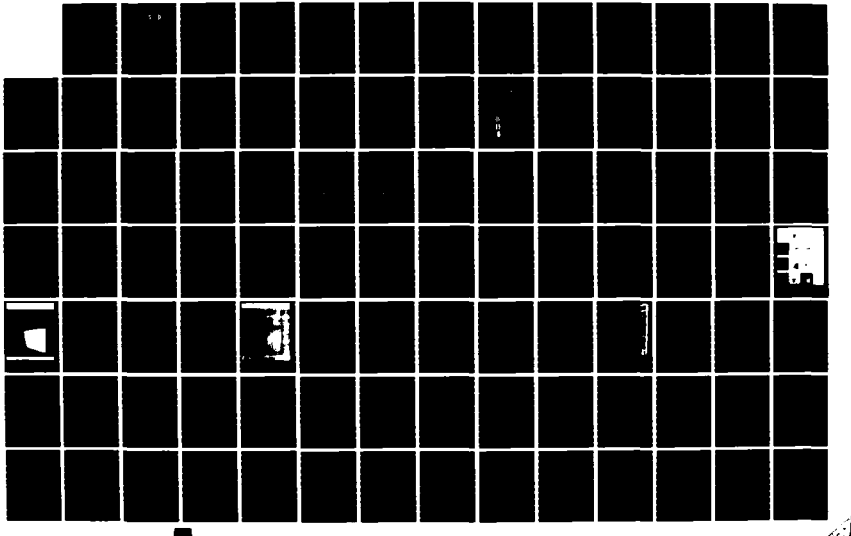
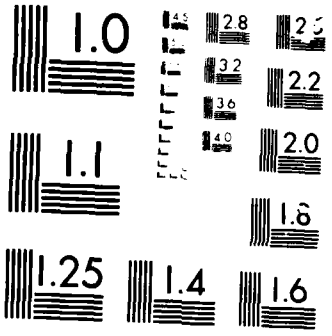
AD-A168 197 DEVELOPMENT OF ALGORITHMS AND HARDWARE FOR STRUCTURED-LIGHT VISION(U) GEORGE WASHINGTON UNIV WASHINGTON DC DEPT OF ELECTRICAL ENGIN.. 1/4

UNCLASSIFIED M H LOEW ET AL. 1986 N00014-83-K-0578 F/G 20/6 NL




1.0
1.1
1.25
1.4
1.6
2.0
2.2
2.8
3.2
3.6
4.0

DEVELOPMENT OF ALGORITHMS AND HARDWARE FOR STRUCTURED-LIGHT VISION

Final Report, Contract No. N00014-83-K-0578
for the
Office of Naval Research

Department of Electrical Engineering and Computer Science
George Washington University
Washington, DC 20052

TABLE OF CONTENTS

LIST OF FIGURES

PART II.B -- SOFTWARE

LIST OF FIGURES

III.B - SOFTWARE

LIST OF PLATES

LIST OF TABLES

DEVELOPMENT OF ALGORITHMS AND HARDWARE FOR STRUCTURED-LIGHT VISION

Final Report, Contract No. N00014-83-K-0578
for the
Office of Naval Research

by

Murray H. Loew
Reza Momenan
Gao Shangkai
James Hargrove

Department of Electrical Engineering and Computer Science
George Washington University
Washington, DC 20052

I. Introduction and Goals

Computer vision is finding increased application in robotics and for shipbuilding, construction, machining, sorting, and inspection. An essential part of a computer vision system is the ability to measure range (distance) to points on the surfaces of three-dimensional objects. This information allows the description of such intrinsic characteristics of objects as orientation, surface condition, and dimensions.

A goal of the work described here was the development, testing, and evaluation of a real-time system for measuring range, suitable for the kinds of applications described above. A second goal was the development of algorithms for description of objects, based on their range-image representations.

In collaboration with the National Bureau of Standards (NBS), George Washington University (GWU) has shown the feasibility, and measured the performance, of a prototype ranging system that uses a technique called structured light; GWU has also derived and implemented algorithms for rapid description of a limited class of objects using only the data that would be supplied by such a system.

II. Background, approach, and role of computer vision

A. Role and competence of structured-light systems

Machine vision attempts to extract information about the objects in a scene from the manner in which the objects modulate and reflect the illumination falling on them. In most cases, normal ambient light sources provide minimal constraints which can be employed to simplify this task. Structured light techniques for machine vision employ illumination sources which provide more direct information than is available from normal ambient light. Nonetheless, many approaches to machine vision have attempted to solve the general vision and image understanding problem without recourse to artificially structured illumination. While this presents many interesting problems from an academic standpoint, and is required in those special applications where ambient illumination must be employed, the speedy development of practi-

cal applications in automated assembly and manufacturing could profit from far greater exploitation of structured-light approaches.

In the majority of near-term applications, such as shipbuilding, construction, machining, welding, assembly, inspection, maintenance, painting, sorting, and materials handling, there is no obstacle to the use of artificially structured illumination. This approach facilitates precision optical ranging and measurement, and greatly simplifies many of the traditional problems of image processing and understanding. Moreover, projectors for structured illumination may be simple and compact, and may be mounted on the manipulator along with the camera.

One of the greatest advantages of the structured light approach is the ability to simplify the determination of depth in the image. This arises from the possibility of knowing the exact camera-relative angle of origin of the ray illuminating any part of the scene. Determination of depth then reduces to a straightforward process of triangulation. In simple applications, a single plane of light may be projected from a manipulator, and its intersection with objects in the field observed by an offset camera. Experiments at NBS have shown this arrangement to be effective for the real-time control of reflexive seek-and-grasp operations, and even for simple object-discrimination tasks.

Additional planes of projected light in such a system enable the direct sensing of three-dimensional tilt of surfaces. When combined with two-dimensional outline images obtained from point-source illumination, such a system is adequate for industrial parts manipulation. With minor modifications (projection onto a surface and examination with a telescope), the system will also work well for automated inspection.

The work described here has made it possible to read the Z-axis coordinate (depth) of any pixel in the scene directly, and thus to define any point of an imaged object immediately in terms of its coordinates in three-dimensional visual space. This ability is central to control of a manipulator that must interact with random objects in real space. However, its most important application is in image understanding, where three-dimensional information is invaluable in resolving ambiguities of projected shape, occlusion, relative size, orientation, segmentation, and the like. So fundamental is this information, that current non-structured (ambient) light techniques devote the majority of their processing time to obtaining three-dimensional descriptions from ambient light cues, or to classifying objects on the basis of two-dimensional cues generated by surface interactions in three dimensions. As a result of the processing bottleneck represented by the difficulty of obtaining three-dimensional information, there are currently no ambient-light vision tech-

Lack of adequate interpreted sensory information is perhaps the greatest single obstacle to the commercial exploitation of robotics. While a full solution to the ambient-light vision problem appears to be many years off, structured-light approaches offer a realizable near-term solution that is applicable in a large variety of important military and industrial settings. It seems likely that any program which could promote the development of commercially available structured-light vision systems would have very favorable consequences for the field of automated manufacturing and in turn for its military and industrial applications. In the next section, we outline such a program.

To be useful in practical applications, a vision system must operate in real time. Essentially, this means that it must be able to accept data as fast as it can be provided, and that it must complete analysis of that data to any given level of complexity as rapidly as analyses at that level are required for uninterrupted operation. Many of the algorithms currently in use for the simpler forms of structured-light vision are within the real-time capacity of standard computer hardware. Others run in "near" real-time, while still others are undergoing development. In all cases, orders-of-magnitude improvement could be expected from application of dedicated specialized hardware, an example of which was built and tested as part of this work.

niques suitably developed for commercial real-time applications except in highly constrained environments (such as flat parts on a conveyor) where three-dimensionality may be ignored safely.

Many techniques have been proposed for obtaining three-dimensional information from ambient light cues. Among them may be mentioned stereopsis, optic flow, shape from shading, and shape from texture. All of these are areas of intense current interest and activity, and many are modeled on psychophysical analogs. However, a practical solution to the very complex problem of three-dimensional ambient light vision may well require a synthesis of many of these approaches, and all of them individually are at best in an experimental state of development. Moreover, all of these approaches are intensely computational in nature, and will require improvements of many orders of magnitude in computing speed to be competitive with structured light techniques that have been demonstrated in real-time vision. They may be adapted in graded levels of complexity according to the task, from simple ranging and parts acquisition to complex image understanding. In many instances these techniques are ready to be moved out of the laboratory and into practical development; in other cases the time to practical development appears significantly shorter than that of any of the ambient light techniques. Many structured light applications are within the real-time computational power of standard computer hardware; others appear to be very close to this goal. This report describes several approaches.

B. SPECIFIC APPROACH

B.1 The Basic Algorithm

The basic algorithm of our system employs triangulation. Figure 1 illustrates distances R_i of points x_i of object A from a reference plane Q, perpendicular to the plane of the paper and including points C and P. It is possible to reconstruct a 3-D representation of object A with respect to a viewer in plane Q.

The following relationship may be derived from the geometry shown in Figure 2:

$$\frac{1}{R_i} = \frac{1}{D} \left(\cot \alpha_i + \cot \beta_i\right)$$

where D is the distance between points C and P, and R_i is called "range" as defined earlier.

Therefore in order to identify a specific point and hence calculate its range we need to measure or calculate α_i and β_i and their corresponding cotangents.

Suppose we have a template M such as the one in Figure 3, and place it in front of reference point P at a fixed distance f_i.

As shown in Figure 4 we can now decide the partition j through which the line (or vector) connecting reference point P to any point x_i passes, which in turn will give us the value of angle α_i, hence cot α_i:

$$\cot \alpha_i = \frac{i \cdot a}{f_1}$$

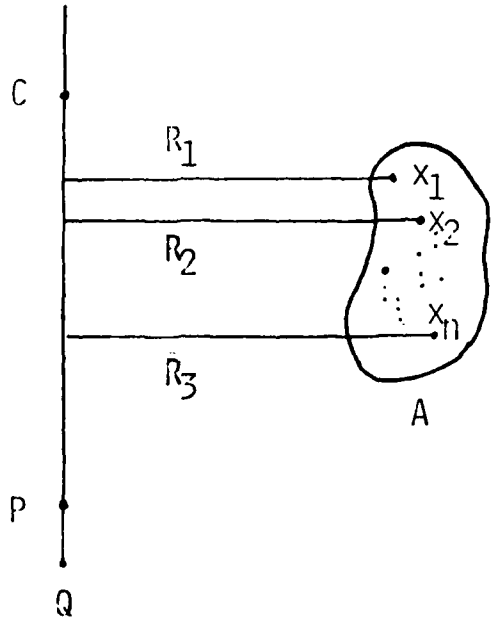


Fig. 1

AN OBJECT AND ITS DISTANCES FROM A REFERENCE PLANE

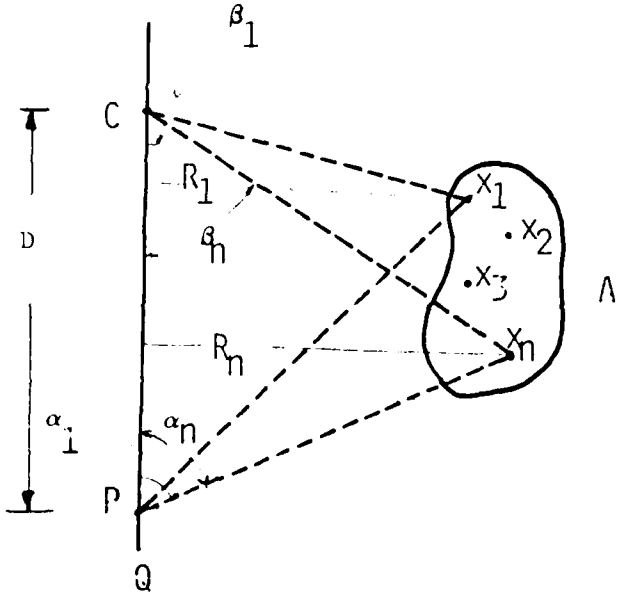


Fig. 2

TRIANGULATION GEOMETRY: R MAY BE FOUND IF α, β AND D ARE KNOWN

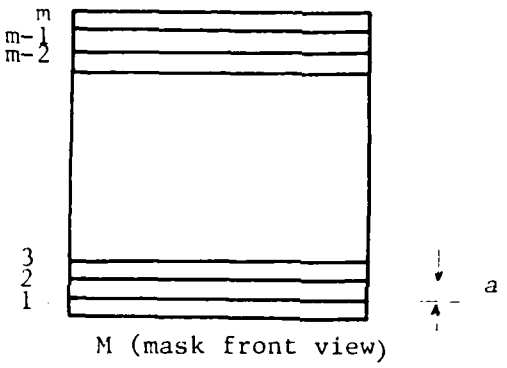


Fig. 3

MASK WITH m BARS EACH OF SIZE a

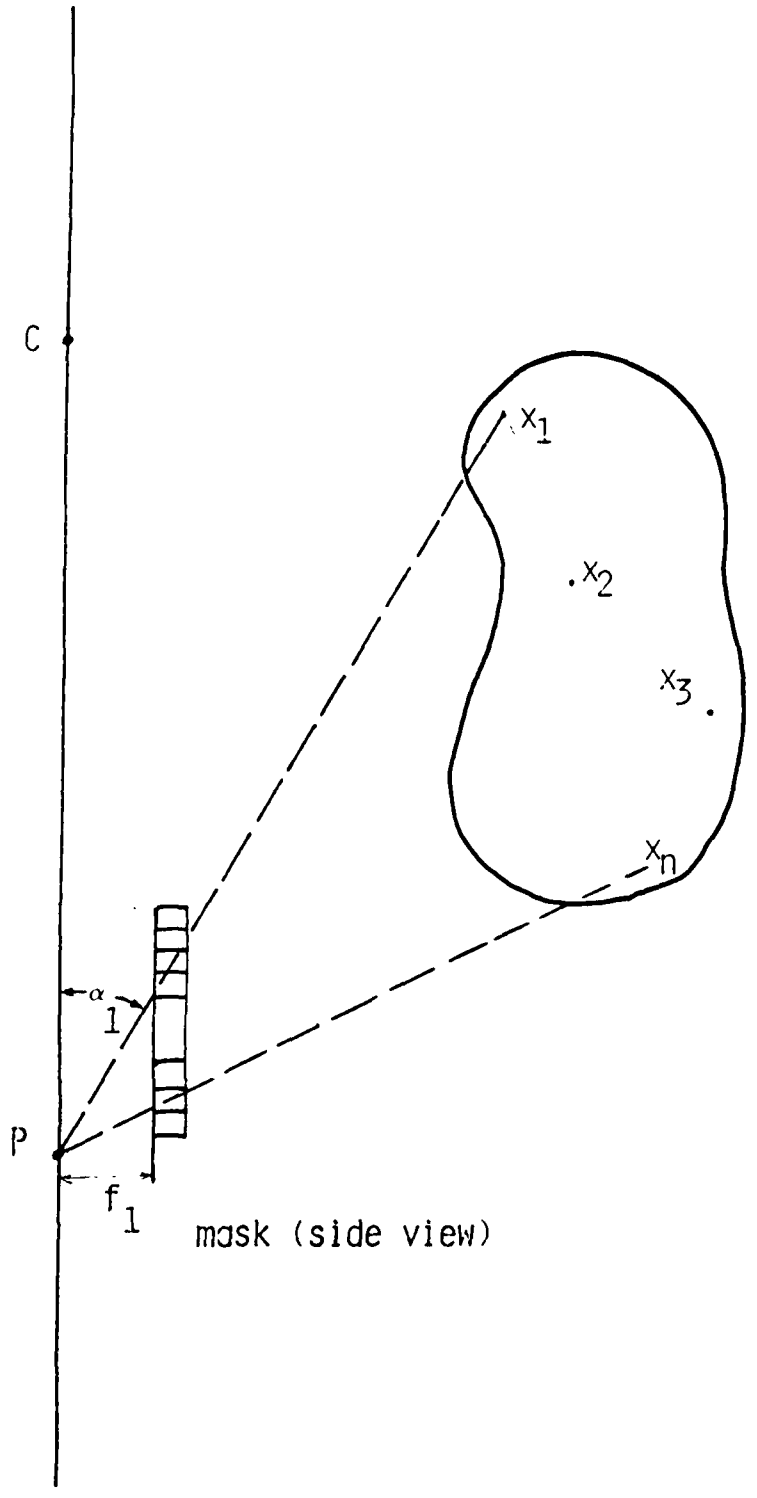


Fig. 4

USING THE MASK TO MEASURE α

where a is the height of each partition.

In the design and construction of this vision system, C is the focal point of a charge-injection device (CID) camera (General Electric Model TN 2500) with a 244 x 248-pixel resolution plane at focal distance f_2 from C, the reference point P represents a high-intensity line source perpendicular to the plane of paper, and template M is made of glass so that the light from source P can pass through and illuminate object A (see Fig. 5).

It is very time consuming if we use a template such as that described above for measuring cot α_i of all points of the object A: the above design would fail to work in real time. Therefore, instead of template M we use a series of coded glass masks.

Figure 6 shows a reference mask "0" and eight masks numbered 1 through 8 which can be used for a (2^8 = 256) x 256 image.

In the following example we will show how such masks are used in finding cot α. For simplicity, however, we will use a 4x4 image which implies $\log_2 4 = 2$ masks. Note that in this example black has the highest gray value, "1", and white the lowest, "0". Also, the following criterion is exploited in comparing two images (one is called "reference" and the other "input" image): if the gray level of a pixel of an input image is equal to or less than the corresponding pixel in the reference image, a zero is stored in a memory corresponding to that pixel.

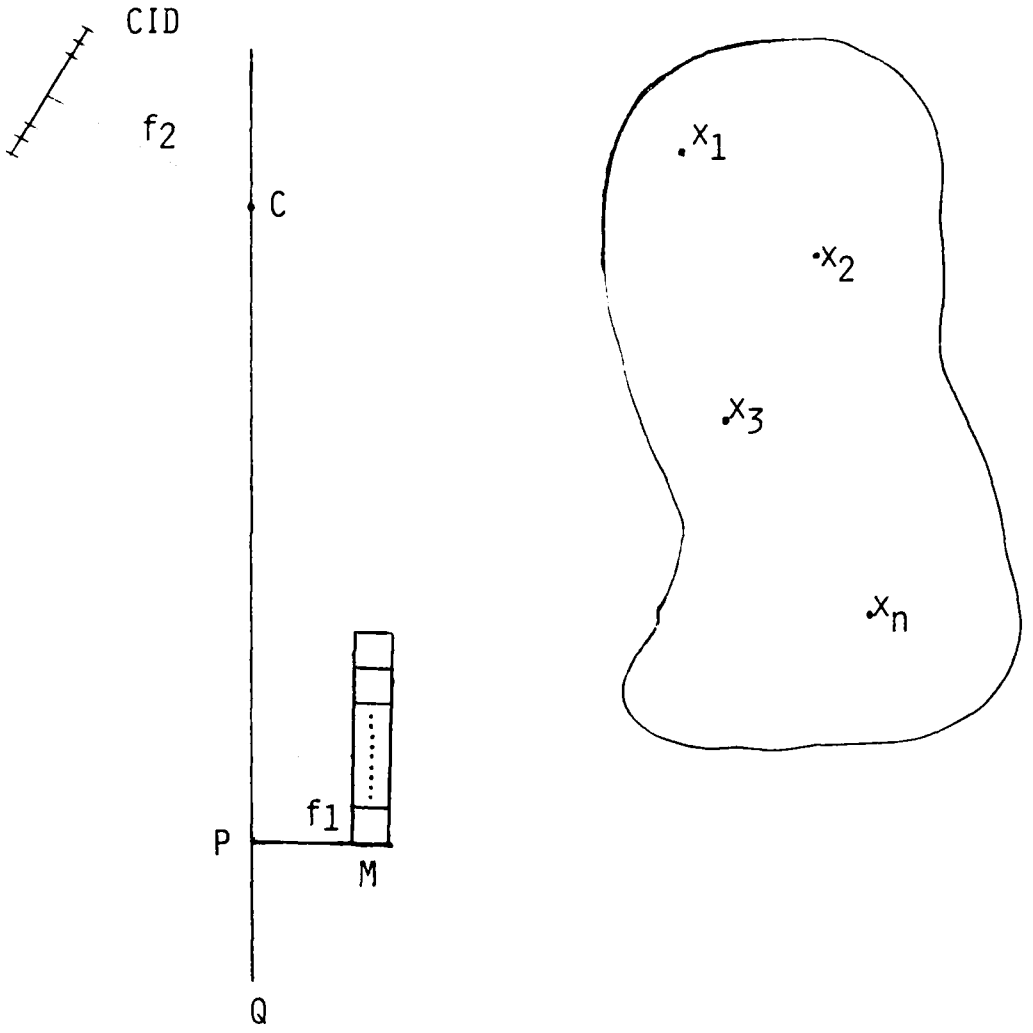


Fig. 5

A RANGING SYSTEM, WITH SOURCE, P, MASK M, AND CID CAMERA FOCUSED AT C

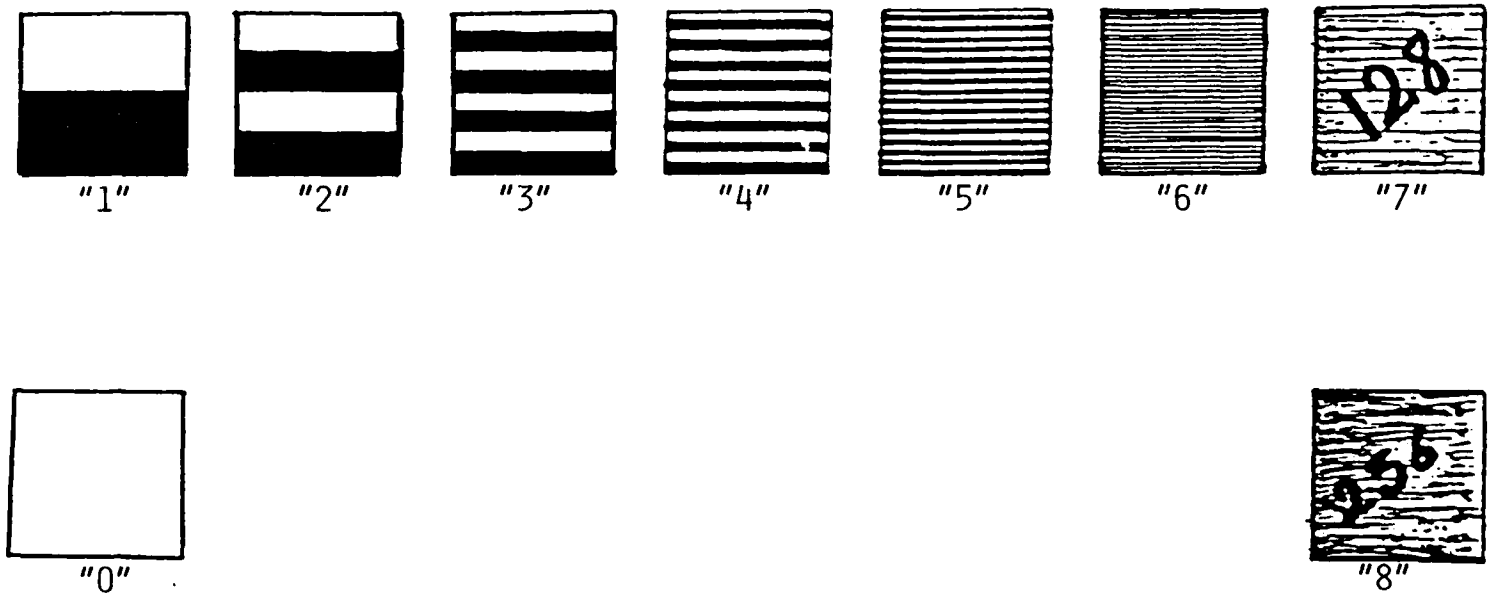


Fig. 6

MASKS OF ALTERNATING TRANSPARENT AND OPAQUE SECTIONS, AND THE REFERENCE MASK

Referring to Figure 7a, we note that the projector P illuminates the whole object A and the absolute gray values of various points of object A (e.g. x_1, x_2, x_3, x_4) are stored in a memory plane called the reference memory after being imaged by the camera. This array is called the reference image.

In Figure 7b the first mask is placed in front of projector P. Since half of mask "1" is opaque, points x_3 and x_4 would not be illuminated; therefore, in comparing the resultant image with the reference image, the algorithm would give points x_1 and x_2 the same gray level, while x_3 and x_4 have a higher gray value. Thus the values "0" for former points and "1" for later points, respectively, will be stored in a memory called "Bit plane memory 1". Note that the values stored in bit plane memories are relative single-bit values for each pixel.

If we proceed in the same manner with mask "2" we will have results such as the ones in bit plane memory-2 of Figure 7c.

In the next step the corresponding values of comparison for each pixel will be collected, in sequential order, as a code (for our example with 4x4 image we have 2 bit planes and hence 2-bit code for each pixel - see Figure 7d). Converting this code to decimal will tell us which partition j illuminated a point x_i, and from the previous discussion we can find cot α.

Note that, depending on the type of image we have (e.g. 4x4, 8x8,...2^nx2^n), we need 2,3,..., n masks in order to have an n-bit code that defines every point of an image.

CONSTRUCTION OF THE BIT PLANE:

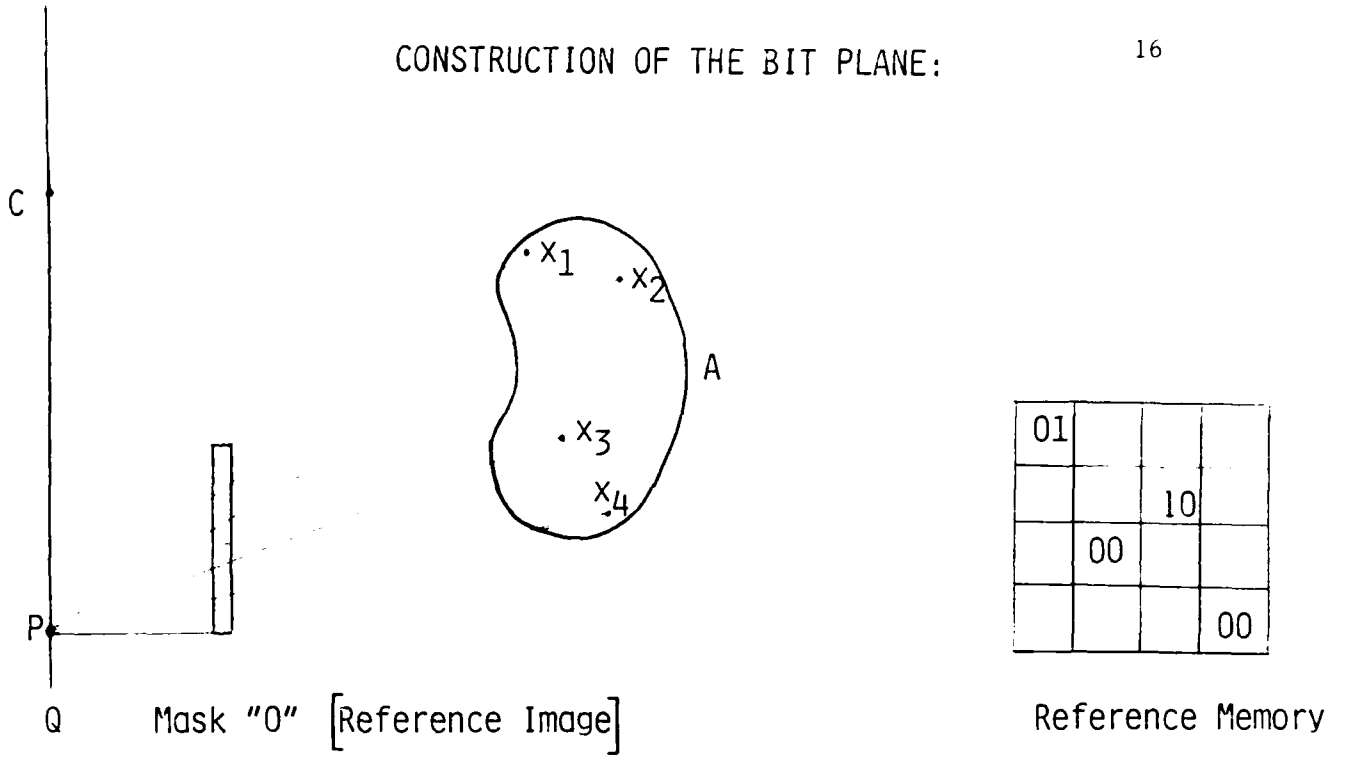


Fig. 7(a)

THE REFERENCE IMAGE, TO ACCOUNT FOR INCIDENT INTENSITY AND OBJECT REFLECTIVITY

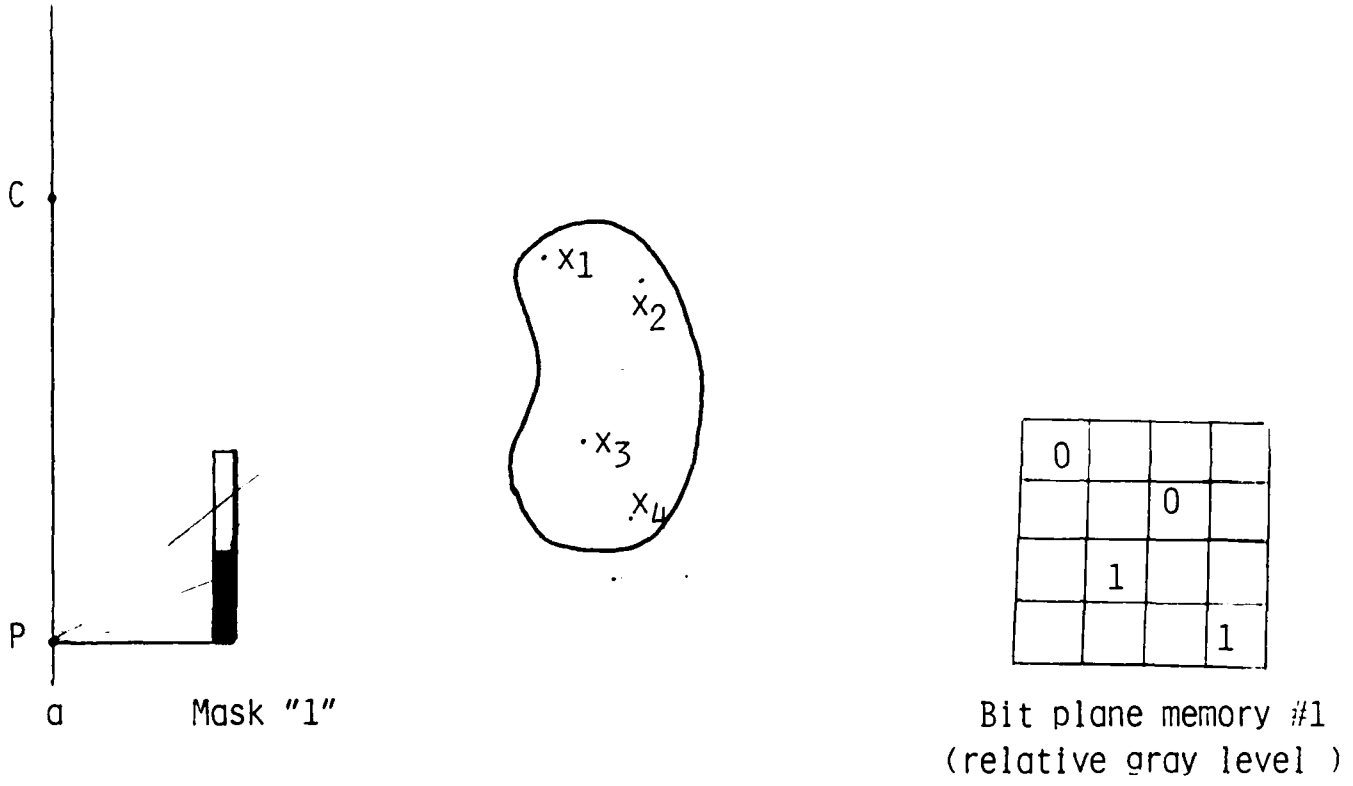
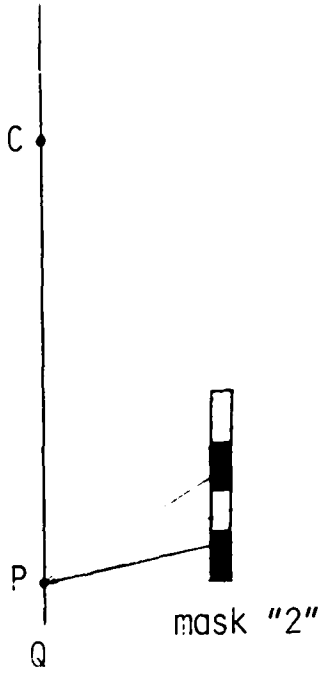
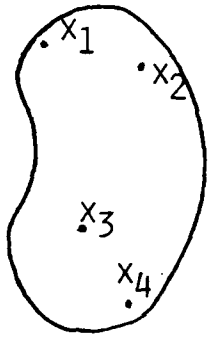
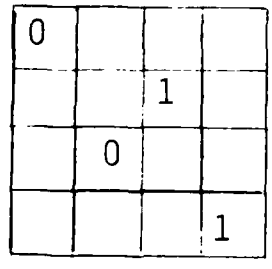


Fig. 7(b)

BIT-PLANE LEVEL ONE; RESULT OF TWO-BAR MASK





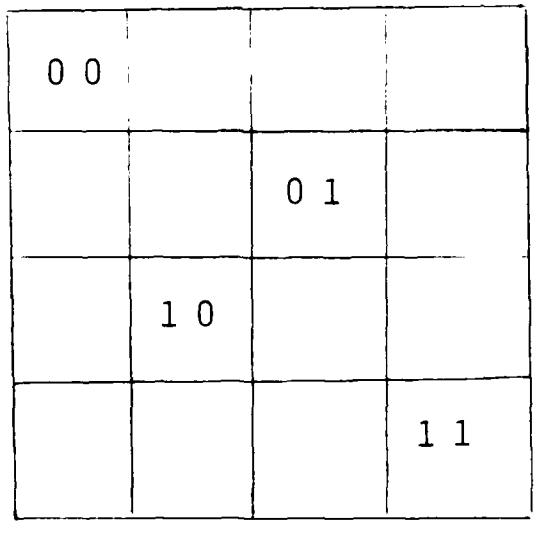


Bit plane memory #2

Fig. 7(c)

BIT PLANE LEVEL TWO; RESULT OF FOUR-BAR MASK

From: Bit plane #1
Bit plane #2



Resultant
Bit Plane

Fig. 7(d)

COLLECTING MASKS' RESULTS INTO A SINGLE CODE

Now that we know how to measure cot α, we need to know the value of cot β. Referring to Figure 8, we suppose we have a camera with IxI CID plane (usually 256 x 256), focal length f_2, and pixel size b x b. Knowing which pixel we are looking at, we can calculate cot β_i from the following relationship:

$$\cot \beta_i = \frac{(n-i) \cdot b}{f_2}$$

According to the above, if we have two look-up tables, one loaded with the values of cot β_i, and the other one with the values of cot α_i calculated from data extracted from the resultant bit plane of Figure 7d, we can find the value corresponding to R_i.

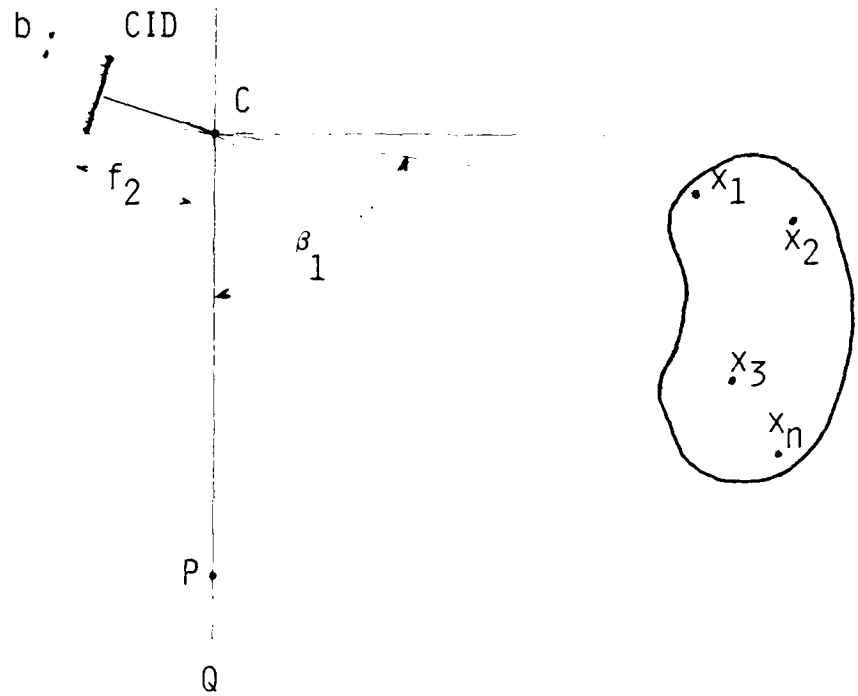


Fig. 8

USING THE CAMERA TO MEASURE β

B.2 'Visible' field of View

By 'visible' field of view or 'visible' range we mean the area which is both illuminated by the projector and within the optical field of the camera. In this section we define the boundaries of this field of view and find the resolution limits for the CID camera.

From Fig. 9 we can write the equations for lines $\bar{A}$, $\bar{B}$, $\bar{C}$ and $\bar{D}$ which constitute the contour of the visible field.

$\bar{A}$: $y_A = (d-x_A) \cdot \cot 2\theta$

$\bar{B}$: $x_B = 0$

$\bar{C}$: $y_C = + x_C \cdot \frac{f_1}{m} - f_1$

Note: $\underline{P}$ is at $x=0$, $y = -f_1$,

$\underline{C}$ is at $x=d$, $y=0$,

and θ is the half-angle of the field-of-view of the camera

$\bar{D}$: $x_D = d$

The intersection of lines $\bar{A}$ and $\bar{C}$ gives the x-y coordinate (Y is actually the range) of the closest point O to the reference plane which is visible.

$$x_0 = \frac{d \cot 2\theta + f_1}{\frac{f_1}{m} + \cot 2\theta}$$

$$y_0 = \frac{\cot 2\theta \, (d-m)}{1 + \frac{m}{f_1} \cot 2\theta}$$

Intersection of $\bar{C}$ and $\bar{D}$, $\bar{A}$ and $\bar{B}$ will yield the locations of the other two closest visible points, one on the projector horizontal axis (Q) and the other on the horizontal axis and at the same height as the camera (E).

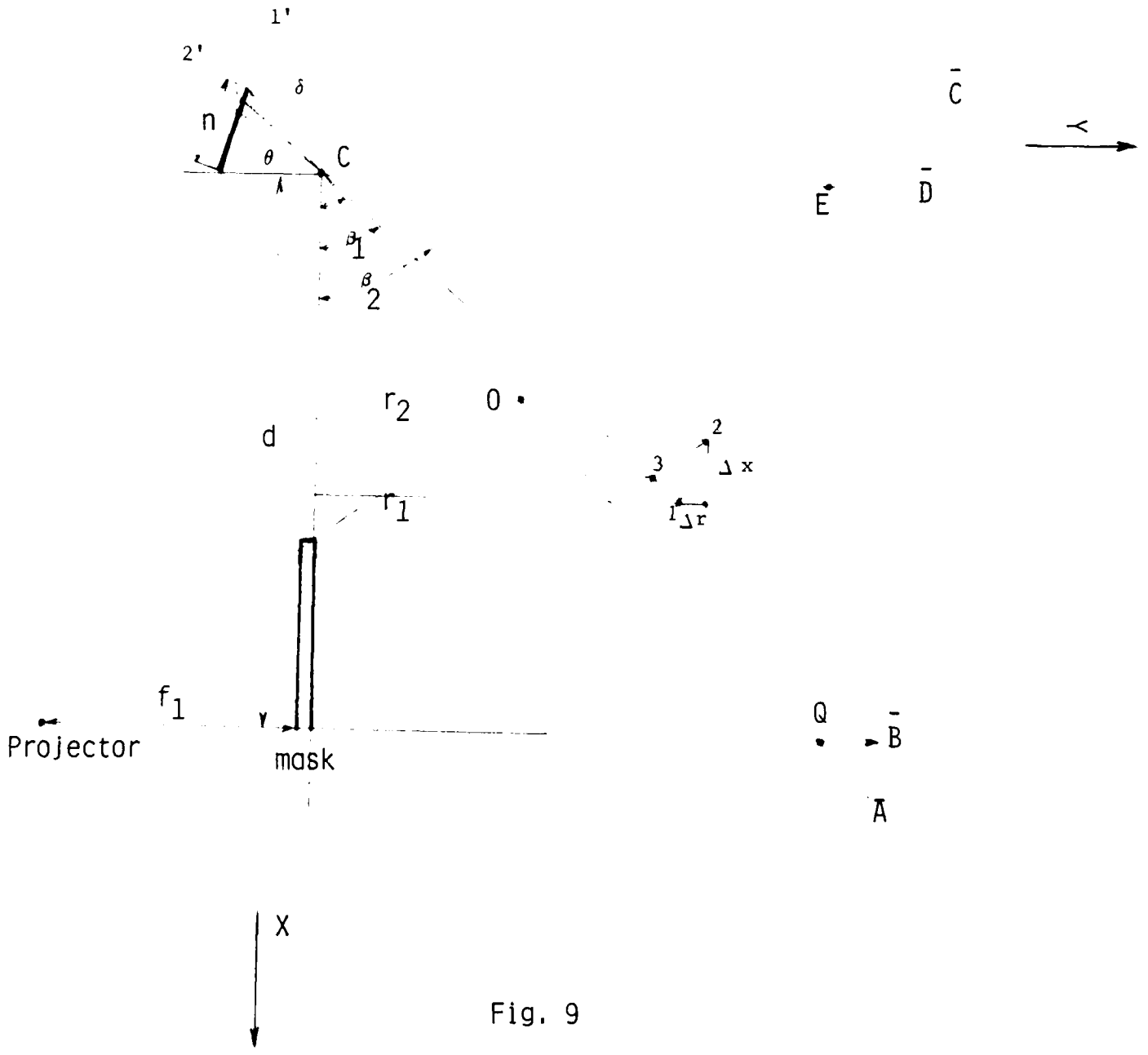


Fig. 9

DEFINING THE VISIBLE FIELD AND GEOMETRY OF THE DEFINITION OF RESOLUTION

That is,

$$x_Q = 0$$

$$y_Q = d \cot 2\theta$$

$$x_E = +d$$

$$y_E = d \cdot \frac{f_1}{m} - f_1 \quad .$$

So the following result expresses the visibility of an object or a point on the object.

$$R_x = y_x \begin{cases} \geq + x \cdot \frac{f_1}{m} - f_1, & \text{for } x_E \geq x \geq x_0 \\ \geq (d - x) \cot 2\theta, & x_0 \geq x \geq 0 \\ \text{Invisible}, & \text{otherwise} \end{cases}$$

Therefore for a point of an object to be in the 'visible' field of view its range must be greater than or equal to $f_1(\frac{x}{m} - 1)$ $x_0 \leq x \leq x_E$, or greater than or equal to $(d-x)\cot 2\theta$ if $0 \leq x \leq x_0$, where all the parameters are as defined previously.

Now we want to find the relationship between the resolution and the range: suppose from a point (x_1, r_1) we want to view another point (x_2, r_2) where:

$$x_2 = x_1 + \Delta x$$

$$r_2 = r_1 + \Delta r$$

Then,

$$\theta_1 = \tan^{-1} \frac{r_1}{d - x_1}$$

$$\beta_2 = \tan^{-1} \frac{r_1 + \Delta r}{d-(x_1 + \Delta x)}$$

and

$$\alpha_1 = 90 - (\theta + \beta_1)$$

$$\alpha_2 = 90 - (\theta + \beta_2)$$

Now the resulting images will be:

$$1' = \frac{n}{2} \pm \left[\frac{n}{2} \cot \theta_1 \cdot \tan \alpha_1 \right]$$

(if β is more than $(90 - \theta)$ the plus sign must be used)

$$2' = \frac{n}{2} \pm \left[\frac{n}{2} \cot \theta_2 \cdot \tan \alpha_2 \right]$$

and the difference (or displacement) of the image by moving from point 1 to point 2 is:

$$\Delta R' = | 1'-2' |$$

Therefore to be able to distinguish between different points we require

$$\text{Pixel Size} \leq \Delta R' \leq n - (\min [1' \text{ and } 2'])$$

In order to be able to resolve a point as a function of its previous location (range and height) its image must differ by value greater than the pixel size of the camera (otherwise both points would be resolved as one) and less than n (the width of CID plane) minus minimum of the image value of either points 1 and 2 (namely 1' and 2'). (See Appendices A and B for tabulation and display of typical values of visible ranges and precision of range estimates.)

B.3 Camera-Projector Set Up

To calculate the range it is necessary to arrange the apparatus as illustrated in Figure 10. Since α_1 or cot α_1 is to be decoded using the masks, the transparency of the stripes in the masks must vary in the Z direction. If, however, the set-up is like that of Figure 11, the variation in the masks is in the Y direction. That results in decoding α_2 or cot α_2, which do not contain any range information.

B.4 Light Source and Slit

An important consideration in this system is the necessity of having a fine light source with the narrowest possible slit while providing the required light intensity. The need for a narrow slit is illustrated in Fig. 12.

As can be seen from Figure 12a the shaded areas are neither completely illuminated nor completely dark. Therefore, in comparison with the reference memory these areas will result in wrong encodings. On the other hand, Figure 12b shows how a perfect (but non-realizable) line slit will result in just two distinct areas: illuminated and dark.

Therefore one must approximate a perfect slit. However, with the light source that we had available (Sunpak 433D) it was not possible to provide enough light through the slit; the reduced intensity resulted in degradation of images and hence of the estimates of range.

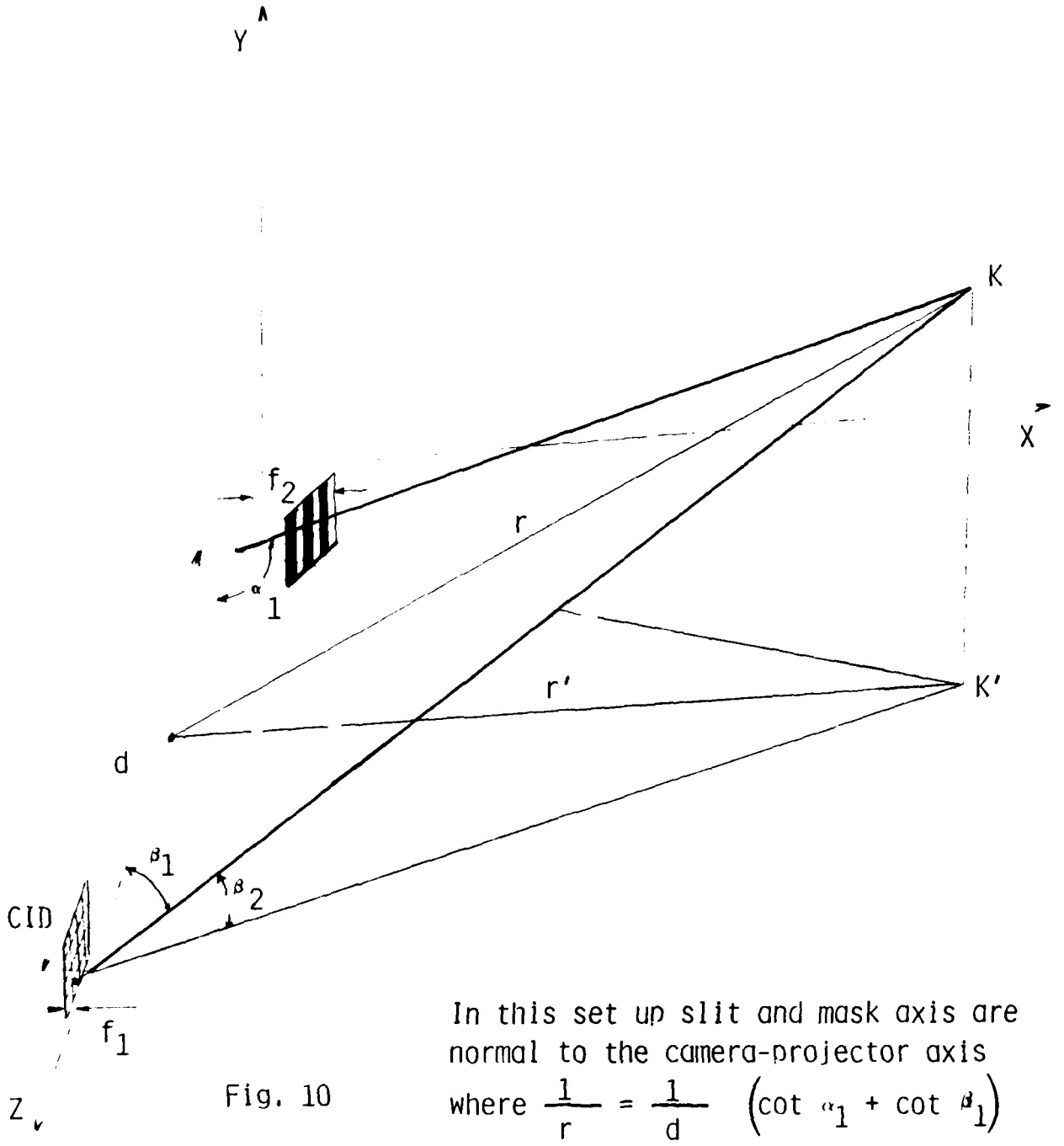


Fig. 10

In this set up slit and mask axis are normal to the camera-projector axis where $\frac{1}{r} = \frac{1}{d}\left(\cot \alpha_1 + \cot \beta_1\right)$

CORRECT ORIENTATION OF APPARATUS FOR MEASURING RANGE

AN INCORRECT ORIENTATION; α_2 WILL BE MEASURED,

WHICH DOES NOT CONTRIBUTE TO RANGE INFORMATION

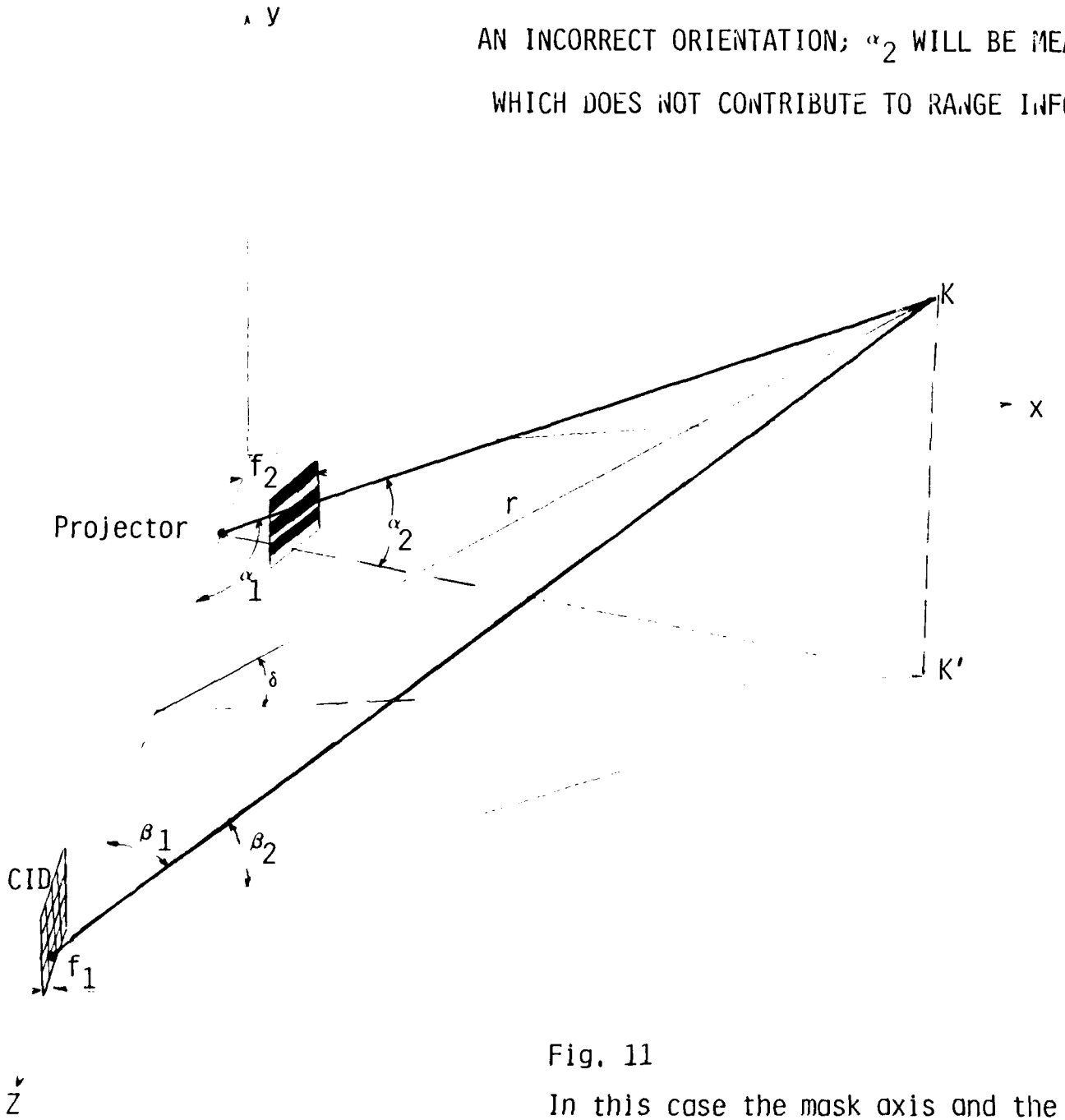
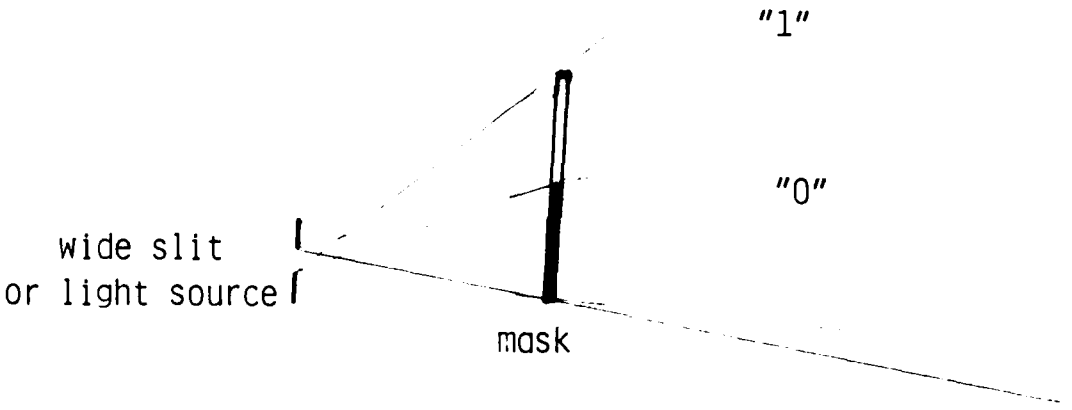


Fig. 11

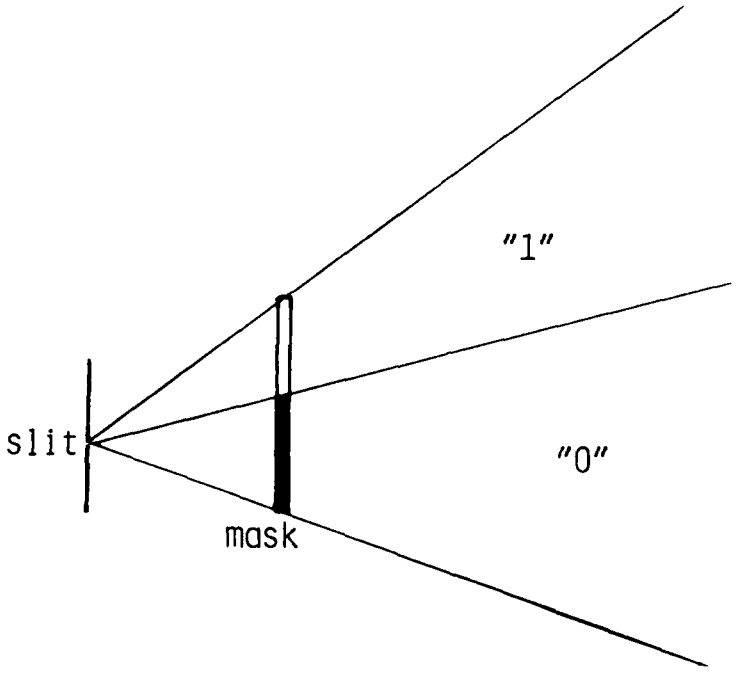
In this case the mask axis and the projector-camera axis are parallel



a) wide slit

Fig. 12

A WIDE SLIT YIELDS AMBIGUOUS REGIONS



b) line slit (perfect slit)

Fig. 12

A PERFECT SLIT YIELDS ONLY DICHOTOMY

To compensate for this problem we had to modify the configuration of Figure 12a, by using an adjustable slit (see Fig. 13). We could adjust the width of the slit to the smallest that would give the sharpest possible images.

