI)
GO TO 28
CALL TSH(IHI)
GO TO 28
CALL RING(IHI)
GO TO 28
CALL STAIR(IHI)
GO TO 28

FILL THE LEFT VIEW RANDOMLY WITH 1 AND 0

LL=0
MM=0
DO 10 N=1,128
DO 10 M=1,128
YFL=RAN(LL,MM)
IF(YFL .LE. A) GO TO 4
YFL=15.0
GO TO 5
YFL=0.0
ILEFT=IFIX(YFL)
IARRAY(M,N)=(ILEFT-8)*16
CONTINUE

CREATE THE RED PATTERN(RIGHT EYE VIEW)

LL=100
MM=100
DO 300 N=1,128
DO 300 M=1,128
HEIGHT=IHI(M,N)
IF(HEIGHT .EQ. 0.0) GO TO 300
DIS=(HEIGHT*AL)/(H-HEIGHT)
IDIS=DIS*W+0.5
YFL=RAN(LL,MM)
IF(YFL .LE. A) GO TO 30
YFL=15.0
GO TO 40
YFL=0.0
IRED=IFIX(YFL)
IARRAY(M,N)=(IRED-8)*16
CONTINUE
CALL PICTUR(128)

FILL THE RIGHT VIEW RANDOMLY WITH 1 AND 0
```

```
LL=0
MM=0
DO 400 N=1,128
DO 400 M=1,128
YFL=RAN(LL,MM)
IF(YFL .LE. A) GO TO 350
YFL=15.0
GO TO 360
YFL=0.0
IRIGHT=IFIX(YFL)
IARRAY(M,N)=(IRIGHT-8)*16
CONTINUE

CREATE THE GREEN PATTERN(LEFT EYE VIEW)

LL=100
MM=100
DO 500 N=1,128
DO 500 M=1,128
HEIGHT=IHI(M,N)
IF(HEIGHT .EQ. 0.0) GO TO 500
DIS=(HEIGHT*AL)/(H-HEIGHT)
IDIS=DIS*W+0.5
YFL=RAN(LL,MM)
IF(YFL .LE. A) GO TO 420
YFL=15.0
GO TO 430
YFL=0.0
IGREEN=IFIX(YFL)
ICOL=N+IDIS
IARRAY(M,ICOL)=(IGREEN-8)*16
CONTINUE
CALL PICTUR(128)
STOP
END
```

APPENDIX C

MAT1 FOR

```
THIS PROGRAM IS MODIFIED FROM MATMUL.FOR WRITTEN BY
DAVID L. DAVIES. IT PERFORMS THE IMAGE TRANSFORMATIONS
USING A 4 BY 4 MATRIX.
 THE INPUT IMAGE  HAS THE GREY LEVEL FROM -128 TO 127.
THE OUTPUT IMAGES ARE RESCALED TO BE DISPLAYED IN COLORS
(RED,GREEN AND BLUE).


STANDARD OPENING FOR TWO PICTURE INPUT, ONE PICTURE OUTPUT
WITH ENTIRE OUTPUT IMAGE AVAILABLE FOR PROCESSING
AT ALL TIMES
SIZE: 128 X 128


COMMAND STRING FORMAT:  OUTPUT.PIC<GREY.PIC,RANGE.PIC


REAL T(4,4)
INTEGER*2 FILSPC(39),DEFEXT(4)
LOGICAL*1 LPIC1(8192),LPIC2(8192),LPIC3(16384),
1 IARRAY(128,128),TEMP(128,128)
EQUIVALENCE(LPIC3(16384),TEMP(128,128))
COMMON IARRAY
DATA DEFEXT/4*3RPIC/
CALL PRINT('ENTER COMMAND STRING')
        CALL PRINT('FORMAT IS:  OUT.PIC<GREY.PIC,RANGE.PIC')
CALL ICSI(FILSPC,DEFEXT,,,0)
IF(IFETCH(FILSPC(1))+IFETCH(FILSPC(16)).NE.0) STOP'FETCH'
IF(IFETCH(FILSPC(20)).NE.0) STOP'FETCH'
IF(LOOKUP(3,FILSPC(20)).NE.40) STOP'ENT'
IF(IENTER(1,FILSPC(1),LOOKUP(2,FILSPC(16))).NE.40) STOP 'FILE'

INITIALIZE BACKGROUND

DO 18 I=1,16384
LPIC3(I)=-128

INITIALIZE ARRAYS
```

```
DO 5 I=1,4
        DO 5 J=1,4
                T(I,J)=0.0
                CONTINUE
T(1,1)=.87
T(1,2)=-.5
T(2,1)=.5
T(2,2)=.87
T(3,4)=1.0
GO TO 7
CALL PRINT (' ENTER T MATRIX VALUES, ROW BY ROW,FORMAT F')
DO 15 I=1,4
                DO 15 J=1,4
                        ACCEPT 105,T(I,J)
FORMAT (F)