As noted above, the use of a non-perfect slit would degrade the range result, especially through the finest masks since the width of the slit would be almost the same as that of the smallest mask division. In the following paragraph this degradation is calculated. It should be pointed out that if the slit causes degradation for a given mask, all the masks having finer divisions will be degraded as well. For example, if we cannot have a sharp image of the mask no. 6, masks no. 7 and 8 will also be degraded.

As explained in the algorithm description, there are eight masks (1-8) which will result in the constitution of an 8-bit code relating to cot α:

$$\cot \alpha \approx [\text{decimal } (B_0\ B_1\ B_2\ B_3\ B_4\ B_5\ B_6\ B_7)] \times \text{constant } (= \frac{a}{f_1})$$

(where a = width of mask's bars, and f_1=distance from mask to slit)

Therefore, if mask i (i=0,...,7) is degraded (i.e., gives bad image) the resulting code will have degradation in 2^{8-i} bars of the finest mask. For example if the last mask (i=7) does not give a good image, the code can be $B_0\ B_1\ B_2$ ... $B_6 0$, or $B_0\ B_1 B_2$ ... $B_6 1$ which means we cannot distinguish between the n-th bar and the (n+1)-th bar of the mask; in turn, that will reduce the range precision. Suppose A is the point for which we are

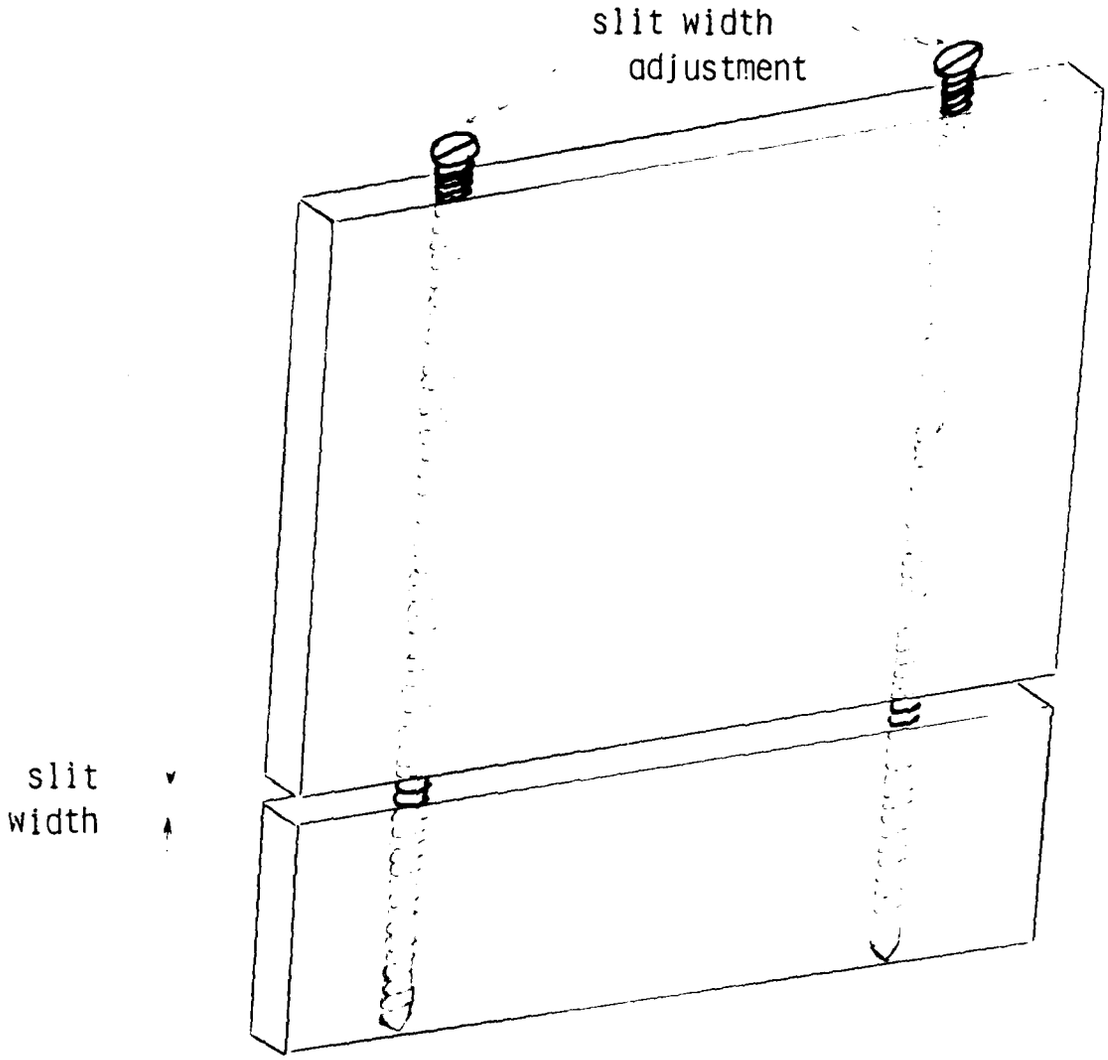


Fig. 13

ADJUSTABLE SLIT USED IN THE RANGING SYSTEM

calculating the range. Let the n-th bar be the one illuminating point A. Therefore,

$$\cot \alpha_1 = n \cdot \frac{a}{f_1}$$

Now if we have image degradation for mask i, we might decode $(n \pm 2^{8-i})$ for cot α which results (see Fig. 14) in

$$\cot \alpha_2 = (n \pm 2^{8-i}) \cdot \frac{a}{f_1}$$

and

$$R = \frac{d}{\cot \alpha + \cot \beta}$$

Let $\cot \beta = m \cdot \frac{b}{f_2} = m \cdot \frac{a}{f_1}$

therefore

$$R' = \frac{d}{(n + m \pm 2^{8-i}) \frac{a}{f_1}}$$

$$R = \frac{d}{(n + m) \frac{a}{f_1}}$$

$$\frac{R}{R'} = \frac{n + m \pm 2^{8-i}}{n + m} \quad \therefore \frac{R}{R'} = 1 \pm \frac{2^{8-i}}{n + m}$$

Now if we consider the 'gray area' created by the width of the slit, from the following drawing we can see that where we have a black stripe the gray field does not affect our result since the gray level of 'gray area' is smaller than black therefore a 'zero' will be stored by the comparator, whereas in

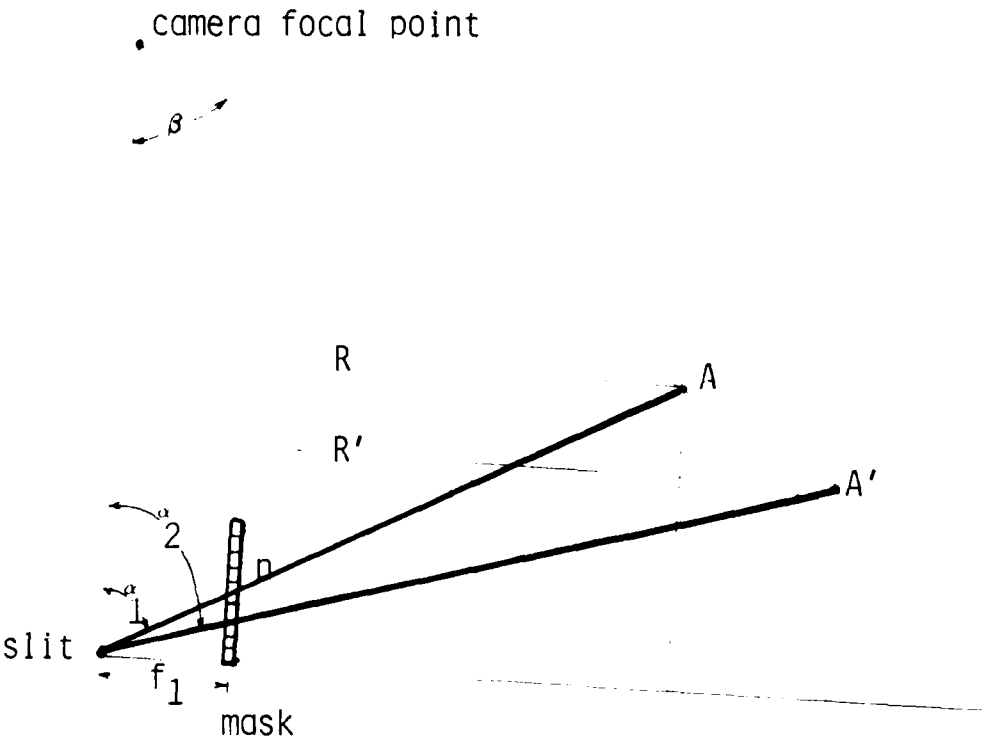


Fig. 14

GEOMETRY FOR EFFECT OF GRAY-LEVEL UNCERTAINTY

ON RANGE RESOLUTION

white stripe the gray field will affect the true comparison. It is for this reason that we use the 'false-black' as a more proper name for 'gray area'.

In the following paragraphs the ratio of false black area to correct detected area is computed.

Fig. 15 shows the effect of false-black (gray-area) on the accuracy of determining range of an object. It will be shown that the false-black area caused by a stripe (white or clear stripe) of the mask depends only on the number n of white-stripe to black-stripe transitions, the width of the slit l, the projector-mask distance f_1, and the range of the object R.

Refering to similar triangles ABC and A'B'C' we have:

$$A'B' = l \cdot \frac{R - f_1}{f_1}$$

also in triangles ABD and A"B"D we can write:

$$A"B" = l \cdot \frac{R - f_1}{f_1}$$

Therefore:

$$A'B' = A"B" = \text{gray area of an alternation of stripes}$$
$$= (\frac{R}{f_1} - 1)l \quad .$$

Hence, for a mask containing n alternations, we have:

$$\text{Total false-black area} = n\ (\frac{R}{f_1} - 1)l$$

The ratio of false-detected area to correctly-detected area due to the false-black problem is therefore:

$$E_n = \frac{\text{total false-black area}}{(\text{detectable-area}) - (\text{false-detected area})}$$

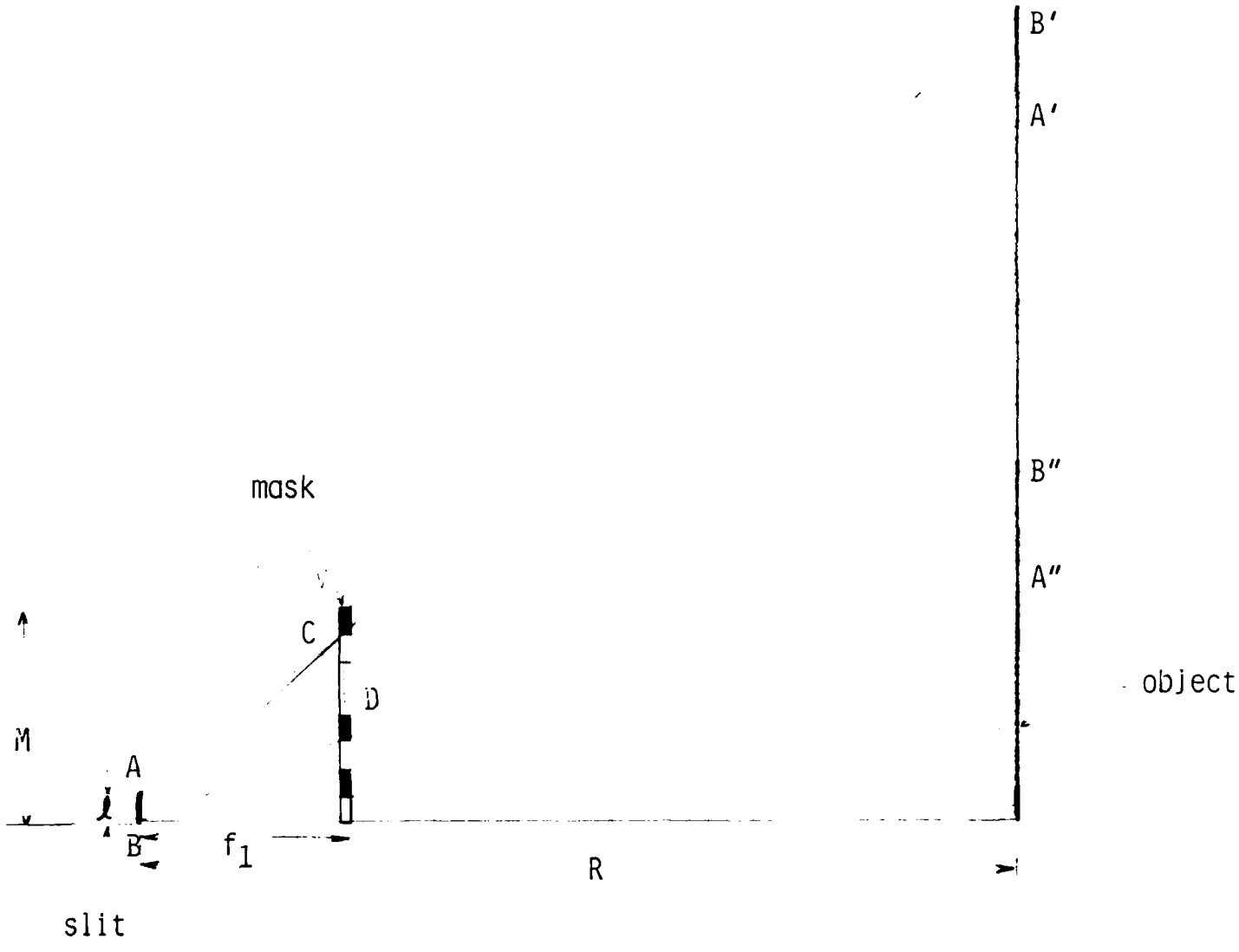


Fig. 15

GEOMETRY FOR CALCULATION OF TOTAL FALSE-BLACK AREA

$$= \frac{n\left(\frac{R}{f_1} - 1\right) I}{M \cdot \frac{R}{f_1} - n\left(\frac{R}{f_1} - 1\right) I}$$

$$E_n = \frac{n\,(R - f_1) I}{MR}$$

where M is the mask width.

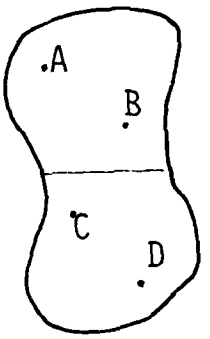
B.5 Hardware-Algorithm Modification

The DAD box compares the live video input with the output of the reference memory (on a pixel-by-pixel basis); if the input pixel is less than or equal to the reference pixel, a zero is stored. If it is greater, a one is stored.

However, considering 'white' the highest gray level and 'black' the lowest gray level, physically it is not possible to have live inputs with gray level higher than reference memory. Therefore, we had to invert the contents of reference memory. This could be done using TTL inverters (Table 1). However, it was easier to invert any input to the DAD box.

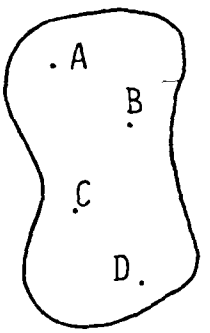
Experiments with the modified system yielded results that were incorrect and unpredictable. Further detection showed that the Gray-code to binary-code converter was causing this randomness and unpredictability because inversion of the reference memory which in turn would invert the 8 bit code of 8 bit-plane memories (i.e. instead of 1101110 the code 0010001 will be decoded). This resulted in the need for another inversion right before bit-plane inputs (Figure 16). The following state tables illustrate the above reasoning:

object	Ref.	Input	Bit-plane(B1)
A	0	1	1
B	0	1	1
C	0	0	0
D	0	0	0



1st video input

object	Ref.	Input	B2
A	0	1	1
B	0	0	0
C	0	0	0
D	0	1	1



2nd video input

object	binary equiv. gray	B_1B_2
A	00	00	11
B	01	01	10
C	10	11	00
D	11	10	01

As we can see B_1B_2 is exactly inverse of true gray code.

Fig. 16

CONSTRUCTION OF CORRECT CODES USING INVERSION

Ref.	Input	Bitplane
0	0	0
0	1	not possible
1	0	0
1	1	0

we have no state '1'

$\overline{\text{Ref.}}$	Input	Bitplane
1	0	0
1	1	not allowed
0	0	0
0	1	1

now we have permissible state '1'

Table 1

B.6 Look-up Tables' Restriction of Resolution and Dynamic Range

The mapping RAMs (look-up tables [L.U.T.s]) are two separate 256 8-bit word memories for storage of the values of cot α and cot β. Values from these two L.U.T.s are added using an eight-bit A.L.U. Therefore the following considerations apply:

a) Since the mapping RAMs are eight-bit, we are allowed to have values just from 0 to 255. The largest dynamic range will be achieved when

$$\frac{a}{f_1} = \frac{b}{f_2}, \quad \text{where}$$

a is the finest mask division

b is the pixel width

f_1 = projector-mask distance, and

f_2 = camera focal length

b) Since the A.L.U. output is eight bits we cannot use the full dynamic range of the L.U.Ts. In order to avoid overflow we have to use half of dynamic range (0-127) of

the L.U.T. This in turn implies the following resolution problem: since the addressing of these memories is by autoincrement and the readout of L.U.T. proceeds from 0th to 255th location, and the corresponding addition in A.L.U. also takes place under the same criteria, we have to load all the locations (256) of look-up tables with 128 (0-128) data. Therefore, every two consecutive locations were loaded with the same value. It is shown in Fig. 8 how the resolution is affected.

Now, $\cot \beta = \frac{b}{f_2}$

and since $\frac{a}{f_1} = \frac{b}{f_2}$ $\therefore \cot \beta_{unit} = \cot \alpha_{unit}$

where α_{unit} is the illumination angle, with respect to the reference plane, as if the object (or a point on the object) were illuminated through the first stripe of the mask, and β_{unit} is the imaging angle, with respect to the reference plane, as if the image of the object were received by the pixel next to the center of CID array.

Now,

$$\cot \alpha_{unit} = \frac{b}{f_1}$$

$$r_A = n \cot \alpha_{unit} + (m+1) \cot \beta_{unit} = (n+m+1) \cot \alpha_{unit}$$

$$r_B = (n+1) \cot \alpha_{unit} + (m+1) \cot \beta_{unit} = (n+m+2) \cot \alpha_{unit}$$

$$r_C = (n+1) \cot \alpha_{unit} + m \cot \beta_{unit} = (n+m+1) \cot \alpha_{unit}$$

$$r_D = (n) \cot \alpha_{unit} + m \cot \beta_{unit} = (n+m) \cot \alpha_{unit}$$

According to the preceding explanation, the contents of m and m+1, and n and n+1 in the look-up tables are equal respectively; therefore, four points A, B, C, and D will be determined as being in the same range from 'reference plane.'

The resolution is affected as a function of range as follows: (Figure 18 is just part of Figure 17) as we can see, the resolution depends on both R and the lateral location of the object.

$$h_A = R \cot \alpha$$

$$\frac{h_A}{R} = \frac{n \cdot a}{f_1}$$

since right sides are equal $\frac{h_A}{R} = \frac{y_D}{R + \Delta R}$

$$\frac{h_D}{R + \Delta R} = \frac{n \cdot a}{f_1}$$

$$\frac{h_A}{h_D} = \frac{R}{R + \Delta R} \therefore \frac{h_D}{h_A} = 1 + \frac{\Delta R}{R} \rightarrow \pm \left(\frac{h_D}{h_A} - 1\right) R$$

The other way to approach the resolution problem is to observe that since

$$\frac{1}{R} = \frac{1}{d} r \qquad \therefore \quad R = \frac{d}{r}$$

$$\Delta R = \pm d \left| \left(\frac{1}{(n+m+1)} - \frac{1}{n+m} \right) \tan \alpha_{unit} \right|$$

$$= \pm d \left| \left(\frac{n+m-n-m-1}{(n+m+1)(n+m)} \quad \frac{a}{f_1} \right) \right|$$

$$\Delta R = \pm d \cdot \frac{a}{f_1} \cdot \frac{1}{(n+m+1)(n+m)}$$

in which $\frac{1}{(n+m+1)(n+m)}$ is a function of h_D< h_A and R.

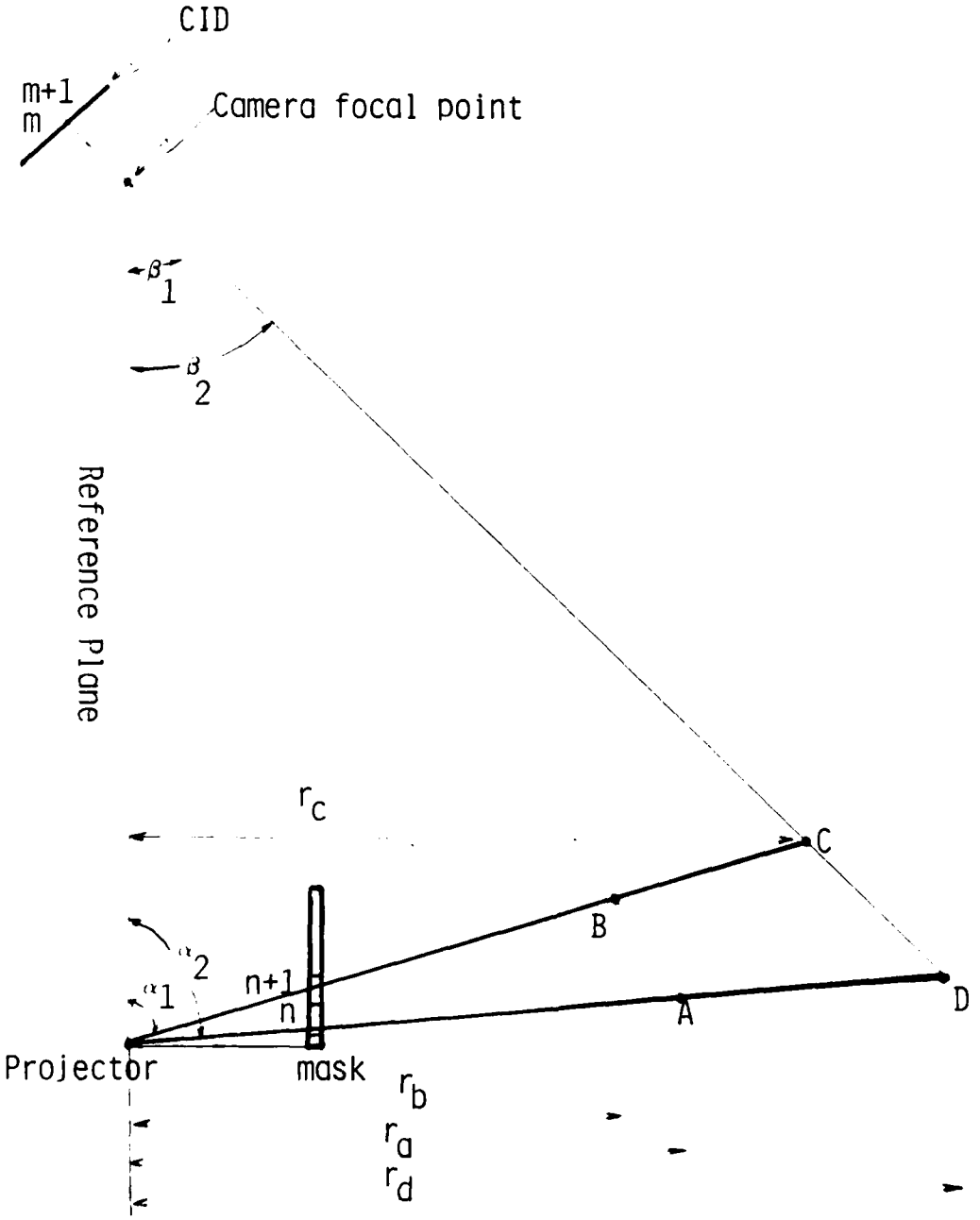


Fig. 17

GEOMETRY FOR EVALUATION OF INTRINSIC RANGE UNCERTAINTY

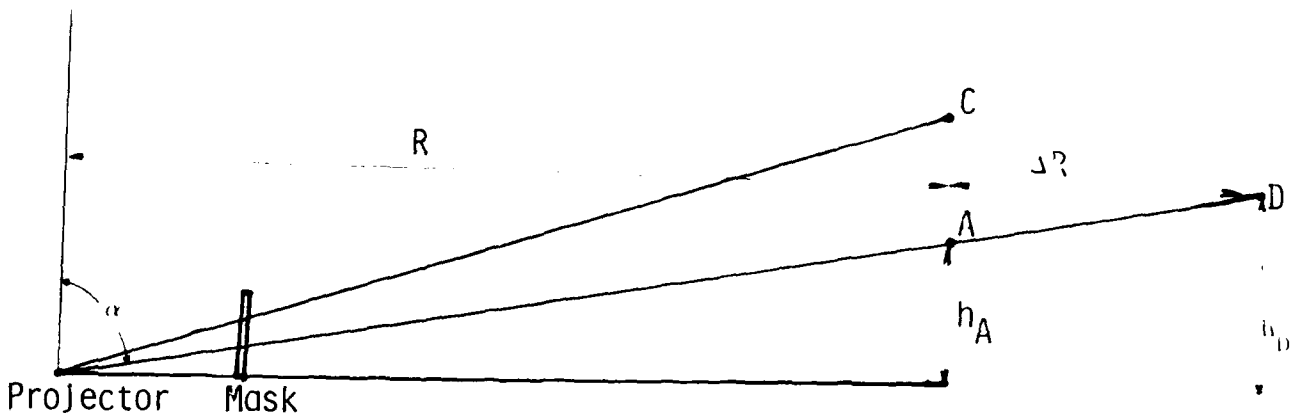


Fig. 18

ANOTHER VIEW OF RANGE UNCERTAINTY

B.7 Dark Objects' Range

One problem implicit in the method of implementing the algorithm is concerned with dark objects (including the whole object or some dark spots on the object with bright background) or holes in the object. The problem arises from the fact that whether it is a dark object or a hole, and whether the mask is covering this area or not, the result on the CID will be the same and therefore a zero will be stored in the bit-planes. Therefore the correct code will not be encoded for that area but will be stored as 0000000 = 0.

B.8 Mask Adjustment

Another fact that one should carefully deal with is mask adjustment. The masks should not only be aligned with respect to each other but they must also be aligned with respect to the rotating drum on which they are mounted (i.e., parallel to the plane of rotation).

Adjusting the masks could be elaborate (such as using a computer and associating the video inputs with different masks). One simple procedure, however, is to use an overhead projector, project the masks on the board and adjust them by comparing the base lines, etc. (This is the method we used.) The problem that might occur with this approach is that if the first mask is not parallel to the rotation plane, then all the other masks will be tilted. To avoid this problem we must first level the projector parallel to the floor and then use the floor as a reference line.

III. Topics investigated

A. Hardware

The design of the prototype structured-light source used a conventional high-fidelity turntable that had been modified by the erection of a metal wall about the circumference of (but not attached to) the platter. A hole (of the size and shape of one mask) was cut into the wall at the front of the device, and a top fabricated to confine the light so that it emerged only from the hole in front. A second wall was built on, and attached to the circumference of, the rotating platter of the turntable. A set of nine holes was cut into that wall for the insertion of the glass masks (eight bit-plane masks and one reference-image mask) described above. At the center of the interior of this circular section was the light source (the photographic flash unit), suspended from a bar attached to the top of the outer wall, and hence stationary.

The original goal was the real-time (30 frames per second) production and processing of range images; a 30 rotation-per-second rate of the turntable would have therefore been required. For reasons described below, processing at that rate was not possible, and the masks were rotated past the front opening by hand, at a very low speed.

The DAD box (so called because of its manufacturer, Digital-Analog Designs, Inc.) was designed to provide rapid storage of the eight bit-plane images, and their aggregation for definition of the eight-bit word needed to describe each pixel. The box (see technical description in Appendix C) also contained a fast arithmetic logic unit and the look-up tables described above. These latter two elements were intended to create range images rapidly, using the techniques described above. The DAD box was controlled by a Franklin 1000 microcomputer, for which software was written (see description and listings in Appendix D) to trigger and synchronize the light source. Although the software could, in principle, operate at a speed that would permit the 30-image-per-second rate, problems with the turntable speed control kept it turning too rapidly for the system. Accordingly, efforts were aimed at providing proof-of-principle rather than achieving maximum speed. The turntable was therefore rotated by hand, pausing at each of the nine masks to illuminate the object and record the result with the CID camera.

B. Software - Range Data Recognition and Object Matching

B.1. Introduction

This section describes a simulation system for range data recognition and the object matching. In fact, it is a range image processing algorithm which uses the data obtained by our computer vision system.

The simulation system began by generating the range data which are the distances from the sensor plane to the surfaces of a convex, plane-faced 3-D object (in a specific orientation). The range image processing program is composed of a range data recognition algorithm and a single view-to-3D object matching algorithm.

The goal of the range data recognition algorithm is to find

(i) how many planes in the range image

(ii) the plane equations

(iii) the node coordinates of the object (visible in the single view).

The matching algorithm is used to prove whether this single view is one of the views of the reference object or not.

Because the range data image is a kind of intensity image, some of the mature techniques in intensity image processing were applied to our range image processing algorithm, including image segmentation, histogram smoothing and chain-code boundary representation. The simulation system achieved the desired results, but it is useful only for convex, plane-faced objects.

B.2 Simulation System

Fig. 1 shows the simulation system we used. Plate 1 is a summary of the steps described below.

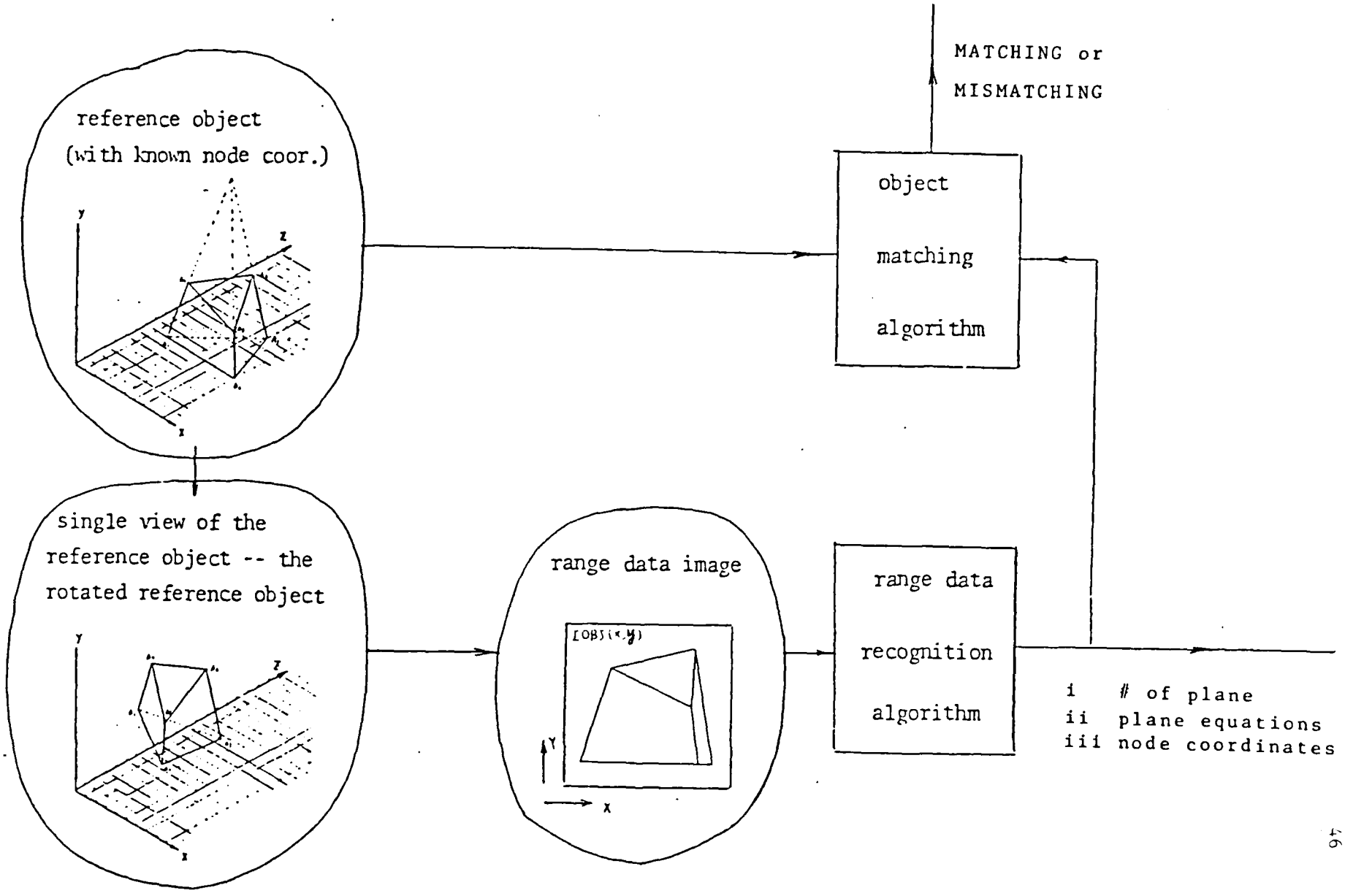


Fig. 1
SUMMARY OF THE SIMULATION PROCEDURE

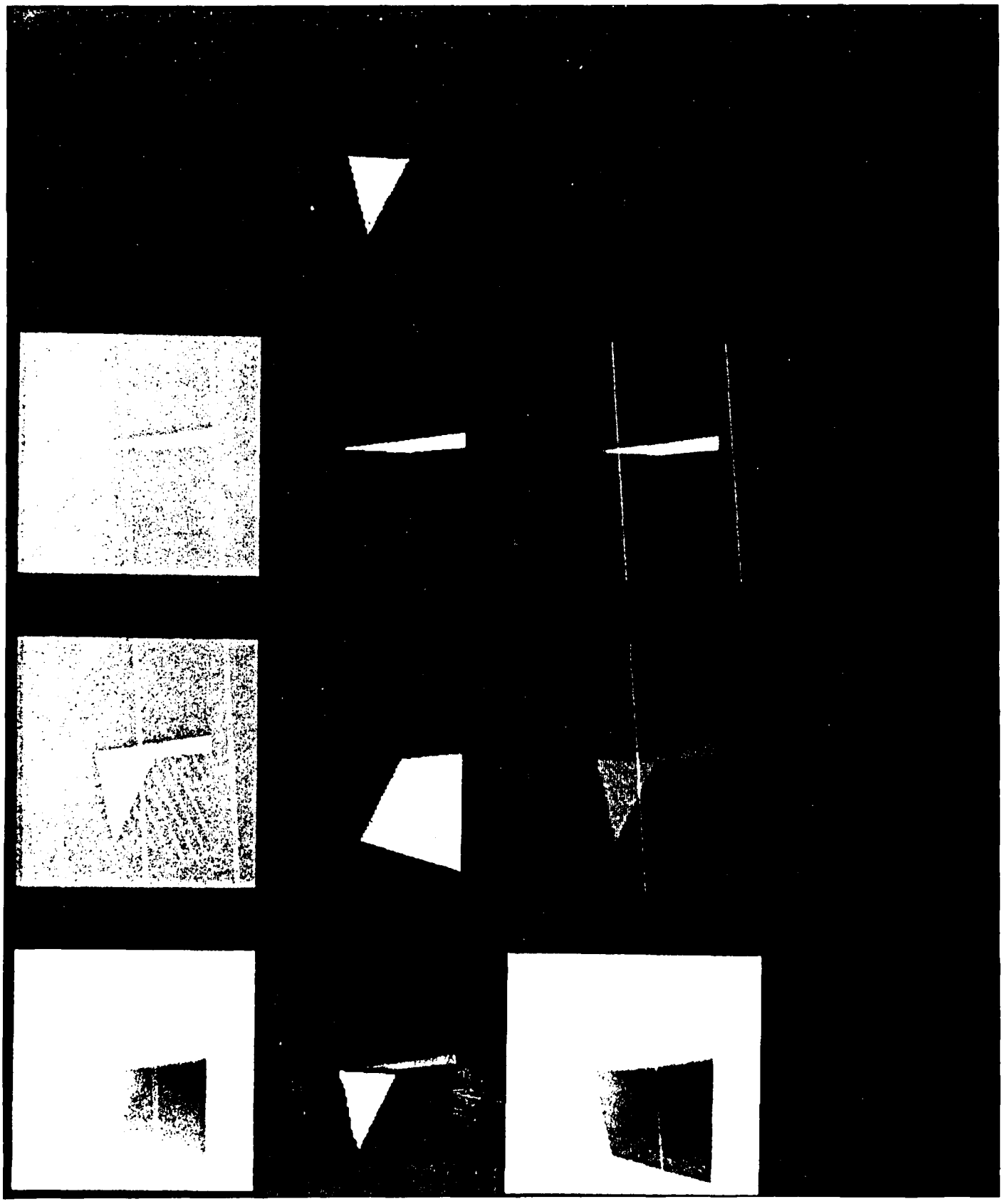


Plate 1 Results of the operation from Fig. 1

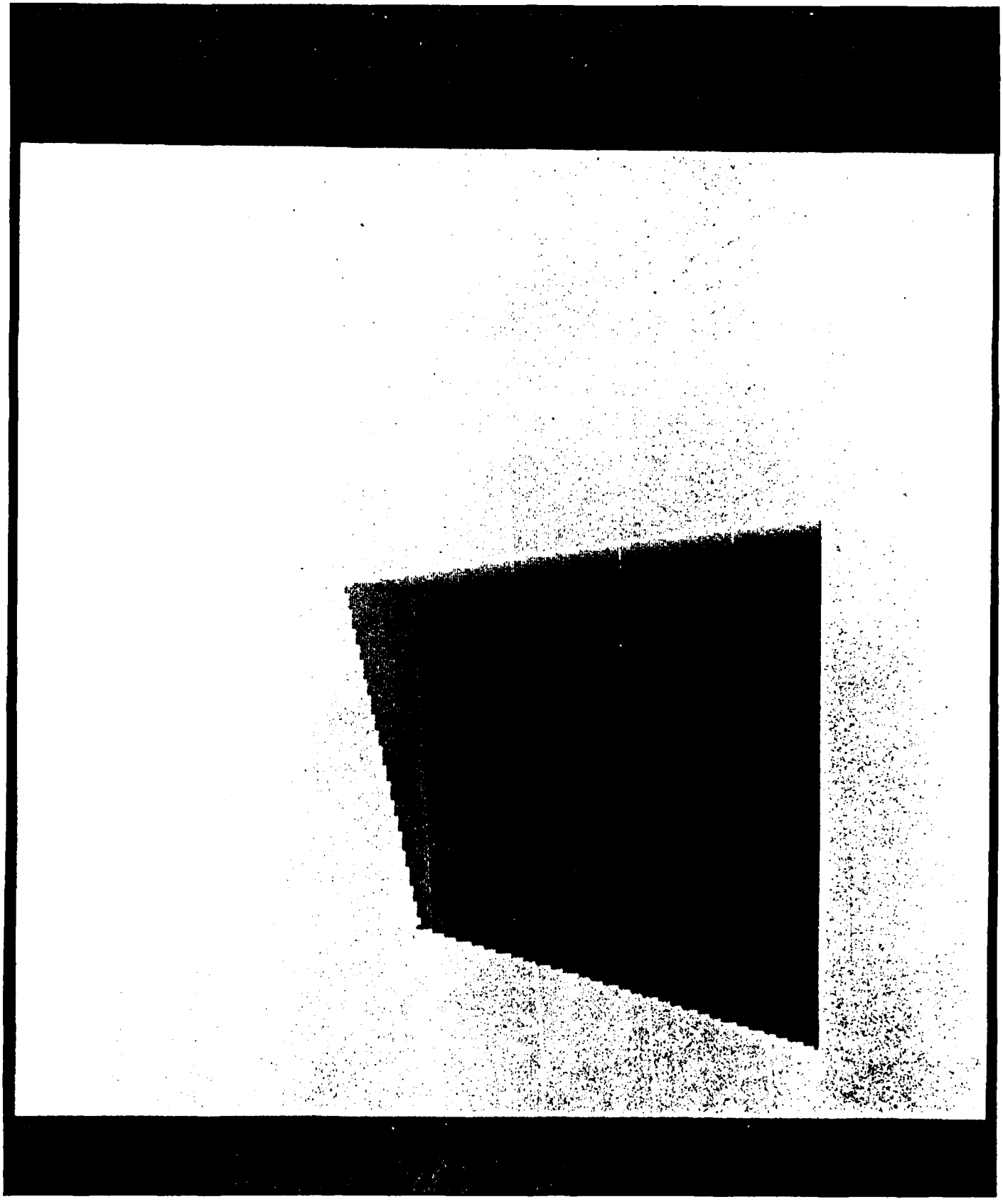


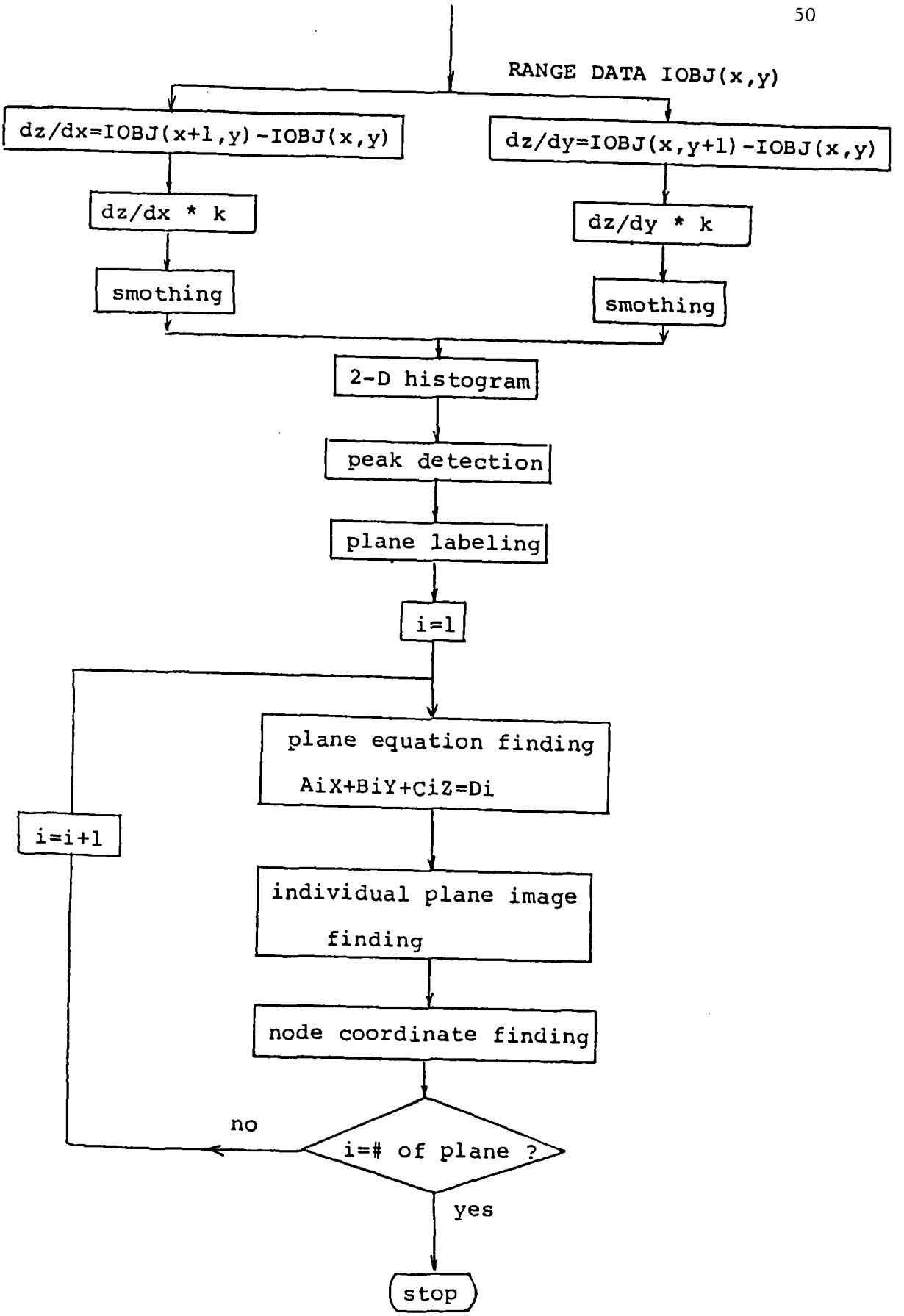
Plate 2 A simulated range image, mapped as gray levels. Darker pixels represent smaller distances

As an example, we chose a prism sitting on the X-Z plane as our reference object; it had six nodes and five planes. As a convex, plane-faced object, it may be represented by just the node coordinates, which will be used in later object matching procedures.

After a simple geometric transformation of the reference object the rotated reference object with known node coordinates and plane equations is chosen for range data generating. The X-Y plane is the sensor plane and the z values are the range values which would be represented in our range data image by the gray levels. Plate 2 shows the intensity range image displayed on the RAMTEK 9400. The darker the pixel on the image, the smaller the distance.

In order to examine the results of the range data recognition algorithm, we store the 3-D node coordinates and the parameters of the plane equations (i.e. A,B,C,D values in plane equation AX+BY+CZ=D, with D equal to either 1 or 0).

The artificial range data are then sent to the range data recognition system. The outputs of the system are the number of the planes (in this specific view), the plane equations and the node coordinates (visible in the view). One can compare the outputs with the original data which are used to generate the range data image to estimate the performances of the range data recognition system.



FLOWCHART OF PLANE-DESCRIPTION PROCEDURE

Fig 2

The object matching system receive the information from both the reference object and the single view. Comparing the node coordinates and plane equations, one can easily make the decision -- matching or mismatching.

B.3 Range Data Recognition

The range data recognition algorithm starts with the range data image IOBJ(x,y), and contains the following three steps:

(i). plane segmentation

(ii). plane equation finding

(iii) node coordinate finding

Fig. 2 is the flowchart of the range data recognition system.

We separate the planes in our single view image based on the different orientation of the individual plane. To find the orientation of the individual plane, it is necessary to compute the slopes in both X and Y directions (i.e. first partial derivative dz/dx and dz/dy). Plates 3(a) and (b) show respectively the slopes dz/dx and dz/dy. The area which is brighter than the background has positive value of the first partial derivative, and the darker area has negative values. Since every plane has its own values of dz/dx and dz/dy, it is possible to separate the planes in the 2-D slope histogram (Fig. 3) by simple peak detection.

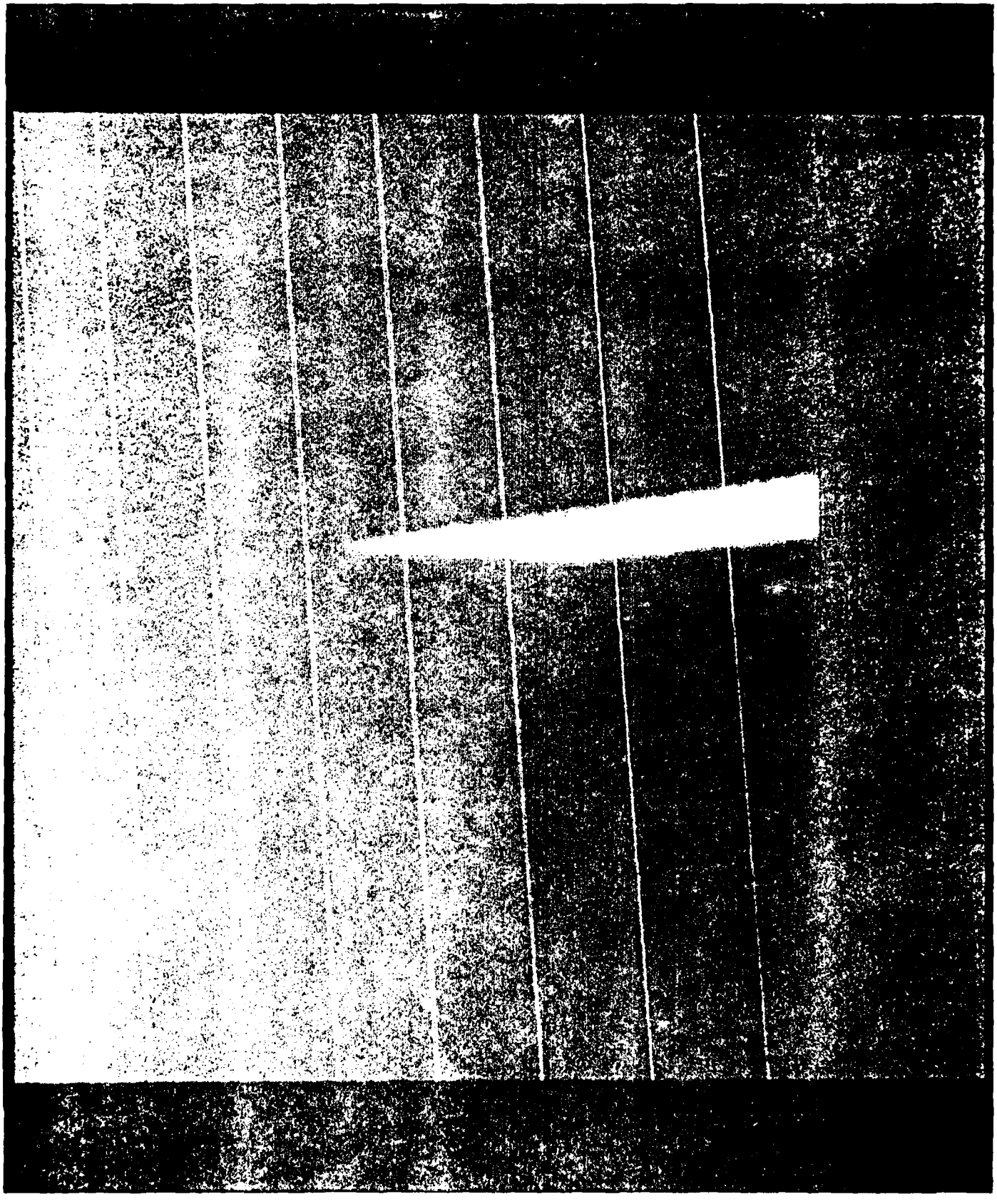
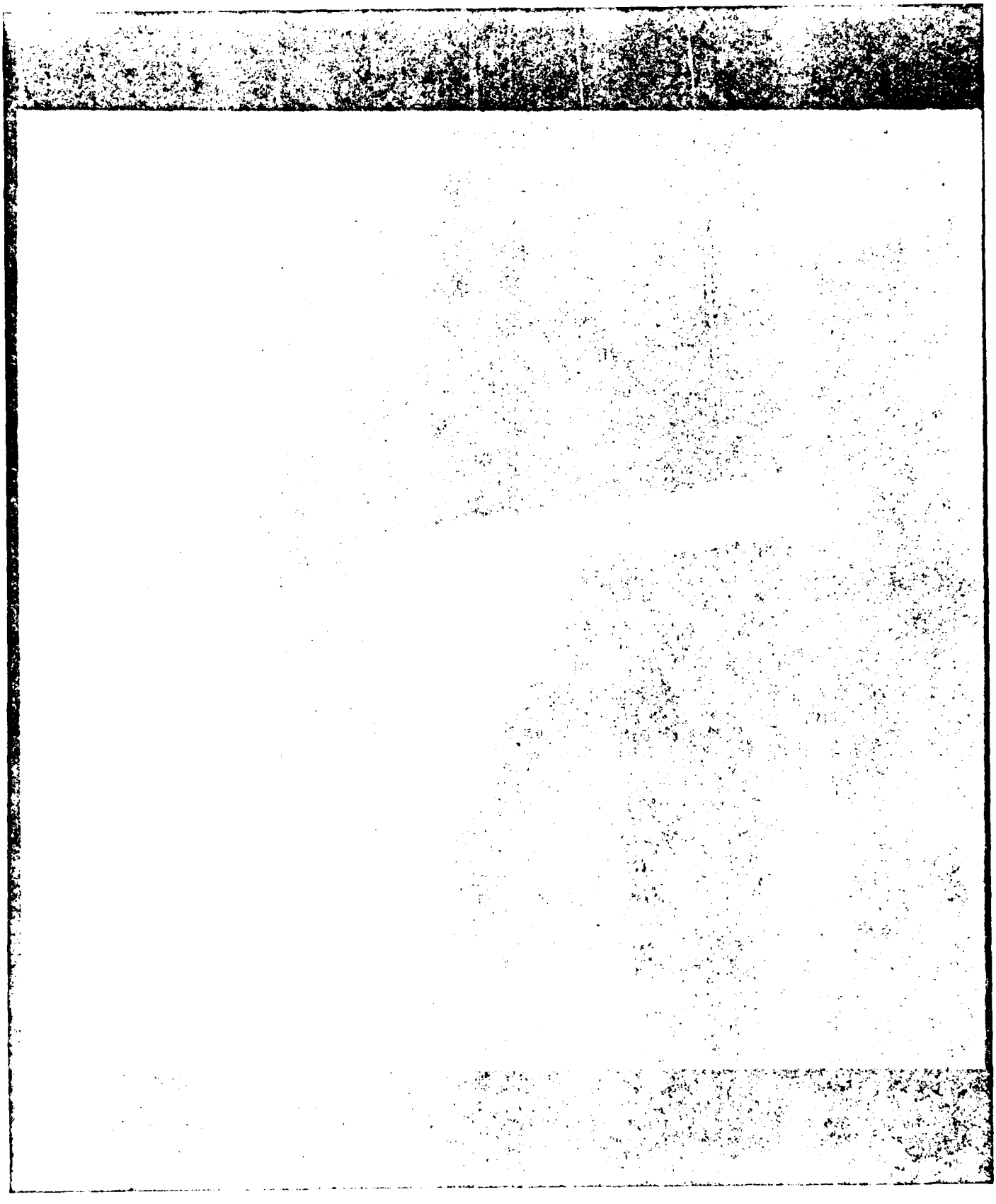


Plate 3 Images of slope mapped as intensity: (a) dz/dx



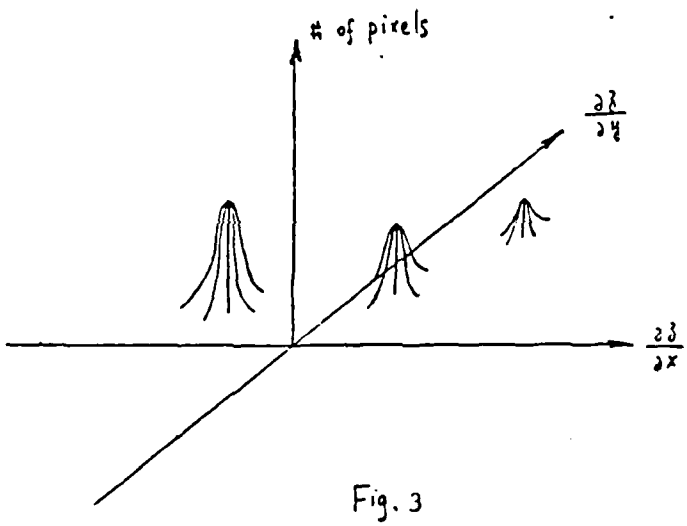


Fig. 3

SLOPE HISTOGRAM FOR IDENTIFICATION OF

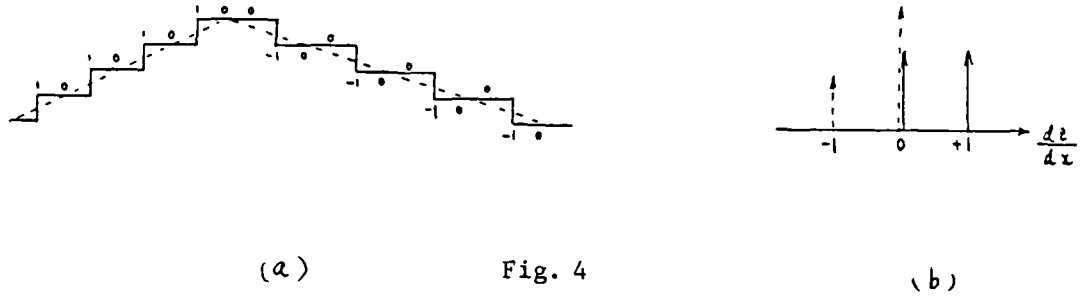
DISTINCT PLANES

An inherent problem in any digitized intensity image is the presence of discontinuities in the first derivative because of the limited gray levels. This problem causes the peak spreading and even overlap in our 2-D slope histogram. For instance, for the very shallow (nearly horizontal to X or Y axes) planes we might find slope value 0,1 in one plane and 0,-1 in another plane (see Fig. 4(a)) so that there would be an overlap in the slope histogram (Fig. 4(b)) and therefore no way to separate these two planes.

To solve the problem, we multiply the slope value by a factor k (say k=5) to increase the number of the gray levels (Fig. 5(a)). After the smoothing procedure (Fig. 5(b)), one can easily find the separated peaks in the slope histogram (Fig. 5(c)). It is then no problem to separate these two planes.

Each strong peak in the 2-D slope histogram implies the presence of a distinct plane in our range data image. Taking the peak as the center and considering the 8 neighbors of the peak (see Fig. 6) we can label the pixels which have their dz/dx values between $(dz/dx)_{min}$ and $(dz/dx)_{max}$ and their dz/dy values between $(dz/dy)_{min}$ and $(dz/dy)_{max}$ as having the same value (see Plate 4).

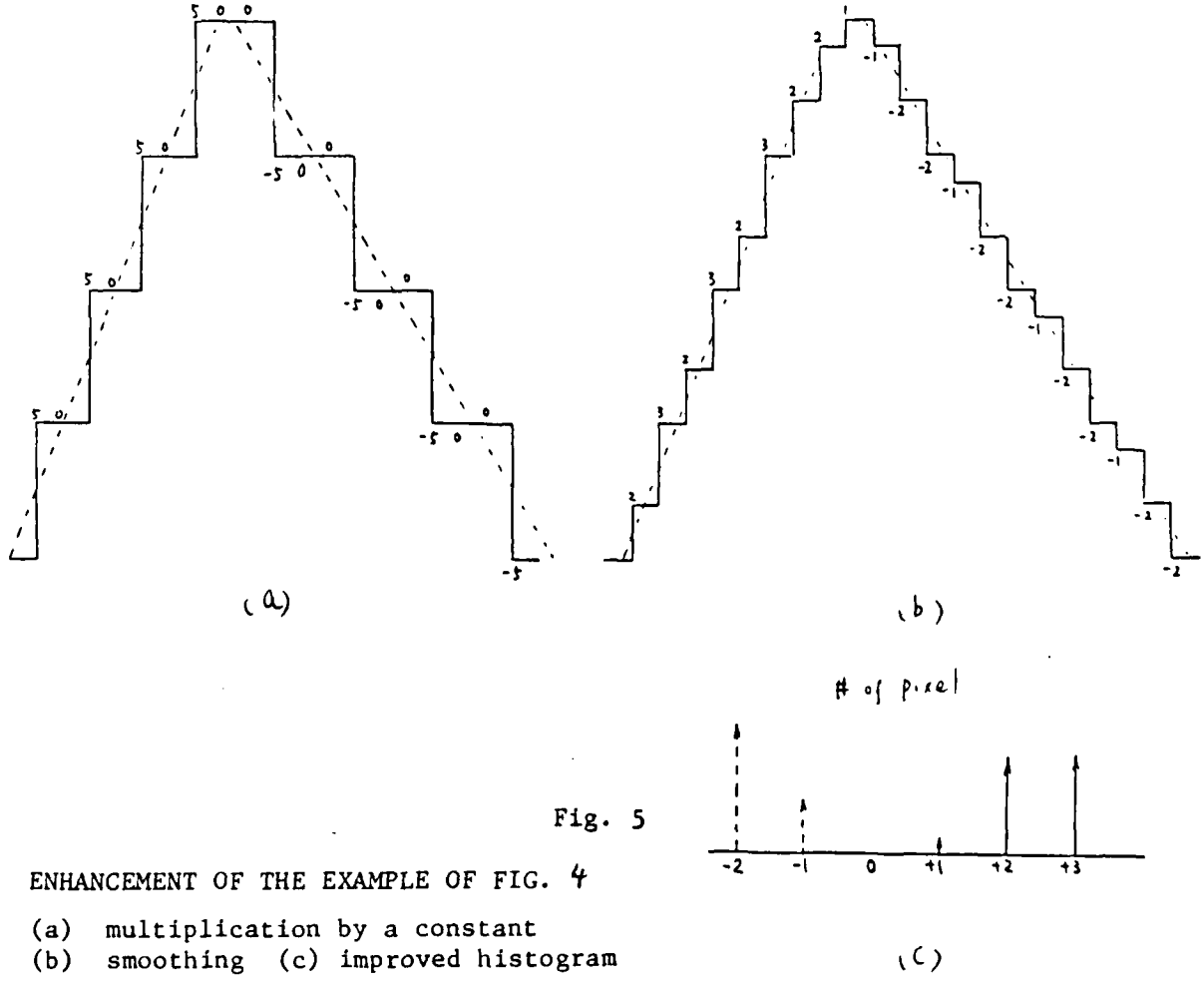
Because of the slope smoothing procedure the boundaries of the planes were blurred. The pixels around the boundaries were reasonably rejected during the plane labeling. The planes appearing in Plate 4 are smaller than those they represent, but this margin makes for more-confident estimates of the planes' equations.



(a) (b)

Fig. 4

EFFECT OF LIMITED DYNAMIC RANGE. (a) Cross-Section of two planes meeting at shallow angle (b) The corresponding histogram, and its poorly-resolved peaks



(a) (b) (c)

Fig. 5

ENHANCEMENT OF THE EXAMPLE OF FIG. 4

(a) multiplication by a constant
(b) smoothing (c) improved histogram

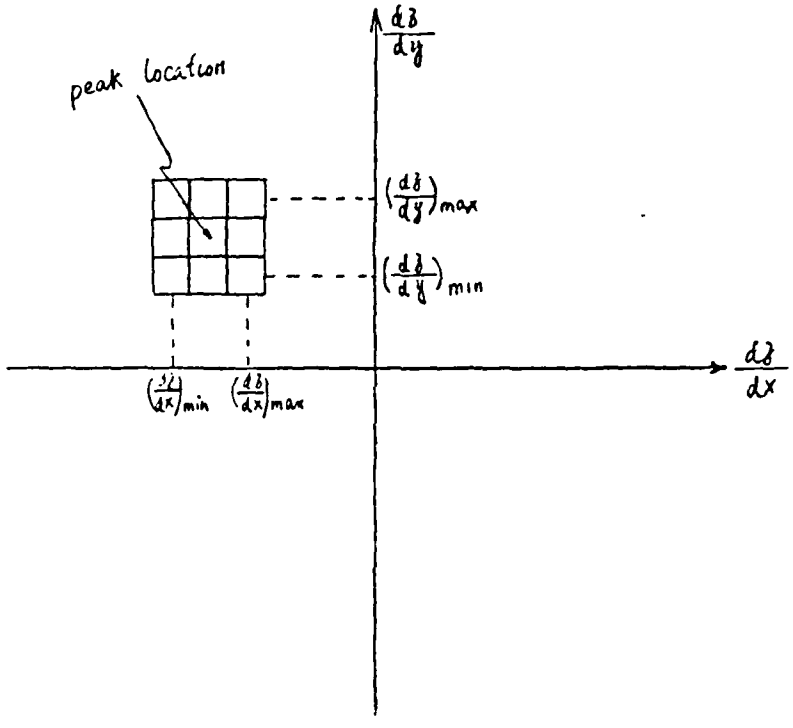


Fig. 6

NEIGHBORHOODS OF A PEAK IN THE 2-D SLOPE HISTOGRAM DEFINE MAXIMA AND MINIMA

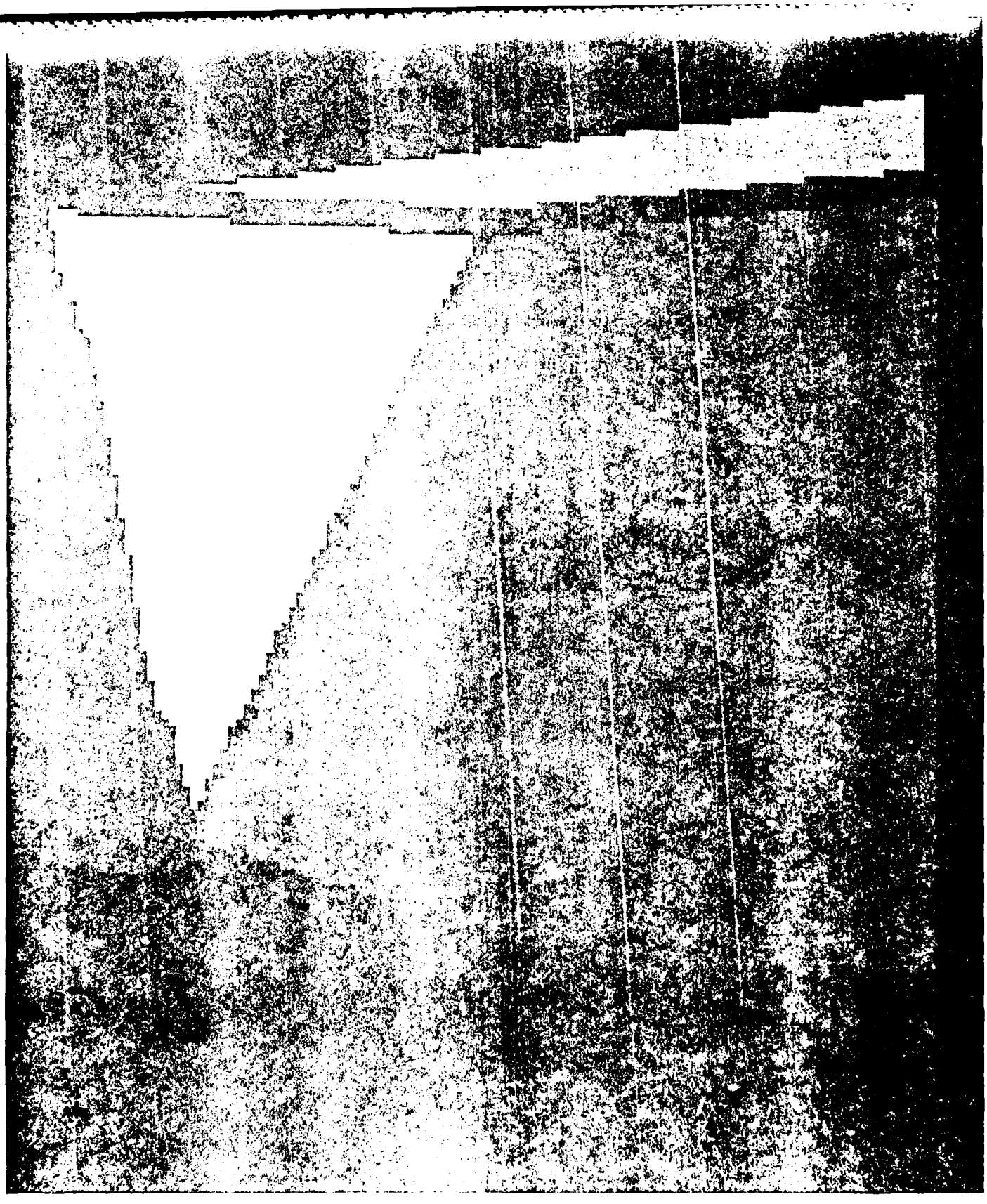


Plate 4 Identification in the range image of the distinct planest[illegible] with slopes within the ranges defined by Figure 6 [illegible] gray level.

Picking up 3 points on a labeled plane (choosing them to be as far apart as possible), one can find the plane equation in the form of AX+BY+CZ=D (D=1 or 0).

Once we learn the plane equation, we can readily solve several problems:

(i) to find the relationship between the planes by their plane equation parameters Ai, Bi, Ci, Di.

(ii) to find the individual plane images (i.e. the pixels whose IOBJ(x,y) value satisfies the plane equation). Plates 5(a),(b),(c) show the individual planes which were finally found. They are exactly the original planes.

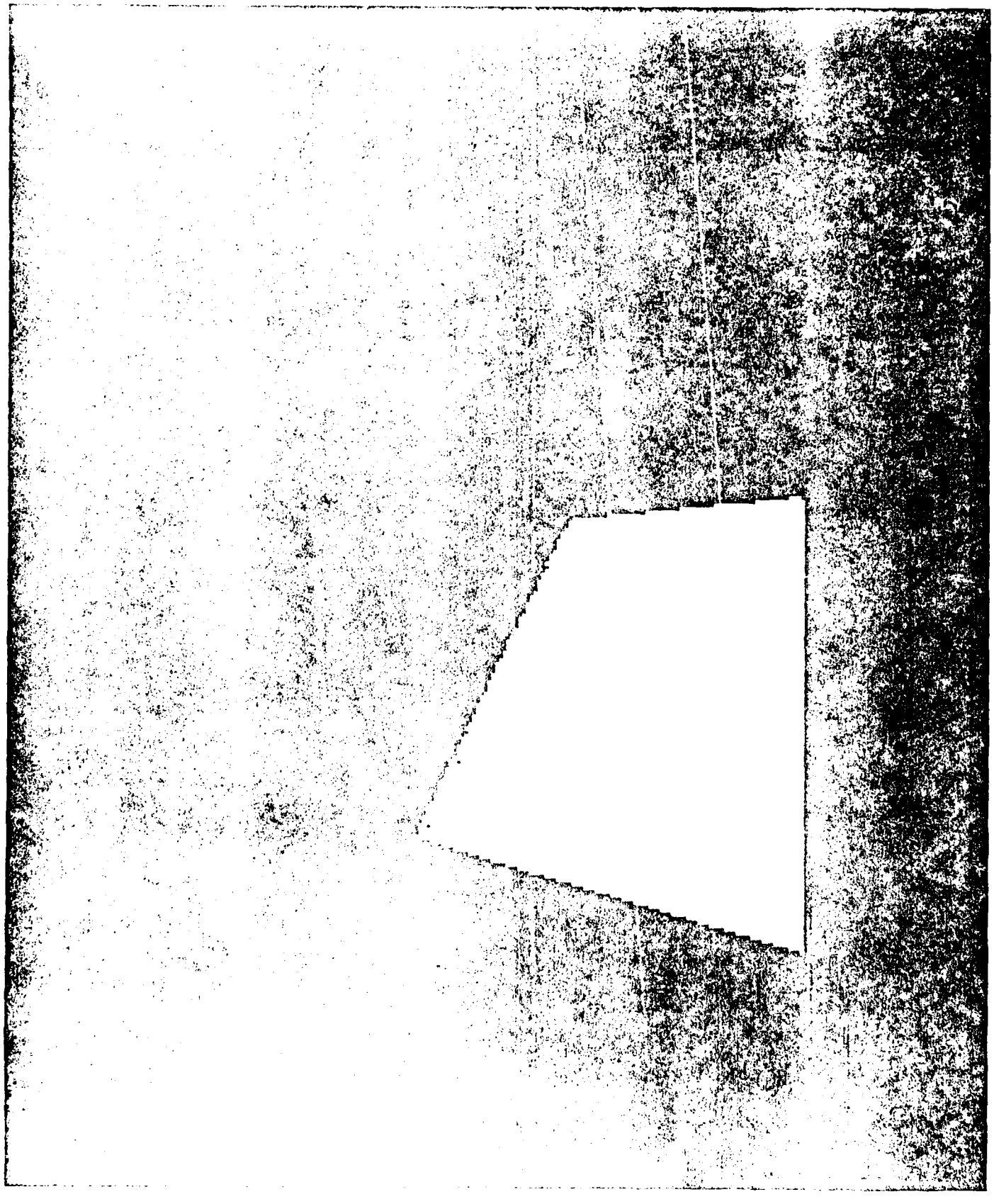
(iii) searching the boundary pixels in the individual plane image and using the chain code as the indicator of the directions, one can find the turning points in the boundaries (i.e. the nodes of the object) in terms of the changes in the chain code.

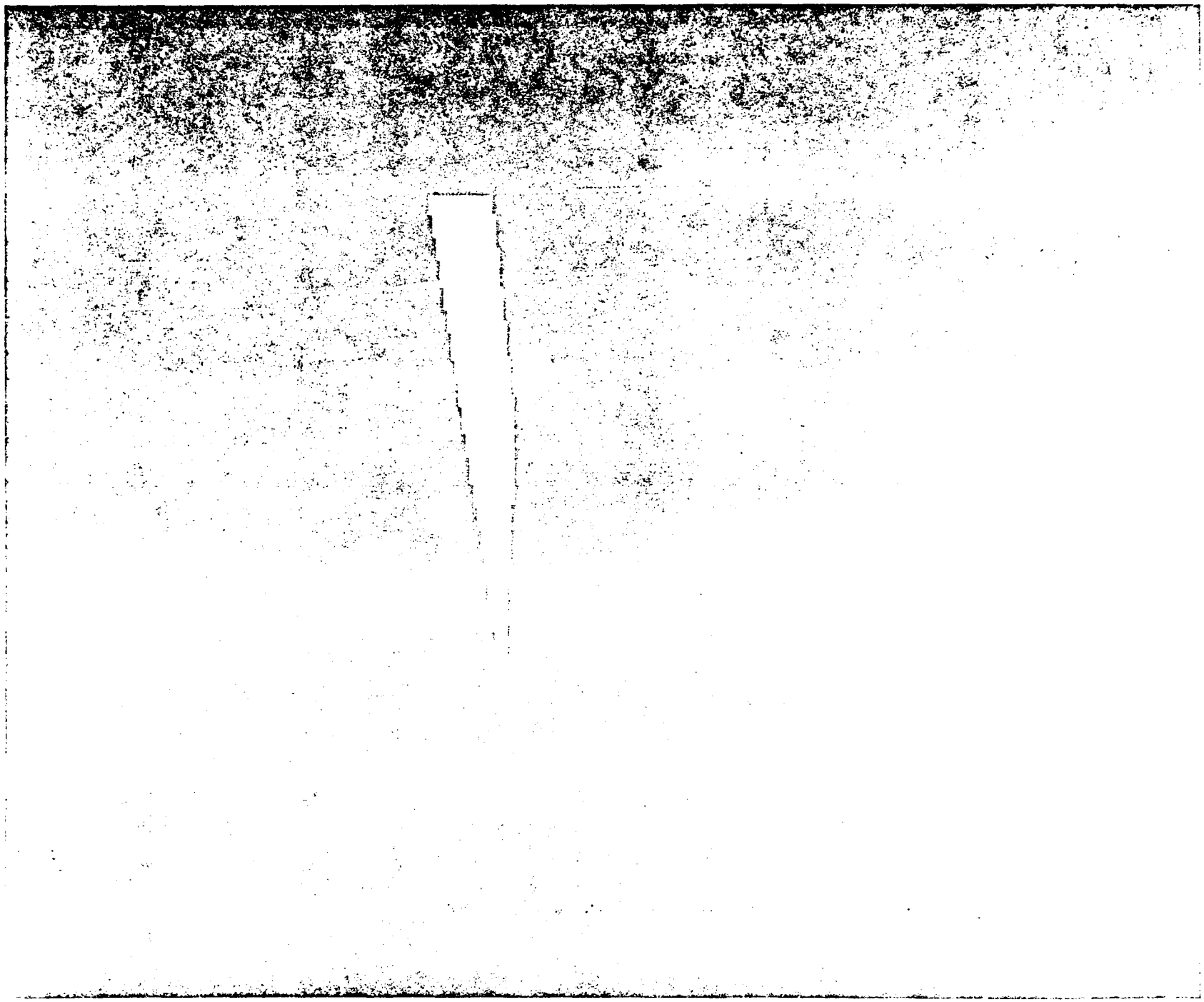
The outputs of our range image recognition program -- the number of planes, the plane equations, and the visible-node coordinates -- offer enough information for the object matching procedure.

B.4 Object Matching

The object matching program will answer the question --- is this single view a specific view of our reference object? The matching procedure includes the following three steps (see Fig. 7):

(i) bottom-node matching





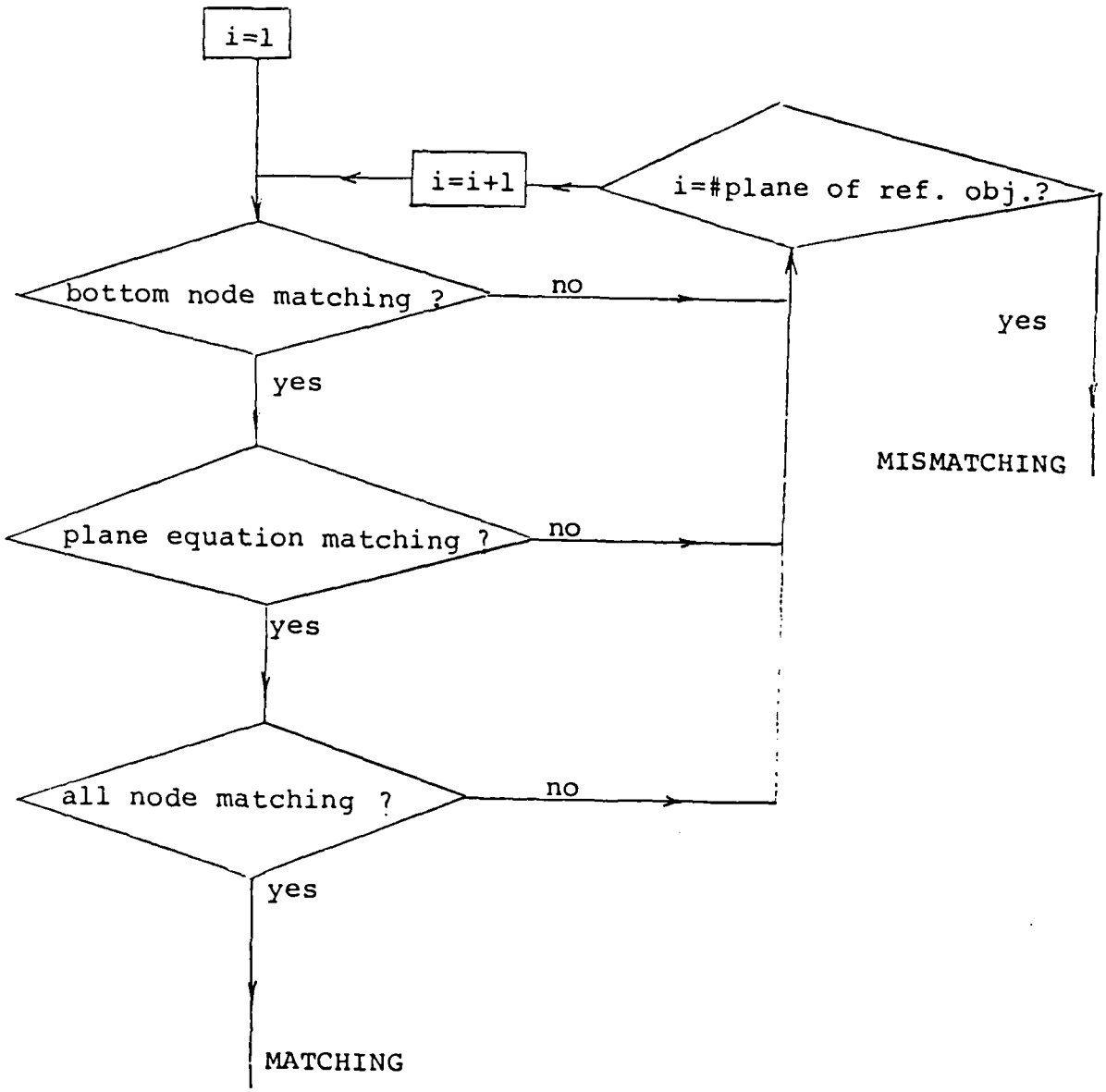


Fig. 7

FLOWCHART OF THE OBJECT-MATCHING PROCEDURE

(ii) plane-equation matching

(iii) all-node matching

The node coordinates and plane equations of the single view are found from the range image recognition program, and those of the reference object are assumed known a priori.

It was assumed that the object we are observing has its bottom plane parallel to the X-Z plane. Therefore, one can choose one of the planes of our reference object as the bottom plane and let it be parallel to X-Z plane (one of the possible positions) when we start the matching procedure.

A parallel transformation is needed for both reference object and the object being observed in order to compare their node coordinates and plane equations. Putting a bottom node at the origin (see Fig. 8) we can first compare the coordinates of the bottom node. It means to compute the total error in 3-D coordinates

$$e_{b.n} = \sum_{i=1}^{N} \left[(x_{ri} - x_{oi})^2 + (y_{ri} - Y_{oi})^2 + (z_{ri} - z_{oi})^2 \right]^{1/2}$$

where N is the number of nodes:

x_{ri}, y_{ri}, z_{ri} are the node coordinates of the reference object;

x_{oi}, y_{oi}, z_{oi} are the node coordinates of the observed object.

Usually a rotation of the reference object about the Y axis has to be done before we learn whether the bottom nodes are matching or not. If it is not, we would put another bottom node of our reference object (but in the same position) to the origin and

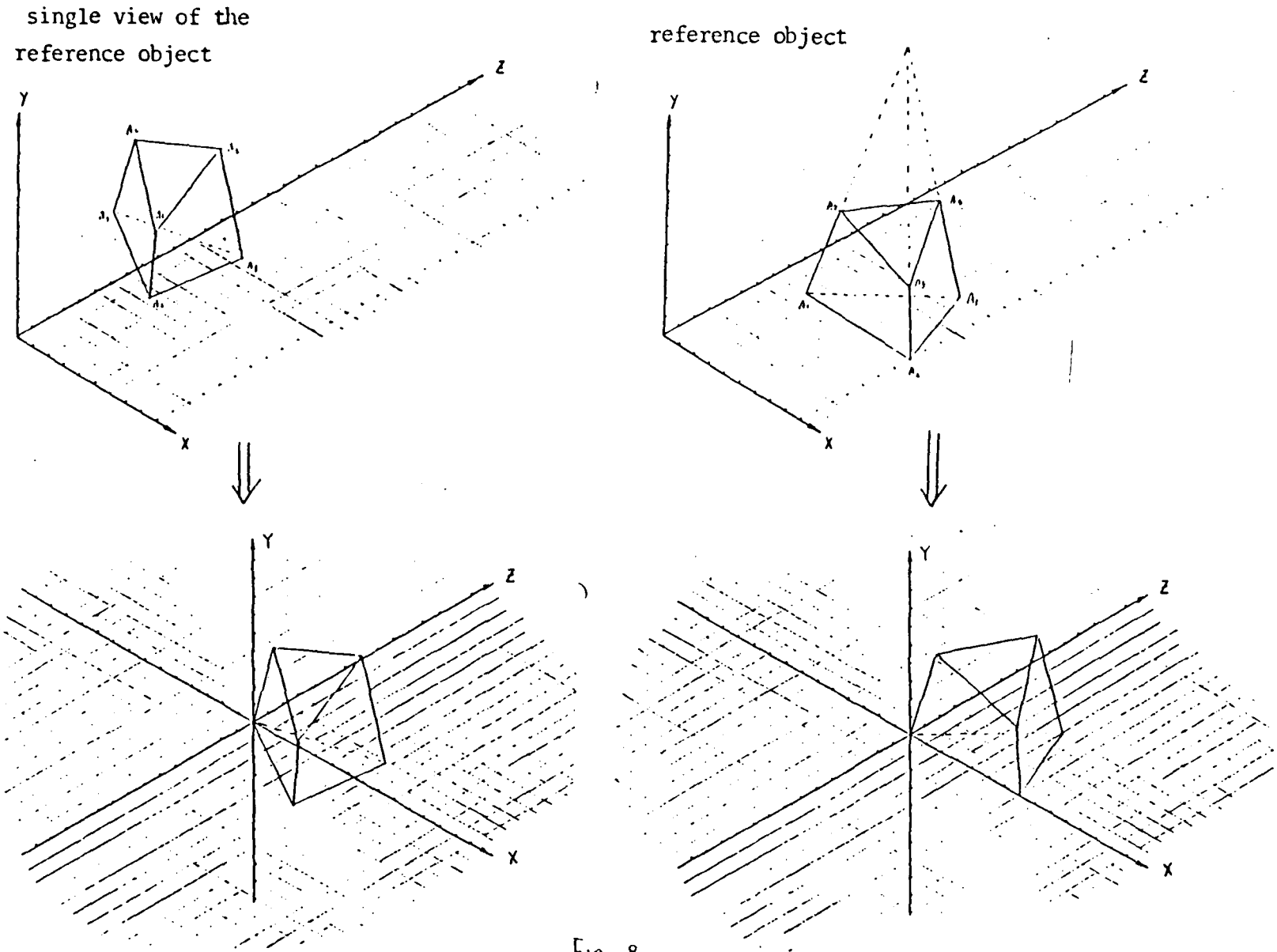


Fig. 8

EXAMPLE OF THE OBJECT-MATCHING PROCEDURE

compare it to the observed object again. If it is still not matching after we try all bottom nodes in this position at the origin, we will change the position of the reference object and go through the same bottom node matching procedure again. If it does match we will proceed with the plane equation matching program. One can simply compute the difference between the parameters of the plane equations

$$e_{p.e.} = \sum_{i=1}^{M} \left[(A_{ri} - A_{oi})^2 + (B_{ri} - B_{oi})^2 + (C_{ri} - C_{oi})^2 + (D_{ri} - D_{oi})^2 \right]^{1/2}$$

where m is the number of planes, and

A_{ri}, B_{ri}, C_{ri}, D_{ri} are the parameters of the plane equation of reference object;

A_{oi}, B_{oi}, C_{oi}, D_{oi} are the parameters of the plane equations of observed object.

Finally, we invoke the all-node matching program if the bottom node matching and the plane equation matching have passed. The goal of the all-node matching program is to check:

(i) if all nodes we found from the range image can find their partners in the reference object;

(ii) if all extra nodes in the reference object are behind the surface of our specific view.

B.5 Results and Conclusions

To examine the simulation system, we compared the original node coordinates and plane equations which we used to generate the range image and those we finally found using the range image recognition system. The results are presented in Table I and Table II respectively. The total error for all 18 node coordinates was 10.87 and the error between the coordinates of the plane equations was 0.01268. This results show the good performance of our recognition system. In addition, the matching procedure has an advantage of requiring both rather small memory space and the amount of the computation because the whole matching procedure does not require image-sized data operations. (Appendix E contains listings of the software used.)

IV. Conclusions and implications for the Navy

The results presented here indicate that structured light is a feasible technique for real-time ranging. Equally, regardless of how a range image is acquired, useful descriptions of objects can be extracted from such an image. The DAD box appears to be a fast processor that can use look-up tables to compute range in real-time, and should be considered for integration into structured-light systems.

Clearly, further work must be done to examine the mechanical aspects of sweeping the masks past the light source, andthe intensity of the light must be augmented. (An alternative to increasing the intensity of the source is the use of a photomultiplier at the camera

Table I - RESULTS OF PLANE-EQUATION DETERMINATION

# of plane	plane equations	
	to generate the data	we finally found
plane #1	0.00556X-0.00148Y+0.00963Z=1	0.00553X-0.00150Y+0.00968Z=1
plane #2	-0.00050X+0.01395Y-0.01087Z=1	-0.00053X+0.01387Y-0.01070Z=1
plane #3	0.00695X+0.00096Y-0.00100Z=1	0.00696X+0.00095Y-0.00101Z=1

Table II- RESULTS OF NODE-COORDINATE DETERMINATION

# of node	node coordinates	
	to generate the data	we finally found
A1	20, 50, 100	20, 50, 100
A2	141, 50, 30	140, 51, 31
A3	156, 50, 127	156, 50, 132
A4	50, 150, 98	51, 150, 98
A5	135, 110, 43	134, 111, 44
A6	138, 170, 119	137, 169, 119

input. Efforts were made in this direction using an NBS-supplied low-light-level [LLL] camera. Irreconcilable optical incompatibilities between the LLL camera and the CID camera, however, made it impossible to make a realistic test of the benefits of such an approach.)

Possible disadvantages of this kind of system include the need for a very fine slit to reduce the size of the region of uncertainty cast by the masks. It is the requirement for the fine slit that leads to the need for a high-intensity light source (as noted above). The system, as it uses visible light, must operate in a darkened environment and hence is probably not suitable where human activity is also involved.

In many manufacturing-related applications, however, structured light is likely to be very useful. Opportunities include inspection tasks: for completeness of structure, or quality of surface finish; and assembly tasks: for parts matching and orientation. Many of the precision and/or hazardous manufacturing and handling responsiblities of the Navy appear to be reasonable candidates for adoption of this technology, which requires of necessity a relatively static platform for installation of the equipment. It is thus far better suited to the manufacturing and quality control environments than, for example, to a mobile-robot application.

Several research papers which bear on the range of prospective applications of this kind of a system appear in Appendix F.

APPENDIX A

CALCULATION AND DISPLAY OF VISIBLE REGION

Camera focal point assumed to be aligned with the first row of the CID plane. (Physical arrangement was alignment with center of CID plane; difference in visible region is small.)

```
LIST
480  INPUT "WHAT IS THE DESIRED CAMERA TILT?";C
482  PRINT ""
484  PRINT ""
486  PRINT ""
488  PRINT "D","KO","YO","KA","YA","KB","KC"
490 C1 = (C / 180) * (3.141592654)
500 A = .042
510 F1 = .142
520 B = .008784
530 F2 = .023
540 C2 =  ATN (B / F2)
545  FOR D = .5 TO 2.5 STEP .5
550 KO = D / ((A / F1) + (1 /  TAN (C1 - C2)))
560 YO = D / (1 + ((F1 / A) / ( TAN (C1 - C2))))
570 KA = D / ((A / F1) + ( COS (C1) /  SIN (C1)))
580 YA = D / (1 + ((F1 *  COS (C1)) / (A *  SIN (C1))))
590 KB = D * ( TAN (C1 - C2))
600  IF C = 90 THEN 630
610 KC = D * ( TAN (C1))
620  PRINT D,KO,YO,KA,YA,KB,KC
625  GOTO 650
630 KC$ = "INFINITY"
640  PRINT D,KO,YO,KA,YA,KB,KC$
650  NEXT D
660  END
```

```
JRUN
WHAT IS THE DESIRED CAMERA TILT?90
```

D	KO	YO	KA	YA	KB	KC
.5	.772636733	.228526358	1.69047619	.5	1.42304189	INFINITY
1	1.54527347	.457052715	3.38095238	1	2.84608379	INFINITY
1.5	2.3179102	.685579073	5.07142858	1.5	4.26912569	INFINITY
2	3.09054693	.91410543	6.76190476	2	5.69216758	INFINITY
2.5	3.86318367	1.14263179	8.45238095	2.5	7.11520948	INFINITY

```
]RUN
WHAT IS THE DESIRED CAMERA TILT?75
```

D	RU	YU	RA	YA	RB	RC
.5	.510490829	.150990245	.886959118	.262340021	.731341777	1.8660254
1	1.02098166	.30198049	1.77391824	.524680041	1.46268356	3.7320508
1.5	1.53147249	.452970735	2.66087735	.787020062	2.19402533	5.5980762
2	2.04196332	.60396098	3.54783647	1.04936008	2.92536711	7.4641016
2.5	2.55245414	.754951226	4.43479559	1.3117001	3.65670889	9.330127

```
]RUN
WHAT IS THE DESIRED CAMERA TILT?60
```

D	KO	YO	KA	YA	KB	KC
.5	.342272505	.10123553	.572655746	.169377051	.429166251	.866025403
1	.684545011	.20247106	1.14531149	.338754103	.858332502	1.73205081
1.5	1.02681752	.303706589	1.71796724	.508131154	1.28749875	2.59807621
2	1.36909002	.404942119	2.29062298	.677508206	1.716665	3.46410161
2.5	1.71136253	.506177649	2.86327873	.846885257	2.14583126	4.33012702

```
JRUN
WHAT IS THE DESIRED CAMERA TILT(45
```

D	KU	YU	KA	YA	KB	KC
.5	.21015917	.0621597547	.385869565	.114130435	.239995264	.5
1	.420318341	.124319509	.771739131	.22826087	.479990528	1
1.5	.630477512	.186479264	1.1576087	.342391304	.719985792	1.5
2	.840636682	.248639019	1.54347826	.456521739	.959981056	2
2.5	1.05079585	.310798773	1.92934783	.570652174	1.19997632	2.5

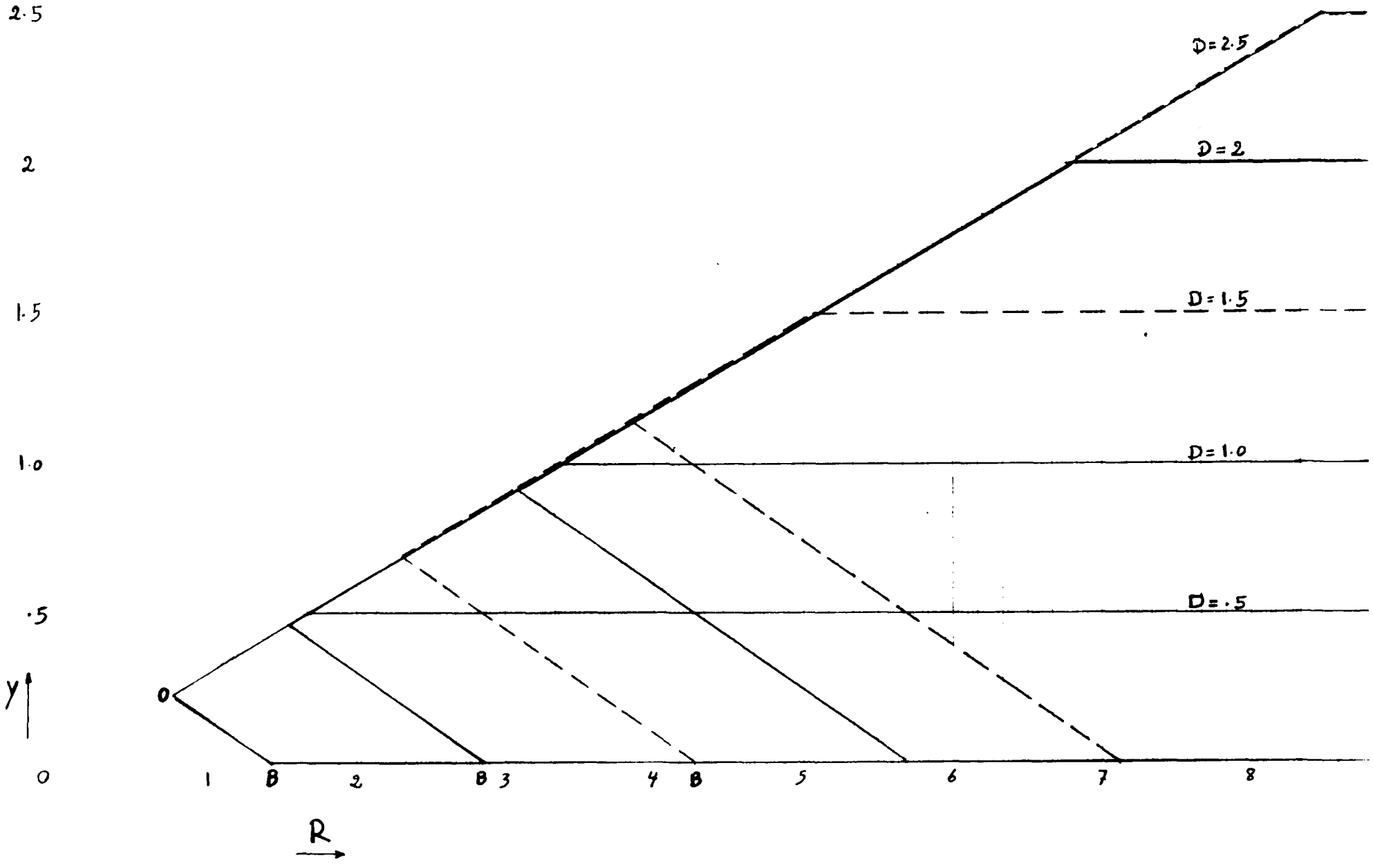
DEON

WHAT IS THE DESIRED CAMERA TILT?30

D	KO	YO	KA	YA	KB	KC
.5	.0889935701	.0263220419	.246569545	.0729290203	.0939388973	.288675135
1	.17798714	.0526440837	.49313909	.145858041	.187877795	.577350269
1.5	.26698071	.0789661256	.739708635	.218787061	.281816692	.866025404
2	.35597428	.105288167	.98627818	.291716081	.375755589	1.15470054
2.5	.44496785I	.131610209	1.23284773	.364645102	.469694486	1.44337567

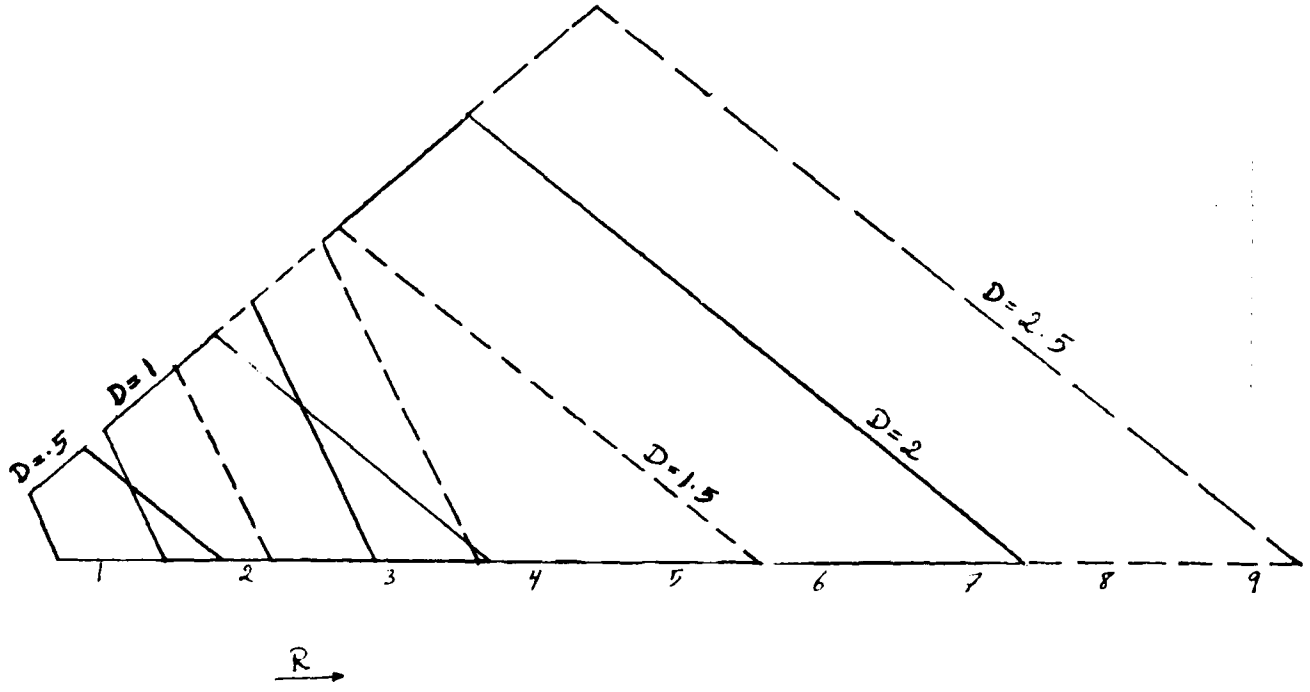
VISIBLE REGION FOR CAMERA TILT OF 90°

FOR DIFFERENT PROJECTOR CAMERA DISTANCES



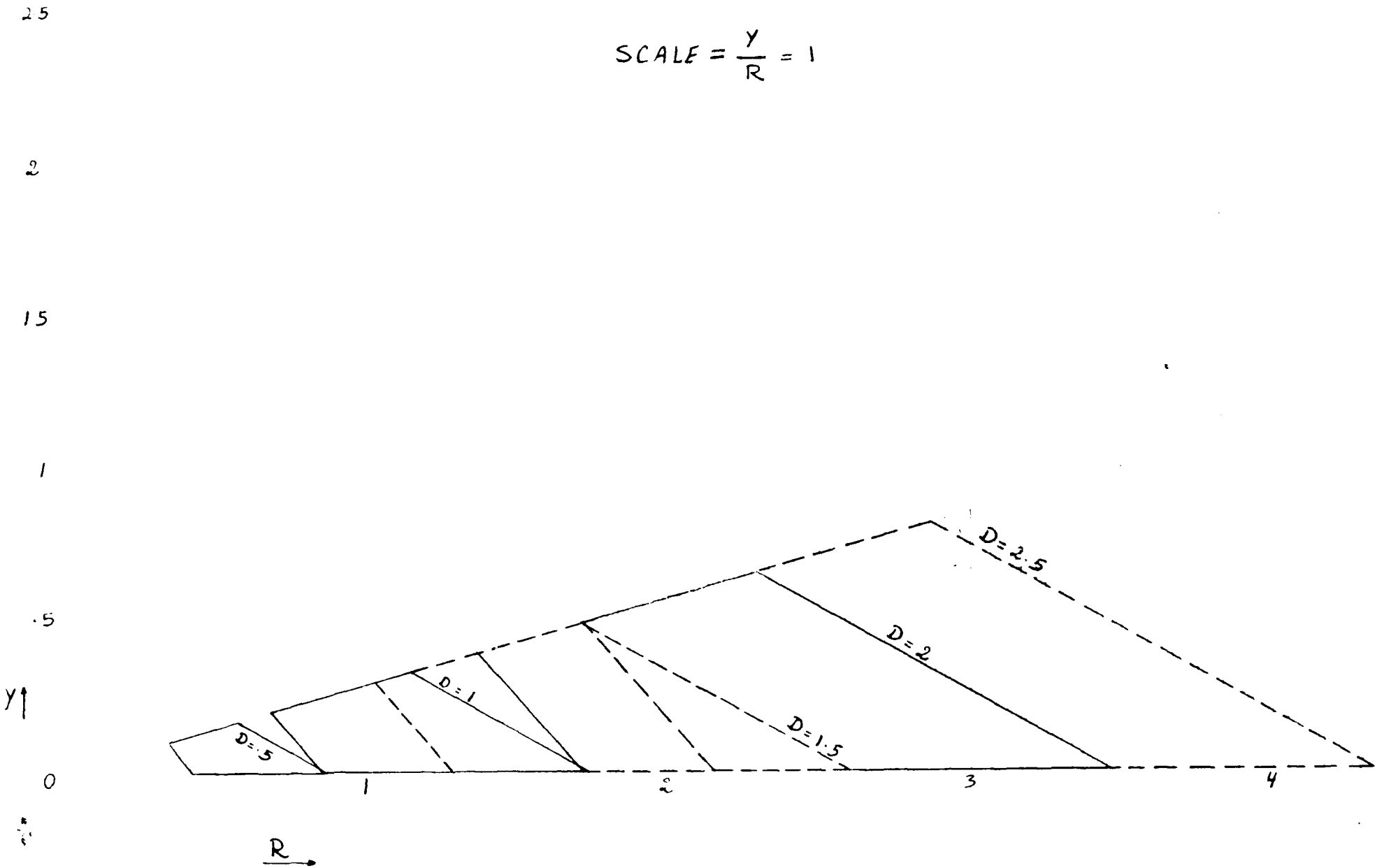
CAMERA TILT = 75°

$$\text{SCALE} = \frac{Y}{R} = 3$$

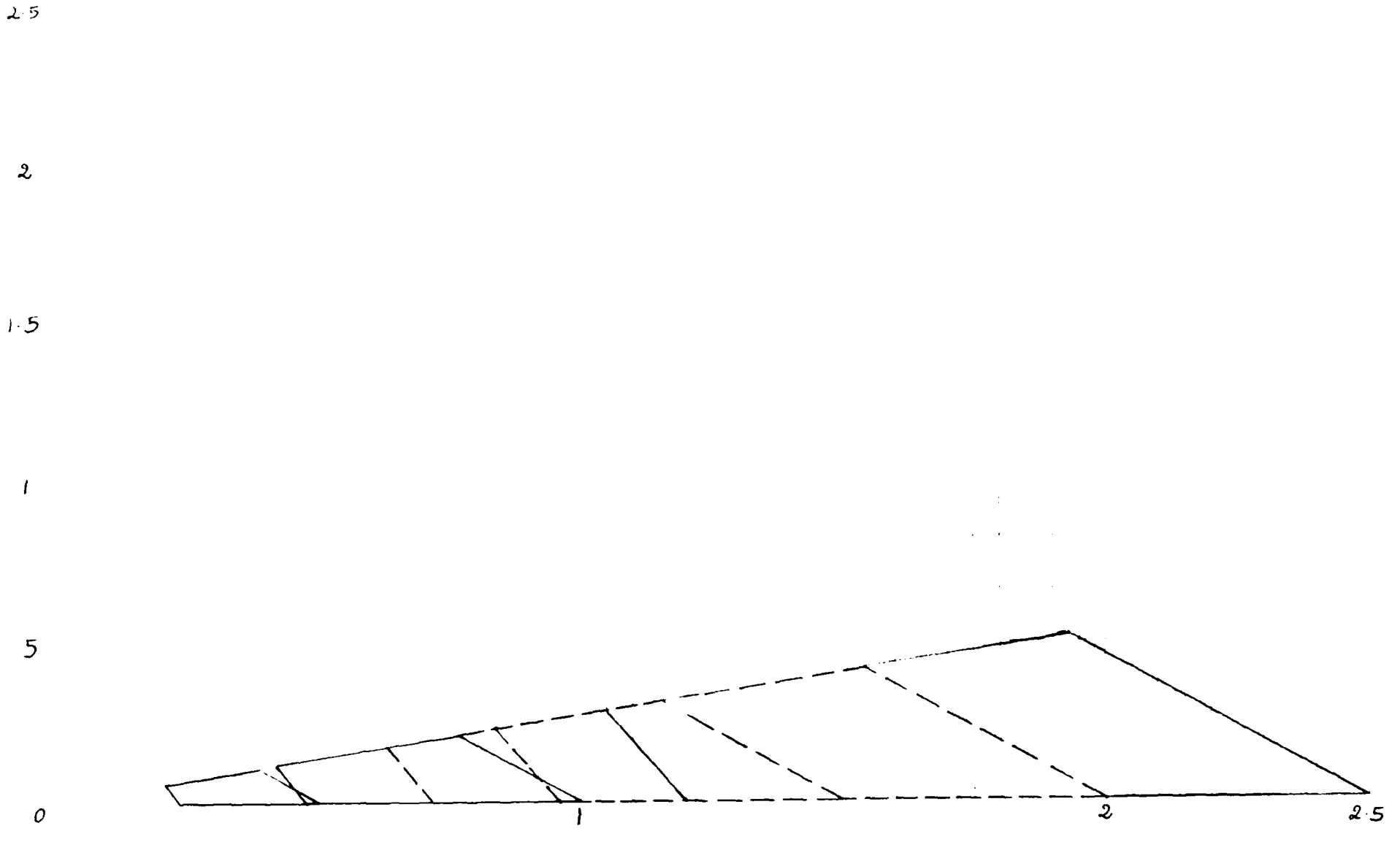


CAMERA TILT = 60°

$$SCALE = \frac{Y}{R} = 1$$



CAMERA TILT = 45°



APPENDIX B

CALCULATION AND PLOTS OF THEORETICAL PRECISION OF RANGE ESTIMATES

A.