CALL PRINT ('ARRAY T HAS VALUES:')
DO 16I=1,4
                TYPE 106,T(I,1),T(I,2),T(I,3),T(I,4)
FORMAT (1X,4F)
                CONTINUE
CALL PRINT('    ')
CALL PRINT(' DO YOU WISH TO CHANGE MATRIX T ? 1 INDICATES YES')
        ACCEPT 104,IFLAG
        IF (IFLAG .EQ.1 ) GO TO 6



READ HALF OF EACH INPUT PICTURE AT ONE TIME

DO 8 IBLK=0,1
IDUM= IREADW(256,LPIC1,0,2)
IDUM = IWRITW(256,LPIC1,0,1)
IDUM = IREADW(4096,LPIC1,8+16*IBLK,2)
IF ((IDUM) .NE. 4096) STOP 'READ'
IF (IREADW(4096,LPIC2,8+16*IBLK,3) .NE. 4096) STOP 'READ--1'



PERFORM THE TRANSFORMATION


DO 2 IY=0,63
        DO 4 IX=0,127
                Z=0.0
                Z=LPIC2((IY)*128+IX+1)
                X=IX
                Y=IY+IBLK*64
```

```
        MATRIX MULTIPLICATION

XT=X*T(1,1)+Y*T(2,1)+Z*T(3,1)+T(4,1)
YT=X*T(1,2)+Y*T(2,2)+Z*T(3,2)+T(4,2)
ZT=X*T(1,4)+Y*T(2,4)+Z*T(3,4)+T(4,4)
IF(ZT .EQ. 0.) GO TO 13
GO TO 19
TYPE 17,XT,YT,ZT
FORMAT(3F10.3)

        END OF MATRIX MULTIPLICATION

IXT=XT/ZT+0.5
                IYT=YT/ZT+0.5
                IF ((IXT.GE.128).OR.(IXT.LT.0)) GO TO 4
                IF ((IYT.GE.128).OR.(IYT.LT.0)) GO TO 4
                LPIC3(IYT*128+IXT+1)=LPIC1((IY)*128+IX+1)
        CONTINUE
CONTINUE
CONTINUE

OUTPUT RESULTS

IF(IWRITW(8192,LPIC3,8,1).NE.8192) STOP'WRITE'
CALL CLOSEC(1)
FORMAT(I)
DO 50 IY=0,127
DO 40 IX=0,127
I=IX+1
J=IY+1
TEMP(I,J)=(LPIC3(IY*128+IX+1)+128)
CONTINUE
WRITE(6,41) ((TEMP(I,J),J=1,128),I=1,128)
FORMAT(16I5)
CONTINUE
DO 60 I=1,128
DO 60 J=1,128
IARRAY(J,I)=(TEMP(I,J)-8)*16
CONTINUE
CALL PICTUR(128)
```

APPENDIX D

SUBROUTINE PICTUR (128)

THIS SUBROUTINE WRITES THE SMALL SIZE PICTORIAL ARRAYS(128,128) AND THE MEDIUM SIZE ARRAYS(256,256) TO THE DISK.

IARRAY=THE INTEGER ARRAYS(-128 TO +127)
ISIZE =THE SIZE OF ARRAYS(128 OR 256)

....

```
      SUBROUTINE PICTUR(ISIZE)
      LOGICAL*1 IARRAY(128,128)
      COMMON IARRAY
      LOGICAL*1 BLOCK(512),S,M,TITLE(7)
      DATA BLOCK,S,M/512*0,'S','M'/
      DATA TITLE/'E','.','E','.','G','.',' '/
      NREC=(ISIZE**2)/512+8
      TYPE 100
100   FORMAT('OSPECIFY THE OUTPUT FILE AS DEV:FILE.EXT'/)
      CALL ASSIGN(1,'RK1:SUPOT.PIC',-13,'NEW','NC',1)
      DEFINE FILE 1 (NREC,256,U,INDEX)
      DO 1 I=1,7
      BLOCK(8+I)=TITLE(I)
      CONTINUE
      IF(ISIZE .EQ. 256)GO TO 10
      BLOCK(4)=S
      GO TO 20
10    BLOCK(4)=M
20    LINES=512/ISIZE
      WRITE(1'1) (BLOCK(I),I=1,512)
      DO 50 N=9,NREC
      DO 40 I=1,LINES
      DO 30 J=1,ISIZE
      K1=(I-1)*ISIZE+J
      K2=(N-9)*LINES+I
      BLOCK(K1)=IARRAY(K2,J)
30    CONTINUE
40    CONTINUE
      WRITE(1'N) (BLOCK(I),I=1,512)
50    CONTINUE
      CALL CLOSE(1)
      RETURN
      END
```

VITA

Supot Charirnwanit was born in Lopburi, Thailand on March 19, 1948. He graduated from the Armed Forces Academy Preparatory School in 1968. He received his Bachelor of Science in Electrical Engineering from the Royal Thai Air Force Academy in February, 1973. In June, 1975 he entered the Graduate School at The University of Tennessee, Knoxville, to further his education for a Master of Science degree in Electrical Engineering.