The following plot shows the sensitivity of the computed range by the system at a specific camera tilt (c), object range (R), camera-projector (d),and the changein range (ΔR) versus the change in object vertical location:

a) ΔR=.01

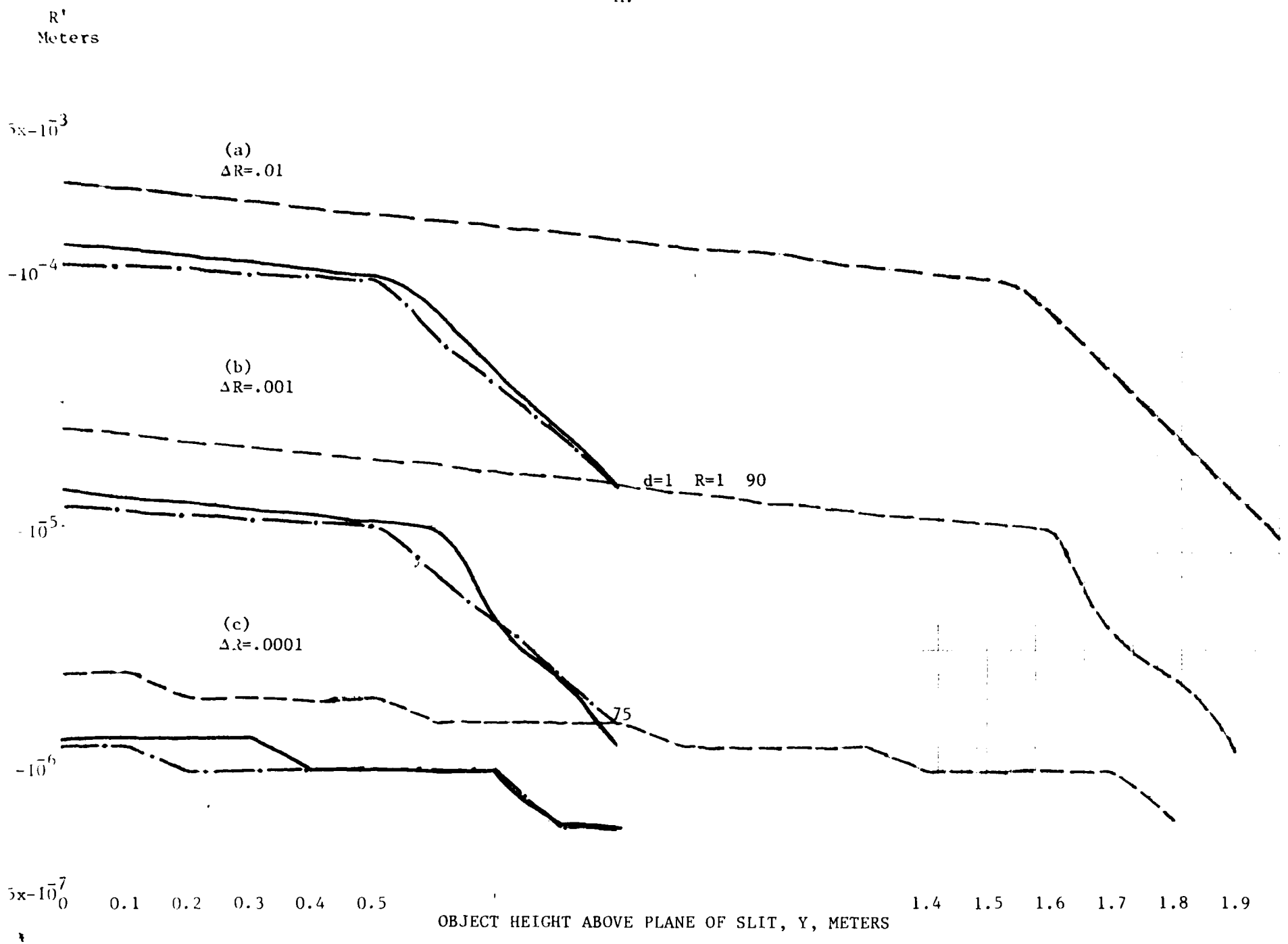
d=1
R=1
c=90° } solid black line

d=1
R=1
C=75° } Red line

d=2
R=1
c=90° } dashed line

b) ΔR=.001
same as above

c) ΔR=.0001
same as above


R'
Meters
5x-10^-3
(a)
ΔR=.01
-10^-4
(b)
ΔR=.001
d=1 R=1 90
-10^-5
(c)
ΔR=.0001
75
-10^-6
5x-10^-7
0 0.1 0.2 0.3 0.4 0.5 1.4 1.5 1.6 1.7 1.8 1.9
OBJECT HEIGHT ABOVE PLANE OF SLIT, Y, METERS

B.

Thc attached plot shows the changes detected in range ($\Delta R'$) due to a change made in camera tilt (c) for the following parameters:

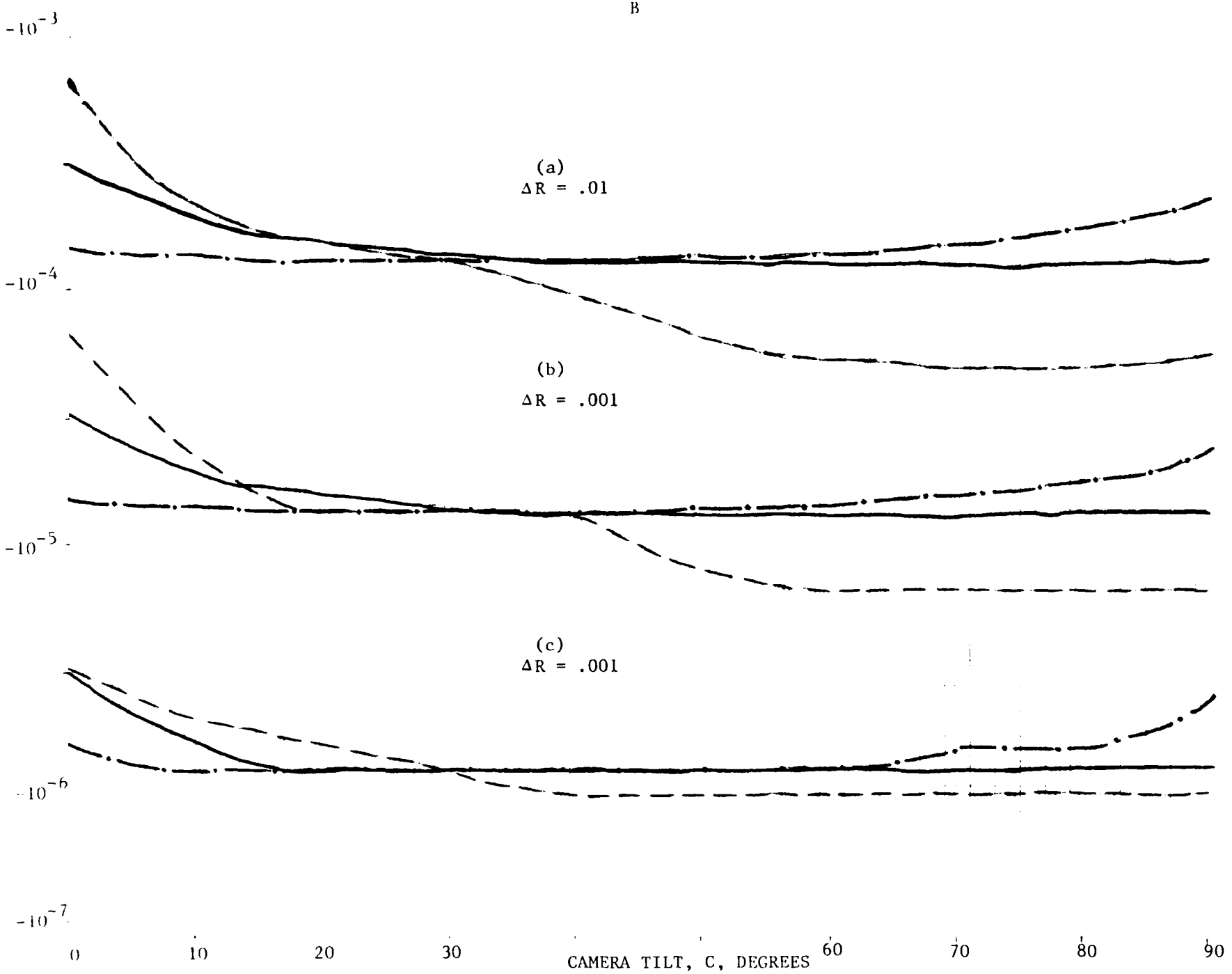
a) ΔR =.01 a change in range

Camera-projector distance (d)	=2	red line
Range (R)	=1	red line
Height of the object (y)	=.5	red line
camera-project distance (d)	=1	solid black line
range of the object (R)	=1	solid black line
Height of the object (y)	=.5	solid black line
d=1		dashed line
R=2		dashed line
y=.5		dashed line

b) ΔR=.001
same as above

c) ΔR=.001
same as above

Therefore the plot shows the sensitivity of the computed range with respect to a change in range of the object versus the camera tilt. Note that the resolution (pixel size) in the CID is 3bμm.

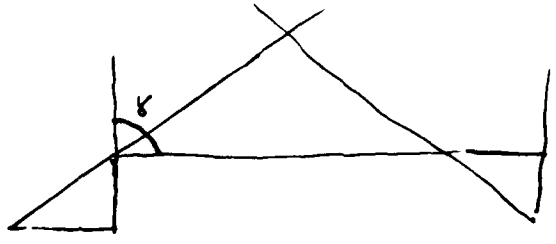

-10^{-3}
(a)
ΔR = .01
-10^{-4}
(b)
ΔR = .001
-10^{-5}
(c)
ΔR = .001
-10^{-6}
-10^{-7}
0
10
20
30
60
70
80
90
CAMERA TILT, C, DEGREES

```
LIST
100  INPUT "ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=";D
110  INPUT "ENTER THE RANGE=";R
130  INPUT "ENTER THE CAMERA TILT=";C
150  INPUT "ENTER THE DESIRED CHANGE IN RANGE=";N
152  REM
153  PRINT "HEIGHT","DELTA R'"
155 C1 = (C / 180) * (3.14159265)
156  REM
157  FOR Y = 0 TO D STEP 0.1
158  REM
159  REM
190 B1 =  ATN (R / (D - Y))
200 A1 =  - (R / ( SIN (B1))) * ( SIN (B1 - C1))
210 D1 = (R / ( SIN (B1))) * ( COS (B1 - C1))
215 F2 = .025
220 M1 = (A1 / D1) * F2
221 V = M1
231  REM
232  REM
240 N1 = N
292 M = 0
294  IF N < 0 THEN L = 1
295  IF N >  = 0 THEN L = 0
296  REM
297  REM
300 A2 = A1 * (( - 1) ^ (M + L + 1)) * (N1) *  COS (C1)
310 D2 = D1 + (( - 1) ^ L) * (N1) * ( SIN (C1))
 320 M2 = (A2 / D2) * F2
 330  REM
322  REM
325 W = M2
330 T = W - V
331  REM
332  REM
340 M3 =  INT ((T * .0000005) * 1000000) / 1000000
342  REM
344  REM
350  PRINT Y, M3
360  NEXT Y
370  END
```

A

READY

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE CAMERA TILT=90
ENTER THE DESIRED CHANGE IN RANGE=.0001
HEIGHT              DELTA R'
0                   -2E-06
.1                  -2E-06
.2                  -2E-06
.3                  -2E-06
.4                  -1E-06
.5                  -1E-06
.6                  -1E-06
.7                  -1E-06
.8                  0
.9                  0
```



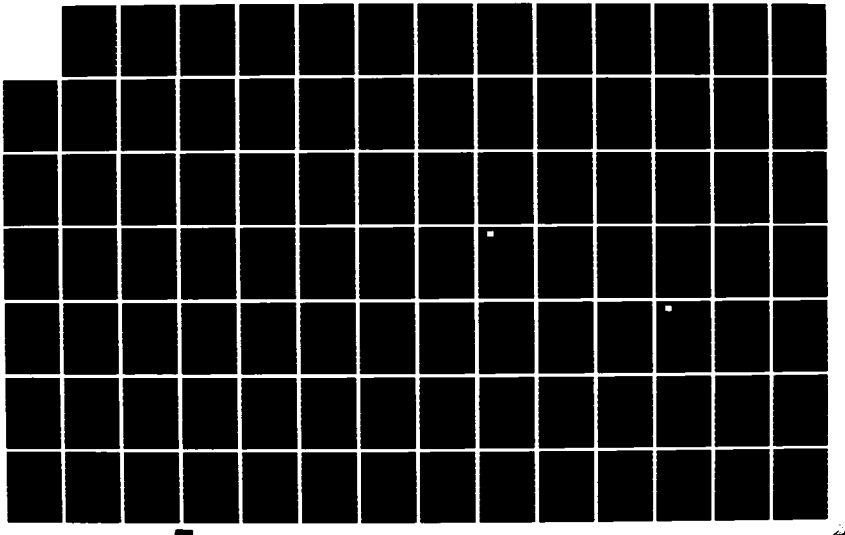
```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE CAMERA TILT=90
ENTER THE DESIRED CHANGE IN RANGE=.001
HEIGHT              DELTA R'
0                   -2.3E-05
.1                  -2.2E-05
.2                  -2E-05
.3                  -1.7E-05
.4                  -1.5E-05
.5                  -1.2E-05
.6                  -1E-05
.7                  -7E-06
.8                  -5E-06
.9                  -2E-06
```

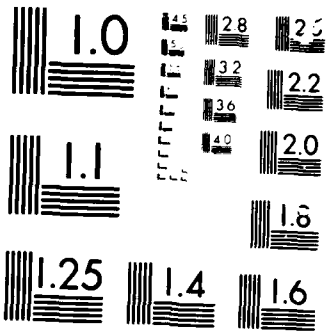
RUN

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE CAMERA DELT=90
ENTER THE DESIRED CHANGE IN RANGE=.01
REFLECTANCE             DELTA R'
0                       -2.48E-04
.1                      -2.23E-04
.2                      -1.98E-04
.3                      -1.73E-04
.4                      -1.49E-04
.5                      -1.24E-04
.6                      -9.9E-05
.7                      -7.4E-05
.8                      -5E-05
.9                      -2.5E-05
```

AD-A168 197 DEVELOPMENT OF ALGORITHMS AND HARDWARE FOR STRUCTURED-LIGHT VISION(U) GEORGE WASHINGTON UNIV WASHINGTON DC DEPT OF ELECTRICAL ENGIN.. 2/4

UNCLASSIFIED M H LOEW ET AL. 1986 N00014-83-K-0578 F/G 20/6 NL




1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE CAMERA TILT=75
ENTER THE DESIRED CHANGE IN RANGE=.0001
WEIGHT              DELTA K'
0                   -2E-06
.1                  -2E-06
.2                  -1E-06
.3                  -1E-06
.4                  -1E-06
.5                  -1E-06
.6                  -1E-06
.7                  -1E-06
.8                  0
.9                  0
```

ENTER THE DISTANCE BETWEEN CAMERA AND PROJECTION
ENTER THE RANGE=1
ENTER THE CAMERA TILT=75
ENTER THE DESIRED CHANGE IN RANGE=.001

HEIGHT	DELTA K'
0	-1.7E-05
.1	-1.6E-05
.2	-1.5E-05
.3	-1.3E-05
.4	-1.2E-05
.5	-1E-05
.6	-9E-06
.7	-7E-06
.8	-5E-06
.9	-3E-06

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE CAMERA TILT=75
ENTER THE DESIRED CHANGE IN RANGE=.01
HEIGHT              DELTA K'
0                    -1.65E-04
.1                   -1.55E-04
.2                   -1.44E-04
.3                   -1.32E-04
.4                   -1.18E-04
.5                   -1.03E-04
.6                   -8.7E-05
.7                   -6.8E-05
.8                   -4.8E-05
.9                   -2.5E-05
```

```
!RUN
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE CAMERA TILT=45
ENTER THE DESIRED CHANGE IN RANGE=.0001
HEIGHT              DELTA R'
0                   -1E-06
.1                  -1E-06
.2                  -1E-06
.3                  -1E-06
.4                  -1E-06
.5                  -1E-06
.6                  -1E-06
.7                  -1E-06
.8                  -1E-06
.9                  0
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE CAMERA TILT=45
ENTER THE DESIRED CHANGE IN RANGE=.001
HEIGHT              DELTA R'
0                    -1.2E-05
.1                   -1.2E-05
.2                   -1.2E-05
.3                   -1.2E-05
.4                   -1.2E-05
.5                   -1.1E-05
.6                   -1E-05
.7                   -9E-06
.8                   -7E-06
.9                   -4E-06
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=2
ENTER THE RANGE=1
ENTER THE CAMERA TILT=90
ENTER THE DESIRED CHANGE IN RANGE=.0001
HEIGHT              DELTA R'
0                   -5E-06
.1                  -5E-06
.2                  -4E-06
.3                  -4E-06
.4                  -4E-06
.5                  -4E-06
.6                  -3E-06
.7                  -3E-06
.8                  -3E-06
.9                  -3E-06
1                   -2E-06
1.1                 -2E-06
1.2                 -2E-06
1.3                 -2E-06
1.4                 -1E-06
1.5                 -1E-06
1.6                 -1E-06
1.7                 -1E-06
1.8                 0
1.9                 0
```

```
SYNTAX ERROR
]RUN
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=2
ENTER THE RANGE=1
ENTER THE CAMERA TILT=90
ENTER THE DESIRED CHANGE IN RANGE=.001
HEIGHT              DELTA R'
0                   -5E-05
.1                  -4.7E-05
.2                  -6.5E-05
.3                  -4.2E-05
.4                  -6E-05
.5                  -4.7E-05
.6                  -5.5E-05
.7                  -3.2E-05
.8                  -5E-05
.9                  -2.7E-05
1                   -2.5E-05
1.1                 -2.2E-05
1.2                 -2E-05
1.3                 -1.7E-05
1.4                 -1.5E-05
1.5                 -1.2E-05
1.6                 -1E-05
1.7                 -7E-06
1.8                 -5E-06
1.9                 -2E-06
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=2
ENTER THE RANGE=1
ENTER THE CAMERA TILT=90
ENTER THE DESIRED CHANGE IN RANGE=.01
HEIGHT              DELTA R'
0                    -4.93E-04
.1                   -4.7E-04
.2                   -4.46E-04
.3                   -4.21E-04
.4                   -3.96E-04
.5                   -3.71E-04
.6                   -3.47E-04
.7                   -3.22E-04
.8                   -2.97E-04
.9                   -2.72E-04
1                    -2.48E-04
1.1                  -2.23E-04
1.2                  -1.98E-04
1.3                  -1.73E-04
1.4                  -1.49E-04
1.5                  -1.24E-04
1.6                  -9.9E-05
1.7                  -7.4E-05
1.8                  -5E-05
1.9                  -2.5E-05
```

RUN

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=2
ENTER THE RANGE=1
ENTER THE CAMERA TILT=75
ENTER THE DESIRED CHANGE IN RANGE=.0001
HEIGHT              DELTA R'
0                   -2E-06
.1                  -2E-06
.2                  -2E-06
.3                  -2E-06
.4                  -2E-06
.5                  -2E-06
.6                  -2E-06
.7                  -2E-06
.8                  -2E-06
.9                  -2E-06
1                   -2E-06
1.1                 -2E-06
1.2                 -1E-06
1.3                 -1E-06
1.4                 -1E-06
1.5                 -1E-06
1.6                 -1E-06
1.7                 -1E-06
1.8                 0
1.9                 0
```

```
ENTER THE DISTANCE BETWEEN CAMERAS AND PROJECTOR=2
ENTER THE RANGE=1
ENTER THE CAMERA TILT=75
ENTER THE DESIRED CHANGE IN RANGE=.01
HEIGHT                DELTA K'
0                      -2.26E-04
.1                     -2.22E-04
.2                     -2.18E-04
.3                     -2.14E-04
.4                     -2.09E-04
.5                     -2.03E-04
.6                     -1.97E-04
.7                     -1.9E-04
.8                     -1.83E-04
.9                     -1.74E-04
1                      -1.65E-04
1.1                    -1.55E-04
1.2                    -1.44E-04
1.3                    -1.32E-04
1.4                    -1.18E-04
1.5                    -1.03E-04
1.6                    -8.7E-05
1.7                    -6.8E-05
1.8                    -4.8E-05
1.9                    -2.5E-05
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=2
ENTER THE RANGE=1
ENTER THE CAMERA TILT=75
ENTER THE DESIRED CHANGE IN RANGE=.1
HEIGHT              DELTA R'
0                    -2.13E-03
.1                   -2.09E-03
.2                   -2.05E-03
.3                   -2.01E-03
.4                    1.96E-03
.5                   -1.90E-03
.6                   -1.86E-03
.7                   -1.78E-03
.8                   -1.71E-03
.9                   -1.63E-03
1                    -1.54E-03
1.1                  -1.44E-03
1.2                  -1.34E-03
1.3                  -1.22E-03
1.4                  -1.09E-03
1.5                  -9.57E-04
1.6                  -8.02E-04
1.7                  -6.3E-04
1.8                  -4.41E-04
1.9                  -2.32E-04
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=2
ENTER THE RANGE=1
ENTER THE CAMERA IDLE=45
ENTER THE DESIRED CHANGE IN RANGE=.0001
HEIGHT              DELTA K'
0                   -1E-06
.1                  -1E-06
.2                  -1E-06
.3                  -1E-06
.4                  -1E-06
.5                  -1E-06
.6                  -1E-06
.7                  -1E-06
.8                  -1E-06
.9                  -1E-06
1                   -1E-06
1.1                 -1E-06
1.2                 -1E-06
1.3                 -1E-06
1.4                 -1E-06
1.5                 -1E-06
1.6                 -1E-06
1.7                 -1E-06
1.8                 -1E-06
1.9                 0
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=2
ENTER THE RANGE=1
ENTER THE CAMERA TILT=45
ENTER THE DESIRED CHANGE IN RANGE=.001
HEIGHT              DELTA K'
0                   -1.1E-05
.1                  -1.1E-05
.2                  -1.1E-05
.3                  -1.2E-05
.4                  -1.2E-05
.5                  -1.2E-05
.6                  -1.2E-05
.7                  -1.2E-05
.8                  -1.2E-05
.9                  -1.2E-05
1                   -1.2E-05
1.1                 -1.2E-05
1.2                 -1.2E-05
1.3                 -1.2E-05
1.4                 -1.2E-05
1.5                 -1.1E-05
1.6                 -1E-05
1.7                 -9E-06
1.8                 -7E-06
1.9                 -4E-06
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=2
ENTER THE RANGE=1
ENTER THE CAMERA TILT=45
ENTER THE DESIRED CHANGE IN RANGE=.1
WEIGHT              DELTA R'
0                   -1.075E-03
.1                  -1.092E-03
.2                  -1.108E-03
.3                  -1.124E-03
.4                  -1.14E-03
.5                  -1.154E-03
.6                  -1.167E-03
.7                  -1.178E-03
.8                  -1.186E-03
.9                  -1.19E-03
1                   -1.19E-03
1.1                 -1.184E-03
1.2                 -1.17E-03
1.3                 -1.144E-03
1.4                 -1.103E-03
1.5                 -1.042E-03
1.6                 -9.52E-04
1.7                 -8.24E-04
1.8                 -6.41E-04
1.9                 -3.79E-04
```

```
DOIN
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=2
ENTER THE CAMERA TILT=90
ENTER THE DESIRED CHANGE IN RANGE=.0001
HEIGHT              DELTA R'
0                   -1E-06
.1                  -1E-06
.2                  0
.3                  0
.4                  0
.5                  0
.6                  0
.7                  0
.8                  0
.9                  0
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=2
ENTER THE CAMERA TILT=90
ENTER THE DESIRED CHANGE IN RANGE=.1
HEIGHT              DELTA R'
0                   -3.95E-04
.1                  -3.44E-04
.2                  -4.76E-04
.3                  -4.17E-04
.4                  -3.57E-04
.5                  -2.98E-04
.6                  -2.38E-04
.7                  -1.79E-04
.8                  -1.19E-04
.9                  -6E-05
```

RUN

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=2
ENTER THE CAMERA TILT=90
ENTER THE DESIRED CHANGE IN RANGE=.01
HEIGHT              DELTA R'
0                   -6.2E-05
.1                  -5.6E-05
.2                  -5E-05
.3                  -4.4E-05
.4                  -3.7E-05
.5                  -3.1E-05
.6                  -2.5E-05
.7                  -1.9E-05
.8                  -1.2E-05
.9                  -6E-06
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=2
ENTER THE RANGE=5
ENTER THE CAMERA TILT=90
ENTER THE DESIRED CHANGE IN RANGE=.0001
HEIGHT              DELTA R'
0                   -1E-06
.1                  -1E-06
.2                  0
.3                  0
.4                  0
.5                  0
.6                  0
.7                  0
.8                  0
.9                  0
1                   0
1.1                 0
1.2                 0
1.3                 0
1.4                 0
1.5                 0
1.6                 0
1.7                 0
1.8                 0
1.9                 0
```

RETURN

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=2
ENTER THE RANGE=.5
ENTER THE CAMERA TILT=90
ENTER THE DESIRED CHANGE IN RANGE=.01
HEIGHT              DELTA R'
0                   -5.3E-05
.1                  -5.3E-05
.2                  -5E-05
.3                  -4.7E-05
.4                  -4.4E-05
.5                  -4.2E-05
.6                  -3.9E-05
.7                  -3.6E-05
.8                  -3.3E-05
.9                  -3E-05
1                   -2.8E-05
1.1                 -2.5E-05
1.2                 -2.2E-05
1.3                 -1.9E-05
1.4                 -1.7E-05
1.5                 -1.4E-05
1.6                 -1.1E-05
1.7                 -8E-06
1.8                 -6E-06
1.9                 -3E-06
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=0
ENTER THE CAMERA TILT=75
ENTER THE DESIRED CHANGE IN RANGE=.0001
HEIGHT              DELTA K'
0                   0
.1                  0
.2                  0
.3                  0
.4                  0
.5                  0
.6                  0
.7                  0
.8                  0
.9                  0
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=5
ENTER THE CAMERA LOLI=25
ENTER THE DESIRED CHANGE IN RANGE=.01
HEIGHT              DELTA R'
0                   -1E-05
.1                  -9E-06
.2                  -8E-06
.3                  -7E-06
.4                  -6E-06
.5                  -5E-06
.6                  -4E-06
.7                  -3E-06
.8                  -2E-06
.9                  -1E-06
```

```
!
!LIST
100   INPUT "ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=";D
110   INPUT "ENTER THE RANGE=";R
120   INPUT "ENTER THE HEIGHT=";Y
130   INPUT "ENTER THE DESIRED CHANGE IN RANGE=";N
150   REM
155   PRINT "CAMERA TILT","DELTA R'"
156   FOR C = 0 TO 90 STEP 10
157 C1 = (C / 180) * (3.1415926534)
166   REM
167   REM
168   REM
169   REM
190 B1 =  ATN (R / (D - Y))
200 A1 =  - (R / ( SIN (B1))) * ( SIN (B1 - C1))
210 D1 = (R / ( SIN (B1))) * ( COS (B1 - C1))
215 F2 = .025
220 M1 = (A1 / D1) * F2
221 V = M1
231   REM
232   REM
240 N1 = N
292 M = 0
294   IF N < 0 THEN L = 1
295   IF N >  = 0 THEN L = 0
296   REM
297   REM
300 A2 = A1 * (( - 1) ^ (M + L + 1)) * (N1) *  COS (C1)
310 D2 = D1 * (( - 1) ^ L) * (N1) * ( SIN (C1))
320 M2 = (A2 / D2) * F2
321   REM
322   REM
325 W = M2
330 T = W - V
331   REM
332   REM
340 M3 =  INT ((T + .0000005) * 1000000) / 1000000
362   REM
364   REM
350   PRINT C,M3
365   NEXT C
370   END
```

R

!RUN

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE HEIGHT=.5
ENTER THE DESIRED CHANGE IN RANGE=.0001
CAMERA TILT          DELTA R'
0                    -9E-06
10                   -8E-06
20                   -8E-06
30                   -1E-06
40                   -1E-06
50                   -1E-06
60                   -1E-06
70                   -1E-06
80                   -1E-06
90                   -1E-06
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE HEIGHT=.5
ENTER THE DESIRED CHANGE IN RANGE=.001
CAMERA TILT       DELTA R'
0                 -5E-05
10                -2.8E-05
20                -1.9E-05
30                -1.4E-05
40                -1.2E-05
50                -1.1E-05
60                -1E-05
70                 1E-05
80                -1.1E-05
90                -1.2E-05
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE HEIGHT=.2
ENTER THE DESIRED CHANGE IN RANGE=.01
CAMERA TILT       DELTA K'
0                 -5E-04
10                -2.83E-04
20                -1.89E-04
30                -1.43E-04
40                -1.18E-04
50                -1.05E-04
60                -1E-04
70                -1E-04
80                -1.08E-04
90                -1.24E-04
```

RUN

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=2
ENTER THE RANGE=1
ENTER THE HEIGHT=.5
ENTER THE DESIRED CHANGE IN RANGE=.0001
CAMERA TILT        DELTA K'
0                  -2E-06
10                 -1E-06
20                 -1E-06
30                 -1E-06
40                 -1E-06
50                 -1E-06
60                 -1E-06
70                 -7E-06
80                 -2E-06
90                 -4E-06
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=2
ENTER THE RANGE=1
ENTER THE HEIGHT=.5
ENTER THE DESIRED CHANGE IN RANGE=.001
CAMERA TILT       DELTA K'
0                 -1.7E-05
10                -1.4E-05
20                -1.2E-05
30                -1.2E-05
40                -1.2E-05
50                -1.3E-05
60                -1.4E-05
70                -1.8E-05
80                -2.4E-05
90                -3.7E-05
```

RUN

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=2
ENTER THE RANGE=1
ENTER THE HEIGHT=.1
ENTER THE DESIRED CHANGE IN RANGE=.01
CAMERA TILT        DELTA R'
0                  -1.67E-04
10                 -1.47E-04
20                 -1.22E-04
30                 -1.16E-04
40                 -1.13E-04
50                 -1.25E-04
60                 -1.43E-04
70                 -1.77E-04
80                 -2.4E-04
90                 -3.73E-04
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE HEIGHT=.7
ENTER THE DESIRED CHANGE IN RANGE=.0001
CAMERA TILT       DELTA R'
0                 -3E-06
10                -3E-06
20                -2E-06
30                -1E-06
40                -1E-06
50                -1E-06
60                -1E-06
70                -1E-06
80                -1E-06
90                -1E-06
```

RUN

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE HEIGHT=.7
ENTER THE DESIRED CHANGE IN RANGE=.001
CAMERA TILT       DELTA R'
0                 -8.5E-05
10                -3.4E-05
20                -1.9E-05
30                -1.3E-05
40                -1E-05
50                -8E-06
60                -7E-06
70                -7E-06
80                -7E-06
90                -7E-06
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE HEIGHT=.7
ENTER THE DESIRED CHANGE ON RANGE=.01
CAMERA TILT       DELTA K'
0                 -8.33E-04
10                -3.4E-04
20                -1.92E-04
30                -1.29E-04
40                -9.8E-05
50                -8.1E-05
60                -7.2E-05
70                -6.8E-05
80                -6.9E-05
90                -7.4E-05
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE HEIGHT=.5
ENTER THE DESIRED CHANGE IN RANGE=.0001
CAMERA TILT        DELTA K'
0                  -4E-06
10                 -2E-06
20                 -2E-06
30                 -1E-06
40                 -1E-06
50                 -1E-06
60                 -1E-06
70                 -1E-06
80                 -1E-06
90                 -2E-06
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE HEIGHT=.3
ENTER THE DESIRED CHANGE IN RANGE=.001
CAMERA TILT       DELTA R'
0                 -5.6E-05
10                -2.3E-05
20                -1.8E-05
30                -1.4E-05
40                -1.3E-05
50                -1.2E-05
60                -1.2E-05
70                -1.3E-05
80                -1.4E-05
90                -1.7E-05
```

IRUN

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE HEIGHT=.8
ENTER THE DESIRED CHANGE IN RANGE=.0001
CAMERA TILT       DELTA R'
0                 -1.2E-05
10                -4E-06
20                -2E-06
30                -1E-06
40                -1E-06
50                -1E-06
60                -1E-06
70                0
80                0
90                0
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=1
ENTER THE HEIGHT=.9
ENTER THE DESIRED CHANGE IN RANGE=.001
CAMERA TILT      DELTA R'
0                -2.9E-04
10               -3.4E-05
20               -1.3E-05
30               -7E-06
40               -5E-06
50               -4E-06
60               -3E-06
70               -3E-06
80               -2E-06
90               -2E-06
```

```
?SYNTAX ERROR
]RUN
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=2
ENTER THE HEIGHT=.5
ENTER THE DESIRED CHANGE IN RANGE=.0001
CAMERA TILT       DELTA R'
0                 -5E-06
10                -2E-06
20                -1E-06
30                -1E-06
40                0
50                0
60                0
70                0
80                0
90                0
```

ENTER THE DISTANCE BETWEEN CAMERA AND PROJECTOR=1
ENTER THE RANGE=2
ENTER THE HEIGHT=.5
ENTER THE DESIRED CHANGE IN RANGE=.001

CAMERA TILT	DELTA R'
0	-5E-05
10	-1.8E-05
20	-9E-06
30	-6E-06
40	-6E-06
50	-4E-06
60	-3E-06
70	-3E-06
80	-3E-06
90	-3E-06

```
?SYNTAX ERROR
]RUN
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=2
ENTER THE HEIGHT=.5
ENTER THE DESIRED CHANGE IN RANGE=.01
CAMERA TILT       DELTA R'
0                 -5E-04
10                -1.77E-04
20                -9.4E-05
30                -6.3E-05
40                -4.5E-05
50                -3.6E-05
60                -3.2E-05
70                -3E-05
80                -2.9E-05
90                -3.1E-05
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=5
ENTER THE HEIGHT=.1
ENTER THE DESIRED CHANGE IN RANGE=.0001
CAMERA (DEG)        DELTA R'
0                   -5E-06
10                  -1E-06
20                  -1E-06
30                  0
40                  0
50                  0
60                  0
70                  0
80                  0
90                  0
```

RUN

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=5
ENTER THE BEIGHT=.5
ENTER THE DESIRED CHANGE IN RANGE=.001
CAMERA TILT        DELTA K'
0                  -5E-05
10                 -1.2E-05
20                 -6E-06
30                 -3E-06
40                 -2E-06
50                 -2E-06
60                 -2E-06
70                 -1E-06
80                 -1E-06
90                 -1E-06
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=3
ENTER THE HEIGHT=.5
?EXTRA IGNORED
ENTER THE DESIRED CHANGE IN RANGE=.01
CAMERA TILT       DELTA R'
0                  -2.5E-04
10                 -1.1E-04
20                 -6.3E-05
30                 -4.5E-05
40                 -3.4E-05
50                 -2.9E-05
60                 -2.6E-05
70                 -2.3E-05
80                 -2.1E-05
90                 -2.0E-05
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=5
ENTER THE HEIGHT=.5
ENTER THE DESIRED CHANGE IN RANGE=.0001
CAMERA TILT       DELTA R'
0                 -5E-06
10                -1E-06
20                0
30                0
40                0
50                0
60                0
70                0
80                0
90                0
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=0
ENTER THE HEIGHT=.5
ENTER THE DESIRED CHANGE IN RANGE=.001
CAMERA TILT       DELTA R'
0                 -5E-05
10                -7E-06
20                -3E-06
30                -1E-06
40                -1E-06
50                -1E-06
60                -1E-06
70                -1E-06
80                0
90                0

 RUN
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=1
ENTER THE RANGE=5
ENTER THE HEIGHT=.5
ENTER THE DESIRED CHANGE IN RANGE=.01
CAMERA TILT        DELTA R'
0                  -5E-04
10                 -6.7E-05
20                 -2.6E-05
30                 -1.5E-05
40                 -1E-05
50                 -7E-06
60                 -6E-06
70                 -5E-06
80                 -5E-06
90                 -5E-06
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=2
ENTER THE RANGE=1.5
ENTER THE HEIGHT=1
ENTER THE DESIRED CHANGE IN RANGE=.0001
CAMERA TILT        DELTA K'
0                  -2E-06
10                 -2E-06
20                 -1E-06
30                 -1E-06
40                 -1E-06
50                 -1E-06
60                 -1E-06
70                 -1E-06
80                 -1E-06
90                 -1E-06
```

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=2
ENTER THE RANGE=1.5
ENTER THE HEIGHT=1
ENTER THE DESIRED CHANGE IN RANGE=.001
CAMERA TILT        DELTA K'
0                   -2.3E-05
10                  -1.6E-05
20                  -1.2E-05
30                  -1E-05
40                  -8E-06
50                  -8E-06
60                  -8E-06
70                  -8E-06
80                  -9E-06
90                  -1.1E-05
```

RETIN

```
ENTER THE DISTANCE BETWEEN  CAMERA AND PROJECTOR=2
ENTER THE RANGE=1.5
ENTER THE HEIGHT=0
ENTER THE DESIRED CHANGE IN RANGE=.01
CAMERA TILT       DELTA R'
0                 -2.9E-04
10                -1.A1E-04
20                -1.13E-04
30                -9.5E-05
60                -8.3E-05
50                -7.8E-05
40                -7.7E-05
70                -8.1E-05
80                -9.1E-05
90                -1.1E-04
```

APPENDIX C

DAD BOX DESCRIPTION

DIGITAL/ANALOG DESIGN
ELECTRONIC DESIGN - PRODUCT DEVELOPMENT

530 BROADWAY
NEW YORK, N.Y. 10012
(212) 966-0410

DIGITAL VIDEO DEVELOPMENT SYSTEM (DVDS) MODEL 7

OPERATORS MANUAL

FOR: NATIONAL BUREAU OF STANDARDS

PROGRAMMABLE AUTOMATION DIVISION

11/15/83

TABLE OF CONTENTS

1.0 System Introduction

The DVDS Model 7 with Comparator/Slicer Option can be used for adaptive thresholding of real-time video images. A full video field can be stored in the reference memory to 8 bit greyscale resolution. The stored image can then be compared with the real-time video input and the resulting one bit image stored in the other, bit plane, memory. Eight different fields may be processed and stored in this way. The bit plane memory may be displayed directly or through a 256 x 8 bit Mapping RAM which implements an arbitrary programmable function. In addition, the host computer can load or unload the reference memory and unload the bit plane memory either directly or through the Mapping RAM.

1.1 Controller

The controller card contains the master clock oscillator, PROMs with all the neccessary timing and sync signals, and the circuitry needed for controlling the dynamic RAMs used in the image memories.

1.2 Image Memories

There are two memory cards, the reference and the bit plane. Each memory card uses 16K dynamic RAMs arranged 256 H by 240 V by 8 deep. They run in real time, synchronous with the video display. Since the RAMs do not access fast enough, they are multiplexed 4 deep. For a read cycle, four pixels are addressed in parallel and are serially shifted out. The write cycle works similarly but in the opposite direction.

1.2.1 Reference Memory

The reference memory stores an eight bit gray scale image. It may be filled with data from the video input or directly written into through the DMA interface from the host computer. It may be displayed through the video output or unloaded through the DMA interface to the computer.

1.2.2 Bit Plane Memory

The bit plane memory is configured as eight 256 X 240 x 1 bit planes. Input data to any of the planes comes from a magnitude comparator. This compares the live video input from the A/D with the image stored in the reference memory on a pixel by pixel basis. An offset may be specified which is added to the pixel values from the reference memory. This provides noise immunity when using the reference memory to remove differential scene lighting. If the input pixel is less than or equal to the reference pixel (plus offset), a zero is stored. If it is greater, a one is stored. When the reference pixel value plus offset exceeds 255 the value stored in the bit plane is automatically zero since the input pixel must be less than 256. Only one plane may be written into at a time. This memory may be displayed through the the video output or unloaded to the computer through the DMA interface. The RAM look-up table may be placed between the bit plane memory and either of these output channels (see 1.5).

1.3 Address Generator

This card generates the addresses used to read from and write to the memory in the video modes. It also generates the refresh addresses for the dynamic RAMs. Its addressing modes are fixed.

1.4 Analog Input/Output

This card is the interface from the camera to the frame store and from the frame store to the CRT monitor. The video input from the camera is low-pass filtered, amplified, and digitized at 5 MHz to 8 bit gray scale resolution. The digitized video is then put onto the system bus destined for the memory. For video output there is a selector that allows the viewing of any of three sources, the reference memory, the bit plane memory and the bit plane memory through the Mapping RAM. With any of these sources either the entire gray scale or any of the eight individual planes may be displayed. The translation from digital to analog is done at 5 MHz in an 8 bit converter.

1.5 Computer Interface

The computer interface card is the link between the frame store and the host computer. It uses an 8 bit bidirectional data bus and an 8 bit address bus. This card allows the user to program the frame store into its various modes. It also has its own address generator for the image memories that allows bidirectional Direct Memory Access (DMA). A 256 x 8 bit RAM look-up table is included for arbitrary translation of bit plane memory data. This can operate on data output to the DAC or through the DMA channel.

1.6 Case and Electrical

The Frame store is packaged in an S-100 type computer case. The motherboard has been modified by adding an A.C. termination on each line. It uses standard S-100 wire wrap cards. There is an internal power supply that uses 120 VAC +- 10%. The on/off switch has a key lock and is located, along with the power indicator LED, on the front panel. Due to several internal reset circuits, after turning the unit off, the user should wait 10 seconds before turning the unit back on. All video connections are made with BNC connectors located on the back panel. The computer interface is via a 37 pin subminiature D type connector on the back panel. The fuseholder is also on the back panel. The fuse is a 3 amp slo-blo type.

2.0 Computer Interface

2.1 Description

The DVDS is designed to be a peripheral to a host computer. Its modes of operation are programmable and once programmed it needs no further intervention to operate. Programming is done by loading registers in the DVDS that control specific functions.

Two 8 bit output ports must be available from the computer. One, the command port, specifies which register is to be loaded. The other, the output data port, carries the data to be loaded. See paragraph 2.2 for the list of registers. These registers are write only, that is they cannot be read. Because the DVDS uses the handshaking line on the command port to initiate register loading, the data port must be loaded before the command port. Since the registers may come up at random on power up, they should be initialized to a known condition before the DVDS is used. This is called booting the system. See the program listing "BOOT". An output port from the DVDS is used to unload the image memory to the host computer.

2.2 List of Registers, Addresses, and Modes

2.2.1 Computer Interface

Address

0 Bit 0 : 0 = register loading during vertical drive only
1 = register loading during entire frame
All other bits are "don't care"

1 Bit 0 : 0 = Reference Memory Live
1 = Reference Memory Frozen

Bit 1 : 0 = Bit Plane Memory Frozen
1 = Bit Plane Memory Live

Bit 2 : 0 = DMA Output Mode
1 = DMA Input Mode

Bit 3 : 0 = Normal (Video IN, OUT) Mode
1 = DMA Mode
Note: In the DMA mode both memories are automatically prevented from writing in data from the A/D and the reference memory is displayed irregardless of any other controls.
All other bits are "don't care"

2 DMA Horizontal Address Register (0-255)

3 DMA Vertical Address Register (0-255)

4 DMA enable. During a read this is a flag, that is, it initiates the read function, during write it contains input pixel data 0-255.

5 Bit 0 : 0 = Display Reference Memory
1 = Display Bit Plane Memory

Bit 1 : 0 = Direct Memory Display
1 = Display Bit Plane Memory through Mapping RAM

Bit 2 : 0 = Display Full grey scale
1 = Display Single Bit of selected Memory
Note: The Single Bit display of either the Reference Memory, the Bit Plane Memory or the Bit Plane through the Mapping RAM may be chosen. The bit is chosen by Register 6.

Bit 3 : 0 = A/D on Input Data Bus
1 = Command Data Bus on Input Data Bus
Note: This allows Data from the Host Computer to be placed on the Bit Plane Memory Input rather than the Input Video. This is useful for testing.

All other Bits are "don't care"

6 Bits 0-2 : Writing into the Bit Plane Memory occurs one plane at a time. These three bits determine which plane (0-7) is active (live).
For the display of a single bit of one of the output sources (Register 5 Bit 2 High) register 6 selects the bit to be displayed.

All other Bits are "don't care"

2.2.2 Mapping RAM

Address

224 Bit 0 : 0 = Normal Operation
1 = Load Masking RAMs

225 write enable for Mapping RAM (0-255)

227 write address register (0-255)

2.2.3 Bit Plane Memory

Address

255 Bit Plane Memory Offset Register (0-255)

Note: This adds a selectable bias to the data from the reference memory before being compared with data from the A/D for the bit plane memory. This is useful for removing the effects of noise.

2.2.4 Operating Modes

Mode	Register 1	Register 5
1. Both Memories Frozen, Reference Memory Displayed.	1	0
2. Reference Memory Live, Bit Plane Memory Frozen, Reference Memory Displayed.	0	0
3. Both Memories Frozen, Bit Plane Memory Displayed.	1	1
4. Bit Plane Memory Live, Reference Memory Frozen, Bit Plane Memory Displayed, Register 6 contains the Plane Number which is Live (0-7).	3	1
5. Both Memories Frozen, Display Bit Plane Memory through Mapping Memory	1	3
6. Bit Plane Memory Live, Display Bit Plane Memory through Mapping RAM. Register 6 contains the Plane Number which is Live (0-7).	3	3
7. Both Memories Frozen, Reference Memory Displayed, DMA Write into Reference Memory.	8	0
8. Both Memories Frozen, Reference Memory Displayed, DMA read from Reference Memory.	13	0
9. Both Memories Frozen, Bit Plane Memory Displayed, DMA read from Bit Plane Memory.	13	1
10. Both Memories Frozen, Bit Plane, DMA read from Bit Plane Memory through the Mapping RAM.	13	3

Note: In any of these modes a single plane of the output source may be viewed by adding 4 to the number in Register 5 and loading Register 6 with the Plane number (0-7)

2.3 Direct Memory Access (DMA)

2.3.1 Introduction

The DVDS allows the host computer to directly access the memories. Frozen images from either memory or from the bit plane memory through the Mapping RAM may be unloaded to the computer via the high speed DMA interface. Additionally, the reference memory can be directly loaded from the computer. The transfer rate in either direction can exceed 200K bytes/second. A DMA address generator is used for both read and write operations. Pixel coordinates may be loaded into the horizontal and vertical address registers for random access of the image memory. Additionally, the DMA address generator will autoincrement after each read or write operation. This allows a starting address to be specified and then the circuit will provide sequential addresses itself. This speeds the data transfer rate substantially. The top left pixel is at address 0 H, 0 V. The top right pixel is at address 255 H, 0 V. The bottom left pixel is at address 0 H, 240 V. The bottom right pixel is at location 255 H, 240 V. The addresses will autoincrement from the last address loaded into the horizontal address register until 255 is reached. Then the vertical address will increment by one and the horizontal address overflows back to 0.

2.3.2 DMA Read

The algorithm for performing DMA read is outlined below. See also the program listings for REF.READ and MOVLOD.OBJ0

1. load register 0 with 1 - allows DMA access during entire frame.

2. load register 1 with 13 - this freezes the images and prepares for a DMA read operation.

3. load register 5 with the proper code for the desired output source (0 = Reference Memory, 1 = Bit Plane Memory, 3 = Bit Plane Memory through the Mapping RAM).

4. load register 2 (DMA horizontal address register) with H pixel coordinate.

5. load register 3 (DMA vertical address register) with V pixel coordinate.

6. load register 4 to assert the DMA read at the previously specified address. The pixel will be sent to the computer via the DVDS output port.

7. for random access go to 4. for sequential access go to 6. and repeat until the desired number of pixels are recieved.

8. load register 1 with 1. - this returns the system to its normal state and keeps the images frozen.

Note: The handshaking lines should be checked after each step

2.3.3 DMA Write (Reference Memory Only)

The proceedure for performing DMA write is similar to the DMA read. Also see the program listing REF.RAMP and MOVLOD.OBJ0

1. load register 0 with 1 - this allows DMA access during the entire frame.

2. load register 1 with 9. - this freezes the image and prepares the unit for write.

3. load register 5 with 0 - this displays the reference memory

4. load register 2 with the pixel H coordinate.

5. load register 3 with the pixel V coordinate.

6. load register 4 with the pixel to be written into the image memory.

7. for random access go to 4. for sequential access go to 6. and repeat until the desired number of pixels are transferred.

8. load register 1 with 1 - this returns the unit to normal operation with the images frozen.

Note: The handshaking line should be checked after each step

2.4 Interfacing Requirements for the Computer

2.4.1 Computer Output Ports

Two output ports must be provided by the computer, the command port and the data port. Both must be 8 bits wide, active high at normal TTL levels. All lines are buffered in the DVDS and present 1 'LS TTL load. 560 ohm pull up resistors to +5 volts are included on these lines in the DVDS. These ports are treated by the unit as one 16 bit port. If seperate ports are used it is important to load the data port before the command port, which has the handshaking lines associated with it. Once data has been set up and latched on both ports the COMPUTER READY line should go high. The DVDS will latch both ports 300 ns. after the rising edge of this signal. COMPUTER READY should be a standard TTL level signal. At this time the DEVICE BUSY line will go High to indicate that the command is being executed. The value loaded into register 0 determines when commands will be executed. In the "V.Drive Only" mode (0), a command will be held until the next vertical blanking interval before execution. This is useful for freezing the memories at the end of a field. Other commands such as DMA transfers should take place at high speed so register 0 is put into the "Anytime" mode (1). Once the DVDS has executed the command from the host computer, the DEVICE BUSY line (TTL) will go low. Also at this time the BUSY strobe will pulse for 1 microsecond. These indicate that the computer may send another command. Any commands sent before this time will be lost.

2.4.2 Computer Input Port

One 8 bit input port to the computer is required to read data from the image memory. This port must be standard level, TTL, active high. After a DMA READ command has been executed, the pixel datum will be placed on the computer input port. The DEVICE READY line will then pulse for 1 microsecond to strobe this information into the computer input port. This signal is at standard TTL levels. Note that the data should be strobed in on the trailing edge of the DEVICE READY line.

3.0 Analog Input/Output

3.1 Description

This card accepts the video input from a camera, filters the signal, digitizes it, and passes it to the image memory. It also recieves digital video from various sources, converts it to analog video, and passes it through a 75 ohm driver to the CRT monitor. In addition, composite sync is available for driving the camera. BNC connectors for video in, video out, and composite sync are located on the back of the DVDS.

3.2 Analog to Digital section

This section accepts the input video from the camera and digitizes it.

input impedance	75 ohms
input signal level	1 volt sync tip to white
sample rate	5 MHz
gray level resolution	256 levels
number of bits	8
filter cutoff	2 MHz, 24 db/octave

A white clip light is provided on the front panel. This will come on when the video signal is too high, causing the analog to digital converter to overflow.

3.3 Digital to Analog section

Either of the stored images or the arithmetic unit may be selected for display. In addition to the full eight bit grey scale display, a single bit plane of any of these sources may be selected for viewing with the bit plane address register (see 2.2.1). The single bit mode output is either full black or full white. Blanking and sync are added digitally so there is no adjustment of sync or set up levels. The composite signal is fitered to remove spurious high frequency components.

output impedance	75 ohms
output level	1 V p-p terminated
sample rate	5 MHz
number of bits	8
filter cutoff	2 MHz, 12 db/octave

3.4 Composite Sync.

Composite sync is used to drive the video camera. The DVDS uses the EIA RS-170 standard.

output impedence	75 ohms
level	4 V p-p terminated
polarity	negative going
horizontal rate	15,734 Hz
horizontal lines	525
active lines	480
vertical rate	60 Hz
frame rate	30/second

Note that because this is a 256 H by 240 V system, the same image is repeated on both fields.

3.5 Camera requirements

The most important requirement is that the camera sync to the system. A camera that will lock to the above RS-170 format will work. To obtain maximum use of the 256 gray levels, it should have a signal to noise ratio greater than 48 dB. The digitizing rate is 5 MHz so the camera should have a bandwidth of at least 2.5 MHz.

3.6 Adjustment proceedure

1) Needed: small screw driver, dual trace oscilloscope, Drawing # 001-018 A/D-D/A component layout.
2) Remove the cover from the machine.
3) Connect the camera.
4) Turn the power on.
5) Point the camera on a bright scene and open the f-stop for maximum contrast.

A/D Adjustment

6) Set both scope channels for 1V/division.
7) Ground both probes and line the traces on the scope screen up on the second line from the bottom. This is 0V.
8) Referring to drawing # 001-018, connect Ch 1 to TP-1 and Ch 2 to TP-2. Unground them and sync to Ch 1. Ch 2 should be between 6.5V and 7.0V.
9) Cap the camera lens. Turn the BLACK LEVEL ADJUST pot so that the lowest portion of the active video (not sync) just touches 0V.

10) Uncap the camera lens and turn the FULL SCALE ADJUST pot so that the highest (brightest) portions of the active video just touch the line on Ch-2. If the video goes above the CH-2 reference, the white clip light on the front panel should turn on.

11) The adjustments in steps 9 and 10 are somewhat interactive so go back and repeat 9 and 10 as required.

D/A Adjustment

12) Either load a full scale ramp into the reference memory or point the camera at a bright light source to create a full scale signal for the D/A.
13) Set CH1 for .5V/division
14) Ground the probe and put the trace on the second line up from the bottom.
15) Connect the probe to TP-4. Unground the scope an A.C. couple it.
16) Turn the D/A REFERENCE ADJUST pot so that the video signal is 1 Volt peak to peak (2 Volts peak to peak if nothing is connected to the output. i.e. unterminated).

This completes the Adjustment procedure.

4.0 Mapping RAM

4.1 Description

The 256 x 8 Mapping RAM can be loaded with an arbitrary transfer function to process the image stored in the Bit Plane Memory. The output of this RAM can be sent to the analog input/output card for display or to the DMA interface for transmission to the computer. Note that due to the pipeline delay of the circuitry, the displayed image through the Mapping RAM is shifted to the right by one pixel.

4.2 Loading the Mapping RAMs

The following is the general algorithm for entering a transfer function. A dedicated address generator is included for loading. The circuitry has an autoincrement feature so it is not necessary to specify each address when loading successive locations.

1. Set register 224 to 1 - this puts the RAMs into the write mode.

2. Load register 227 with the starting address. This is usually 0.

3. To write into the mapping RAM, load register 225 with the desired data. Loading this register initiates the write function into the RAM.

4. The address will automatically increment, so for successive addresses go to step 3. To load random locations go to step 2.

5. When completed, load register 224 with 0 to put the RAMs into the normal mode.

5.0 Address Generator

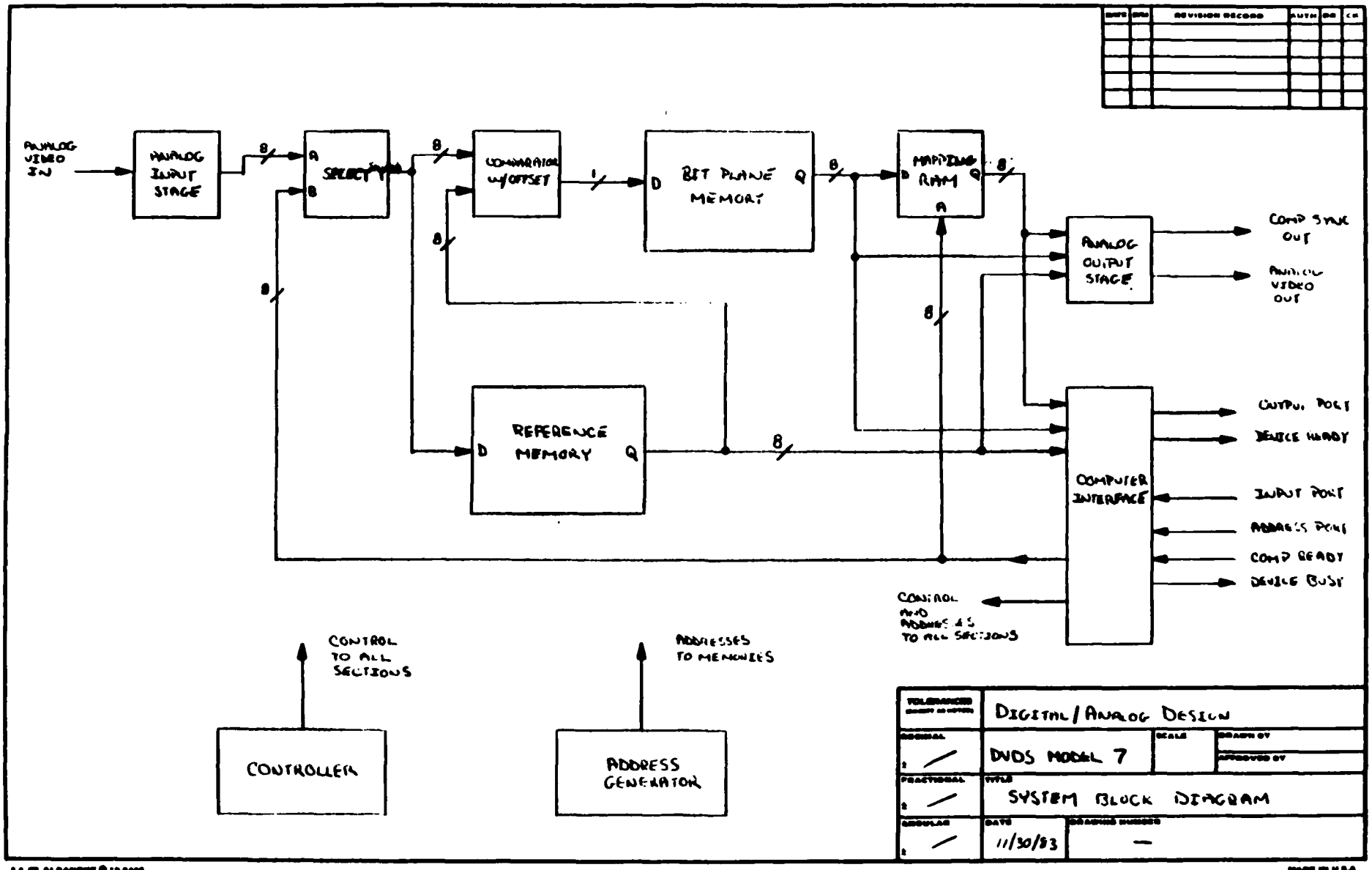
5.1 Description

This card generates the video read and write addresses which are then used by the image memories. It also generates the refresh signals for the dynamic RAMs used in the image memory. The addressing modes are fixed.

6.0 Computer Interface Connector list

1	Data Port	Bit 0 (LSB)	[1]	20	Computer Ready		[18]
2	Data Port	Bit 1	[2]	21	Device Busy (Strobe)		[19]
3	Data Port	Bit 2	[3]	22	GND		[20]
4	Data Port	Bit 3	[4]	23	Device Busy (Strobe)Inv.		[21]
5	Data Port	Bit 4	[5]	24	Output Port Bit 0 (LSB)		[22]
6	Data Port	Bit 5	[6]	25	Output Port Bit 1		[23]
7	Data Port	Bit 6	[7]	26	Output Port Bit 2		[24]
8	Data Port	Bit 7	[8]	27	Output Port Bit 3		[25]
9	GND		[9]	28	Output Port Bit 4		[26]
10	Address Port	Bit 0 (LSB)	[10]	29	Output Port Bit 5		[27]
11	Address Port	Bit 1	[11]	30	Output Port Bit 6		[28]
12	Address Port	Bit 2	[12]	31	Output Port Bit 7		[29]
13	Address Port	Bit 3	[13]	32	Device Ready		[30]
14	Address Port	Bit 4	[14]	33	Not Connected		[31]
15	Address Port	Bit 5	[15]	34	Device Ready (Inv.)		[32]
16	Address Port	Bit 6	[16]	35	Device Busy		[33]
17	Address Port	Bit 7	[17]	36	Device Busy (Inv.)		[34]
18				37			
19							

Notes: All signals are TTL levels active high except those marked (Inv.) which are active low. Numbering is for the 37 pin D type subminiature connector on the rear panel. Numbers in brackets are for P1, the 34 pin cable socket on interface board #10001 (drawings 001-002, 001-003, 001-004 001-005 and 001-019).


ANALOG VIDEO IN
ANALOG INPUT STAGE
8
A
SELECT
B
8
COMPARATOR w/OFFSET
1
D
BIT PLANE MEMORY
Q
8
MAPPING RAM
D
Q
A
8
ANALOG OUTPUT STAGE
COMP SYNC OUT
ANALOG VIDEO OUT
8
8
8
D
REFERENCE MEMORY
Q
8
COMPUTER INTERFACE
OUTPUT PORT
DEVICE READY
INPUT PORT
ADDRESS PORT
COMP READY
DEVICE BUSY
CONTROL AND ADDRESS TO ALL SECTIONS
CONTROL TO ALL SECTIONS
ADDRESSES TO MEMORIES
CONTROLLER
ADDRESS GENERATOR
REVISION RECORD
DIGITAL/ANALOG DESIGN
DVDS MODEL 7
SCALE
DRAWN BY
APPROVED BY
SYSTEM BLOCK DIAGRAM
11/30/83
—

DIGITAL/ANALOG DESIGN
ELECTRONIC DESIGN · PRODUCT DEVELOPMENT

530 BROADWAY
NEW YORK, N.Y 10012
(212) 966-0410

Jim Hall

DIGITAL VIDEO DEVELOPMENT SYSTEM (DVDS) VERSION 7

OPERATORS MANUAL

FOR: NATIONAL BUREAU OF STANDARDS

PROGRAMMABLE AUTOMATION DIVISION

11/15/82

TABLE OF CONTENTS

7.0 Apple Interface

1.0 System Introduction

1.1 Controller

The controller card contains the master clock oscillator, PROMs with all the neccessary timing and sync signals, and the circuitry needed for controlling the dynamic RAMs used in the image memories.

1.2 Image Memories

There are two memory cards, the reference and the bit plane. Each memory card uses 16K dynamic RAMs arranged 256 H by 240 V by 8 deep. They run in real time, synchronous with the video display. Since the RAMs do not access fast enough, they are multiplexed 4 deep. For a read cycle, four pixels are addressed in parallel and are serially shifted out. The write cycle works similarly but in the opposite direction.

1.2.1 Reference Memory

The reference memory stores an eight bit gray scale image. It may be filled with data from the video input or directly written into through the DMA interface from the host computer. It may be displayed through the video output or unloaded through the DMA interface to the computer.

1.2.2 Bit Plane Memory

The bit plane memory is configured as eight 256 X 240 planes. Input data to any of the planes comes from a magnitude comparator. This compares the live video input with the output of the reference memory on a pixel by pixel basis. If the input pixel is less than or equal to the reference pixel, a zero is stored. If it is greater, a one is stored. Only one plane may be written into at a time. This memory may be displayed through the video output or unloaded to the computer through the DMA interface. The arithmetic unit may be placed between the bit plane memory and either of these output channels (see 1.6).

1.3 Address Generator

This card generates the addresses used to read from and write to the memory in the video modes. It also generates the refresh addresses for the dynamic RAMs. Its addressing modes are fixed.

1.4 Analog Input/Output

This card is the interface from the camera to the frame store and from the frame store to the CRT monitor. The video input from the camera is amplified and digitized at 5 MHz to 8 bit gray

scale resolution. The digitized video is then put onto the system bus destined for the memory. There is a selector that allows the viewing of any of three sources and either the entire gray scale or any of the eight individual planes. The translation from digital to video is done at 5 MHz in an 8 bit digital to analog converter.

1.5 Arithmetic Unit

The arithmetic unit (AU) is used to process the output of the bit plane memory. It can perform both arithmetic and logic functions. RAMs loaded from the computer are included for mapping both operands.

1.6 Computer Interface

The computer interface card is the link between the frame store and the host computer. It uses an 8 bit bidirectional data bus and an 8 bit address bus. This card allows the user to program the frame store into its various modes. It also has its own address generator for the image memory that allows bidirectional Direct Memory Access (DMA).

1.7 Case and Electrical

The Frame store is packaged in an S-100 type computer case. The motherboard has been modified by adding terminating resistors. It uses standard S-100 wire wrap cards. There is an internal power supply that uses 120 VAC +- 10%. The on/off switch has a key lock and is located, along with the indicator light, on the front panel. Due to several internal reset circuits, after turning the unit off, the user should wait 10 seconds before turning the unit back on. All video connections are made with BNC connectors located on the back panel. The computer interface is via a 37 pin subminiature D type connector on the back panel. The fuseholder is also on the back panel. The fuse is a 3 amp slo-blo type. Additionally, the three unregulated voltages on the bus are individually fused. The +8 volt line uses a 7 amp fuse while the +18 and -18 lines use 2 amp fuses.

2.0 Computer Interface

2.1 Description

The DVDS is designed to be a peripheral to a host computer. Its modes of operation are programmable and once programmed it needs no further intervention to operate. Programming is done by loading registers in the DVDS that control specific functions.

Two 8 bit output ports must be available from the computer. One, the command port, specifies which register is to be loaded. The other, the output data port, carries the data to be loaded. See paragraph 2.2 for the list of registers. These registers are write only, that is they cannot be read. Because the DVDS uses the handshaking line on the command port to initiate register loading, the data port must be loaded before the command port. Since the registers may come up at random on power up, they should be initialized to a known condition before the DVDS is used. This is called booting the system. See the program listing "BOOT". An output port from the DVDS is used to unload the image memory to the host computer.

2.2 List of Registers, Addresses, and Modes

2.2.1 Computer Interface

(Register)
Address

0 Bit 0 : 0 = register loading during vertical drive only
1 = register loading during entire frame
All other bits are "don't care"

1 Bit 0 : 0 = Reference Memory Live
1 = Reference Memory Frozen
Bit 1 : 0 = Bit Plane Memory Frozen
1 = Bit Plane Memory Live
Bit 2 : 0 = DMA Output Mode
1 = DMA Input Mode
Bit 3 : 0 = Normal (Video IN, OUT) Mode
1 = DMA Mode
All other bits are "don't care"

2 DMA Horizontal Address Register (0-255)

3 DMA Vertical Address Register (0-255)

4 DMA enable. During a read this is a flag, that is, it initiates the read function, during write it contains input pixel data 0-255.

5 Bit 0 : 0 = Display Reference Memory
1 = Display Bit Plane Memory
Bit 1 : 0 = Direct Memory Display
1 = Display Bit Plane Memory through Arithmetic Unit (A.U.)
Bit 2 : 0 = Display Full grey scale
1 = Display Single Bit of selected Memory
Note: The Single Bit display of either the Reference Memory, the Bit Plane Memory or the Bit Plane through the A.U. may be chosen. The bit is chosen by Register 6.

Bit 4 : 0 = A/D on Input Data Bus
1 = Command Data Bus on Input Data Bus
Note: This allows Data from the Host Computer to be placed on the Bit Plane Memory Input rather than the Input Video. This is useful for testing.

All other Bits are "don't care"

6 Bits 0-2 : Writing into the Bit Plane Memory occurs one plane at a time. These three bits determine which plane (0-7) is active (live).
For the display of a single bit of one of the output sources (Register 5 Bit 3 High) register 6 selects the bit to be displayed.

All other Bits are "don't care"

2.2.2 Arithmetic Unit

Address

224 Bit 0 : 0 = Normal Operation
1 = Load Masking RAMs
Bits 1-4: "Don't care"
Bits 5-7: Arithmetic Function
000 = CLEAR
001 = Horizontal Line Number Minus Bit Plane Memory
010 = Bit Plane Memory Minus Horizontal Number
011 = Bit Plane Memory Plus Horizontal Line
100 = Bit Plane Memory EXOR Horizontal Line
101 = Bit Plane Memory OR Horizontal Line
110 = Bit Plane Memory AND Horizontal Line
111 = PRESET

225 write enable for Image Mask RAMs (0-255)

226 write enable for Line Mask RAMs (0-255)

227 write address register (0-255)

255 Position Factor (0-255)

2.2.3 Operating Modes

Mode	Register 1	Register 5
1. Both Memories Frozen, Reference Memory Displayed.	1	0
2. Reference Memory Live, Bit Plane Memory Frozen, Reference Memory Displayed.	0	0

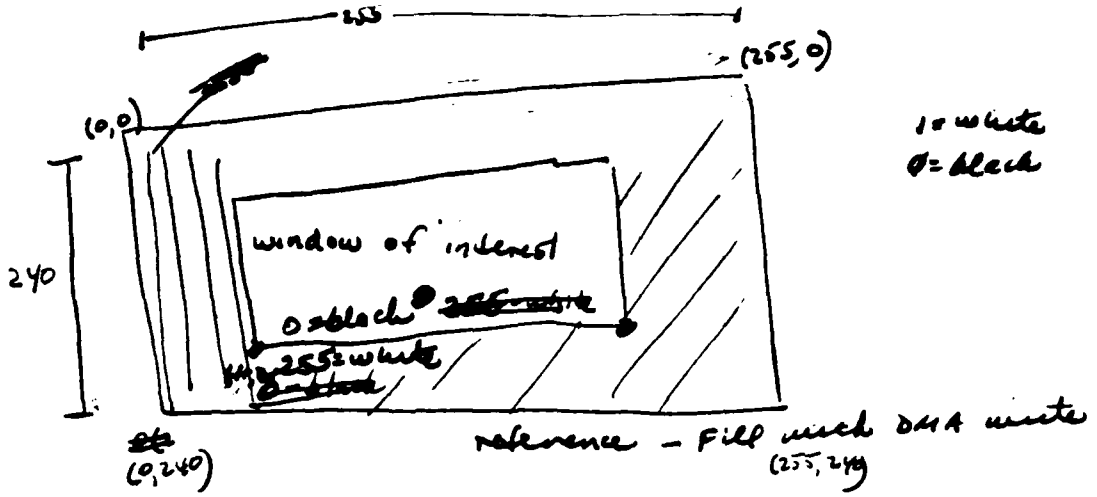
3.	Both Memories Frozen, Bit Plane Memory Displayed.	1	1
4.	Bit Plane Memory Live, Reference Memory Frozen, Bit Plane Memory Displayed, Register 6 contains the Plane Number which is Live (0-7).	3	1
5.	Both Memories Frozen, Display Bit Plane Memory through Arithmetic Unit.	1	3
6.	Bit Plane Memory Live, Display Bit Plane Memory through Arithmetic Unit. Register 6 contains the Plane Number which is Live (0-7). Register 224 contains A.U. function.	3	3
7.	Both Memories Frozen, Reference Memory Displayed, DMA Write into Reference Memory.	8	0
8.	Both Memories Frozen, Reference Memory Displayed, DMA read from Reference Memory.	12	0
9.	Both Memories Frozen, ~~Reference Memory~~ Displayed, DMA read from Bit Plane Memory.	12	1
10.	Both Memories Frozen, Reference Memory Displayed, DMA read from Bit Plane Memory through the Arithmetic Unit. Register 224 contains A.U. function.	12	3

Note: In any of these modes a single plane of the output source may be viewed by adding 4 to the number in Register 5 and loading Register 6 with the Plane number (0-7)

2.3 Direct Memory Access (DMA)

2.3.1 Introduction

The DVDS allows the host computer to directly access the memories. Frozen images from either memory or from the bit plane memory through the A.U. may be unloaded to the computer via the high speed DMA interface. Additionally, the reference memory can be directly loaded from the computer. The transfer rate in either direction can exceed 200K bytes/second. A DMA address



1 = white
0 = black

- select bit plane

  fringe

  bit plane should have windowed view

Inputs

leftwin - vertical

rhtwin - vertical

topwin - horiz. [max 255]

botwin - horiz. [min 0]

horizontal address

0 → 2

vert address

0 → 3

DMA write

0 → 1

~~mov bh, 240~~

~~mov cx, 255~~

generator is used for both read and write operations. Pixel coordinates may be loaded into the horizontal and vertical address registers for random access of the image memory. Additionally, the DMA address generator will autoincrement after each read or write operation. This allows a starting address to be specified and then the circuit will provide sequential addresses itself. This speeds the data transfer rate substantially. The top left pixel is at address 0 H, 0 V. The top right pixel is at address 255 H, 0 V. The bottom left pixel is at address 0 H, 240 V. The bottom right pixel is at location 255 H, 240 V. The addresses will autoincrement from the last address loaded into the horizontal address register until 255 is reached. Then the vertical address will increment by one and the horizontal address overflows back to 0.

2.3.2 DMA Read

The algorithm for performing DMA read is outlined below. See also the program listings for REF.RAMP and MOVLOD.OBJ0

1. load register 0 with 1 - allows DMA access during entire frame.

2. load register 1 with 1.5 - this freezes the images and prepares for a DMA read operation.

3. load register 5 with the proper code for the desired output source (0 = Reference Memory, 1 = Bit Plane Memory, 3 = Bit Plane Memory through the ALU)

4. load register 2 (DMA horizontal address register) with H pixel coordinate.

5. load register 3 (DMA vertical address register) with V pixel coordinate.

6. load register 4 to assert the DMA read at the previously specified address. The pixel will be sent to the computer via the DVDS output port.

7. for random access go to 4. for sequential access go to 6. and repeat until the desired number of pixels are recieved.

8. load register 1 with 1. - this returns the system to its normal state and keeps the images frozen.

Note: The handshaking lines should be checked after each step

2.3.3 DMA Write (Reference Memory Only)

The proceedure for performing DMA write is similar to the DMA read. Also see the program listing REF.READ and MOVLOD.OBJO

1. load register 0 with 1 - this allows DMA access during the entire frame.

2. load register 1 with 8. - this freezes the image and prepares the unit for write.

3. Load register 5 with 0 - this displays the reference memory

4. load register 2 with the pixel H coordinate.

5. load register 3 with the pixel V coordinate.

6. load register 4 with the pixel to be written into the image memory.

7. for random access go to 4. for sequential access go to 6. and repeat until the desired number of pixels are transferred.

8. load register 1 with 1 - this returns the unit to normal operation with the images frozen.

Note: The handshaking line should be checked after each step

2.4 Interfacing Requirements for the Computer

2.4.1 Computer Output Ports

Two output ports must be provided by the computer, the command port and the data port. Both must be 8 bits wide, active high at normal TTL levels. All lines are buffered in the DVDS and present 1 LS TTL load. 470 ohm pull up resistors to +5 volts are included on these lines in the DVDS. These ports are treated by the unit as one 16 bit port. If seperate ports are used it is important to load the data port before the command port, which has the handshaking lines associated with it. Once data has been set up and latched on both ports the COMPUTER READY line should go high. The DVDS will latch both ports soon after the rising edge of this signal. COMPUTER READY should be a standard TTL level signal. At this time the DEVICE BUSY line will go High to indicate that the command is being executed. The value loaded into register 0 determines when commands will be executed. In the "V.Drive Only" mode (0), a command will be held until the next

vertical blanking interval before execution. This is useful for freezing the memories at the end of a field. Other commands such as DMA transfers should take place at high speed so register 0 is put into the "Anytime" mode (1). Once the DVDS has executed the command from the host computer, the DEVICE BUSY line (TTL) will go low. Also at this time the BUSY strobe will pulse for 1 microsecond. These indicate that the computer may send another command. Any commands sent before this time will be lost.

2.4.2 Computer Input Port

One 8 bit input port to the computer is required to read data from the image memory. This port must be standard level, TTL, active high. After a DMA READ command has been executed, the pixel datum will be placed on the computer input port. The DEVICE READY line will then pulse for 1 microsecond to strobe this information into the computer input port. This signal is at standard TTL levels. Note that the data should be strobed in on the trailing edge of the DEVICE READY line.

3.0 Analog Input/Output

3.1 Description

This card accepts the video input from a camera, digitizes it, and passes it to the image memory. It also recieves digital video from various sources, selects the source, converts it to analog video, and passes it to the CRT monitor. In addition, composite sync is available for driving the camera. BNC connectors for video in, video out, and composite sync are located on the back of the DVDS.

3.2 Analog to Digital section

This section accepts the input video from the camera and digitizes it.

input impedance	75 ohms
input signal level	1 volt sync tip to white
sample rate	5 MHz
gray level resolution	256 levels
number of bits	8

A white clip light is provided on the front panel. This will come on when the video signal is too high, causing the analog to digital converter to overflow.

3.3 Digital to Analog section

Either of the stored images or the arithmetic unit may be selected for display. In addition to the full eight bit grey scale display, a single bit plane of any of these sources may be selected for viewing with the bit plane address register (see 2.2.1). The single bit mode output is either full black or full white. Blanking and sync are added digitally so there is no adjustment of sync or set up levels.

output impedance	75 ohms
output level	1 V p-p terminated
sample rate	5 MHz
number of bits	8

3.4 Composite Sync

Composite sync is used to drive the video camera. The DVDS uses the EIA RS-170 standard.

output impedence	75 ohms
level	4 V p-p terminated
polarity	negative going
horizontal rate	15,734 Hz
horizontal lines	525
active lines	480
vertical rate	60 Hz
frame rate	30/second

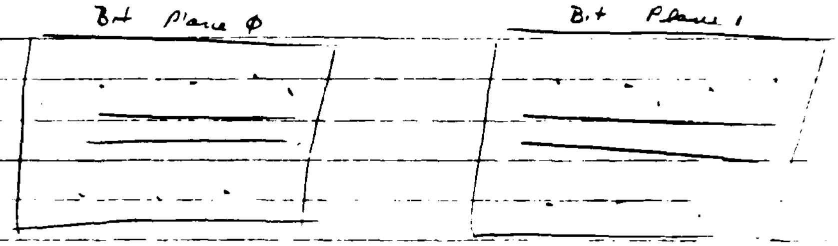
Note that because this is a 256 H by 240 V system, the same image is repeated on both fields.

3.5 Camera requirements

The most important requirement is that the camera sync to the system. A camera that will lock to the above RS-170 format will work. To obtain maximum use of the 256 gray levels, it should have a signal to noise ratio greater than 48 dB. The digitizing rate is 5 MHz so the camera should have a bandwidth of at least 2.5 MHz.

3.6 Adjustment proceedure

1) Needed: small screw driver, dual trace oscilloscope, Drawing #F-026 A/D-D/A component layout.
2) Remove the cover from the machine.
3) Connect the camera.
4) Turn the power on.
5) Point the camera on a bright scene and open the f-stop for maximum contrast.



"And" Bit Planes 0 & 1 together

Send result ~~to bit plane 2~~ (cleaned up)
thru AU

Inputs to ALU = pixel & line number

3Φ12
XX_CCCCO

Possibilities for bit planes 0 and 1

0	1		Result Desired
0	0	→	0
0	1	→	0
1	0	→	0
1	1	→	1

1. ~~Initialize all Bit Planes~~
2. Clear Line mask to all zero
3. Set image mask to Φ except for) 1 1 0 0 0 0 0 0 — $2^6 + 2^7$ — 64 [19]
4. Display image thru key 5 → image + line in

If 3 bit planes are to be used

0 — 0 — 0

0 — 0 Set image mask to Φ except for

1 1 1 0 0000 = 224

192
32
224

16
14
64
16
224

A/D Adjustment

6) Set both scope channels for 1V/division.
7) Ground both probes and line the traces up on the second line from the bottom. This is 0V.
8) Referring to drawing # F-026, connect Ch 1 to TP-1 and Ch 2 to TP-2. Unground them and sync to Ch 1. Ch 2 should be at approximately +6.7V.
9) Cap the camera lens. Turn the CLAMP LEVEL ADJUST pot so that the lowest portion of the active video (no sync) just touches 0V.
10) Uncap the camera lens and turn the FULL SCALE ADJUST pot so that the highest (brightest) portions of the active video just touch the 6.7V line on Ch-2. If the video goes above the CH-2 reference, the white clip light on the front panel should turn on.
11) The adjustments in steps 9 and 10 are somewhat interactive so go back and repeat 9 and 10 as required.

D/A Adjustment

12) Set CH1 for .5V/division
13) Ground the probe and put the trace on the scope centerline.
14) Connect the probe to TP-3. Unground the scope.
15) Turn the D/A REFERENCE ADJUST pot so the scope reads - 1.0 Volts.
16) Connect the probe to TP-4. AC couple the scope.
17) Turn the output LEVEL ADJUST pot so that the video signal is 1 Volt peak to peak (2 Volts peak to peak if nothing is connected to the output. i.e. unterminated).

This completes the Adjustment procedure.

4.0 Arithmetic Unit

4.1 Description

The heart of the unit is eight bit ALU (2 X 74S381). The two operands to the ALU are an output pixel from the bit plane memory and the vertical line (address) of that pixel. The pixel is first passed through a PROM that is programmed to perform a gray code to binary conversion. It is then passed through a 256 X 8 mapping RAM to perform an arbitrary transfer function. The other operand, the line number, is also passed through an identical mapping RAM before going to the ALU. The output of the arithmetic unit can be sent to the analog input/output card for display or to the DMA interface and then to the computer. Note that due to the pipeline delay of the processor, the displayed image through the AU is shifted to the right by one pixel.

4.1.1 Functions

The ALU can perform the following functions:

1) clear
2) line - memory
3) memory - line
4) memory + line
5) memory EXOR line
6) memory OR line
7) memory AND line
8) preset

Note that no provision for numeric overflow or underflow is made. See section 2.2.2 for detailed programming information.

4.2 Loading the Mapping RAMs

The following is the general algorithm for entering a transfer function. The RAMs use a common address generator for loading. The circuitry has an autoincrement feature so it is not necessary to specify each address when loading successive locations.

1. Set register 224 to 0 - this puts the RAMs into the write mode.

2. Load register 227 with the starting address. This is usually 0.

3. To write into the image mapping RAM, load register 225 with the desired data. To write into the line mapping RAM, load register 226 with the desired data. Loading these registers performs the write function in the RAM.

4. The address will automatically increment, so for successive addresses go to step 3. To load random locations go to step 2.

5. When completed, load register 224 with a number representing the desired ALU function.

5.0 Address Generator

5.1 Description

This card generates the video read and write addresses which are then used by the image memories. It also generates the refresh signals for the dynamic RAMs used in the image memory. The addressing modes are fixed.

6.0 Connector list

6.1 Computer Interface - P1 on L(N)-011 to P1 on F-035

1	Data Port	Bit 0 (LSB)	[1]	20	Computer Ready		[18]
2	Data Port	Bit 1	[2]	21	Device Busy (Strobe)		[19]
3	Data Port	Bit 2	[3]	22	GND		[20]
4	Data Port	Bit 3	[4]	23	Device Busy (Strobe)	Inv.	[21]
5	Data Port	Bit 4	[5]	24	Output Port Bit 0 (LSB)		[22]
6	Data Port	Bit 5	[6]	25	Output Port Bit 1		[23]
7	Data Port	Bit 6	[7]	26	Output Port Bit 2		[24]
8	Data Port	Bit 7	[8]	27	Output Port Bit 3		[25]
9	GND		[9]	28	Output Port Bit 4		[26]
10	Address Port	Bit 0 (LSB)	[10]	29	Output Port Bit 5		[27]
11	Address Port	Bit 1	[11]	30	Output Port Bit 6		[28]
12	Address Port	Bit 2	[12]	31	Output Port Bit 7		[29]
13	Address Port	Bit 3	[13]	32	Device Ready		[30]
14	Address Port	Bit 4	[14]	33			[31]
15	Address Port	Bit 5	[15]	34	Device Ready (Inv.)		[32]
16	Address Port	Bit 6	[16]	35	Device Busy		[33]
17	Address Port	Bit 7	[17]	36	Device Busy (Inv.)		[34]
18				37			
19							

Notes: All signals are TTL levels active high except those marked (Inv.) which are active low. Numbering is for the 37 pin D type subminiature connector on the rear panel. Numbers in brackets are for the 34 pin cable socket on L(N)-011 and F-035

6.2 Arithmetic Unit Connector - P2 on L(N)-011 to P1 on N-028

1	DMA Vertical Address 0 (LSB)	11	ALU Output Port Bit 2
2	DMA Vertical Address 0	12	ALU Output Port Bit 3
3	DMA Vertical Address 2	13	ALU Output Port Bit 4
4	DMA Vertical Address 3	14	ALU Output Port Bit 5
5	DMA Vertical Address 4	15	ALU Output Port Bit 6
6	DMA Vertical Address 5	16	ALU Output Port Bit 7
7	DMA Vertical Address 6	17	DMA ALU LATCH ENABLE
8	DMA Vertical Address 7	18	ALU LATCH CLOCK
9	ALU Output Port Bit 0 (LSB)	19	Output Port Select (OPS)
10	ALU Output Port Bit 1	20-34	Spare

6.3 Address Connector - P2 on N-028 to P1 on L-007

1	Read Vertical Address 0 (LSB)	6	Read Vertical Address 5
2	Read Vertical Address 1	7	Read Vertical Address 6
3	Read Vertical Address 2	8	Read Vertical Address 7
4	Read Vertical Address 3	9-16	Spare
5	Read Vertical Address 4		

7.0 Apple interface

7.1 Introduction

The Apple Interface contains the hardware necessary to interface the DVDS to an Apple II microcomputer. It provides for two 8 bit output ports, one 8 bit input port and all necessary handshaking lines. It normally resides in slot #4 of the Apple's peripheral bus.

7.2 Output Ports

The output ports are memory mapped locations. The first port contains the address of the DVDS register to be loaded. This is called the Command Address Port. When the card is in slot #4 its

address is 49356 (COCC HEX). The second port sends the data to be loaded into the addressed register. This is called the Command Data Port. With the card in slot #4 its address is 49357 (COCD Hex).

7.3 Input Ports

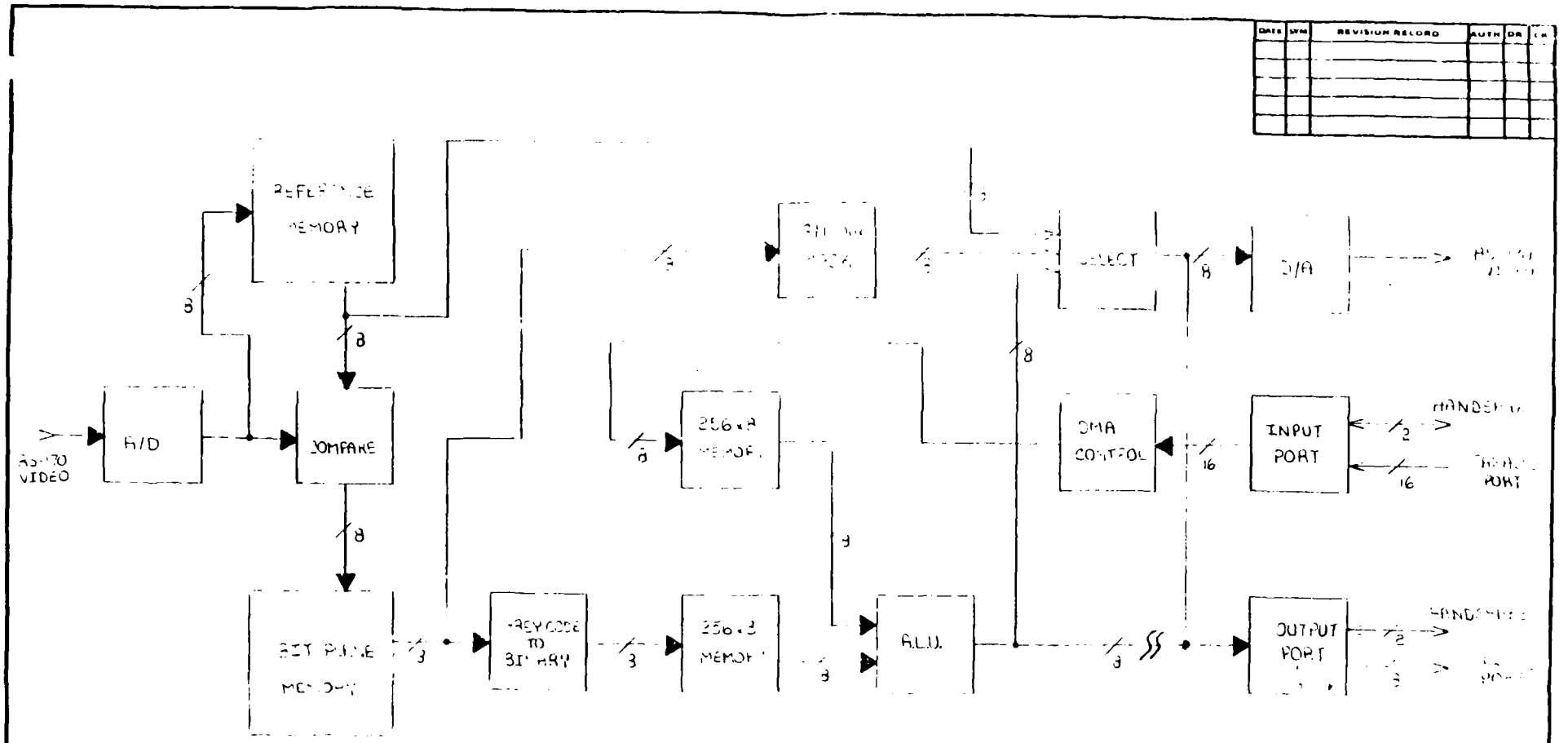
The input port is used to receive DMA data from the DVDS. In slot #4 its address is 49344 (COC1 HEX). Data is strobed into this memory mapped register by the DEVICE READY (Inv.) line from the DVDS. It then can be read by the computer.

7.4 Handshaking Lines

A single COMPUTER READY line is provided for both output ports. The decoded write pulse for the Command Address Port also serves as the COMPUTER READY line. Thus the Command Data Port is loaded first followed by the Command Address Port. Loading this register signals the DVDS that a command must be executed.

The Apple Interface uses two handshaking lines provided by the DVDS, DEVICE BUSY and DEVICE READY STOBE (Inv.). Both are mapped into memory location 49345 (COC1 HEX), which is the status register. DEVICE BUSY goes active (high) upon activation of the COMPUTER READY line. It remains high until the DVDS has completed execution of the command. It then goes low. DEVICE BUSY is bit 1 of the status register.

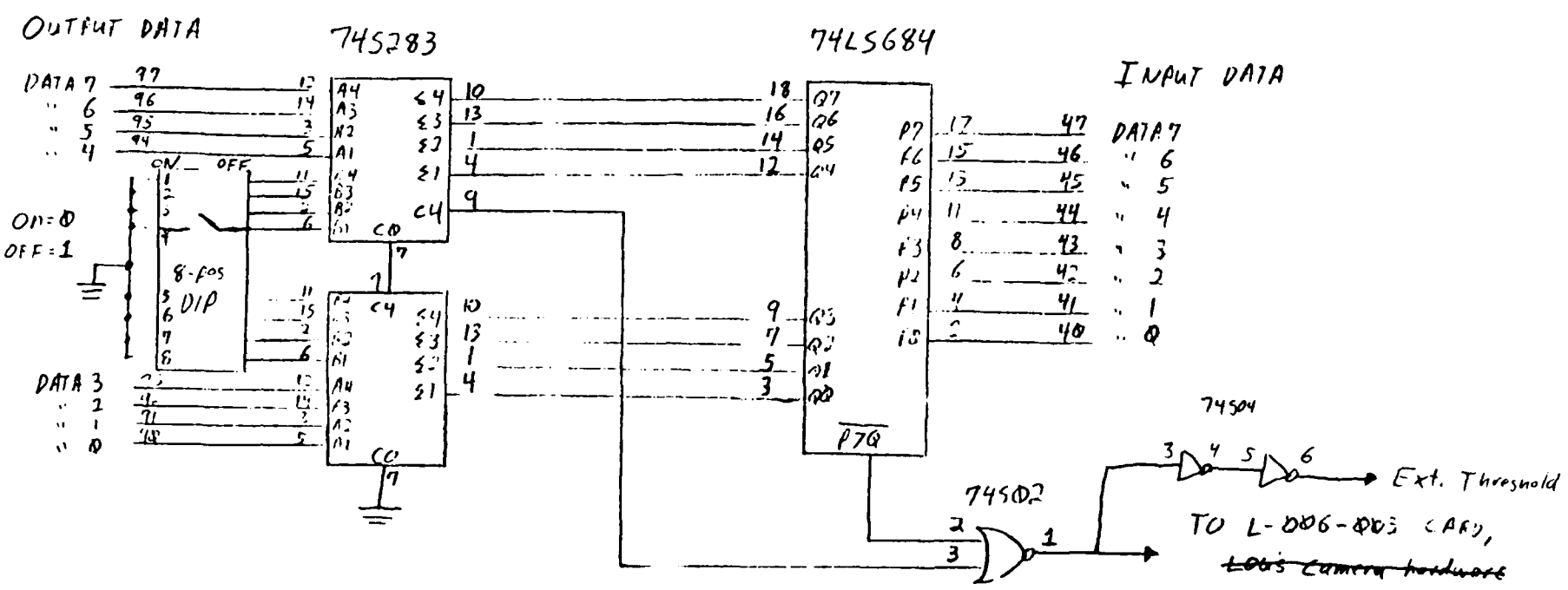
When the DVDS performs a DMA Read command it leaves the data in the input register and sets (forces high) a flag connected to bit 0 of the status register. The Apple may monitor this bit to wait until the DMA transfer is complete. Reading the input register resets this bit to ready it for the next transfer.



DATE	SYM	REVISION RECORD	AUTH	DR	CK

NOTES:

TOLERANCES (EXCEPT AS NOTED)	DIGITAL/ANALOG [illegible]		
DECIMAL	[illegible]	SCALE	DRAWN BY
FRACTIONAL			APPROVED BY
ANGULAR	TITLE [illegible]		
	DATE	DRAWING NUMBER	


OUTPUT DATA
74S283
74LS684
INPUT DATA
DATA 7
6
5
4
ON
OFF
ON=0
OFF=1
8-pos
DIP
DATA 3
2
1
0
C4
C0
P7Q
74S04
74S02
Ext. Threshold
TO L-006-003 CARD,
~~L-006 Camera hardware~~
=1 whenever
is greater than sum of reference
memory and DIP setting

Blue Box only

DAD box wiring

11/29/83

Signals	output pins	
INTRB	N.C.	
OBFB	18	
ACKB	30, 32	
INTRA	N.C	
bit 4	N.C.	
bit 5	N.C.	(earlier versions → 24 for flash)
ACKA	30, 32	
OBFA	N.C.	
INTRB	N.C	
IBFB	N.C	
STBB	N.C.	
INT a	N.C.	
STBA	26	
IBFA	28	
BIT 6	N.C.	
BIT 7	32	(for VSYNC if required)

use appro. wiring on 8255A's (use 7426 on its output iff you need to drive the flash from bit 5, output)

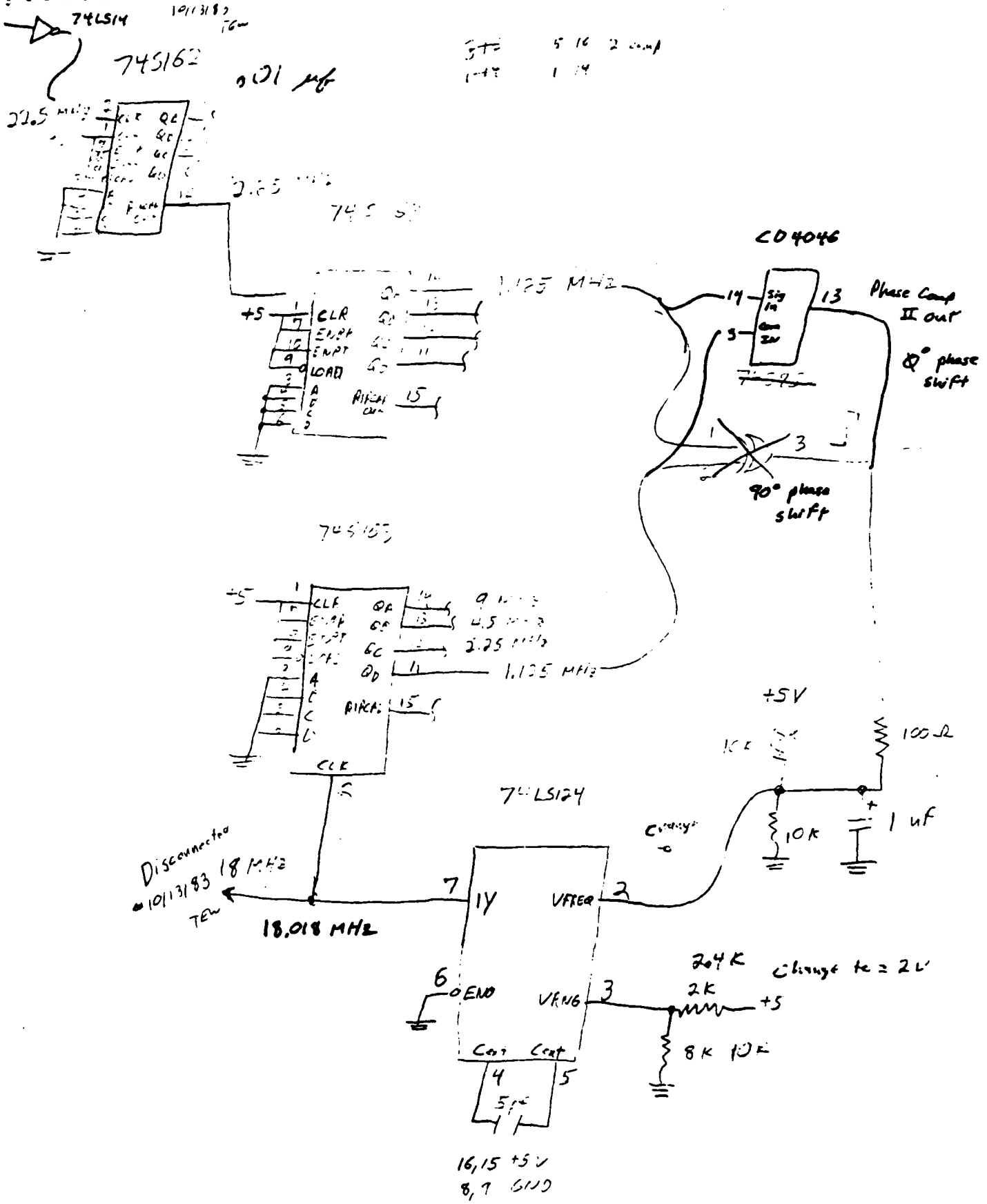
ISBx 350 wiring for output to OAO box

11/24/93

Function

E1 - E2 port A output

INTRB	E7 - NC	N.C
OBFB	E9 - E14	Computer Ready (pin 18)
ACKB	E11 - E-26	$\overline{\text{Device Busy}}$
INTRA	E13 - NC	N.C
BIT 4	E19 - E20	N.C
BIT 5	E21 - E22	N.C
ACKA	E23 - E24	$\overline{\text{Device Busy}}$
OBFA	E25 - NC	N.C
	E-24 - E26	connect ACK_A, ACK_B


74LS14
10/13/83
TEW
74S162
.01 μf
22.5 MHz
2.25 MHz
74S 57
CD4046
1.125 MHz
+5
CLR
ENPT
ENPT
LOAD
A
B
C
D
RIPPLE CO
Phase Comp II out
90° phase shift
74S163
9 MHz
4.5 MHz
2.25 MHz
1.125 MHz
RIPPLE
CLK
+5V
100Ω
10K
1 uf
74LS124
Change
Disconnected 10/13/83 18 MHz TEW
18.018 MHz
1Y
VFREQ
END
VRNG
Cext
Cext
24K
2K
8K 10K
Change to = 2V
16, 15 +5V
8, 7 GND

APPENDIX D

SOFTWARE FOR FRANKLIN

```
LIST

1   DIM RANGE%(1,256)
2 LINE = 226
3 MASK = 225
4 AREG = 227
5   ONERR  GOTO 10
6   GOSUB 1000: REM  ...INIT
10   HOME
20   PRINT "WELCOME TO THE DARKSIDE...."
30   VTAB 10
35   PRINT "0 - END
40   PRINT "1   LOAD IMAGES
50   PRINT "2 - DISPLAY RANGES
55   PRINT "3 - LOAD LUTS
56   PRINT "4 - LOAD FLASH SYNC
57   PRINT "5 - LOAD RANGE TABLE
58   PRINT "6 - INIT SYSTEM
59   PRINT "7 - SET THRESHOLD
60   PRINT "8 - DISPLAY BP (16)
61   PRINT "9 - DISPLAY BP ALU
90   VTAB 20
100   GET IN$
110   IF  ASC (IN$) = 49 THEN  GOSUB 1700
120   IF  ASC (IN$) = 50 THEN  GOSUB 40000
130   IF  ASC (IN$) = 51 THEN  GOSUB 10000
140   IF  ASC (IN$) = 52 THEN  GOSUB 20000
150   IF  ASC (IN$) = 53 THEN  GOSUB 50000
157   POKE D,10
160   IF  ASC (IN$) = 48 THEN  GOTO 63000
170   IF  ASC (IN$) = 54 THEN  GOSUB 1000
180   IF  ASC (IN$) = 55 THEN  GOSUB 30000
190   IF  ASC (IN$) = 56 THEN  GOSUB 25000
200   IF  ASC (IN$) = 57 THEN  GOSUB 26000
500   GOTO 10
1000   REM  ...THE SYSTEM WILL BE
1020   REM  ...KNOWN STATE. REF MEM
1030   REM  ...WILL THEN BE LOADED
1040   REM  ...WITH A CURRENT IMAGE
1050   REM  ...AND SUBSEQUENT BIT
1060   REM  ...PLAIN IMAGES ALSO
1070   REM  ...LOADED. THIS MAY
1080   REM  ...WITH OR WITHOUT THE
1090   REM  ...FLASH.LOOKUP TABLES
1100   REM  ...INITIALIZED TO A
1101   REM  ...WILL ALSO BE LOADED
1140   REM  ...WILL THEN DISPLAY
1150   REM  ...A SHALL WIDOW REP-
1160   REM  ...RESENTING SAMPLED
1170   REM  ...AREA IN TERMS OF
1180   REM  ...DISTANCE.
1190   REM
1200   REM
1210   REM
1220   REM
1230   REM
1240   REM
```

```
1250  REM  ...SYSTEM INITIALZATION
1260  REM
1270  REM
1280 D = 49357
1290 A = 49356
1300  REM  ...D IS THE DATA PORT.
1310  REM  ...A IS THE COM PORT.
1320  REM
1330  REM
1340  POKE D,1: POKE A,0
1341  REM
1350  REM  ...SET TO "LOAD ANY-
1360  REM  ...TIME" DURING V-
1370  REM  ...TRACE.
1380  REM
1381  FOR I = 1 TO 20: NEXT
1382  REM
1383  REM  ...ALLOW TIME TO
1384  REM  ...ACCEPT LOAD COMMAND
1400  REM
1410 THRESH = 0
1420  POKE THRESH,0: POKE A,255
1430  POKE D,0: POKE A,1
1440  POKE D,1: POKE A,2
1450  POKE D,0: POKE A,3
1460  POKE D,0: POKE A,5
1470  POKE D,96: POKE A,224
1480  REM ...SET THRESH TO 0
1490  REM  ...SET REF LIVE,BIT
1500  REM  ...PLANE FROZEN.
1510  REM  ...SET DMA HORIZONTAL
1520  REM  ...ADDRESS = 0
1530  REM  ...SET DMA VERTICAL
1540  REM  ...ADDRESS = 0
1550  REM  ... SET DISPLAY TO
1560  REM  ...AND GRAYSCALE MODE.
1570  REM  ...SET ALU TO ADD MODE.
1580  REM
1590  REM
1600  RETURN
1601  REM
1620  REM
1630  REM
1635  HOME
1640  PRINT "SELECT NORMAL OR "
1650  PRINT "FLASH MODE.       "
1660  PRINT "NORMAL = N"
1670  PRINT "FLASH  = F  "
1675  GET IN$
1676 FLSH = 0
1680  IF  ASC (IN$) = 70 THEN FLSH = 1
1690  REM
1700  REM  ...LOAD IMAGE.
1720  REM
1730  REM
1740  HOME
1750  PRINT "MANUAL LOAD    = M"
1760  PRINT "REALTIME LOAD = R"
1770  GET IN$
1771  REM
1772  POKE D,0: POKE A,5
1780  HOME
1790  PRINT "ALIGN REF MASK"
1800  PRINT ""
1810  PRINT ""
1820  PRINT "TYPE A   SPACE"
```

```
1830  PRINT "LIVE    = TAB"
1840  PRINT "NEXT    = RETURN"
1850  GET IN$
1860  IF  ASC (IN$) <  > 32 THEN 1920
1870  CALL 20480
1880  REM  ...FREEZE REF MEM
1890  GOTO 1780
1900  REM
1910  REM
1920  IF  ASC (IN$) <  > 9 THEN 1980
1950  POKE D,0: POKE A,1
1960  REM  ...REF LIVE (REPEAT)
1970  REM
1975  REM
1976  GOTO 1780
1980  IF  ASC (IN$) <  > 13 THEN 2000
1985  REM
1990  GOTO 5000: REM  ...EXIT
2000  GOTO 1780: REM  ...TRAP
2100  REM  ------------------------
2200  REM
2400  REM
3000  REM
4000  REM    ...LOAD BIT PLANES
4005  HOME
4010  POKE D,5: POKE A,5
4015  POKE D,1: POKE A,1
4016  REM
4017  REM        ...BIT PLANE FROZEN
4018  REM      ...BIT PLANE DISPLAYED
4020  REM
4030  FOR I = 0 TO 7
4060  REM
4070  REM     ...SELECT PLANE
4080  REM
4090  POKE D,(I): POKE A,6
4100  REM
4200  HOME
4300  PRINT "SPACE  = FREEZE
4400  PRINT "TAB    = REPEAT
4500  PRINT "RETURN = NEXT
4600  PRINT "PLANE# =",(I + 1)
4700  REM
4800  REM
4900  GET IN$
5000  REM
5100  REM     --------------------
5200  IF  ASC (IN$) <  > 32 THEN 5300
5210  CALL 20480
5220  REM     ...FREEZE PLANE
5230  REM
5240  GOTO 4200
5250  REM     ------------------------
5260  REM
5270  REM
5280  REM     ---------------------
5300  IF  ASC (IN$) <  > 9 THEN 5400
5310  POKE D,3: POKE A,1
5320  REM    ..BIT PLANE LIVE
5330  REM
5340  REM
5350  GOTO 4200
5360  REM    ------------------------
5370  REM
5380  REM
5390  REM
```

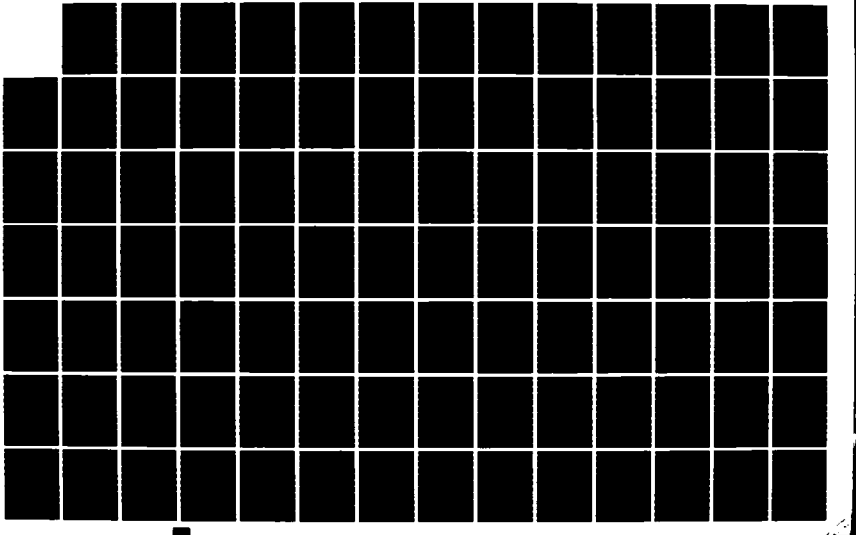
```
5400  REM
5410  IF  ASC (INI)  >  13 THEN 4200
5420  NEXT I
5440  REM
5450  REM
5500  POKE D,3: POKE A,5
5600  REM  ...DISPLAY FROZE REF
6000  REM
6100  RETURN
10000  REM ----------
11000  REM
11100  HOME
11105  VTAB 10
11110  PRINT "LOADING L.U. TABLES
12000  REM ...LOAD HOST RAM
13000  REM
14000  REM
15000  POKE D,1: POKE A,224
15100  REM ...SET TO LOAD MODE
15200  POKE D,0: POKE A,227
15300  REM ...INIT RAM ADDRESS
15400  REM
15410  REM ...LOAD LINE RAM
15420  REM
15500  FOR I = 0 TO 127
15600  FOR J = 0 TO 1
15700  POKE D,I
15800  POKE A,LINE
15900  NEXT J
16000  NEXT I
16100  REM
16200  REM
16300  REM
16400  REM ...LOAD MASK RAM
16500  REM
16600  POKE D,0: POKE A,227
16700  FOR I = 127 TO 0 STEP  - 1
16800  FOR J = 0 TO 1
16900  POKE D,I
17000  POKE A,MASK
17100  NEXT J
17200  NEXT I
17300  REM
17400  REM
17500  POKE D,96: POKE A,224
17600  REM ...SET MODE NORMAL
17700  REM
17800  REM
19999  RETURN
20000  REM ----------
20100  REM ...LOADS FLASH CODE
20110  REM
20115  HOME
20120  REM
20125  PRINT "LOADING....
20130  FOR I = 0 TO 47
20140  READ TEST
20150  POKE (20480 + I),TEST
20155  NEXT I
20160  DATA  173
20170  DATA  96
20180  DATA  192
20190  DATA  96
20200  DATA  1
20210  DATA  ...
20220  DATA  ...
```

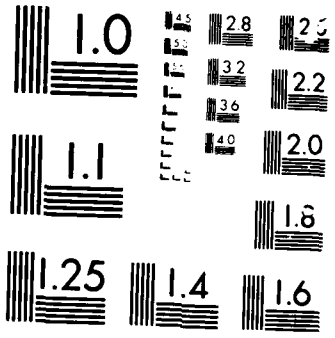
```
20230   DATA  80
20240   DATA  173
20250   DATA  98
20260   DATA  192
20270   DATA  48
20280   DATA  251
20290   DATA  234
20300   DATA  169
20310   DATA  0
20320   DATA  162
20330   DATA  0
20340   DATA  160
20350   DATA  0
20360   DATA  169
20370   DATA  1
20380   DATA  141
20390   DATA  205
20400   DATA  192
20410   DATA  141
20420   DATA  88
20430   DATA  192
20440   DATA  141
20450   DATA  89
20460   DATA  192
20470   DATA  162
20480   DATA  13
20490   DATA  160
20500   DATA  255
20510   DATA  136
20520   DATA  208
20530   DATA  253
20540   DATA  202
20550   DATA  208
20560   DATA  248
20570   DATA  141
20580   DATA  204
20590   DATA  192
20600   DATA  141
20710   DATA  88
20720   DATA  192
20730   DATA  96
20740   REM
20750   REM
20760   RETURN
20770   REM ================
25000   POKE D,3: POKE A,5
25010   RETURN : REM  DISPLAY BF (160
26000   POKE D,1: POKE A,5
26100   RETURN
30000   REM ********************
30100   REM
30200   REM
30300   REM ...THRESHOLD SETTING
30400   REM
30500   HOME
30600   PRINT "THRESHOLD = ",THRESH
30700   VTAB 10
30800   INPUT "NEW = ";THRESH
30900   POKE D,THRESH: POKE A,255
31000   VTAB 15
31100   PRINT "TAB = EXIT"
31200   GET IN#
31300   IF  ASC (IN#) = 9 THEN 35000
31400   GOTO 30000
35000   RETURN
40000   REM  ****************
```

```
40100  REM
40200  REM
40300  REM  ...DISPLAY RANGES
40400  POKE D,13: POKE A,1
40500  POKE D,3: POKE A,5
40600  REM
40700  HOME
40800  PRINT "(X,Y)        ";X,Y
40900  REM
41000  REM  ...ENA MODE
41200  PRINT
41300 X = (X - 4)
41400 Y = (Y - 10)
41500  FOR J = 0 TO 7
41600  FOR I = 0 TO 19
41700  HTAB ((J + 1) * 4)
41800  POKE 9,(Y + I)
41900  POKE A,2
42000  POKE D,(X + J)
43000  POKE A,2
44000  POKE D,0
45000  POKE A,4
45100 VECTR =  PEEK (49344)
45200 IRAN = RANGE%(I,VECTR)
45300  PRINT IRAN
45400  NEXT I
45500  VTAB I
45600  NEXT J
45700  VTAB 22
45810  PRINT "",X + 4,Y + 10
45900  INPUT "(X,Y) ";X,Y
45990  GOTO 41200
45910  RETURN
50000  REM
50100  REM
50200  REM
50300  REM
50400  REM
50500  REM
50600  REM
50700  REM
51000  REM
52000  REM
53000  REM  ...RANGE TABLE
54000  REM
54100  REM
54110  HOME
54120  PRINT "TRANSLATION = 1"
54130  PRINT "DIRECT      = 2"
54135  VTAB 10
54140  GET IN$
54145  IF  ASC (IN$) = 49 THEN 54200
54146  IF  ASC (IN$) = 50 THEN 54210
54147  GOTO 54110
54200  GOTO 55000
54210  GOTO 54220
54220  FOR I = 0 TO 255
54230 RANGE%(I,1) = I
54235  PRINT I,RANGE%(I,1)
54240  NEXT I
54250  RETURN
55000  HOME
55100  INPUT "DISTANCE =  ";RA
55200  VTAB 10
55600  REM
55000  REM
```

AD-A168 197 DEVELOPMENT OF ALGORITHMS AND HARDWARE FOR STRUCTURED-LIGHT VISION(U) GEORGE WASHINGTON UNIV WASHINGTON DC DEPT OF ELECTRICAL ENGIN.. 3/4

UNCLASSIFIED M H LOEW ET AL. 1986 N00014-83-K-0578 F/G 20/6 NL





MICROCOPY

```
58000  REM
59000 G = .0000360
59100  REM
59200  FOR I = 0 TO 255
59300 RANGE%(1,I) = (RA / (I + 1) * G)
59310  PRINT I,RANGE%(1,I)
59400  NEXT I
59500  FOR I = 1 TO 3000: NEXT
60000  REM
60001  REM   ==========
60100  RETURN
63000  HOME
63001  PRINT "CPU DOUBLE ERROR HALT"
63002  VTAB 15
63003  END

]
```

APPENDIX E

S/W FOR OBJECT DESCRIPTION AND MATCHING

Computer vision system

```
GGGGGGGGGG  5555555555555555555555  The George Washington University -- SEARCH  VAX/VMS V4.1  555555555555555555555  GGGGGGGGGG
GGGGGGGGGG  5555555555555555555555                                               555555555555555555555  GGGGGGGGGG
GGGGGGGGGG  5555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555  GGGGGGGGGG

                    FFFFF   AAA     CCCC   GGGG   AAA     000
                    F      A   A  C      G      A   A  0   0
                    F      A   A  C      G      A   A  0   0
                    FFFF   A   A  C      G      A   A  0   0
                    F      AAAAA  C      G GGG  AAAAA  0   0
                    F      A   A  C      G   G  A   A  0   0
                    F      A   A   CCCC   GGG   A   A   000

VV      VV    IIIIII      SSSSSSSS    IIIIII      000000    NN      NN
VV      VV    IIIIII      SSSSSSSS    IIIIII      000000    NN      NN
VV      VV      II      SS              II      00      00  NN      NN
VV      VV      II      SS              II      00      00  NN      NN
VV      VV      II      SS              II      00      00  NNNN    NN
VV      VV      II      SS              II      00      00  NNNN    NN
VV      VV      II        SSSSSS        II      00      00  NN  NN  NN
VV      VV      II        SSSSSS        II      00      00  NN  NN  NN
VV      VV      II              SS      II      00      00  NN    NNNN
VV      VV      II              SS      II      00      00  NN    NNNN
  VV  VV        II              SS      II      00      00  NN      NN
  VV  VV        II              SS      II      00      00  NN      NN
    VV        IIIIII    SSSSSSSS    IIIIII      000000    NN      NN
    VV        IIIIII    SSSSSSSS    IIIIII      000000    NN      NN

FFFFFFFFFF    000000    RRRRRRRR        ;;;;      333333      333333      666666
FFFFFFFFFF    000000    RRRRRRRR        ;;;;      333333      333333      666666
FF          00      00  RR      RR      ;;;;    33      33  33      33  66
FF          00      00  RR      RR      ;;;;    33      33  33      33  66
FF          00      00  RR      RR              33      33  66
FF          00      00  RR      RR              33      33  66
FFFFFFF     00      00  RRRRRRRR        ;;;;        33      33    66666666
FFFFFFF     00      00  RRRRRRRR        ;;;;        33      33    66666666
FF          00      00  RR  RR          ;;;;        33      33  66      66
FF          00      00  RR  RR          ;;;;        33      33  66      66
FF          00      00  RR    RR          ;;    33      33  33      33  66      66
FF          00      00  RR    RR          ;;    33      33  33      33  66      66
FF            000000    RR      RR      ;;      333333      333333      666666
FF            000000    RR      RR      ;;      333333      333333      666666

File _DUA1:[FACGAO.VISION]VISION.FOR;336 (22616,10,0), last revised on  9-DEC-1985 15:43, is a 41 block sequential file owned by
UIC [EECS,FACGAO]   The records are variable length with implied (CR) carriage control   The longest record is 71 bytes

Job VISION (32) queued to SYS$PRINT on 9-DEC-1985 15:43 by user FACGAO, UIC [EECS,FACGAO], under account EECS at priority 4,
started on printer _LPA0  on 9-DEC-1985 15:43 from queue LPA0

GGGGGGGGGG  5555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555  GGGGGGGGGG
GGGGGGGGGG  5555555555555555555555  Digital Equipment Corporation - VAX/VMS Version V4.1  555555555555555555555  GGGGGGGGGG
GGGGGGGGGG  5555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555  GGGGGGGGGG
```

```
c*********************************************************************
c*                                                                   *
c*                  COMPUTER VISION SYSTEM                           *
C*                                                                   *
C*                                                                   *
c*  Purpose                                                          *
c*  =======                                                          *
c*     This is a program for object recognition and matching in the  *
c*  computer vision system                                           *
c*                                                                   *
c*                                                                   *
c*  Description                                                      *
c*  ===========                                                      *
c*     The program start with an artificial range data. The data     *
c*  are the range values from a specific view of the reference       *
c*  object                                                           *
c*                                                                   *
c*     The object recognition  program  solve  following   three     *
c*  problems                                                         *
c*   (i)   find the number of plans                                  *
c*   (ii)  find the corresponding plan equations                     *
c*   (iii) find the node coordinates.                                *
c*                                                                   *
c*     The matching program is to answer the question -- whether     *
c*  tha range data are one view of the one of our reference          *
c*  objects  The matching procedure includes following three steps:  *
c*   (i)   bottom node matching                                      *
c*   (ii)  plane equation maching                                    *
c*   (iii) all node matching                                         *
c*                                                                   *
c*                                                                   *
c*  Calling relationship                                             *
c*  ====================                                             *
c*     Main program 'vision'                                         *
c*        |                                                          *
c*        |-- iniramfip              initialize RAMTEK               *
c*        |                                                          *
c*        |-- range_data             read the artificial range data  *
c*        |-- lo                     load range data to RAMTEK       *
c*        |                                                          *
c*        |-- differ                 compute dz/dx                   *
c*        |-- smoth                  smoothing dz/dx                 *
c*        |-- smoth                  smoothing dz/dx again           *
c*        |-- lo                     load dz/dx to RAMTEK            *
c*        |                                                          *
c*        |-- differ                 compute dz/dy                   *
c*        |-- smoth                  smoothing dz/dy                 *
c*        |-- smoth                  smoothing dz/dy again           *
c*        |-- lo                     load dz/dy to RAMTEK            *
c*        |                                                          *
c*        |-- subback                subtract the background from    *
c*        |-- subback                  dz/dx and dz/dy               *
c*        |                                                          *
c*        |                                                          *
c*        |                                                          *
c*        |                                                          *
c*        |                                                          *
c*        |                                                          *
```

```
c*       !                                                              *
c*       ! -- histo                  compute the 2-D histogram of       *
c*       !                             dz/dx and dz/dy                  *
c*       ! -- lo                     load histogram to RAMTEK           *
c*       ! -- lo                     load separated plan to RAMTEK      *
c*       !                                                              *
c*       ! -- plane                                                     *
c*       ! -- lo                                                        *
c*       ! -- edge                   find the individual plan           *
c*       ! --                        equations, the edge coor  of       *
c*       ! --                        the plan and the node coor         *
c*       ! -- plane                                                     *
c*       ! -- lo                                                        *
c*       ! -- edge                                                      *
c*       !                                                              *
c*       !                                                              *
c*       !                                                              *
c*       ! -- matching               object matching                    *
c*             !                                                        *
c*             ! -- roan             rotate the ref. object             *
c*             !                                                        *
c*             ! -- plane                                               *
c*             ! --                  reference object plan              *
c*             ! --                    forming                          *
c*             ! -- plane                                               *
c*             !                                                        *
c*             ! -- sorting          rank plane equa. (object)          *
c*             ! -- sorting          rank plane equa. (view)            *
c*                                                                      *
c*                                                                      *
c*  Major variables                                                     *
c*  ===============                                                     *
c*  (i)  related to specific view                                       *
c*        iobj      : 256*256 integer array, range data                 *
c*        idetx     : 256*256 integer array, dz/dx                      *
c*        idety     : 256*256 integer array, dz/dy                      *
c*        ihis      : 256*256 integer array, 2-D histogram              *
c*        ia        : 256*256 integer auxiliary array                   *
c*        peq         5*5 real array, plane equa.                       *
c*        ix        : 1000*2 integer array , edge coor.                 *
c*        iy          1-D real array(size 1000),edge chain code         *
c*        c         : 30*3 real array, node coor.                       *
c*        nopln     : integer variable, # of planes                     *
c*        nonode    : integer variable, # of nodes                      *
c*        nonob     : integer variable, # of bottom nodes               *
c*                                                                      *
c*  (ii) related to reference object                                    *
c*        a         : 5*6*3 real array, node coor.                      *
c*                    ! ! !--- 3-D coor.                               *
c*                    ! !----- # of nodes                              *
c*                    !------- # of positions                           *
c*        pins      : 5*5 real array, plane equa.                       *
c*        b         : 20*3 real array, node coor                        *
c*        no_plane  : integer variable, # of planes                     *
c*        no_node   : integer variable, # of nodes                      *
c*        no_nodebo : integer variable, # of bottom nodes               *
c*                                                                      *
c*                                                                      *
c**********************************************************************
```

```
      dimension pln(4,3),iq(10,2),g(3,4)
      dimension ip(10),c(30,3),b(20,3),peq(5,5)
      dimension ihis(256,256),ix(1000,2),iy(1000)
      integer*2 iobj(256,256),idetx(256,256),idety(256,256)
      integer*2 ia(256,256)

c     call iniramfip(ierr)

c      ********************
c      *  read the data   *
c      ********************

      call range_data(iobj)

c     call lo(iobj,256,0,0,2 ,-20)
c     call lo(iobj,256,0,512,2 2,-60)

c      ***************************************
c      *  compute first partial derivative   *
c      ***************************************

      call differ(iobj,idetx,5 0,0)
c          write(5,1111) ((idetx(i,j),i=120,145),j=45,175)
1111      format(26i3)
c     call lo(idetx,256,960,512,10 ,128)

      call smoth(idetx)

c          write(5,1111) ((idetx(i,j),i=120,145),j=45,175)

      call smoth(idetx)

c          write(5,1111) ((idetx(i,j),i=120,145),j=45,175)

c     call lo(idetx,256,320,0,15 ,128)
c     call lo(idetx,256,320,512,10 ,90)

      call differ(iobj,idety,5 0,1)
      call smoth(idety)
c          write(5,1111) ((idety(i,j),i=120,145),j=45,175)
      call smoth(idety)
c          write(5,1111) ((idety(i,j),i=120,145),j=45,175)
c     call lo(idety,256,640,0,1 5,128)
c     call lo(idety,256,640,512,4 0,90)


c      *********************************
c      *   subtracte the background    *
c      *********************************

      call subback(iobj,idetx)
      call subback(iobj,idety)

c      ***************************************
c      *  find the 2D-histogram of gray level  *
```

```
c          ****************************************

           call histo(idetx,idety,ihis)

c          ----------------------------
c            to desply 2d-histogram
c          ----------------------------
c          do i=1,256
c            do j=1,256
c              ia(i,j)=ihis(i,j)/30
c            end do
c          end do

c               write(5,1112) ((ihis(i,j),i=125,140),j=110,170)
1112            format(16i5)


c          call lo(ia,256,960,0,1 ,0)

c          ***************************************
c          *  find the equations of the planes   *
c          ***************************************

           write(5,9994)

c          ========================================================
c           find the no. of plane (i e. the peak in the 2-D histo.
c          ========================================================

             nopln=0
           do i=1,256
             do j=1,256
               if (ihis(i,j).lt.300) goto 60
                 nopln=nopln+1
                 iq(nopln,1)=i
                 iq(nopln,2)=j
60           end do
           end do

             nopl=nopln
           do i=2,nopln
             do j=1,i-1
               id=(iq(j,1)-iq(i,1))**2+(iq(j,2)-iq(i,2))**2
               if (id.gt.8) goto 70

               ie=ihis(iq(i,1),iq(i,2))-ihis(iq(j,1),iq(j,2))
               if(ie.gt.0) goto 75
               iq(i,1)=0
               iq(i,2)=0
                nopl=nopl-1
                goto 71

75             iq(j,1)=0
               iq(j,2)=0
                nopl=nopl-1
                goto 71
70            end do
71          end do

           do i=1,nopln
```

```
            if(iq(i,1) eq 0 and iq(i,2) eq 0) goto 72
              goto 73
72            do 1=i,nopln
                iq(1,1)=iq(1+1,1)
                iq(1,2)=iq(1+1,2)
              end do
73          end do

            nopln=nopl
            write(5,9998)nopln
9998        format(1x,'nopln - ',i4)

            do i=1,nopln
              write(5,1113) iq(i,1)-128,iq(i,2)-128,ihis(iq(i,1),iq(i,2))
1113          format(1x,'dz/dy,dz/dx,his  -- ',3i10)
            end do
c           ============================================================
c            find individul plane (i e. having same dz/dx and dz/dy)
c           ============================================================

              do i=1,256
                 do j=1,256
                    ia(i,j)=0
                 end do
              end do

              do i=1,256
                 do j=1,256
                     m=idetx(i,j)+128
                     n=idety(i,j)+128
                if(m.eq.255) goto 13

                   do kk=1,nopln

                if(m.ge.(iq(kk,1)-1) and.m le.(iq(kk,1)+1)
     1 and n ge (iq(kk,2)-1).and.n le.(iq(kk,2)+1))
     2 ia(i,j)=kk*70

                   end do
13              end do
              end do

c                write(5,1111) ((ia(i,j),i=120,145),j=45,175)
c           call lo(ia,256,0,256,1 ,0)

c            ======================
c            find plane equations
c            ======================

            do kk=1,nopln
               lp=0
              do i=1,256
                do j=1,256

                  if (ia(i,j) eq 0) goto 23
                  if (ia(i,j) ne kk*70) goto 23
                  if (lp eq 1) goto 25
                     lp=1
                  pln(1,1)=float(i)
                  pln(1,2)=float(j)
```

```
                goto 23
25              pln(2,1)=float(i)
                pln(2,2)=float(j)
23            end do
            end do

            lp=0
            iym=nint((pln(1,1)+pln(2,1))/2.0)
          do i=1,256
             if (ia(iym,i).ne.kk*70) goto 26
             if (lp.eq.1) goto 27
                 lp=1
                ixmin=i
                 goto 26
27               ixmax=i
26        end do

          idix1=abs(pln(1,2)-ixmin)
          idix2=abs(pln(1,2)-ixmax)

            if (idix1.gt.idix2) goto 28
               pln(3,1)=float(iym)
               pln(3,2)=float(ixmax-2)
                 goto 29
28             pln(3,1)=float(iym)
               pln(3,2)=float(ixmin+2)


 29       do i=1,3
            pln(i,3)=iobj(pln(i,1),pln(i,2))
          end do


            call plane(pln,d)

             peq(kk,2)=pln(4,1)
             peq(kk,3)=pln(4,2)
             peq(kk,4)=pln(4,3)
             peq(kk,5)=d

           write(5,9994)
           write(5,1000)
1000       format(1x,'The plane equations which we finally find')
           write(5,30) kk,peq(kk,2),peq(kk,3),peq(kk,4),peq(kk,5)
30         format(1x,'plane #'i1,'---   ',e12.5,' x',e12.5,' y',e12.5,
     1' z= ',e12.5)

         end do

c        **********************************
c        *   find individul plane image   *
c        **********************************

         no=0
       do kk=1,nopln
         do i=1,256
           do j=1,256
             if (iobj(i,j).eq.255) goto 55
             d1=float(i)*peq(kk,2)+float(j)*peq(kk,3)
             d1=d1+float(iobj(i,j))*peq(kk,4)-peq(kk,5)
```

```
                d1=abs(d1)

               if(d1 gt 0 013) goto 55
               ia(i,j)=1
                goto 50

55            ia(i,j)=0
50           end do
          end do

          is=kk*320

c                 write(5,1111) ((ia(i,j),i=120,145),j=45,175)
c       c   call lo(ia,256,is,256,200,0)

c         ********************************
c         *   find node coordinates      *
c         ********************************

          call edge(ia,256,ix,iy,n)

c         do jkl=1,n
c           write(5,8181) ix(jkl,1),ix(jkl,2),iy(jkl)
8181        format(1x,'edge coor. and chain -- ',3i7)
c         end do

c          ========================
c          find the tuning points
c          ========================

            no=no+1
           c(no,1)=float(ix(1,1))
           c(no,2)=float(ix(1,2))


             iy(1)=iy(2)+iy(3)+iy(4)
           do i=3,n-4
             iy(i-1)=iy(i)+iy(i+1)+iy(i+2)
              iyy=abs(iy(i-1)-iy(i-2))
             if (iyy le 1 ) goto 90
             if((iy(i) eq 1 or iy(i) eq 8)
      * and (iy(i+1) eq 1 or iy(i+1) eq 8)
      * and (iy(i+2) eq 1 or iy(i+2) eq 8)) goto 90

                no=no+1
              c(no,1)=float(ix(i+1,1))
              c(no,2)=float(ix(i+1,2))

90         end do

         end do

           do kj=1,no
c            write(5,9995) kj,c(kj,1),c(kj,2)
9995         format(1x,'node  # ',i2,' -- ',2f7.2)
           end do

9994       format(//)

c          ========================
```

```
c             find the node coor
c            ======================

              noo=no
            do i=2,no
              do j=1,i-1
                d=(c(j,1)-c(i,1))**2+(c(j,2)-c(i,2))**2
                if (d gt 10 ) goto 700

             c(j,1)=(c(j,1)+c(i,1))/2
             c(j,2)=(c(j,2)+c(i,2))/2
                c(i,1)=0
                c(i,2)=0
                 noo=noo-1
                 goto 771

700             end do
771           end do

c            write(5,9994)
c            write(5,9993) noo
9993         format(1x,'noo -- ',i3)
c            do kj=1,no
c             write(5,9995) kj,c(kj,1),c(kj,2)
c            end do

            nonode=0
            do i=1,no
              if(c(i,1) eq 0. and c(i,2) eq 0) goto 772
               nonode=nonode+1
                c(nonode,1)=c(i,1)
                c(nonode,2)=c(i,2)
772          end do

           write(5,9994)
           write(5,9996) nonode
9996       format(1x,'no  of nodes ',i5)

           do i=1,nonode
            write(5,9999) c(i,1),c(i,2)
9999        format(1x,'nodes -- ',2e15.6)
           end do

c           ==================
c            node ranking
c           ==================

c             ---------------------------------------
c              find the minimum y value in node coor.
c             ---------------------------------------

             ymin=c(1,2)
           do i=2,nonode
             cd=c(i,2)-ymin
             if (cd gt 0 ) goto 120
              ymin=c(i,2)
120        end do

c          write(5,9991) ymin
9991       format(1x,'ymin -- ',f7.0)
```

```
c            ------------------- ----------------------------------------
c             separate the nodes as bottom node and non-bottom nodes
c                  n1 --- bottom
c                  n2 --- non-bottom
c            ------------------------------------------------------------

               nonob=0
               n1=0
               n2=9
             do i=1,nonode
               cd=c(i,2)-ymin
               if(cd.gt.2 ) goto 122
                nonob=nonob+1
                n1=n1+1
                b(n1,1)=c(i,1)
                b(n1,2)=c(i,2)
                 goto 121
122            n2=n2+1
               b(n2,1)=c(i,1)
               b(n2,2)=c(i,2)
121          end do

             write(5,9994)
             write(5,9990) nonob
9990         format(1x,'nonob -- ',i5)

c              ------------------------------------
c               rank the codes in such order :
c                (i)  bottom nodes first
c                (ii) from left to right
c              ------------------------------------

             do i=1,n1-1
               m=i
               ii=i+1
               sm=b(i,1)

               do j=ii,n1
                 if(sm.le b(j,1)) goto 130
                   sm=b(j,1)
                   m=j
130            end do

               do j=1,2
                 t=b(i,j)
                  b(i,j)=b(m,j)
                  b(m,j)=t
               end do

              end do

              do i=1,n1
                c(i,1)=b(i,1)
                c(i,2)=b(i,2)
              end do


             do i=10,n2-1
               m=i
```

```
            ii=i+1
            sm=b(i,1)

            do j=ii,n2
              if(sm le b(j,1)) goto 131
                sm=b(j,1)
                m=j
131         end do

            do j=1,2
              t=b(i,j)
              b(i,j)=b(m,j)
              b(m,j)=t
            end do

          end do

          do i=n1+1,n2-9+n1
             ii=i-n1+9
            c(i,1)=b(ii,1)
            c(i,2)=b(ii,2)
          end do

          do i=1,nonode
            ii=nint(c(i,1))
            jj=nint(c(i,2))
            c(i,3)=iobj(ii,jj)
          end do

           write(5,9994)
          do i=1,nonode
            write(5,9989) c(i,1),c(i,2),c(i,3)
9989        format(1x,'ranked nodes -- ',3f8.0)
          end do

c         **********************
c         *  object matching   *
c         **********************

c       call matching(nopln,nonode,nonob,c,peq,icode)

          end
```

```
BBBBBBBBBB   000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000   BBBBBBBBBB
BBBBBBBBBB   0000000000000000000000  The George Washington University -- SEASCF VAX/VMS V4.1  0000000000000000000000   BBBBBBBBBB
BBBBBBBBBB   000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000   BBBBBBBBBB

                         FFFFF   AAA    CCCC   GGGG   AAA    OOO
                         F      A   A  C      G      A   A  O   O
                         F      A   A  C      G      A   A  O   O
                         FFFF   A   A  C      G      A   A  O   O
                         F      AAAAA  C      G GGG  AAAAA  O   O
                         F      A   A  C      G   G  A   A  O   O
                         F      A   A   CCCC   GGG   A   A   OOO

IIIIII  NN      NN  IIIIII  RRRRRRRR      AAAAAA    MM      MM  FFFFFFFFFF  IIIIII  PPPPPPPP
IIIIII  NN      NN  IIIIII  RRRRRRRR      AAAAAA    MM      MM  FFFFFFFFFF  IIIIII  PPPPPPPP
  II    NN      NN    II    RR      RR  AA      AA  MMMM  MMMM  FF            II    PP      PP
  II    NN      NN    II    RR      RR  AA      AA  MMMM  MMMM  FF            II    PP      PP
  II    NNNN    NN    II    RR      RR  AA      AA  MM  MM  MM  FF            II    PP      PP
  II    NNNN    NN    II    RR      RR  AA      AA  MM  MM  MM  FF            II    PP      PP
  II    NN  NN  NN    II    RRRRRRRR    AA      AA  MM      MM  FFFFFFFF      II    PPPPPPPP
  II    NN  NN  NN    II    RRRRRRRR    AA      AA  MM      MM  FFFFFFFF      II    PPPPPPPP
  II    NN    NNNN    II    RR  RR      AAAAAAAAAA  MM      MM  FF            II    PP
  II    NN    NNNN    II    RR  RR      AAAAAAAAAA  MM      MM  FF            II    PP
  II    NN      NN    II    RR    RR    AA      AA  MM      MM  FF            II    PP
  II    NN      NN    II    RR    RR    AA      AA  MM      MM  FF            II    PP
IIIIII  NN      NN  IIIIII  RR      RR  AA      AA  MM      MM  FF          IIIIII  PP
IIIIII  NN      NN  IIIIII  RR      RR  AA      AA  MM      MM  FF          IIIIII  PP

                FFFFFFFFFF    000000    RRRRRRRR      ;;;;    77777777
                FFFFFFFFFF    000000    RRRRRRRR      ;;;;    77777777
                FF          00      00  RR      RR    ;;;;          77
                FF          00      00  RR      RR    ;;;;          77
                FF          00      00  RR      RR                  77
                FF          00      00  RR      RR                  77
                FFFFFFFF    00      00  RRRRRRRR      ;;;;        77
                FFFFFFFF    00      00  RRRRRRRR      ;;;;        77
                FF          00      00  RR  RR        ;;;;      77
                FF          00      00  RR  RR        ;;;;      77
                FF          00      00  RR    RR        ;;    77
                FF          00      00  RR    RR        ;;    77
                FF            000000    RR      RR    ;;    77
                FF            000000    RR      RR    ;;    77
```

File _DUA1:[FACGAO.VISION]INIRAMFIP.FOR;7 (5517,6,0), last revised on 28-AUG-1985 10:35, is a 2 block sequential file owned by UIC [OVERHEAD,SYSTEM]. The records are variable length with implied (CR) carriage control. The longest record is 65 bytes.

Job INIRAMFIP (8) queued to SYS$PRINT on 9-DEC-1985 15:22 by user FACGAO, UIC [EECS,FACGAO], under account EECS at priority 4, started on printer _LPA0: on 9-DEC-1985 15:29 from queue LPA0.

```
BBBBBBBBBB   000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000   BBBBBBBBBB
BBBBBBBBBB   000000000000000000000000  Digital Equipment Corporation - VAX/VMS Version V4.1  000000000000000000000000   BBBBBBBBBB
BBBBBBBBBB   000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000   BBBBBBBBBB
```

```
      SUBROUTINE iniramfip(ierr)
c
c init ramtek_fip levels 3 & 4
c NOTE  this initialization assumes files std003.ini & std004.ini
c       are in [ee208] directory
c
c       input & output are 5 & 6 respectively
c
      CHARACTER*1 yn
      CALL lev3ini(ierr)
      CALL lev4ini(ierr)
      WRITE(5,100)
100   FORMAT('$RAMTEK full reset (answer y/n/Y/N) ?= ')
      READ(5,101)yn
101   FORMAT(a1)
      IF(yn .EQ. 'Y' .OR. yn .EQ. 'y')THEN
       CALL rset(ierr)
      END IF
      CALL lovlt(ierr)
      RETURN
      END
```

```
LLLLLLLLLL   0000000000000000000000000000000000000000000000000000000000000000000000000000000000000   LLLLLLLLLL
LLLLLLLLLL   000000000000000000000000  The George Washington University -- SEASCF VAX/VMS V4 1  000000000000000000000000   LLLLLLLLLL
LLLLLLLLLL   0000000000000000000000000000000000000000000000000000000000000000000000000000000000000   LLLLLLLLLL

                         FFFFF   AAA    CCCC   GGGG   AAA    000
                         F      A   A  C      G      A   A  0   0
                         F      A   A  C      G      A   A  0   0
                         FFFF   A   A  C      G      A   A  0   0
                         F      AAAAA  C      G GGG  AAAAA  0   0
                         F      A   A  C      G   G  A   A  0   0
                         F      A   A   CCCC   GGG   A   A   000

RRRRRRRR      AAAAAA    NN      NN    GGGGGGGG  EEEEEEEEEE            DDDDDDDD      AAAAAA    TTTTTTTTTT    AAAAAA
RRRRRRRR      AAAAAA    NN      NN    GGGGGGGG  EEEEEEEEEE            DDDDDDDD      AAAAAA    TTTTTTTTTT    AAAAAA
RR      RR  AA      AA  NN      NN  GG          EE                    DD      DD  AA      AA      TT      AA      AA
RR      RR  AA      AA  NN      NN  GG          EE                    DD      DD  AA      AA      TT      AA      AA
RR      RR  AA      AA  NNNN    NN  GG          EE                    DD      DD  AA      AA      TT      AA      AA
RR      RR  AA      AA  NNNN    NN  GG          EE                    DD      DD  AA      AA      TT      AA      AA
RRRRRRRR    AA      AA  NN  NN  NN  GG          EEEEEEEE              DD      DD  AA      AA      TT      AA      AA
RRRRRRRR    AA      AA  NN  NN  NN  GG          EEEEEEEE              DD      DD  AA      AA      TT      AA      AA
RR  RR      AAAAAAAAAA  NN    NNNN  GG    GGGGGG  EE                  DD      DD  AAAAAAAAAA      TT      AAAAAAAAAA
RR  RR      AAAAAAAAAA  NN    NNNN  GG    GGGGGG  EE                  DD      DD  AAAAAAAAAA      TT      AAAAAAAAAA
RR    RR    AA      AA  NN      NN  GG        GG  EE                  DD      DD  AA      AA      TT      AA      AA
RR    RR    AA      AA  NN      NN  GG        GG  EE                  DD      DD  AA      AA      TT      AA      AA
RR      RR  AA      AA  NN      NN    GGGGGG    EEEEEEEEEE  ________  DDDDDDDD    AA      AA      TT      AA      AA
RR      RR  AA      AA  NN      NN    GGGGGG    EEEEEEEEEE  ________  DDDDDDDD    AA      AA      TT      AA      AA

                 FFFFFFFFFF    000000    RRRRRRRR            222222      11
                 FFFFFFFFFF    000000    RRRRRRRR            222222      11
                 FF          00      00  RR      RR        22      22  1111
                 FF          00      00  RR      RR        22      22  1111
                 FF          00      00  RR      RR                22    11
                 FF          00      00  RR      RR                22    11
                 FFFFFFFF    00      00  RRRRRRRR                22      11
                 FFFFFFFF    00      00  RRRRRRRR                22      11
                 FF          00      00  RR  RR                22        11
                 FF          00      00  RR  RR                22        11
                 FF          00      00  RR    RR            22          11
                 FF          00      00  RR    RR            22          11
                 FF            000000    RR      RR        2222222222  111111
                 FF            000000    RR      RR        2222222222  111111
```

File _DUA1 [FACGAO VISION]RANGE_DATA.FOR;21 (15769,58,0), last revised on 18-SEP-1985 09:28, is a 8 block sequential file owned by UIC [EECS,FACGAO]. The records are variable length with implied (CR) carriage control. The longest record is 61 bytes.

Job RANGE_DATA (9) queued to SYS$PRINT on 9-DEC-1985 15:23 by user FACGAO, UIC [EECS,FACGAO], under account EECS at priority 4, started on printer _LPA0 on 9-DEC-1985 15:32 from queue LPA0.

```
LLLLLLLLLL   0000000000000000000000000000000000000000000000000000000000000000000000000000000000000   LLLLLLLLLL
LLLLLLLLLL   000000000000000000000000  Digital Equipment Corporation - VAX/VMS Version V4 1  000000000000000000000000   LLLLLLLLLL
LLLLLLLLLL   0000000000000000000000000000000000000000000000000000000000000000000000000000000000000   LLLLLLLLLL
```

```
      subroutine range_data(iobj)
      dimension pln(4,3),p(3,4)
      integer*2 iobj(256,256)


      do i=1,256
        do j=1,256
          iobj(i,j)=255
        end do
      end do


c     ****************************
c       find the plane equa.
c     ****************************

c     ------------------------------
c       plane  #1 -- A1,A2,A3,A4
c     ------------------------------

      pln(1,1)=49.76
      pln(1,2)=150.
      pln(1,3)=98.214

      pln(2,1)=134.852
      pln(2,2)=110.
      pln(2,3)=42.928

      pln(3,1)=141.244
      pln(3,2)=50.
      pln(3,3)=30.

      call plane(pln,d)

      do i=1,3
        p(1,i)=pln(4,i)
      end do
        p(1,4)=d

c     ------------------------------
c       plane  #2 -- A4,A5,A6
c     ------------------------------

      pln(1,1)=49.76
      pln(1,2)=150.
      pln(1,3)=98.214

      pln(2,1)=134.852
      pln(2,2)=110
      pln(2,3)=42.928

      pln(3,1)=137.674
      pln(3,2)=170.
      pln(3,3)=119.818

      call plane(pln,d)

      do i=1,3
        p(2,i)=pln(4,i)
      end do
```

```
          p(2,4)=d

c         ----------------------------
c           plane  #3 -- A2,A3,A5,A6
c         ----------------------------

          pln(1,1)=141.244
          pln(1,2)=50.
          pln(1,3)=30.

          pln(2,1)=134.852
          pln(2,2)=110.
          pln(2,3)=42.928

          pln(3,1)=137.674
          pln(3,2)=170.
          pln(3,3)=119.818

          call plane(pln,d)

          do i=1,3
            p(3,i)=pln(4,i)
          end do
            p(3,4)=d

          write(5,1)
1         format(1x,'plane equa. to generate ori. data')
            do i=1,3
          write(5,2) i,p(i,1),p(i,2),p(i,3),p(i,4)
2         format(1x,'plane #',i1,'---  ',e12.5,'x ',e12.5,'y ',
     *e12.5,'z= ',e12.5)
            end do

c         ******************************
c           find the range data
c         ******************************

c         -------------
c           plane #1
c         -------------

          do i=20,50
               jj=nint(3.360*i-17.2)
            do j=50,jj
              iobj(i,j)=nint((p(1,4)-p(1,1)*i-p(1,2)*j)/p(1,3))
            end do
          end do

          do i=50,135
               jj=nint(-0.470*i+173.392)
            do j=50,jj
              iobj(i,j)=nint((p(1,4)-p(1,1)*i-p(1,2)*j)/p(1,3))
            end do
          end do

          do i=135,141
               jj=nint(-9.387*i+1375.82)
            do j=50,jj
              iobj(i,j)=nint((p(1,4)-p(1,1)*i-p(1,2)*j)/p(1,3))
            end do
```

```
      end do


c     -------------
c       plane #2
c     -------------

      do i=50,135
         j1=nint(-0.47*i+173.392)
         j2=nint(0.227*i+138.680)
        do j=j1,j2
          iobj(i,j)=nint((p(2,4)-p(2,1)*i-p(2,2)*j)/p(2,3))
        end do
      end do

      do i=135,138
         j1=nint(21.26*i-2757.16)
         j2=nint(0.227*i+138.680)
        do j=j1,j2
          iobj(i,j)=nint((p(2,4)-p(2,1)*i-p(2,2)*j)/p(2,3))
        end do
      end do


c     -------------
c       plane #3
c     -------------

      do i=135,137
         j1=nint(-9.387*i+1375.82)
         j2=nint(21.26*i-2757.16)
        do j=j1,j2
          iobj(i,j)=nint((p(3,4)-p(3,1)*i-p(3,2)*j)/p(3,3))
        end do
      end do

      do i=138,141
         j1=nint(-9.387*i+1375.82)
         j2=nint(-6.34*i+1042.82)
        do j=j1,j2
          iobj(i,j)=nint((p(3,4)-p(3,1)*i-p(3,2)*j)/p(3,3))
        end do
      end do

      do i=141,157
         jj=nint(-6.34*i+1042.82)
        do j=50,jj
          iobj(i,j)=nint((p(3,4)-p(3,1)*i-p(3,2)*j)/p(3,3))
        end do
      end do


      return
      end
```

```
WWWWWWWWWW    5555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555    WWWWWWWWWW
WWWWWWWWWW    5555555555555555555555  The George Washington University -- SEASCF VAX/VMS V4.1  5555555555555555555555    WWWWWWWWWW
WWWWWWWWWW    5555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555    WWWWWWWWWW


                              FFFFF   AAA    CCCC   GGGG   AAA    OOO
                              F      A   A  C      G      A   A  O   O
                              F      A   A  C      G      A   A  O   O
                              FFFF   A   A  C      G      A   A  O   O
                              F      AAAAA  C      G GGG  AAAAA  O   O
                              F      A   A  C      G   G  A   A  O   O
                              F      A   A   CCCC   GGG   A   A   OOO


                                   LL            OOOOOO
                                   LL            OOOOOO
                                   LL          OO      OO
                                   LL          OO      OO
                                   LL          OO      OO
                                   LL          OO      OO
                                   LL          OO      OO
                                   LL          OO      OO
                                   LL          OO      OO
                                   LL          OO      OO
                                   LL          OO      OO
                                   LL          OO      OO
                                   LLLLLLLLLL    OOOOOO
                                   LLLLLLLLLL    OOOOOO


                            FFFFFFFFFF    OOOOOO    RRRRRRRR       ;;;;    44    44
                            FFFFFFFFFF    OOOOOO    RRRRRRRR       ;;;;    44    44
                            FF          OO      OO  RR      RR     ;;;;    44    44
                            FF          OO      OO  RR      RR     ;;;;    44    44
                            FF          OO      OO  RR      RR             44    44
                            FF          OO      OO  RR      RR             44    44
                            FFFFFFFF    OO      OO  RRRRRRRR       ;;;;    4444444444
                            FFFFFFFF    OO      OO  RRRRRRRR       ;;;;    4444444444
                            FF          OO      OO  RR  RR         ;;;;          44
                            FF          OO      OO  RR  RR         ;;;;          44
                            FF          OO      OO  RR    RR         ;;          44
                            FF          OO      OO  RR    RR         ;;          44
                            FF            OOOOOO    RR      RR     ;;            44
                            FF            OOOOOO    RR      RR     ;;            44
```

File _DUA1 [FACGAO.VISION]LO.FOR;4 (16191,36,0), last revised on 10-SEP-1985 15:24, is a 1 block sequential file owned by UIC [EECS,FACGAO]. The records are variable length with implied (CR) carriage control. The longest record is 49 bytes.

Job LO (10) queued to SYS$PRINT on 9-DEC-1985 15:23 by user FACGAO, UIC [EECS,FACGAO], under account EECS at priority 4, started on printer _LPA0: on 9-DEC-1985 15:27 from queue LPA0.

```
WWWWWWWWWW    5555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555    WWWWWWWWWW
WWWWWWWWWW    5555555555555555555555  Digital Equipment Corporation - VAX/VMS Version V4.1  5555555555555555555555    WWWWWWWWWW
WWWWWWWWWW    5555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555    WWWWWWWWWW
```

```
subroutine lo(iobj,n,ix,iy,scale,ioffset)
integer*2 iobj(256,256),ia(256,256)

do i=1,256
  do j=1,256
    ia(i,j)=iobj(j,257-i)*scale+ioffset
  end do
end do

call lohs(ia,256,ix,iy,ierr)

return
end
```

```
CCCCCCCCCC  1111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111  CCCCCCCCCC
CCCCCCCCCC  1111111111111111111  The George Washington University -- SEASCF VAX/VMS V4 1  1111111111111111111  CCCCCCCCCC
CCCCCCCCCC  1111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111  CCCCCCCCCC
```

```
FFFFF   AAA    CCCC   GGGG   AAA    000
F      A   A  C      G      A   A  0   0
F      A   A  C      G      A   A  0   0
FFFF   A   A  C      G      A   A  0   0
F      AAAAA  C      G GGG  AAAAA  0   0
F      A   A  C      G   G  A   A  0   0
F      A   A   CCCC   GGG   A   A   000
```

```
DDDDDDDD      IIIIII    FFFFFFFFFF  FFFFFFFFFF  EEEEEEEEEE  RRRRRRRR
DDDDDDDD      IIIIII    FFFFFFFFFF  FFFFFFFFFF  EEEEEEEEEE  RRRRRRRR
DD      DD      II      FF          FF          EE          RR      RR
DD      DD      II      FF          FF          EE          RR      RR
DD      DD      II      FF          FF          EE          RR      RR
DD      DD      II      FF          FF          EE          RR      RR
DD      DD      II      FFFFFFFF    FFFFFFFF    EEEEEEEE    RRRRRRRR
DD      DD      II      FFFFFFFF    FFFFFFFF    EEEEEEEE    RRRRRRRR
DD      DD      II      FF          FF          EE          RR  RR
DD      DD      II      FF          FF          EE          RR  RR
DD      DD      II      FF          FF          EE          RR    RR
DD      DD      II      FF          FF          EE          RR    RR
DDDDDDDD      IIIIII    FF          FF          EEEEEEEEEE  RR      RR
DDDDDDDD      IIIIII    FF          FF          EEEEEEEEEE  RR      RR
```

```
FFFFFFFFFF    000000    RRRRRRRR        ;;;;        11        333333
FFFFFFFFFF    000000    RRRRRRRR        ;;;;        11        333333
FF          00      00  RR      RR      ;;;;      1111      33      33
FF          00      00  RR      RR      ;;;;      1111      33      33
FF          00      00  RR      RR                11                33
FF          00      00  RR      RR                11                33
FFFFFFFF    00      00  RRRRRRRR        ;;;;        11            33
FFFFFFFF    00      00  RRRRRRRR        ;;;;        11            33
FF          00      00  RR  RR          ;;;;        11              33
FF          00      00  RR  RR          ;;;;        11              33
FF          00      00  RR    RR          ;;        11      33      33
FF          00      00  RR    RR          ;;        11      33      33
FF            000000    RR      RR      ;;        111111      333333
FF            000000    RR      RR      ;;        111111      333333
```

File _DUA1 [FACGAO VISION]DIFFER FOR;13 (13601,7,0), last revised on 11-SEP-1985 10:51, is a 2 block sequential file owned by UIC [EECS,FACGAO] The records are variable length with implied (CR) carriage control. The longest record is 51 bytes.

Job DIFFER (11) queued to SYS$PRINT on 9-DEC-1985 15:23 by user FACGAO, UIC [EECS,FACGAO], under account EECS at priority 4, started on printer _LPA0 on 9-DEC-1985 15:29 from queue LPA0

```
CCCCCCCCCC  1111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111  CCCCCCCCCC
CCCCCCCCCC  1111111111111111111  Digital Equipment Corporation - VAX/VMS Version V4 1  1111111111111111111  CCCCCCCCCC
CCCCCCCCCC  1111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111  CCCCCCCCCC
```

```
      subroutine differ(iobj,idet,scale,id)
      integer*2 iobj(256,256),idet(256,256)

      if (id eq 1) goto 100

      do i=1,256
         do j=1,255
            idet(i,j)=iobj(i,j+1)-iobj(i,j)
               if (abs(idet(i,j)) lt 20) goto 1
               idet(i,j)=idet(i,j-1)
                goto 2
1           idet(i,j)=idet(i,j)*scale
2        end do
      end do

      do i=1,256
         idet(i,256)=idet(i,255)
      end do

      return

100   do j=1,256
         do i=1,255
            idet(i,j)=iobj(i+1,j)-iobj(i,j)
                if(abs(idet(i,j)).lt.20) goto 3
                idet(i,j)=idet(i-1,j)
                 goto 4
3           ide:(i,j)=idet(i,j)*scale
4        end do
      end do


      do i=1,256
         idet(256,i)=idet(255,i)
      end do


      return
      end
```

DDDDDDDDDD 2222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222 DDDDDDDDDD
DDDDDDDDDD 2222222222222222222222 The George Washington University -- SEASCF VAX/VMS V4 1 2222222222222222222222 DDDDDDDDDD
DDDDDDDDDD 2222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222 DDDDDDDDDD

```
FFFFF   AAA    CCCC   GGGG   AAA    OOO
F      A   A  C      G      A   A  O   O
F      A   A  C      G      A   A  O   O
FFFF   A   A  C      G      A   A  O   O
F      AAAAA  C      G GGG  AAAAA  O   O
F      A   A  C      G   G  A   A  O   O
F      A   A   CCCC   GGG   A   A   OOO
```

```
  SSSSSSSS  MM       MM    000000    TTTTTTTTTT  HH       HH
  SSSSSSSS  MM       MM    000000    TTTTTTTTTT  HH       HH
SS          MMMM   MMMM  OO    OO      TT      HH       HH
SS          MMMM   MMMM  OO    OO      TT      HH       HH
SS          MM MM MM MM  OO    OO      TT      HH       HH
SS          MM  MMM  MM  OO    OO      TT      HH       HH
  SSSSSS    MM       MM  OO    OO      TT      HHHHHHHHHH
  SSSSSS    MM       MM  OO    OO      TT      HHHHHHHHHH
        SS  MM       MM  OO    OO      TT      HH       HH
        SS  MM       MM  OO    OO      TT      HH       HH
        SS  MM       MM  OO    OO      TT      HH       HH
        SS  MM       MM  OO    OO      TT      HH       HH
SSSSSSSS    MM       MM    000000      TT      HH       HH
SSSSSSSS    MM       MM    000000      TT      HH       HH
```

```
FFFFFFFFFF    000000    RRRRRRRR        ;;;;       11        000000
FFFFFFFFFF    000000    RRRRRRRR        ;;;;       11        000000
FF          00      00  RR      RR      ;;;;     1111      00      00
FF          00      00  RR      RR      ;;;;     1111      00      00
FF          00      00  RR      RR                 11      00    0000
FF          00      00  RR      RR                 11      00    0000
FFFFFFFF    00      00  RRRRRRRR        ;;;;       11      00  00  00
FFFFFFFF    00      00  RRRRRRRR        ;;;;       11      00  00  00
FF          00      00  RR  RR          ;;;;       11      0000    00
FF          00      00  RR  RR          ;;;;       11      0000    00
FF          00      00  RR    RR          ;;       11      00      00
FF          00      00  RR    RR          ;;       11      00      00
FF            000000    RR      RR      ;;       111111      000000
FF            000000    RR      RR      ;;       111111      000000
```

File _DUA1 [FACGAO.VISION]SMOTH.FOR;10 (6740,22,0), last revised on 21-SEP-1985 16:59, is a 2 block sequential file owned by UIC [EECS,FACGAO]. The records are variable length with implied (CR) carriage control. The longest record is 63 bytes.

Job SMOTH (12) queued to SYS$PRINT on 9-DEC-1985 15:23 by user FACGAO, UIC [EECS,FACGAO], under account EECS at priority 4, started on printer _LPA0: on 9-DEC-1985 15:29 from queue LPA0.

DDDDDDDDDD 2222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222 DDDDDDDDDD
DDDDDDDDDD 2222222222222222222222 Digital Equipment Corporation - VAX/VMS Version V4.1 2222222222222222222222 DDDDDDDDDD
DDDDDDDDDD 2222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222 DDDDDDDDDD

```
subroutine smoth(idetx)
integer*2 idetx(256,256), idety(256,256)

do i=2,255
    do j=2,255
        ka=idetx(i-1,j-1)+idetx(i-1,j)+idetx(i-1,j+1)
        kb=idetx(i,j-1)+idetx(i,j)+idetx(i,j+1)
        kc=idetx(i+1,j-1)+idetx(i+1,j)+idetx(i+1,j+1)
          idety(i,j)=nint(float(ka+kb+kc)/9.)
    end do
end do

do i=1,256
  do j=1,256
    idetx(i,j)=idety(i,j)
  end do
end do

return
end
```

```
XXXXXXXXXX  6666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666  XXXXXXXXXX
XXXXXXXXXX  6666666666666666666  The George Washington University -- SEASCF VAX/VMS V4.1  6666666666666666666666  XXXXXXXXXX
XXXXXXXXXX  6666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666  XXXXXXXXXX
```

```
FFFFF   AAA    CCCC   GGGG   AAA    OOO
F      A   A  C      G      A   A  O   O
F      A   A  C      G      A   A  O   O
FFFF   A   A  C      G      A   A  O   O
F      AAAAA  C      G GGG  AAAAA  O   O
F      A   A  C      G   G  A   A  O   O
F      A   A   CCCC   GGG   A   A   OOO
```

```
  SSSSSSSS  UU      UU  BBBBBBBB    BBBBBBBB      AAAAAA      CCCCCCCC  KK      KK
  SSSSSSSS  UU      UU  BBBBBBBB    BBBBBBBB      AAAAAA      CCCCCCCC  KK      KK
SS          UU      UU  BB      BB  BB      BB   AA      AA  CC        KK      KK
SS          UU      UU  BB      BB  BB      BB   AA      AA  CC        KK      KK
SS          UU      UU  BB      BB  BB      BB   AA      AA  CC        KK    KK
SS          UU      UU  BB      BB  BB      BB   AA      AA  CC        KK    KK
  SSSSSS    UU      UU  BBBBBBBB    BBBBBBBB     AA      AA  CC        KKKKKK
  SSSSSS    UU      UU  BBBBBBBB    BBBBBBBB     AA      AA  CC        KKKKKK
      SS    UU      UU  BB      BB  BB      BB   AAAAAAAAAA  CC        KK    KK
      SS    UU      UU  BB      BB  BB      BB   AAAAAAAAAA  CC        KK    KK
      SS    UU      UU  BB      BB  BB      BB   AA      AA  CC        KK      KK
      SS    UU      UU  BB      BB  BB      BB   AA      AA  CC        KK      KK
SSSSSSSS    UUUUUUUUUU  BBBBBBBB    BBBBBBBB     AA      AA    CCCCCCCC  KK      KK
SSSSSSSS    UUUUUUUUUU  BBBBBBBB    BBBBBBBB     AA      AA    CCCCCCCC  KK      KK
```

```
FFFFFFFFFF    000000    RRRRRRRR        ;;;;      888888
FFFFFFFFFF    000000    RRRRRRRR        ;;;;      888888
FF          00      00  RR      RR      ;;;;    88      88
FF          00      00  RR      RR      ;;;;    88      88
FF          00      00  RR      RR              88      88
FF          00      00  RR      RR              88      88
FFFFFFFF    00      00  RRRRRRRR        ;;;;      888888
FFFFFFFF    00      00  RRRRRRRR        ;;;;      888888
FF          00      00  RR  RR           ;;;;    88      88
FF          00      00  RR  RR           ;;;;    88      88
FF          00      00  RR    RR           ;;    88      88
FF          00      00  RR    RR           ;;    88      88
FF            000000    RR      RR      ;;        888888
FF            000000    RR      RR      ;;        888888
```

File _DUA1 [FACGAO.VISION]SUBBACK.FOR;8 (17057,12,0), last revised on 12-SEP-1985 11:03, is a 1 block sequential file owned by UIC [EECS,FACGAO]. The records are variable length with implied (CR) carriage control. The longest record is 53 bytes.

Job SUBBACK (13) queued to SYS$PRINT on 9-DEC-1985 15:23 by user FACGAO, UIC [EECS,FACGAO], under account EECS at priority 4, started on printer _LPA0: on 9-DEC-1985 15:28 from queue LPA0.

```
XXXXXXXXXX  6666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666  XXXXXXXXXX
XXXXXXXXXX  6666666666666666666  Digital Equipment Corporation - VAX/VMS Version V4.1  6666666666666666666666  XXXXXXXXXX
XXXXXXXXXX  6666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666  XXXXXXXXXX
```

```
      subroutine subback(iobj,idet)
      integer*2 iobj(256,256),idet(256,256)

c     ************************************
c     subtracte the background
c     ************************************


      do i=1,256
        do j=1,256
          if (iobj(i,j) ne 255) goto 20
          idet(i,j)=255
20      end do
      end do


      return
      end
```

```
FFFFEEEEEE    3333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333    EEEEEEEEEE
EEEEEEEEEE    3333333333333333333333  The George Washington University -- SEASCF VAX/VMS V4 1  3333333333333333333333    EEEEEEEEEE
EEEEEEEEEE    3333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333    EEEEEEEEEE

                    FFFFF   AAA    CCCC   GGGG   AAA    OOO
                    F      A   A  C      G      A   A  O   O
                    F      A   A  C      G      A   A  O   O
                    FFFF   A   A  C      G      A   A  O   O
                    F      AAAAA  C      G GGG  AAAAA  O   O
                    F      A   A  C      G   G  A   A  O   O
                    F      A   A   CCCC   GGG   A   A   OOO

HH      HH    IIIIII      SSSSSSSS  TTTTTTTTTT    000000
HH      HH    IIIIII      SSSSSSSS  TTTTTTTTTT    000000
HH      HH      II      SS              TT       00      00
HH      HH      II      SS              TT       00      00
HH      HH      II      SS              TT       00      00
HH      HH      II      SS              TT       00      00
HHHHHHHHHH      II        SSSSSS        TT       00      00
HHHHHHHHHH      II        SSSSSS        TT       00      00
HH      HH      II              SS      TT       00      00
HH      HH      II              SS      TT       00      00
HH      HH      II              SS      TT       00      00
HH      HH      II              SS      TT       00      00
HH      HH    IIIIII    SSSSSSSS        TT         000000
HH      HH    IIIIII    SSSSSSSS        TT         000000

FFFFFFFFFF    000000    RRRRRRRR        ;;;;       11        222222
FFFFFFFFFF    000000    RRRRRRRR        ;;;;       11        222222
FF          00      00  RR      RR      ;;;;     1111      22      22
FF          00      00  RR      RR      ;;;;     1111      22      22
FF          00      00  RR      RR                11              22
FF          00      00  RR      RR                11              22
FFFFFFFF    00      00  RRRRRRRR        ;;;;       11            22
FFFFFFFF    00      00  RRRRRRRR        ;;;;       11            22
FF          00      00  RR  RR          ;;;;       11          22
FF          00      00  RR  RR          ;;;;       11          22
FF          00      00  RR    RR          ;;       11        22
FF          00      00  RR    RR          ;;       11        22
FF            000000    RR      RR        ;;     111111    2222222222
FF            000000    RR      RR        ;;     111111    2222222222
```

File _DUA1 [FACQAO.VISION]HISTO.FOR;12 (17244,26,0), last revised on 12-SEP-1985 11:11, is a 2 block sequential file owned by UIC [EECS,FACQAO]. The records are variable length with implied (CR) carriage control. The longest record is 49 bytes.

Job HISTO (14) queued to SYS$PRINT on 9-DEC-1985 15:24 by user FACQAO, UIC [EECS,FACQAO], under account EECS at priority 4, started on printer _LPA0: on 9-DEC-1985 15:30 from queue LPA0.

```
EEEEEEEEEE    3333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333    EEEEEEEEEE
EEEEEEEEEE    3333333333333333333333  Digital Equipment Corporation - VAX/VMS Version V4 1  3333333333333333333333    EEEEEEEEEE
EEEEEEEEEE    3333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333333    EEEEEEEEEE
```

```
      subroutine histo(idetx,idety,ihis)
      integer*2 idetx(256,256),idety(256,256)
      dimension ihis(256,256)

      do i=1,256
        do j=1,256
          ihis(i,j)=0
        end do
      end do

      do i=1,256
        do j=1,256
          if(idetx(i,j) eq 255) goto 1
          ii=idetx(i,j)+128
          jj=idety(i,j)+128
          ihis(ii,jj)=ihis(ii,jj)+1
1       end do
      end do

      return
      end
```

```
JJJJJJJJJJ  8888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888  JJJJJJJJJJ
JJJJJJJJJJ  88888888888888888888  The George Washington University -- SEASCF VAX/VMS V4.1  88888888888888888888  JJJJJJJJJJ
JJJJJJJJJJ  8888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888  JJJJJJJJJJ

                    FFFFF   AAA    CCCC   GGGG   AAA    000
                    F      A   A  C      G      A   A  0   0
                    F      A   A  C      G      A   A  0   0
                    FFFF   A   A  C      G      A   A  0   0
                    F      AAAAA  C      G GGG  AAAAA  0   0
                    F      A   A  C      G   G  A   A  0   0
                    F      A   A  CCCC   GGG   A   A   000

          PPPPPPPP    LL            AAAAAA    NN      NN  EEEEEEEEEE
          PPPPPPPP    LL            AAAAAA    NN      NN  EEEEEEEEEE
          PP      PP  LL           AA    AA   NN      NN  EE
          PP      PP  LL           AA    AA   NN      NN  EE
          PP      PP  LL           AA    AA   NNNN    NN  EE
          PP      PP  LL           AA    AA   NNNN    NN  EE
          PPPPPPPP    LL           AA    AA   NN  NN  NN  EEEEEEEE
          PPPPPPPP    LL           AA    AA   NN  NN  NN  EEEEEEEE
          PP          LL           AAAAAAAAAA   NN    NNNN  EE
          PP          LL           AAAAAAAAAA   NN    NNNN  EE
          PP          LL           AA    AA   NN      NN  EE
          PP          LL           AA    AA   NN      NN  EE
          PP          LLLLLLLLLL   AA    AA   NN      NN  EEEEEEEEEE
          PP          LLLLLLLLLL   AA    AA   NN      NN  EEEEEEEEEE

          FFFFFFFFFF    000000    RRRRRRRR       ;;;;      222222      666666
          FFFFFFFFFF    000000    RRRRRRRR       ;;;;      222222      666666
          FF          00      00  RR      RR     ;;;;    22      22  66
          FF          00      00  RR      RR     ;;;;    22      22  66
          FF          00      00  RR      RR                    22  66
          FF          00      00  RR      RR                    22  66
          FFFFFFFF    00      00  RRRRRRRR       ;;;;        22    66666666
          FFFFFFFF    00      00  RRRRRRRR       ;;;;        22    66666666
          FF          00      00  RR  RR         ;;;;      22      66      66
          FF          00      00  RR  RR         ;;;;      22      66      66
          FF          00      00  RR    RR         ;;    22        66      66
          FF          00      00  RR    RR         ;;    22        66      66
          FF            000000    RR      RR       ;;    2222222222    666666
          FF            000000    RR      RR       ;;    2222222222    666666

File _DUA1 [FACGAO.VISION]PLANE.FOR;26 (4166,20,0), last revised on 17-OCT-1985 17:12, is a 3 block sequential file owned by UIC
[EECS,FACGAO]   The records are variable length with implied (CR) carriage control.  The longest record is 52 bytes

Job PLANE (15) queued to SYS$PRINT on 9-DEC-1985 15:24 by user FACGAO, UIC [EECS,FACGAO], under account EECS at priority 4, started
on printer _LPA0  on 9-DEC-1985 15:31 from queue LPA0.

JJJJJJJJJJ  8888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888  JJJJJJJJJJ
JJJJJJJJJJ  88888888888888888888  Digital Equipment Corporation - VAX/VMS Version V4.1  88888888888888888888  JJJJJJJJJJ
JJJJJJJJJJ  8888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888888  JJJJJJJJJJ
```

```
      subroutine plane(pln,d)
      dimension pln(4,3)

      a1=pln(2,1)-pln(1,1)
      b1=pln(2,2)-pln(1,2)
      c1=pln(2,3)-pln(1,3)

      a2=pln(3,1)-pln(1,1)
      b2=pln(3,2)-pln(1,2)
      c2=pln(3,3)-pln(1,3)

      d1=b1*c2-b2*c1
      d2=a2*c1-a1*c2
      d3=a1*b2-a2*b1

      d=d1*pln(1,1)+d2*pln(1,2)+d3*pln(1,3)
c     write(5,1) a1,b1,c1
1     format(1x,'a1,b1,c1 -- ',3e15.6)

c     write(5,2) a2,b2,c2
2     format(1x,'a2,b2,c2 -- '3e15.6)

c     write(5,3) d1,d2,d3,d
3     format(1x,'d1,d2,d3,d(in plane) -- ',4e15.6)


c     write(5,10) d
10    format(1x,'d= ',e15.6)
      if (abs(d) lt.1 ) goto 100

      pln(4,1)=d1/d
      pln(4,2)=d2/d
      pln(4,3)=d3/d
        d=1
c     write(5,11) pln(4,1),pln(4,2),pln(4,3),d
11    format(1x,'plane eq   '4e15.6)
      return

100    d=0
      if (d1 ne 0 ) goto 101
      if (d2 ne 0 ) goto 102

      pln(4,1)=0
      pln(4,2)=0
      pln(4,3)=1
       return

101   pln(4,1)=1
      pln(4,2)=d2/d1
      pln(4,3)=d3/d1
       return

102   pln(4,1)=0
      pln(4,2)=1
      pln(4,3)=d3/d2
       return

       end
```

```
MMMMMMMMMM    1111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111    MMMMMMMMMM
MMMMMMMMMM    1111111111111111111  The George Washington University -- SEASCF VAX/VMS V4 1  1111111111111111111    MMMMMMMMMM
MMMMMMMMMM    1111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111    MMMMMMMMMM
```

```
FFFFF   AAA    CCCC   GGGG   AAA    000
F      A   A  C      G      A   A  0   0
F      A   A  C      G      A   A  0   0
FFFF   A   A  C      G      A   A  0   0
F      AAAAA  C      G GGG  AAAAA  0   0
F      A   A  C      G   G  A   A  0   0
F      A   A   CCCC   GGG   A   A   000
```

```
EEEEEEEEEE  DDDDDDDD      QQQQQQQQ  EEEEEEEEEE
EEEEEEEEEE  DDDDDDDD      QQQQQQQQ  EEEEEEEEEE
EE          DD      DD  QQ          EE
EE          DD      DD  QQ          EE
EE          DD      DD  QQ          EE
EE          DD      DD  QQ          EE
EEEEEEEE    DD      DD  QQ          EEEEEEEE
EEEEEEEE    DD      DD  QQ          EEEEEEEE
EE          DD      DD  QQ  QQQQQQ  EE
EE          DD      DD  QQ  QQQQQQ  EE
EE          DD      DD  QQ      QQ  EE
EE          DD      DD  QQ      QQ  EE
EEEEEEEEEE  DDDDDDDD      QQQQQQ    EEEEEEEEEE
EEEEEEEEEE  DDDDDDDD      QQQQQQ    EEEEEEEEEE
```

```
FFFFFFFFFF    000000    RRRRRRRR        ;;;;      222222      333333
FFFFFFFFFF    000000    RRRRRRRR        ;;;;      222222      333333
FF          00      00  RR      RR      ;;;;    22      22  33      33
FF          00      00  RR      RR      ;;;;    22      22  33      33
FF          00      00  RR      RR                      22          33
FF          00      00  RR      RR                      22          33
FFFFFFFF    00      00  RRRRRRRR        ;;;;          22          33
FFFFFFFF    00      00  RRRRRRRR        ;;;;          22          33
FF          00      00  RR  RR          ;;;;        22              33
FF          00      00  RR  RR          ;;;;        22              33
FF          00      00  RR    RR          ;;      22          33      33
FF          00      00  RR    RR          ;;      22          33      33
FF            000000    RR      RR      ;;      2222222222    333333
FF            000000    RR      RR      ;;      2222222222    333333
```

File _DUA1 [FACGAO.VISION]EDGE.FOR;23 (18743,10,0), last revised on 14-OCT-1985 15:49, is a 15 block sequential file owned by UIC [EECS,FACGAO] The records are variable length with implied (CR) carriage control. The longest record is 59 bytes.

Job EDGE (16) queued to SYS$PRINT on 9-DEC-1985 15:24 by user FACGAO, UIC [EECS,FACGAO], under account EECS at priority 4, started on printer _LPA0 on 9-DEC-1985 15:33 from queue LPA0

```
MMMMMMMMMM    1111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111    MMMMMMMMMM
MMMMMMMMMM    1111111111111111111  Digital Equipment Corpo  ion - VAX/VMS Version V4.1  1111111111111111111    MMMMMMMMMM
MMMMMMMMMM    1111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111    MMMMMMMMMM
```

```
      subroutine edge(ipic,m,ix,iy,n)
      integer*2 ipic(256,256)
      dimension ia(8),ix(1000,2),iy(1000)

      do i=1,1000
        iy(i)=0
        ix(i,1)=0
        ix(i,2)=0
      end do

c     *************************
c      search the boundary
c     *************************
c
c       ============================
c          search the start point
c       ============================
        do i=1,m
         do j=1,m
          if (ipic(i,j).eq.1) goto 41
         end do
        end do

41       i0=i
         j0=j
c       write(5,3) i,j
3       format(1x,'start point at (',i3',',i3,')')
c       ==================
c          go clockwise
c       ==================
        icha=2
         n=1
100      ix(n,1)=i
         ix(n,2)=j
         iy(n)=icha

c        write(5,4) n,icha
4        format(1x,'n= ',i3,' direction   ',i5)

         if (n gt 1 and i eq i0 and j eq j0) goto 1000
         n=n+1
         ia(1)=ipic(i-1,j+1)
         ia(2)=ipic(i,j+1)
         ia(3)=ipic(i+1,j+1)
         ia(4)=ipic(i+1,j)
         ia(5)=ipic(i+1,j-1)
         ia(6)=ipic(i,j-1)
         ia(7)=ipic(i-1,j-1)
         ia(8)=ipic(i-1,j)
        if (icha eq 1) then
         if (ia(7) eq 1) goto 111
         if (ia(8) eq 1) goto 112
         if (ia(1) eq 1) goto 113
         if (ia(2) eq 1) goto 114
         if (ia(3) eq 1) goto 115
         if (ia(4) eq 1) goto 116
111       icha=7
           i=i-1
           j=j-1
          goto 100
```

```
112           icha=8
               i=i-1
              goto 100
113           icha=1
               i=i-1
               j=j+1
              goto 100
114           icha=2
               j=j+1
              goto 100
115           icha=3
               i=i+1
               j=j+1
              goto 100
116           icha=4
               i=i+1
              goto 100
             else if (icha eq 2) then
              if (ia(1) eq 1) goto 211
              if (ia(2) eq 1) goto 212
              if (ia(3) eq 1) goto 213
              if (ia(4) eq 1) goto 214
              if (ia(5) eq 1) goto 215
211           icha=1
               i=i-1
               j=j+1
              goto 100
212           icha=2
               j=j+1
              goto 100
213           icha=3
               i=i+1
               j=j+1
              goto 100
214           icha=4
               i=i+1
              goto 100
215           icha=5
               i=i+1
               j=j-1
              goto 100
             else if (icha eq 3) then
              if (ia(1) eq 1) goto 311
              if (ia(2) eq 1) goto 312
              if (ia(3) eq 1) goto 313
              if (ia(4) eq 1) goto 314
              if (ia(5) eq 1) goto 315
              if (ia(6) eq 1) goto 316
311           icha=1
               i=i-1
               j=j+1
              goto 100
312           icha=2
               j=j+1
              goto 100
313           icha=3
               i=i+1
               j=j+1
              goto 100
314           icha=4
```

```
                i=i+1
               goto 100
315            icha=5
                i=i+1
                j=j-1
               goto 100
316            icha=6
                j=j-1
               goto 100
              else if (icha eq 4) then
               if (ia(3) eq 1) goto 411
               if (ia(4) eq 1) goto 412
               if (ia(5) eq 1) goto 413
               if (ia(6) eq 1) goto 414
               if (ia(7) eq 1) goto 415
411            icha=3
                i=i+1
                j=j+1
               goto 100
412            icha=4
                i=i+1
               goto 100
413            icha=5
                i=i+1
                j=j-1
               goto 100
414            icha=6
                j=j-1
               goto 100
415            icha=7
                i=i-1
                j=j-1
               goto 100
              else if (icha eq 5) then
               if (ia(3) eq 1) goto 511
               if (ia(4) eq 1) goto 512
               if (ia(5) eq 1) goto 513
               if (ia(6) eq 1) goto 514
               if (ia(7) eq 1) goto 515
               if (ia(8) eq 1) goto 516
511            icha=3
                i=i+1
                j=j+1
               goto 100
512            icha=4
                i=i+1
               goto 100
513            icha=5
                i=i+1
                j=j-1
               goto 100
514            icha=6
                j=j-1
               goto 100
515            icha=7
                i=i-1
                j=j-1
               goto 100
516            icha=8
                i=i-1
```

```
            goto 100
          else if (icha eq 6) then
           if (ia(5) eq 1) goto 611
           if (ia(6) eq 1) goto 612
           if (ia(7) eq 1) goto 613
           if (ia(8) eq 1) goto 614
           if (ia(1) eq 1) goto 615
611         icha=5
             i=i+1
             j=j-1
           goto 100
612        icha=6
             j=j-1
           goto 100
613        icha=7
             i=i-1
             j=j-1
           goto 100
614        icha=8
             i=i-1
           goto 100
615        icha=1
             i=i-1
             j=j+1
           goto 100
          else if (icha eq 7) then
           if (ia(5) eq 1) goto 711
           if (ia(6) eq 1) goto 712
           if (ia(7) eq 1) goto 713
           if (ia(8) eq 1) goto 714
           if (ia(1) eq 1) goto 715
           if (ia(2) eq 1) goto 716
711        icha=5
             i=i+1
             j=j-1
           goto 100
712        icha=6
             j=j-1
           goto 100
713        icha=7
             i=i-1
             j=j-1
           goto 100
714        icha=8
             i=i-1
           goto 100
715        icha=1
             i=i-1
             j=j+1
           goto 100
716        icha=2
             j=j+1
           goto 100
          else if (icha eq 8) then
           if (ia(7) eq 1) goto 811
           if (ia(8) eq 1) goto 812
           if (ia(1) eq 1) goto 813
           if (ia(2) eq 1) goto 814
           if (ia(3) eq 1) goto 815
811         icha=7
```

```
                i=i-1
                j=j-1
              goto 100
812           icha=8
                i=i-1
              goto 100
813           icha=1
                i=i-1
                j=j+1
              goto 100
814           icha=2
                j=j+1
              goto 100
815           icha=3
                i=i+1
                j=j+1
              goto 100
            end if

1000          n=n-1
            return
            end
```

```
FFFFFFFFFF  4444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444  FFFFFFFFFF
FFFFFFFFFF  444444444444444444  The George Washington University -- SEASCF VAX/VMS V4 1  444444444444444444444  FFFFFFFFFF
FFFFFFFFFF  4444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444  FFFFFFFFFF

                FFFFF   AAA    CCCC   GGGG   AAA    000
                F      A   A  C      G      A   A  0   0
                F      A   A  C      G      A   A  0   0
                FFFF   A   A  C      G      A   A  0   0
                F      AAAAA  C      G GGG  AAAAA  0   0
                F      A   A  C      G   G  A   A  0   0
                F      A   A   CCCC   GGG   A   A   000


           RRRRRRRR      000000      AAAAAA     NN      NN
           RRRRRRRR      000000      AAAAAA     NN      NN
           RR      RR  00      00  AA      AA   NN      NN
           RR      RR  00      00  AA      AA   NN      NN
           RR      RR  00      00  AA      AA   NNNN    NN
           RR      RR  00      00  AA      AA   NNNN    NN
           RRRRRRRR    00      00  AA      AA   NN  NN  NN
           RRRRRRRR    00      00  AA      AA   NN  NN  NN
           RR  RR      00      00  AAAAAAAAAA   NN    NNNN
           RR  RR      00      00  AAAAAAAAAA   NN    NNNN
           RR    RR    00      00  AA      AA   NN      NN
           RR    RR    00      00  AA      AA   NN      NN
           RR      RR    000000    AA      AA   NN      NN
           RR      RR    000000    AA      AA   NN      NN


           FFFFFFFFFF    000000    RRRRRRRR        7777777
           FFFFFFFFFF    000000    RRRRRRRR        7777777
           FF          00      00  RR      RR            77
           FF          00      00  RR      RR            77
           FF          00      00  RR      RR            77
           FF          00      00  RR      RR            77
           FFFFFFFF    00      00  RRRRRRRR          77
           FFFFFFFF    00      00  RRRRRRRR          77
           FF          00      00  RR  RR          77
           FF          00      00  RR  RR          77
           FF          00      00  RR    RR      77
           FF          00      00  RR    RR      77
           FF            000000    RR      RR    77
           FF            000000    RR      RR    77

File _DUA1 [FACGAO.VISION]ROAN.FOR;7 (5197,8,0), last revised on 16-OCT-1985 16:34, is a 2 block sequential file owned by UIC
[EECS,FACGAO]  The records are variable length with implied (CR) carriage control  The longest record is 54 bytes.

Job ROAN (17) queued to SYS$PRINT on 9-DEC-1985 15:24 by user FACGAO, UIC [EECS,FACGAO], under account EECS at priority 4, started
on printer _LPA0: on 9-DEC-1985 15:30 from queue LPA0:

FFFFFFFFFF  4444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444  FFFFFFFFFF
FFFFFFFFFF  444444444444444444444  Digital Equipment Corporation - VAX/VMS Version V4.1  444444444444444444444  FFFFFFFFFF
FFFFFFFFFF  4444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444  FFFFFFFFFF
```

```
      subroutine roan(a1,a3,b1,b3,angle)

c      write(5,20) a1,a3,b1,b3
20     format(1x,'a1,a3,b1,b3 -- ',4f7.1)

       a=sqrt(a1**2+a3**2)
       b=sqrt(b1**2+b3**2)

       x=b3/b
        fi=asin(x)

       y=a3/a
        angle=asin(y)


c      write(5,1) x,fi
1      format(1x,'x,asin(x) -- ',2e15.6)
c      write(5,2) y,angle
2      format(1x,'y,asin(y) -- ',2e15.6)

       angle=-(angle-fi)
c      write(5,3) angle
3      format(1x,'angle -- ',e15.6)

       b=-b1*sin(angle)+b3*cos(angle)
        d=abs(a3-b)

      if (d.lt.3.0) goto 10
        angle=3.1415926/2.-angle

       b=-b1*sin(angle)+b3*cos(angle)
        d=abs(a3-b)

     if (d.lt.3.0) goto 10
        write(5,5)
5       format(1x,'Fail to find the rotation angle')

10     return
       end
```

APPENDIX F

RELEVANT TECHNICAL PAPERS WRITTEN DURING THE COURSE OF THIS WORK

PIPE[1]: A SPECIALIZED COMPUTER ARCHITECTURE FOR ROBOT VISION.

Ernest W. Kent

Sensory-Interactive Robotics Group

The National Bureau of Standards[2]

1. PIPE is a registered trademark of Digital/Analog Design Associates, Inc. of New York.

2. This work is the product of United States Government employees, and is not subject to U.S. copyright.

PIPE (Pipelined Image Processing Engine), is an experimental, multi-stage, multi-pipelined image processing device. It can acquire images from a variety of sources, such as analog or digital television cameras, ranging devices, and conformal mapping arrays. It can process sequences of images in real time, through a series of local neighborhood and point operations, under the control of a host device. Its output can be configured for monitors, robot vision systems, iconic to symbolic mapping devices, and image processing computers. In addition to a forward flow of images through successive stages of operations as in a traditional pipeline, other paths between the stages of the device permit concurrent, interacting pipelining of image flow in other directions. In particular, recursive paths returning images into each stage, and feedback of the results of operations from each stage to the preceding stage are supported. The architecture facilitates a variety of functions such as relaxation and interactions of images over time. Numerous operations are supported; within each stage these include arithmetic and Boolean neighborhood and point operations on images. Between-stage operations on each pixel include thresholding, Boolean and arithmetic operations, functional mappings, and a variety of functions for combining pixel data converging via the multiple pipelined image paths. The device also implements alternative processing modes, including "MIMD" operations specific to regions of interest defined by the host device or by previous operations on the image, and variable resolution pyramid operations.

Requirements of Robot Vision.

A robot vision system has requirements which differ in some respects from those of other types of machine vision. Since the function of a robot is to perform physical actions in space and time similar to those performed by humans, it is not surprising that these requirements are similar to those imposed on biological vision systems. In some machine vision applications, such as interpretation of images from diagnostic or satellite equipment, each new picture is a new problem; in robot vision, like biological vision, the input is a stream of images in which each frame differs from the last by some small displacement of the camera or of the objects in the scene. In many machine vision tasks the important function is to recognize certain kinds of objects, but in robot vision, again like biological vision, most of the vision system's time is spent providing information about the position of things in space for guidance and servoing. This is true after objects have already been recognized, before they are recognized, and even if they cannot be recognized by the system. The robot must understand the spatial occupancy of its environment and its own relation to it in order to avoid striking surfaces, whether or not those surfaces are part of recognized objects. Ideally the robot vision system should provide a description of the geometric properties of unrecognized objects sufficient to permit the robot to manipulate them; for example, to remove a foreign object from the workspace. Most importantly, a robot vision system shares with the biological system the necessity of synchronization with real-time events.

From these considerations, we can derive some important properties of a robot vision system. Because the robot's function is oriented towards actions and events which extend over time, the appropriate unit of analysis is the image sequence rather than a single image. This implies that the system must capture and operate on image sequences of a length appropriate to the speed of events. Because the robot's world possesses continuity, the system should take advantage of information discovered in previous views. This suggests that the system should not only build internal models of the environment from successive views, but also that it should be able to make use of hypotheses from this model in interpreting subsequent images. The importance of servoing over classification implies that the system must provide information at many levels of analysis. That is, it may be required to supply information on range to points, on inclinations of edges and surfaces, on translation and rotation velocities of features, and similar descriptive properties of objects in space and time. These must be made available to the

robot control system as rapidly as they are discovered, prior to and independently of classification. Above all, the system must operate in real-time; a late answer is no answer for a robot guidance system. It is this which compels us to examine special-purpose architectures as a means for accomplishing the other criteria.

The NBS Robot Vision System

The general plan of a robot system which incorporates all of these functions is easy enough to sketch, and the basic ideas are included in Figure 1, which is adapted from a robot system being developed by the Sensory-Interactive Robotics Group at NBS. On the left is a sensory processing hierarchy, in the center a knowledge representation system, and on the right a task-decomposition and control hierarchy. This entire system could be considered a "special purpose architecture", in the sense that it is a special purpose machine which has computers as components. However, most of the elements are currently implemented on individual computers of traditional design, and in this chapter I intend to focus primarily on some particular vision elements within this system which, for reasons of required processing speed, have been implemented on special purpose architectures in the sense of specially-designed hardware.

Before considering these elements in detail, a brief review of the system operations will help clarify their tasks and design goals. The sensory processing hierarchy accepts data from the sensors (in particular cameras for vision sensing) and attempts to form a hierarchical syntactic description of the current view of the world. Note that symbolic and parametric information is made collaterally available to the system's knowledge representation at every level of this process. The task-decomposition and control hierarchy on the opposite side accepts goals in the form of external commands. It attempts to use generic knowledge of how to choose actions together with particular knowledge of the current state of the world to generate actions which accomplish the goals. Knowledge of the current state of the world is made collaterally available to every level of the task-decomposition and control hierarchy from the system knowledge representation.

The knowledge representation contains much more than the information currently available from the sensory processing hierarchy. In addition to information which comes from <u>a priori</u> knowledge sources, and knowledge of the control hierarchy's current state, the knowledge representation contains a description of the world built up over all past views from the

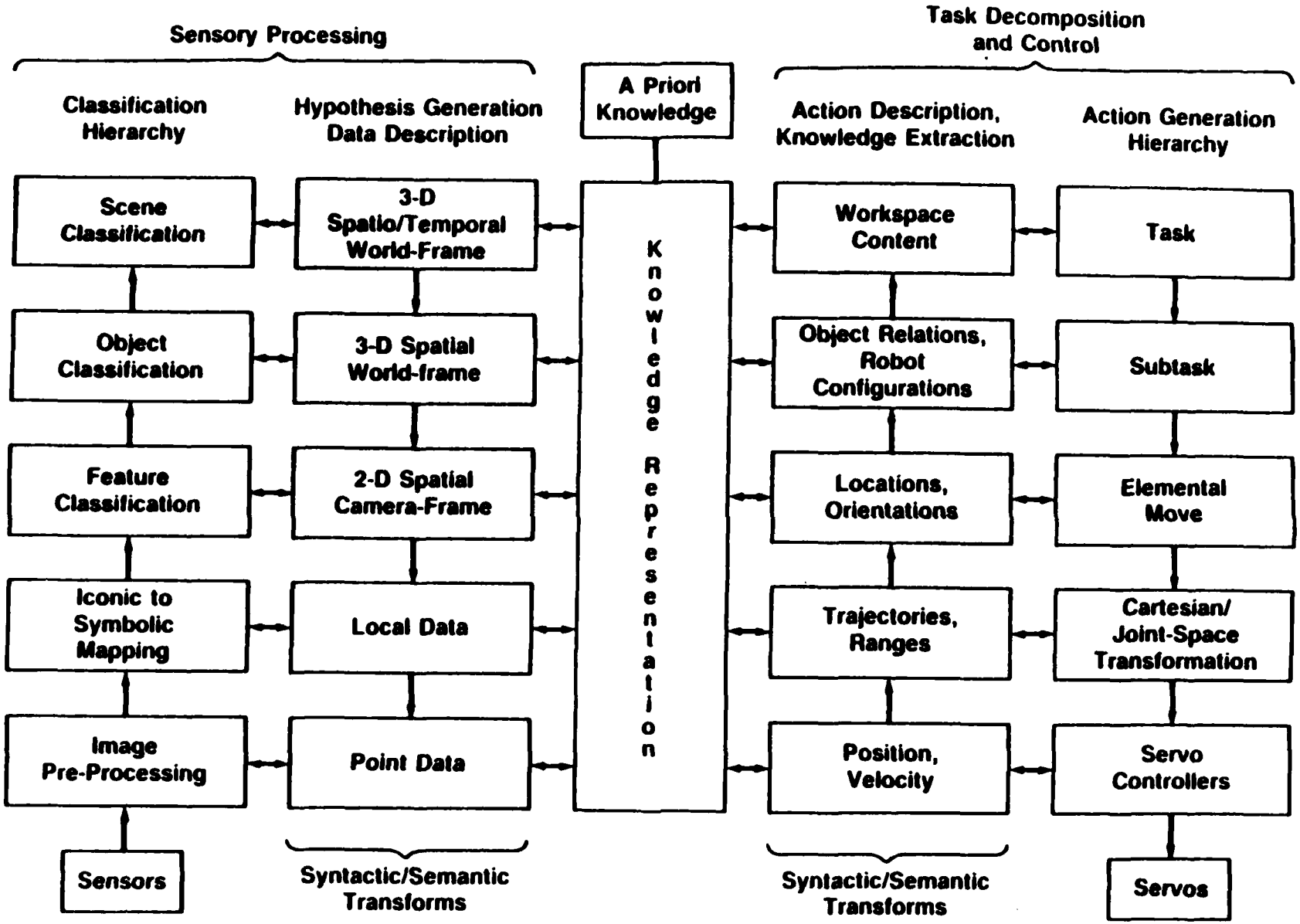


Figure 1. The elements of the NBS image-processing configuration in relation to the NBS robot system.

camera. It thus contains much information which is not extractable from the current viewing window, but which bears on the interpretation of that which is. The current scene descriptions from the sensory processing hierarchy must be reconciled with this information, and the sensory processing hierarchy in turn may be guided by it. Similarly, the knowledge representation's model of the world must be formulated into specific answers to any particular instantaneous requirement of the task-decomposition and control hierarchy. In turn, the state of the action-generating processes provides guidance for the knowledge representation in interpreting its input from the sensory system. There is thus a two-way flow between the knowledge representation and the sensory processing system which "servos" the internal model of the world to the observed data, and which provides hypotheses that guide the processing and interpretation of the data. A similar reciprocal flow links the knowledge representation's internal model of the world with the questions and information produced by the control hierarchy.

The dimension along which the control hierarchy is divided into functional levels (task, subtask, elemental cartesian move, joint-space velocity) is not the same as the dimension along which the vision processing hierarchy is divided into levels (image-plane point properties, image-plane features, world-frame objects.) The knowledge representation, which is not itself hierarchically structured, contains information relevant to all of the different descriptions of the world required by these levels. Its information is maintained in a semantic form from which syntactic and parametric descriptions of the world adapted to the requirements of any of the functional modules can be produced. The representation scheme of this semantic form is chosen principally for convenience in maintaining and organizing the information. The syntactic forms of the various levels of the sensory and control systems are chosen primarily for functional utility in the modules concerned. The "syntactic/semantic transform" modules extract level-specific information from the knowledge representation and instantiate it into the frame and symbols needed for any given functional module. In the other direction, they contain systems for incorporating level-specific syntactic and parametric sensory or control information into the internal model.

This diagram outlines a general conception of the relations of sensory and other knowledge in a robot system. What is vastly more difficult is to specify the algorithms and hardware required to give substance to the boxes in such a diagram. A first generation system was constructed entirely from micro-computers. It used binary image processing of both normal and structured-light images. The knowledge representation and the range of

requests acceptable from the control hierarchy were very limited in scope. Nonetheless, this system could accept CAD descriptions of simple parts, recognize them, and provide servo information that allowed the control system to manipulate them in real-time. A second generation system has been under development for some time. This project includes much more elaborate structures for knowledge representation, and a correspondingly richer sensory processing capability which employs gray-scale vision. Most of this second generation system development effort consists of software improvements still running in a multi-microcomputer dataflow (as opposed to distributed) system. With the move to gray-scale vision, however, it became apparent that the early stages of image processing involved computations which could not be handled in real-time by microcomputers. Further, it was felt that for these early image-processing functions a sufficiently good understanding of the requirements of robot vision existed to justify the development of special-purpose vision architectures. Accordingly, an image preprocessor (called PIPE, for Pipelined Image Processing Engine) and a feature extractor (called ISMAP for Iconic to Symbolic MAPper) were designed. The first prototypes of these devices are now in operation. Their relations are depicted in Figure 2, which shows the data-flow paths for the PIPE and ISMAP elements, to and from the upper levels of the system (indicated here as "host memory").

These devices will replace microcomputers as the first two elements of the sensory processing hierarchy in the second generation of the robot system depicted in figure 1. The first of these elements is an initial processing stage (image pre-processing) which accepts an image consisting of an array of gray-scale values and produces a similar array of symbolic values which encode features of the gray-scale array, such as edges, or textures. This process of feature detection produces an iconic description of image features from an iconic description of image intensities. That is, for both the input and the output of this process, the global geometric relations of the input values or the output features are implicit in their location in the image array. The feature detection process transforms one iconic array into the other by making local properties explicit as symbols. In most cases the process attempts to describe local properties (features) which achieve some independence of circumstances such as illumination.

Following the feature detection process, the second element of the system performs a feature extraction step (iconic to symbolic mapping.) This begins the process of producing a relational feature description of objects which is independent of circumstances of viewing position. In this step, the iconic image of features, in which symbol values are indexed by location, is

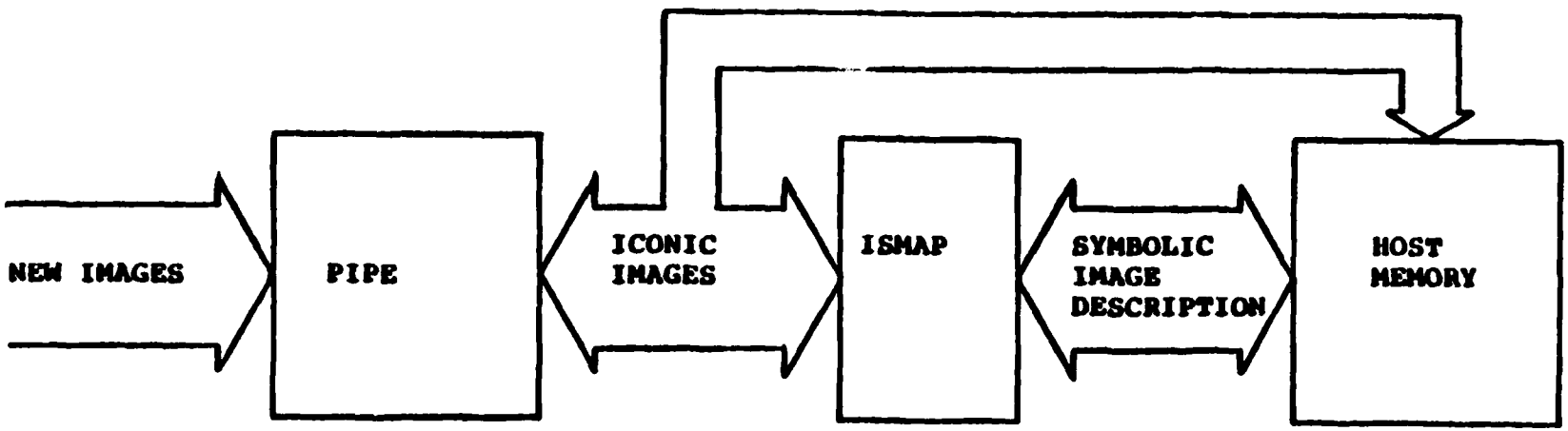


Figure 2. Major Image-Flow relationships between PIPE, ISMAP, and the host devices.

mapped into a space in which location is indexed by feature value. This produces a representation in which the data which was previously explicit (the feature type) is now implicit in the location of the data in the representation. The image location of the features, which was previously implicit in the iconic representation, is now the explicit data represented by values in the new space. This accomplishes two goals; it permits finding the locations of features of interest by direct indexing rather than by exhaustively searching the image, and it extracts locations as data to which subsequent operations can be applied. These subsequent operations attempt to find meaningful relations among the location data which correspond to geometric relations of features. The geometric relations discovered then serve as input to subsequent classification processes.

Design Philosophy of PIPE

In designing the PIPE and ISMAP devices to play these roles in the system, we attempted to optimize the design for the special requirements of robot vision discussed above. The principal goals selected were: 1) real-time processing of images at field-rate, 2) provision for interactions between related images, such as those arising from dynamic image sequences or from stereoscopic views, 3) provision of the ability to apply different algorithms to different regions of the image in real time, 4) ability to perform multi-resolution image processing, and 5) provision for guiding processing by knowledge-based commands and "hypothesis images" supplied from the upper levels of the system.

PIPE is a hardware device specialized for parallel image processing rather than a fully general purpose parallel computer. Through its design, it facilitates a variety of common and important image-processing techniques, as well as several experimental approaches. Within the broad limits of the processes it supports, it is an extremely fast and flexible device. On the other hand, it is not a general purpose computer and it is not possible to program arbitrary algorithms on it, or at least not in an efficient manner. In most cases we have found that processes which are well suited to PIPE may be substituted for others which are not, while accomplishing the same image-processing goal. PIPE is intended as a processor for local operations on images; it is not designed to perform efficiently operations that require global knowledge of the image. It is intended that PIPE operate in conjunction with a host, such as the upper levels of the NBS robot vision system, which will perform global image operations, relieved of the processing burden of large scale repetitive local operations. Thus, PIPE itself accepts iconic data images, and typically produces iconic

images whose pixel values are Boolean vectors describing local properties of the pixel neighborhood. PIPE relieves the upper levels of the system of costly low-level local processing which must be performed over the entire image space.

The basic design of PIPE was partly inspired by an earlier proposed machine[1,2] which was in turn adapted from biological models of image processing. The essential organization is a three-dimensional architecture consisting of a sequence of image-processing planes (Figure 3.) Each processing plane has storage arrays which receive images, and operators which act on them. The storage arrays may be considered to be in-register with one another in the third dimension, so that each pixel neighborhood in an array occupies a step in a pipeline of processes extending up through the stack of planes. The result is an image-flow architecture in which the images move upwards through the stack as subsequent images replace them from below. At each stage the operations on the pixels provide interaction in the lateral directions with neighbors in the same array, and in the vertical directions with neighbors in the preceding and succeeding arrays. Logically the machine can be considered as a bundle of bidirectional pipeline processors with lateral interactions.

In practice, PIPE actually consists of stages with storage arrays and computational modules (figure 4.) which operate over every pixel neighborhood in the arrays in a single field time (1/60 sec.) Images are transferred from stage to stage at field-rate (60 images/sec) by three concurrent pathways which provide for interacting, image-flow transfers between stages. These interconnect a variable number of identical modular image-processing stages. The three pathways, shown in figure 3, are: the forward pathway, which acts as a traditional pipelined image-processing path; the retrograde pathway, which carries images in the opposite direction (i.e., from the output of a stage to the input of its predecessor); and the recursive pathway, which carries an image from the output of a stage back into the input of the same stage.

At the input to each stage (labeled "combining logic" in figure 4.) the images carried by the three pathways may be subjected individually to any arithmetic or Boolean operation. Any linear arithmetic or Boolean operation may then be used to combine them into a final input image, prior to its storage in one of two buffers within the stage.

Within each stage, the computational operators may act on images stored in either or both of the two buffers. These operators are contained in the sections marked "operations" in figure 4. Each stage can perform two simultaneous and independent

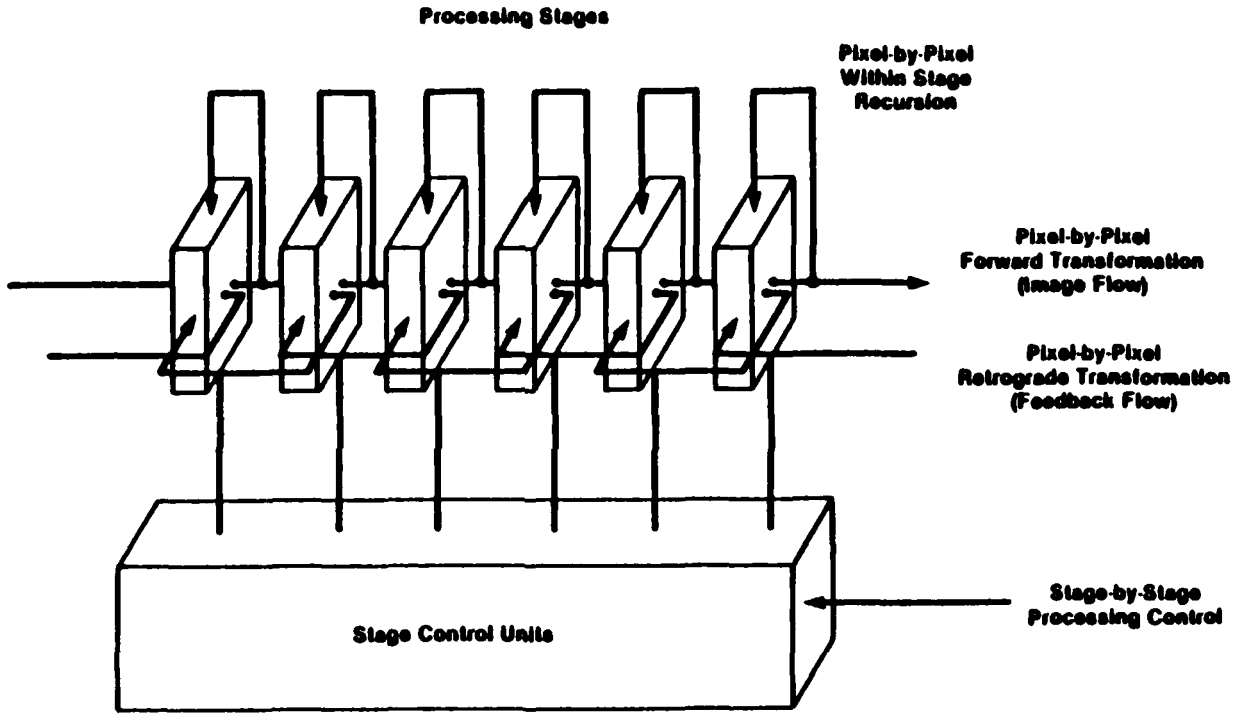


Figure 3. Major Image-Flow connections between processing stages in PIPE.

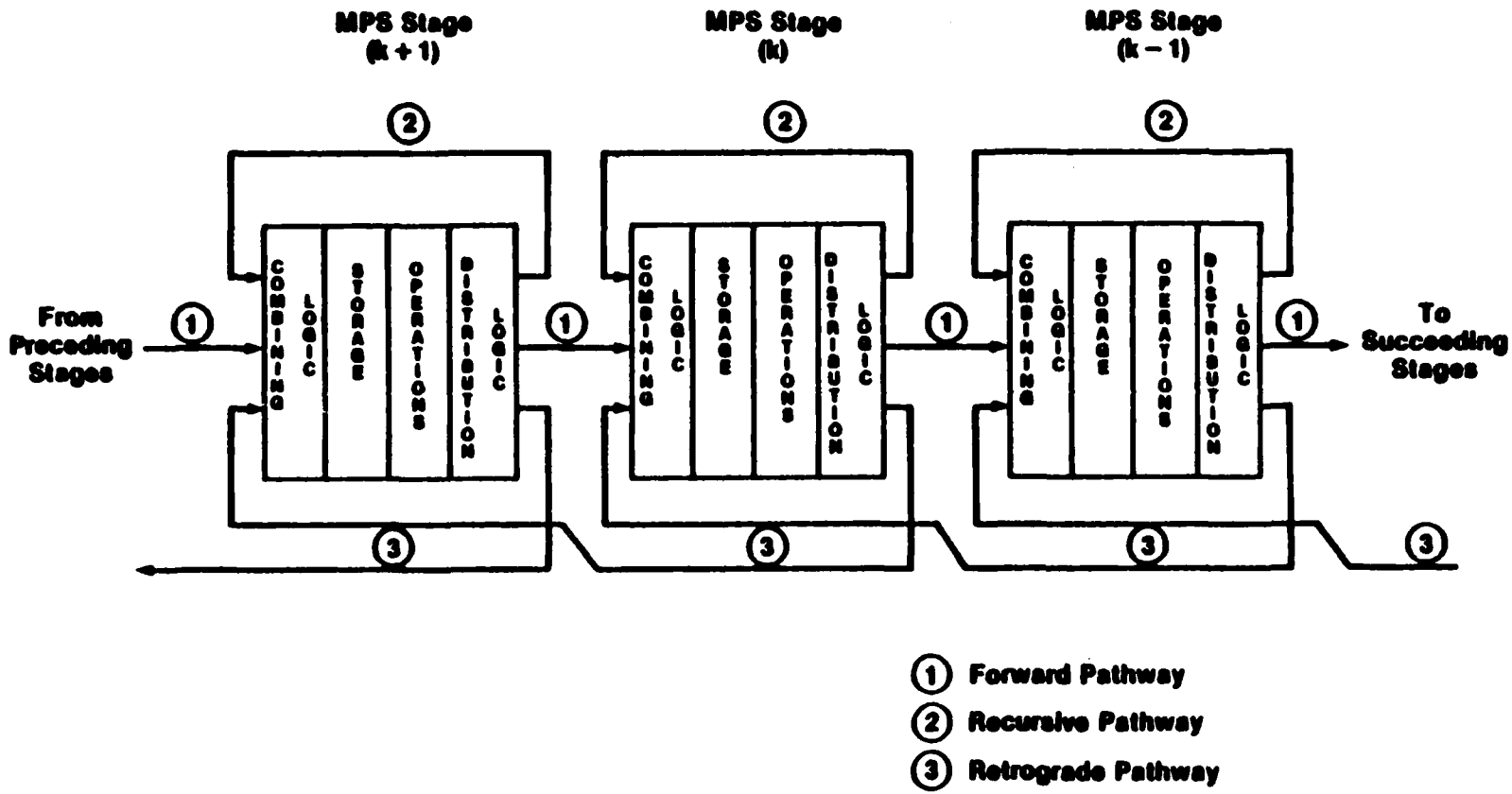


Figure 4. Image-Flow connectivity in relation to the major elements of a hardware PIPE stage.

arithmetic or Boolean neighborhood operations. Following the neighborhood operations, and prior to output from the stage, the images resulting from the neighborhood operations, or either of the images in the buffers, may undergo a further transformation by an arbitrary function of one or two arguments. If the function is of two arguments, the second argument may be drawn from any source within the stage, including the transformations of same or the other image. The forward, recursive, and retrograde pathways, in any combination, may accept images from the result of any of these operations or from any of the buffers. This is controlled by the section marked "distribution logic" in figure 4.

The representation of figure 4 shows the actual physical grouping of processing elements and storage as they exist in the machine for structural reasons. Functionally, the combining logic of one stage and the operations and distribution sections of the preceding stage may form a more convenient conceptual processing unit for many purposes. Figure 5 shows the architecture of PIPE redrawn in this fashion, where the processors are the conceptual rather than the physical units. In this figure the frame-buffer storage elements can be unbundled from the processing units, so that the tri-directional image-flow relations are easier to visualize.

In an alternative mode, one of the two image buffers in each stage may serve as a map for selecting the processing algorithms being applied to the contents of the other buffer. In this mode, PIPE functions as multi-instruction stream multi-data stream (MIMD) machine, with one buffer defining regions of interest over which each set of algorithms shall be applied, on a pixel-by-pixel basis, as the image is processed. In the prototype version, sixteen such alternative processing algorithms may be selected for different regions of the image within a single field time. However, this is easily increased (up to 256 processing algorithms) simply by adding additional storage to each stage to hold the appropriate tables and parameters.

The third mode permits PIPE to function as a multi-resolution pyramid machine. In this mode, the images carried by the forward pathway are reduced in size by one half at each stage, while sizes of the images carried by the retrograde pathway are doubled at each stage. The images carried by the recursive pathway remain unchanged in resolution. Any combination of stages may operate in this mode, under program control.

In addition to the pathways mentioned, PIPE contains four "wild card" busses which may be used to transport images from higher levels of processing, or from any buffer in the machine,

into any other buffer in the machine. It also has two special stages, for input and output, which communicate with the sensors, with processors in upper levels of the system, or with special auxiliary devices. DMA channels allow video display or streaming input and output from any buffer in the machine.

In any of PIPE's operating modes, the operations of every stage are completely independent, and can be completely reconfigured in the inter-field time by an associated stage-sequencer control unit, which in turn may select stage configurations from a stored sequence, or on command from the higher levels.

Operation of PIPE

The initial version of PIPE consists of a sequence of identical image processing stages, sandwiched between a special input processor and a special output processor. The input processor accepts an image from any device that encodes two-dimensional images. It serves as a buffer between the rest of the image processing stages and the outside world. Each successive processing stage receives image data in an identical format, operates on it, and passes it on to the next stage for further processing. This sequence is repeated every television field-time. When an image emerges at the far end of the sequence, it is processed by the special output stage and presented to upper levels of the robot vision system or to a host computer.

The image processing stages between the input and output stages are all identical and interchangeable, but can each perform different operations on the image sequences that they encounter. Usually, each image processing stage receives three input images and transmits three output images. The input images arrive from the processing stage immediately behind each stage, from the processing stage immediately ahead, and from a result of the preceding operation performed by the image processing stage itself. Similarly, the results of processing a current image are transmitted by each stage to the next processing stage in the sequence, to the immediately-preceding processing stage, and recursively back into the image processing stage itself. These three outputs are usually not identical, and each may furnish part or all of the inputs to other stages for the subsequent step in processing. The three inputs may be weighted and combined in each image processing stage, in any fashion, before they are processed.

In addition to these input and output paths, the four 'wildcard' paths may be sources or destinations for input and output. Unlike the three principal paths connecting the stages,

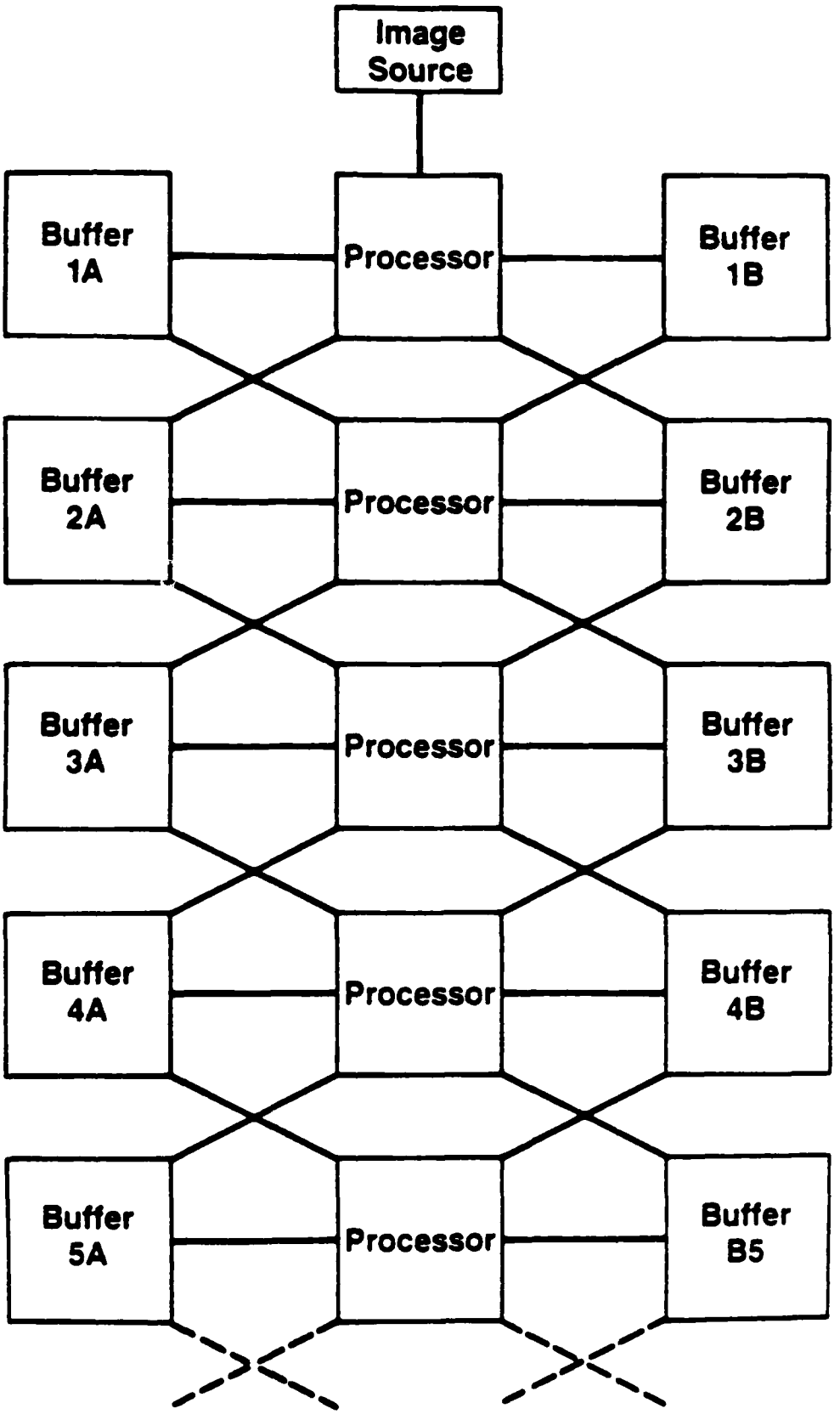


Figure 5. Image-Flow connectivity in relation to conceptual functional processors of PIPE.

these wildcard paths are common to all stages, so that only one stage can write to a particular wildcard path at a time, but any or all stages can accept input from them. The wildcard paths allow images to be moved arbitrarily between stages, instead of having to step through from stage to stage. There are no restrictions on the number of destinations for an image output to a wildcard path.

Although there are physically only three pathways between stages (excluding the "wildcard" busses), every pixel neighborhood in an image is processed and sent over these paths in every field time. The result is that PIPE simulates a fully parallel image-flow machine; each pixel appears to have a real-time, private line to an homologous pixel processor in three target stages. There are numerous reasons for requiring the three input and output paths from each image processing stage. It is clear that the forward path allows a chain of operations to be performed on sequential images, giving rise in real time to a transformed image stream (with a constant delay). Similarly, the recursive path allows a pipeline of arbitrary length to be simulated by any stage. It also facilitates the use of algorithms that perform many iterations before converging to a desired result (e.g., relaxation algorithms, or the simulation of large neighborhood operators by successive applications of smaller neighborhood operators). The path to the preceding image processing stage allows operations to be performed using temporal as well as spatial neighborhoods. It also allows information inserted at the output stage by the upper levels of the system to participate in the processing directly. This, for example, allows expectations or image models to be used to guide the processing at all levels, on a pixel-by-pixel basis.

It is helpful in understanding the functions of these processing pathways to consider each in isolation first. If only the forward input path is operative (i.e., the combining weights for the retrograde and recursion paths are set to zero), we have a simple image pipeline processor which can sequentially apply a variety of neighborhood operators to the series of images flowing through it. It can perform either arithmetic or Boolean neighborhood operations and, by thresholding, convert an arithmetic image into a Boolean image. For example, it might be used to smooth an arithmetic gray scale image, apply edge detection operators to it, threshold the "edginess" value to form a binary edge image and then apply Boolean neighborhood operations to find features in the edges. The operation types and parametric values for these operations would be set individually for each stage by the stage control units, which in turn would be instructed (for example from the upper levels of the system) via the input marked "stage-by-stage processing control" in Figure 3.

A second single-path case results if both the forward and retrograde paths' combining functions are zero. Assume that images had previously been loaded into all the processing stages. The recursive path would then cause the image field in each stage to pass through the forward or backward transformation operation recursively, while the images "marched in place". A variety of relaxation operations can be implemented in this way.

For the final single path case, consider that the weights assigned to the forward and recursive paths are zero, leaving only the retrograde pathway active. When the set of such paths is considered in isolation, it becomes clear that it forms a processing chain that is a retrograde counterpart of the forward pipeline. It would, in fact be possible to select appropriate retrograde transformations, insert fields of data at the back of the device, process them through to the front, and get the same result as running the system in the normal direction. The purpose of this is not to provide a bidirectional image processor, but to permit input (at the "output" end of the device) of synthesized images. Such images influence the processing of the normally flowing images by direct interaction, and correspond to "expectancies", "models", "hypotheses", or "attention functions."

The retrograde images are not only able to affect processing of the forward images, but are affected themselves by interaction with them. (The effects that the two image sequences exert on each other may be different because the neighborhood operators on the forward and backward paths are independent). Retrograde images will usually be generated by knowledge-based processes in higher level components of the robot vision system. They may initially appear in Boolean form, but, as shown in Figure 6, provision is made for all four possible combinations of arithmetic and Boolean inputs and outputs in the combining logic between stages. This permits a descending Boolean image to be instantiated into arithmetic image values by interaction with the ascending arithmetic image. This occurs in the same stage in which the ascending arithmetic image representation is thresholded to become a Boolean image (Stage "N" of figure 6.) Both the ascending data image and the descending "hypothesis" image can pass across this interface. A major function of PIPE will be to explore the effectiveness of various approaches to hypothesis-guided iconic image processing.

There are a great many ways in which various combinations of these pathways can be used in processing by operating on combinations of processed images arriving over the three pathways. I will consider only a few illustrative examples.

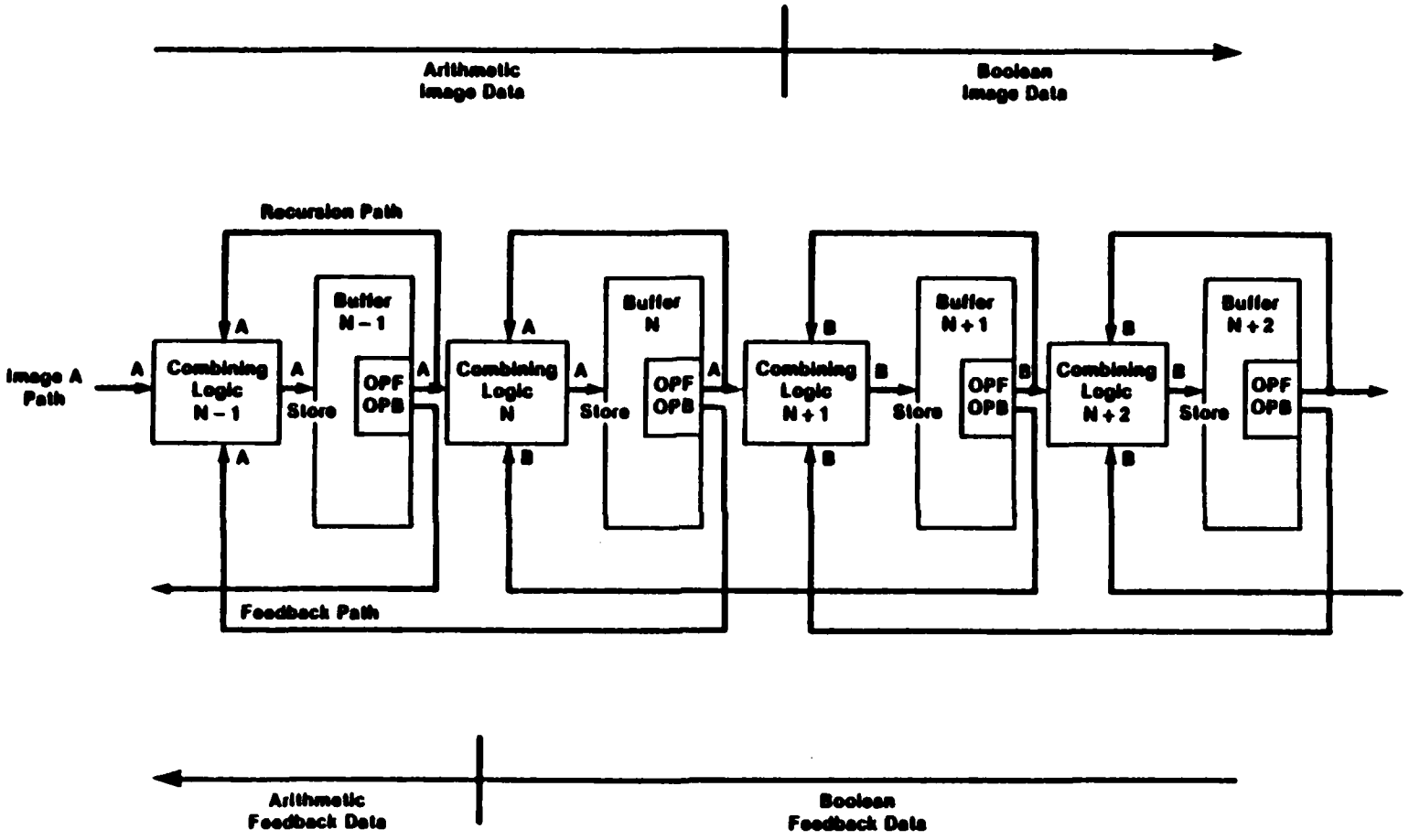


Figure 6. Modes of interaction between arithmetic and Boolean images.

If the preceding and succeeding image fields are considered to contain future and past instances of a field, respectively (as is true in a dynamic image), then forward path corresponds to a path from the future, recursion to a path from the present, and the retrograde path to one from the past. The weighted sum of the three paths' contents the forms a convolution operation on the temporal neighborhood of a pixel. This may occur at the same time as a spatial neighborhood convolution operation is being performed on the contemporary spatial neighborhood in each stage, so that a combined spatio-temporal convolution is achieved.

Boolean information can be processed in an interesting way by combining the outputs of the forward operator from the previous stage and the recursive input from the current stage. Consider the case of a single stage treated in this fashion for eight field-times, using "SHIFT recursive then OR recursive with forward" as the combining operation. Let the incoming images from the previous stage (forward path) have Boolean values resulting from thresholding of eight successive and independent feature detection operations such as oriented edge detection, texture measures, etc. The second stage will accumulate images from the eight preceding Boolean operations into an image composed of eight-bit Boolean vectors, each bit representing the presence or absence of an independent image property at that location. Subsequent Boolean neighborhood operations may then apply independent operators to each bit plane of a neighborhood of such vectors.

HARDWARE DETAILS OF THE PIPE STAGES.

Input Stage

A special input stage is used to capture and buffer images from input devices. This allows PIPE to accept digital or analog signals from any device using standard RS-170 television signals and timing. Either of two selectable analog signals is digitized by an eight-bit real-time digitizer. The input stage is capable of acquiring a digitized image of 256 x 240 pixels while remaining synchronized with RS-170 signals. Alternatively, it can capture 256 x 256 pixel images from non-RS-170 signals while internally employing non-standard pixel rates. It can continually capture such images at standard television field rates, and place them in either of the two field buffers contained in the input stage. While storing an image into one of these buffers the input stage can also simultaneously store an image into either buffer,

such as a difference image, formed by an ALU operation between the incoming image and a previously captured image. The contents of either of the buffers in the input stage can be sent to the first of the processing stages, while the next image is being acquired.

PIPE accepts eight-bit input data, and this precision is maintained throughout the machine. Intermediate arithmetic operations within subsequent stages are carried to sufficient precision to insure no loss of accuracy when the result is rounded to eight bits for transmission to subsequent stages. The data may be treated as either unsigned eight-bit numbers, or as two's complement signed numbers with the high bit indicating the sign, or as boolean vectors of eight independent bits. All stages may independently select the representation employed, so that unsigned input data may be processed until an operation which generates negative values occurs, treated as signed data thereafter until a thresholding operation occurs, and then treated as Boolean data.

Processing Stages

Following the Input stage, there are a series of modular processing stages (MPS). The MPSs are the "stages" referred to in the preceding sections, and are the elements which perform most of PIPE's processing. All MPSs are of identical modular construction, and are physically interchangeable simply by switching circuit boards. Thus, any MPS can operate at any position in the processing chain, and the processing chain can have a variable length. Eight MPSs are employed for the present development phase of PIPE. The block diagram of a MPS is portrayed in figure 7.

The pre-storage input section of the Nth MPS accepts three eight-bit 256 x 256 pixel images as input. These come from the forward output of the N-1st MPS, from the recursive output of the operation performed on the previous contents of the Nth MPS, and from the retrograde output of the N+1st MPS. Each data stream may consist, independently of the other two, of arithmetic or Boolean (eight-bit Boolean vector) data, but a given data stream entering a MPS must be entirely Boolean or arithmetic within any single image field.

Before generating a final eight-bit image from the three data streams, the input section of each MPS performs an arbitrary table-lookup transformation on each them independently and simultaneously (forward, backward, and recursive L.U.T. in figure 7.) Each of the three lookup tables is one of three sets of 32 tables selectable by the stage operation micro-instruction. The

resulting three Boolean and/or arithmetic data streams are then combined through independently-programmable full-function ALUs into a single arithmetic or Boolean data stream (figure 7, ALU-A and ALU-B.) This data stream is then used to load either of the two selectable field buffers within the MPS (buffer A and buffer B in the figure.) Alternatively, either or both buffers can be filled using the wildcard busses or by direct DMA from the host. The contents of both of these field buffers are then available to subsequent operations of the MPS. External device access to the data in these buffers is also available; an external device may read from or write into either buffer in a random access manner at 400,000 pixels/sec., with auto-indexed addressing supported on command. The wildcard busses provide streaming access to external devices (including monitors) at pixel rates.

The hardware that implements the output functions of the MPS, subsequent to the field buffer storage step, is physically contained on a separate circuit card to allow it to be replaced with other special functional modules, should this be desirable. This circuitry is represented by the area to the right of the frame buffers in Figure 7. For neighborhood operations, an eight-bit image is selected by reading the contents of one of the two field buffers in the MPS. The image is transformed by a single-valued mapping through one of 32 program-selectable lookup-tables (pre-nop L.U.T.), and the pixels of the resulting image are passed to two neighborhood operators (NOP A,and NOP B), of which there are two kinds. The first type of neighborhood operator is an arithmetic convolution operation, while the second is a Boolean operation. For either operator, the neighborhood of operation is (at present) 3 x 3 pixels square, and the operation is accomplished in 200 nsec. Pixel neighborhoods are generated by passing the data stream through a 3-line buffer.

In the arithmetic case, the convolution operation uses arbitrary positive or negative eight-bit neighborhood weights, and maintains twelve-bit accuracy in its intermediate results. The final eight-bit arithmetic result busses is produced by non-biased rounding, from a 20-bit sum. This insures that no loss of precision occurs within a stage due to arithmetic underflow or overflow. The full eight bit precision of the input is thus maintained between stages throughout the machine. In the Boolean case, the neighborhood operation consists of arbitrary Boolean operations (a sum-of-products AND-OR array equivalent) between the set of all the pixels of the data neighborhood, and the set of all corresponding pixels of an arbitrarily specified comparison neighborhood. Any bit of either neighborhood may be independently defined as true, false (complemented), or "don't care". Each of the eight bit-planes forms an independent set of inputs, subject to independent neighborhood operations. As a

result, eight independent one-bit results are obtained from a single pass of the data through the pipeline, yielding an orthogonal eight-bit Boolean vector as output.

Both neighborhood operators are applied independently and simultaneously. They operate on the same data stream, using neighborhood operations which may be different. Their outputs, or the contents of either of the field buffers, may be independently subjected to a second transformation by either of two programmable functions. The first of these is a lookup-table mapping function (TVF L.U.T. in figure 7.) This transformation may be a function of one or two eight-bit arguments. If two arguments are used, they may be taken from homologous pixels of either of the NOP outputs or either of the field buffers. The lookup-table is program-selectable from a number of stored tables which depends on the number of arguments to the input. The other function, with inputs selectable from the same sources, is an ALU with two eight-bit inputs (ALU C.)

Finally, the contents of either of the buffers, the results of either of the neighborhood operators, and the results of either of the two functions of two arguments, may be sent to the three output pathways, or to the four wildcard busses, in any combination, by a crossbar switching network shown at the extreme right in figure 7.

These basic features of the processing stages may be altered in operation by one of two special processing modes. The MIMD, or "region of interest" mode allows each MPS to switch between alternative operation sets on a pixel-by-pixel basis. In this mode, one image buffer of the stage contains a map of the operations to be performed on homologous pixels of the image buffer undergoing operations. In this mode, the contents of the operation-controlling buffer are treated as offsets into the on-board micro-operation store of the stage, and select the operative micro-operation code for each pixel-time. Each micro-operation word controls the routing of data-flow within the stage, the ALU functions, the identity of the look-up tables employed, and the selection of output paths. Potentially, up to 256 different alternative operation sets could be specified by the eight-bit contents of each pixel in the map. In practice, the number of alternative operation sets selectable during a field processing time will be limited by the amount of memory available within the stage to store them, which may be enlarged at will. The operation sets stored in the available memory may be changed arbitrarily between fields.

In "Pyramid Mode", PIPE allows the construction of multiresolution, "pyramid", sequences of images. The basic

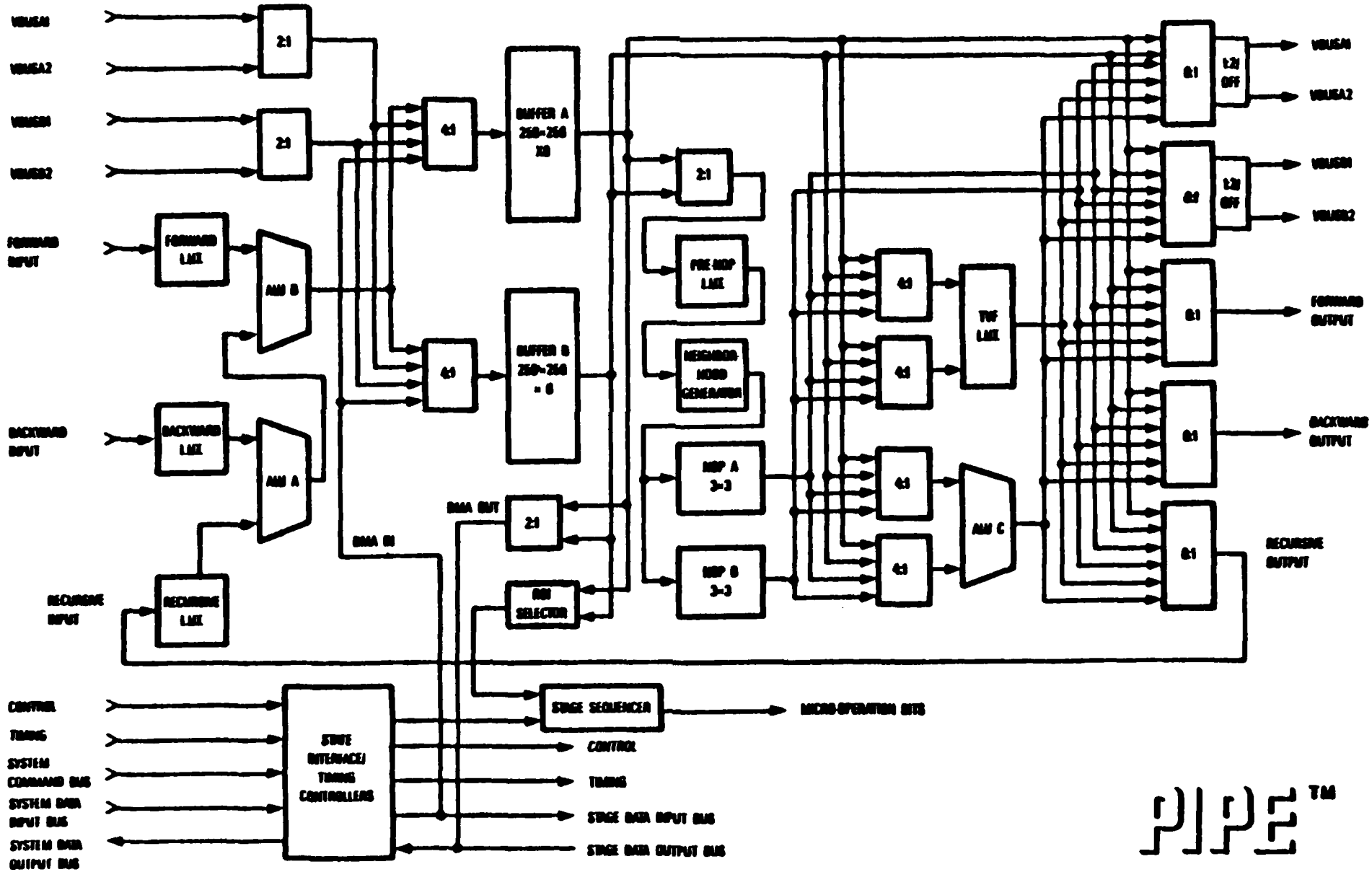


Figure 7. The internal architecture of a PIPE processing stage.

operations available in PIPE for constructing image pyramids are sampling and pixel doubling. Sampling is used to reduce the resolution of an image, while doubling is used to increase the size of an image.

Both the sampling and doubling operations are performed by manipulating addressing rates within a stage. Sampling is achieved via the forward pathway by incrementing the destination image addresses half as fast as the source addresses. That is, on each row, the first pixel in the source image is written to the first pixel in the destination image. The second source pixel is also written to the first destination pixel. The address of the destination pixel is then incremented, and the procedure is repeated. The same process is used to sample into every other row in the destination image. The result is that the destination image is one quarter the resolution of the source image. Doubling is accomplished via the retrograde pathway by the inverse of the sampling process. That is, the addresses in the source image are now being incremented at half the rate of those in the destination image. For each row in the source (reduced-resolution) image, two identical rows are output in the destination image. For each pixel in each row of the source image, two identical pixels are stored in the destination image.

The simple operations of image sampling and pixel doubling are not of themselves very useful except for a narrow range of applications. However, they may be combined with the other operations in the MPS, so that a much broader class of operations becomes possible. Prior to sending the images over the forward and backward paths, they may pass through the operations of the output section of the MPS, and prior to storage, they may pass through the operations of the input section of the destination MPS. For example, the neighborhood operator can be used to smooth the image before sampling. By iterating the neighborhood operation prior to sampling, the effects of neighborhoods larger than three by three can be obtained, allowing, for example, the construction of "Gaussian" pyramids [3] using the hierarchical discrete correlation procedure of Burt[3]. By passing an image through one neighborhood operator into the forward path, through the other into the recursive path, and by passing the retrograde path directly to the look-up table of the input section of the N-1st MPS, the pyramidal neighborhood operations of Tanimoto's Hierarchical Cellular Logic[4] may be realized.

Edge effects that arise when a neighborhood operator is applied are dealt with in the same manner for all resolutions of images, and for borders of MIMD operation regions as well as for frame borders. PIPE automatically provides the replication or zeroing of border pixels. If a neighborhood has a row or a column

that lies outside the boundaries of the image (either beyond the image buffer itself or beyond the extent of a low-resolution image, or beyond the bound of a MIMD operation type), the non-existent pixels are zeroed or replaced by the pixels in the border row or column. For a three by three neighborhood, this is equivalent both to reflecting the image and to repeating the border pixels. This is achieved in the same way as the varying resolution images are constructed, i.e., by manipulating the address lines of the buffer.

Output Stage

The output stage performs a role at the end of the processing chain similar to that of the input stage at its beginning. The final MPS delivers its forward image output to either one of a pair of field buffers in the output stage, and can simultaneously read from the other buffer of the output stage. The data read from the output stage is used as the input to the retrograde path of the final MPS. Without interrupting the image-processing, either buffer of the output stage can be read from or written into by an external device, which is both the consumer of the processed forward data-flow and the supplier of data for the retrograde path.

Sequencer and Stage Control

Prior to run time, the pipeline modules must be set up with the individual operations to be carried out. The upper levels of the system must load each stage with appropriate instructions for all the processing steps to be employed. Each stage has storage for up to 256 128-bit micro-operation words, each of which can specify the entire set of operations for the stage. This store is loaded by the host or upper levels of the vision system. Each stage also has control circuitry which allows a micro-operation word to be selected from the stored set by external command. The selection command can come either from the host or from PIPE's Sequencer. In either case the selection can completely reconfigure the stage operation during the inter-field time by selecting a new stage operation set for the next field-time, or a group of stage operation sets from which members are to be selected on a pixel-by-pixel basis in MIMD mode during the next field-time.

Normally, the cycle-by-cycle selection of the operations stored in each stage will performed by the Sequencer module. When active, this unit issues an operation selection command to every stage of PIPE at the beginning of each field-time. The nature and order of these operation selection commands are determined by a program in the sequencer module which specifies the order of

commands to the stages, including loops and branches, so that the coordination of stage operations to effect various PIPE algorithms is accomplished. This sequencer program is loaded from the host prior to run time. At any time, the host can override the sequencer program and intervene in the stage operation selection process directly. In operation, the upper levels of the system may instruct the sequencer to select a stage program, instruct it to branch in the specified sequence of operations, or permit it to follow the pre-set sequence of operations (which may contain branch points on repetition counts.)

Programming and running PIPE thus consists of specifying the operations to be performed by each stage, loading the corresponding operators, parameters, and tables into the stages, and then loading the sequence of operations for the stages into the sequencer module. For program development, the contents of any buffer and the output of any operator in the system can be displayed on a video monitor, while the sequencer is single-stepped.

INPUT/OUTPUT MODES

In keeping with its role as a real-time vision processor, PIPE has several rapid means for transferring information to and from the host device. The wildcard busses may be output directly, either as digital streams or after conversion to analog signals. The analog outputs provide for interface to monitors or other display devices, while the digital outputs provide streaming I/O at video rates to any specialized device which can accept this rate of input. This streaming I/O mode is represented in figure 8-a. Figure 8-b presents a parallel port I/O scheme which allows the host device access to any of the PIPE image buffers in a random access fashion. These parallel port transfers can also function in auto-increment and DMA modes. The most sophisticated method of transferring image information to the host uses the ISMAP device to transfer symbolic descriptions of the image to the host's address space. This transfer may be bi-directional, and can take any PIPE buffer as a source or destination. This I/O technique is illustrated in Figure 8-c.

ISMAP

The associated device, ISMAP, will map processed iconic images into symbolic (property-indexed) structures. ISMAP describes the processed images produced by PIPE by mapping the iconic image of Boolean vectors produced by PIPE into ordered list structures in the address space of processors in the upper levels of the system, in real time. A major function of ISMAP is to map PIPE's image addresses into a space ordered by symbolic

picture feature descriptors. This saves processors in the upper levels of the system the necessity of scanning the processed image to find locations of items of interest. Physically, ISMAP resides in the PIPE backplane as an integrated part of the system.

In each frame time, ISMAP scans the entire image of iconically-ordered feature codes produced by PIPE, and prepares three organized descriptions of the feature set of the image in a symbolically-ordered space in the address space of the host. The three descriptions of the image's feature content produced by ISMAP are: 1) a histogram of feature types, organized by feature type, 2) a cumulative histogram of feature types organized by feature type, and 3) lists, organized by feature type, of the image-coordinates of every feature in the image. The values in the cumulative histogram serve as pointers to the heads of the lists of image locations. For example, if the host needs the locations of all edges with a certain angle of inclination, it can find the beginning and the length of a compact list of those locations, in its own address space, simply by looking at the cumulative histogram entry for the desired edge direction. It may first use the histogram to determine what edge directions are prominent in the image, or perform any of a variety of other algorithms on this information without the burden of examining the image-space in order to count or locate features of interest.

ISMAP may also run in reverse, creating images in host buffers from feature lists created or selected by the host. This permits ISMAP to be the first level of the upper system which can generate hypothesis images for PIPE, which allows the PIPE/ISMAP combination to perform operations such as Hough transforms easily.

CONMAP

ISMAP is one of two PIPE auxiliary devices. Another, CONMAP, which is currently under construction, stands at the front of PIPE as a geometric pre-processor for input images. The CONMAP device accepts iconic images and remaps them into topologically identical, but geometrically different iconic images prior to their acquisition by PIPE. In its final form, CONMAP will implement fully general conformal mappings on images. There are a variety of uses for such transforms. Log-polar mappings have been suggested by Weiman and Chaikin[5], as a means of converting complex image properties[6] such as rotation and scale, into simple translations. Jain[6] has employed a similar transformation for utilizing the effects of camera motion in image understanding. Other applications include simulation of lens geometries which permit non-uniform resolution (e.g. a high-

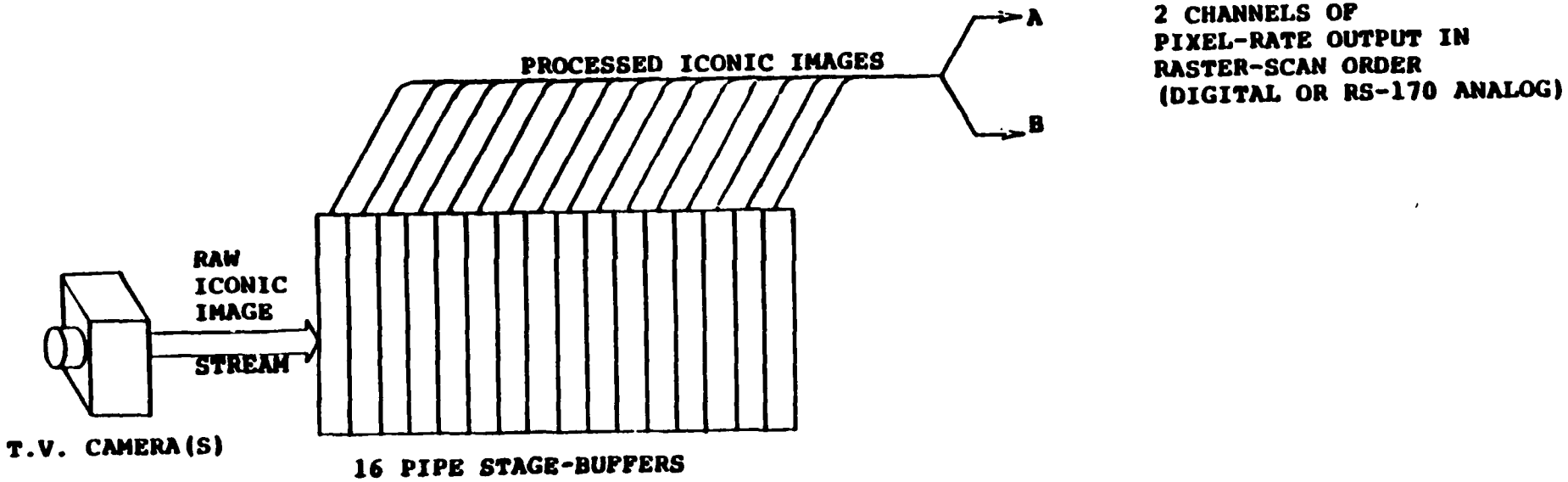
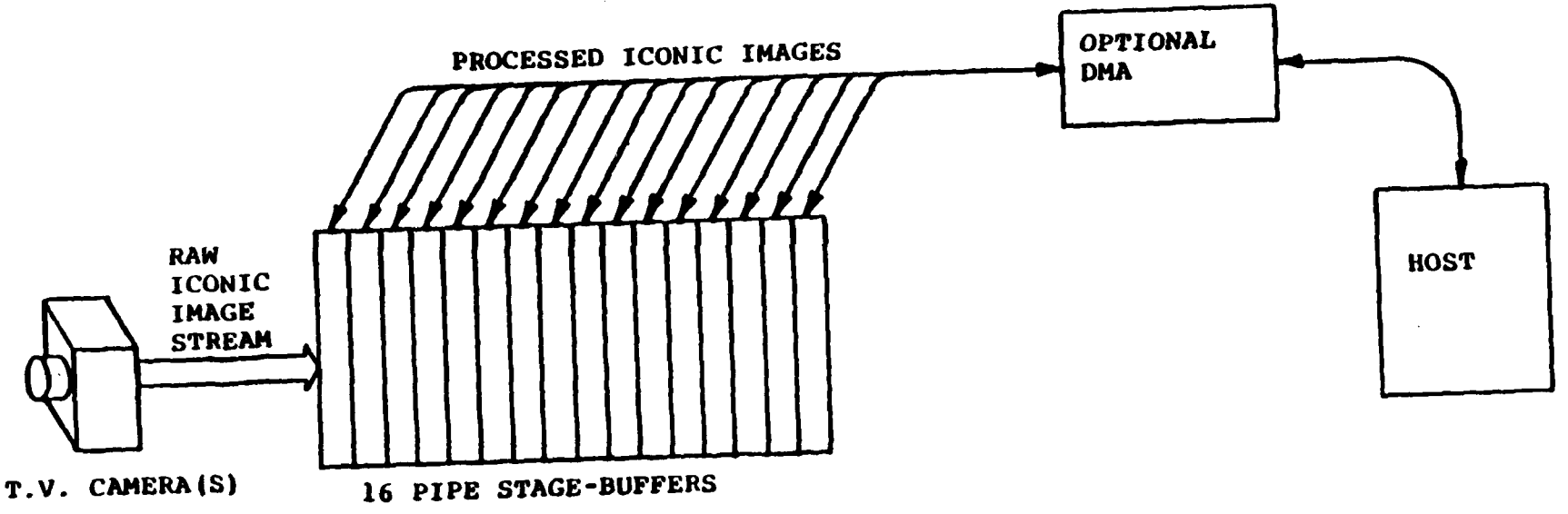


Figure 8. The I/O modes supported by PIPE. a.) streaming pixel I/O, b.) parallel port random access, c.) bi-directional ISMAP operation. *(8 b and 8-c on next pages)*

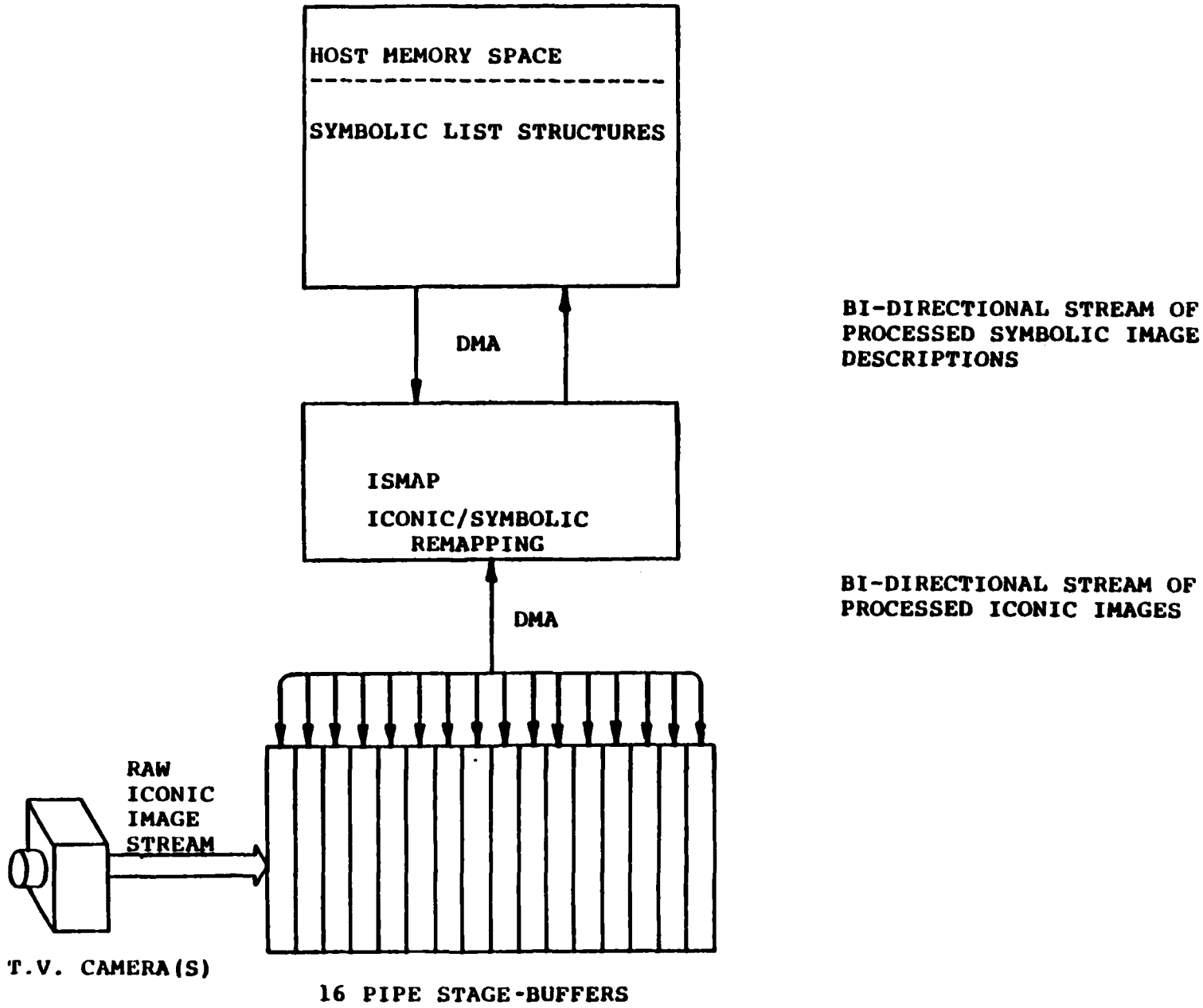
BI-DIRECTIONAL PARALLEL PORT TRANSFERS:

- o RANDOM ACCESS
- o AUTO-INCREMENT
- o DMA



PARALLEL PORT I/O

Fig. 86


HOST MEMORY SPACE
SYMBOLIC LIST STRUCTURES
DMA
ISMAP
ICONIC/SYMBOLIC
REMAPPING
DMA
RAW
ICONIC
IMAGE
STREAM
T.V. CAMERA(S)
16 PIPE STAGE-BUFFERS
BI-DIRECTIONAL STREAM OF
PROCESSED SYMBOLIC IMAGE
DESCRIPTIONS
BI-DIRECTIONAL STREAM OF
PROCESSED ICONIC IMAGES

ISMAP I/O

resolution "fovea" with lower-resolution periphery.) CONMAP will transform images at field rate, and its operation will be transparent to PIPE except for a one-field delay.

PIPE's SYSTEM SOFTWARE.

PIPE is provided with a software toolkit which includes a number of highly-developed programming systems. A simulator exists, although it is not used when a PIPE machine is available, since the other software development tools permit interactive test and debugging of algorithms in real-time on the machine. All PIPE system software is graphics-based and runs in color-coded formats on the screens of the host.

At the bottom level, a software "keyboard" permits interactively displaying and setting any bit, byte, or word in the machine's microcoded operation stores. This can be done while PIPE is running algorithms, and the effects observed. This program can also save code to, or load code from disk files.

Microcoded instruction lists for the operation store can be produced and stored in disk files by a graphics-based assembler. This program presents diagrammatic icons portraying the logical functions of the processing stages on the screen, and interactively fills in data-flow paths and operations as the user specifies them. The program has an expert-system knowledge of PIPE. It will only inquire about options as they become necessary based on user choices, and it will reject contradictory or illegal choices.

Figure 9. demonstrates a PIPE programming diagram. Spatial progression of stages is from left to right. Temporal progression of machine cycles is from top to bottom. A single row indicates the state of the machine in a single field time; a single column indicates the successive states of a single stage. Diagrams such as this illustrate the space-time systolic nature of PIPE programs, and can be transferred directly to the graphics screens of the system software tools for program generation.

Another graphics-oriented program, similar to an assembler, generates programs for the global sequencer which, in turn, controls selection of words in the micro-operation stores of all PIPE's stages on a cycle-by-cycle basis. This program generates disk files which can be loaded into PIPE's system controller.

PIPE employs many tables of great complexity. A table-generating program is available to simplify their production. For example, extremely complex tables are required for the bit-slice arithmetic in the convolvers. The table entries have no simple

relationship to the weights of the neighborhood mask. The table-generating program will present a graphic representation of the neighborhood, query the user for mask values, and prepare the required tables and save them in disk files for later loading into PIPE. A variety of other table types are also handled. A related program finds the optimal sequence of 3 x 3 kernels for the production of any N x N convolution.

At the next level, PIPE is programmable in PIPE Command Language (PCL). In PCL, it is possible to refer to stages, storage areas, and operational units of the machine, to command their states, and to load them from buffers in the host.

A graphics-oriented interactive monitor program permits real-time manipulation of PIPE with PCL. This functions much like a low-level monitor program on a traditional computer, except that the command set is the full set of a powerful macro-assembly language for the machine. The monitor is useful principally in debugging programs that have been generated by other means, but it is possible to build short test programs with it.

The principal means of generating PCL programs is by means of a low-level compiler which accepts commands in PIPE Intermediate Format (PIF). PIF is a higher-level language which permits the programmer to command successive states of machine operations, to refer to named disk files, and to associate the files with the machine entities. Such files may be the micro-operation lists, sequencer programs, and tables generated by auxiliary programs. These files represent operations of broad general utility, and form a library upon which PIF programmers can draw.

This compiler can operate either from PIF programs stored in disk files, or interactively with the user as he issues PIF commands. Most of the existing applications software for PIPE has been written in PIF. It is intended as the intermediate format which will be generated by compilers for higher-level image-processing languages now under construction.

Software tools already available for PIPE would permit a competent PIPE programmer to write all PIPE software required for most applications at a realistic level and with reasonable efficiency, although the task would be made easier if higher-level software tools currently being produced were available now. A growing body of basic application routines, for feature detection, image enhancement, and similar elementary functions already exists. About one day's time is sufficient for a

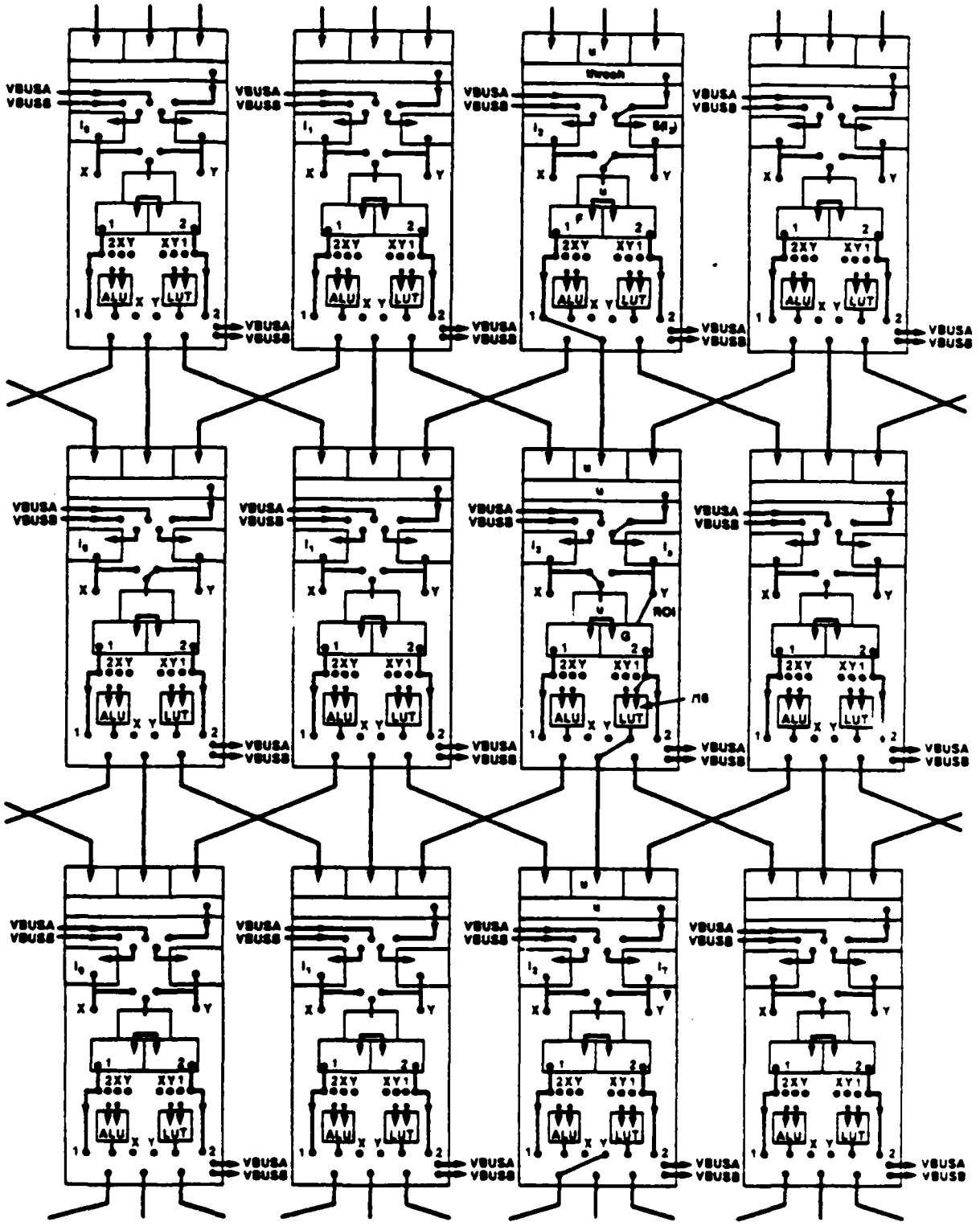


Figure 9. A PIPE programming diagram. Spatial progression of stages is from left to right. Temporal progression of machine cycles is from top to bottom. A single row indicates the state of the machine in a single field time; a single column indicates the successive states of a single stage.

competent programmer to write such a routine. Experience suggests that a doctoral-level computer scientist can become an expert PIPE programmer in less than one month's time.

DISCUSSION.

PIPE is designed as a front-end processor for low-level iconic-to-iconic image processing. It is intended to perform transformations on images to extract features similar to those in the primal sketch of Marr.[7] These features make intensity changes and local geometric relations explicit in images, while maintaining the spatial representation. In this, PIPE differs from many processors designed for image-processing. These other processors are usually designed to perform both local and global image-processing tasks, often in an interactive environment.

A recent survey by Reeves[8] divides image-processing tasks into two classes. Low level image processing usually modifies parts of images, but maintains the image array. Higher level processing, however, works on symbolic representations of the contents of images. Low level processing has usually given rise to architectures based on single instruction stream, multiple data stream (SIMD) structures. The higher level functions are usually carried out using processors based on multiple instruction stream, multiple data stream (MIMD) structures. The design of PIPE allows it to act as a SIMD pipeline, or as a (restricted) MIMD pipeline. The MIMD mode is entered whenever the region-of-interest operators are used. The limitations on these operators are that there are at most 256 different operators available per stage, and that using the region of interest generally precludes using some other operators, such as the functions of two arguments. Using the retrograde pathway to insert expectations from the host into the image analysis process also blurs the distinction between high level and low level processes.

Some general features of PIPE's architecture, multiple pipelined planes of processing, and the concept of the iconic-to-symbolic remapping performed by ISMAP, are drawn in spirit from a more elaborate machine proposed but never constructed by McCormick, Kent, and Dyer.[1,2] That device was in turn inspired by certain observations on the nature of processing in the visual cortex. Although PIPE is in some respects a simpler device, it also carries that analogy further with the implementation of the backward pathway which emulates the connectivity in the biological vision system, where, with the exception of the final link between the retina and the lateral geniculate nucleus, there are in fact more fibers descending from higher to lower

levels of processing than vice versa. The arrangement of interactions among the three pathways, with combination of images into stage buffers and separate operations available into emerging pathways also is drawn from this model.

CONCLUSIONS.

This paper has described a new image pre-processor, consisting of a sequence of identical stages, each of which can perform a number of point and neighborhood operations. An important feature of the processor is the provision of forward, recursive, and backward paths to allow image data to participate in temporal as well as spatial neighborhood operations. The backward pathway also allows expectations or image models to be inserted into the system by the host, and to participate in the processing in the same way as images acquired from the input device. The region-of-interest operator is also a powerful, and unique, feature of PIPE, allowing the results of feature-extraction processes to guide further image analysis. PIPE also provides a multi-resolution capability, enabling global events to be made local. This is important in a machine that has only local operators. Much research needs to be done to explore the capabilities of the device but early experiments indicate that the system will have a wide range of applications in low-level real-time image processing.

References

1. B. McCormick, E. W. Kent, and C. Dyer, A Visual Analyzer for Real-Time Interpretation of Time-Varying Imagery., in: "Multicomputers and Image Processing 3.", K. Preston and L. Uhr (Eds.), Academic Press, 1982.

2. B. McCormick, E. W. Kent, and C. Dyer, A Cognitive Architecture for Computer Vision. in: "Fifth Generation Computer Systems.", T. Moto-Oka (Ed.), North Holland, 1982.

3. P. J. Burt, Fast hierarchical correlations with Gaussian-like kernels. Proc. Fifth International Joint Conference on Pattern Recognition, Miami, Florida, 1980.

4. S. L. Tanimoto, A Hierarchical Cellular Logic for Pyramid Computers. J. Parallel and Distributed Computing, 1, 105-132, 1984.

5. C. Weiman, and G. Chaikin, Logarithmic Spiral Grids for Image Processing and Display., Computer Graphics and Image Processing, 11, 197-226, 1979.

6. R. Jain, Segmentation of Frame Sequence Obtained by a Moving Observer., General Motors Research Publications: GMR-4247, 1983.

7. D. Marr, Early processing of visual information. Phil. Trans. Royal Society B.275, 1976.

8. A. P. Reeves, Parallel computer architectures for image processing. Computer Vision, Graphics, and Image Processing 25, 1984, 68-88.

Pattern Recognition Letters 3 (1985) 335-341
North-Holland

September 1985

A new method for characterization of shape

O. SKLIAR* and M.H. LOEW

Department of Electrical Engineering and Computer Science, George Washington University, Washington, DC 20052, USA

Received 28 December 1984
Revised 29 May 1985

Abstract: A method is presented that uses a diffusion-like process to describe the shape of a region. Convexity is not required, the descriptor is invariant under several common transformations, is applicable in the n-dimensional case, and is easy to compute.

Key words: Shape characterization, image-processing, diffusion process, pattern recognition.

1. Introduction

Shape description is an essential component of any image-understanding system. Many approaches to description of shape have been proposed and used in the fields of image processing and computer vision. Pavlidis (1978) suggested a taxonomy of shape descriptors based on: (1) whether just the boundary, or the entire interior of the object was examined (the techniques were called external and internal, respectively); (2) whether the characterization was made on the basis of a scalar transform (in which a picture is transformed into an array of scalar features), or a space transform (a picture is transformed into another picture); and (3) whether the procedure is or is not information-preserving in the sense that the original image can be reconstructed from the shape descriptors.

Existing methods include the $\psi - s$ *curve*, in which ψ is computed as the angle made between a fixed line and a tangent to the boundary of the region; it is plotted against s, the arc length of the boundary traversed. For a closed boundary, the function is periodic, and may be associated with segmentation of the boundary in terms of straight lines and circular arcs (Ballard and Brown, 1982). Other methods evaluate *eccentricity* (or elongatedness) in a variety of ways, including length-to-width ratio and ratio of the principal axes of inertia; *compactness* (e.g., perimeter^2/area, and Danielsson's method (Danielsson, 1979)); the *slope-density function*, which is a histogram of ψ collected over the boundary; *curvature*, the derivative of ψ as a function of s; projections of the figure onto an axis (the *signatures*); *concavity* with a tree of regions that will create the convex hull of the original object; *shape numbers* based on chain-coding of the boundary; and the *medial-axis transform*, which transforms the original object to a stick figure that approximates the skeleton of the figure.

We present here a new shape measure that allows rapid assignment of labels that are both intuitively appealing and rigorously based. The descriptor can be computed easily on existing hardware and may be implemented immediately on future parallel-processing systems. Regions need not be convex (although the modest requirement is imposed that each region be simply-connected; i.e., have a single inside and a single outside). This is a significant advantage in light of the comment by Pavlidis (1978) that there exist a number of shape description techniques applicable *only* to convex objects, while

* Visiting from the Department of Physics, National University of Costa Rica.

0167-8655/85/$3.30

some of the general ones perform much better if restricted to that class. The method described below works equally well for convex and non-convex regions. Further, the approach can be extended immediately to three-dimensional objects.

This is the first in a series of papers examining the behavior of a diffusion-type shape descriptor. With respect to the taxonomy noted above, it is internal, scalar, and non-information preserving.

2. Method

The diffusion-type procedure simulates the release at an initial time of a given number of particles from each pixel along the boundary of a region to be studied. At each instant of discrete time thereafter, new values of pixel contents are computed based on an assumed diffusion constant and the isotropic assumption (i.e, that the diffusion law applies equally in all directions for all parts of the region under study). The process consists of an initial transient and a subsequent steady-state condition. In steady-state all pixels contain the same number of particles. During the transient, however, the number of particles in each boundary pixel depends upon the shape of the boundary. The concentration is greater in concavities than in convexities, with straight or nearly-straight regions having intermediate concentrations. It is necessary therefore to stop the diffusion process during the transient to detect these characteristics of the boundary. When the simulated diffusion process is stopped, the sequence of numbers of particles in the boundary pixels can be used to generate a shape-related code.

This approach is implemented easily on digital computers so that the effects of changes in the following relevant process parameters can be studied: constant of diffusion, stopping-time, and initial number of particles per pixel.

Let $N_{i,j}(t)$ be the number of particles contained in the pixel at coordinates (i, j) at time t. Then the fundamental algorithm to be utilized is:

$$\begin{aligned} N_{i,j}(t+1) = {} & N_{i,j}(t) - 4KN_{i,j}(t) \\ & + K(N_{i-1,j}(t) + N_{i+1,j}(t) \\ & + N_{i,j+1}(t) + N_{i,j-1}(t)). \end{aligned} \tag{1}$$

Equation (1) expresses the requirement that the number of particles in a given pixel of the image at time $t+1$ equals the number of particles that were there at t, minus the number of particles that were transferred by the assumed diffusion process to the (4-)neighboring pixels, plus the number of incoming particles from those same neighbors, based on their respective contents at t. Neighbors that lie outside the region do not participate in the process of equation (1).

Though in this preliminary communication we will consider only the two-dimensional case, the approach can be generalized easily to any number of dimensions. In the three-dimensional case the basic algorithmic equation is:

$$\begin{aligned} N_{i,j,k}(t+1) = {} & N_{i,j,k}(t) - 6KN_{i,j,k}(t) \\ & + K(N_{i-1,k,j}(t) + N_{i+1,j,k}(t) \\ & + N_{i,j-1,k}(t) + N_{i,j+1,k}(t) \\ & + N_{i,j,k-1}(t) + N_{i,j,k+1}(t)). \end{aligned} \tag{2}$$

In general, for the n-dimensional case, if we call $N_{x_1,x_2,\ldots,x_n}(t)$ the number of particles contained in the pixel x at coordinates $x_1, x_2, \ldots, x_n$ at time t, then the following equation will apply:

$$\begin{aligned} & N_{x_1,x_2,\ldots,x_n}(t+1) \\ & = N_{x_1,x_2,\ldots,x_n}(t) - 2nKN_{x_1,x_2,\ldots,x_n}(t) \\ & \quad + K(N_{x_1-1,x_2,\ldots,x_n}(t) + N_{x_1+1,x_2,\ldots,x_n}(t) \\ & \quad + N_{x_1,x_2-1,\ldots,x_n}(t) + N_{x_1,x_2+1,\ldots,x_n}(t) \\ & \quad + \cdots + N_{x_1,x_2,\ldots,x_n-1}(t) + N_{x_1,x_2,\ldots,x_n+1}(t)). \end{aligned}$$

For the problem that we are considering we do not need to adjust the parameter K to experimental data - as should be done in the case of simulation of a real diffusion process of matter or heat. So, for purposes of computation we can assign to K any value in the range $0 < K < 1$. The smaller K is, the higher will be the degree of detail of the results of the diffusion-type process, but of course at the expense of additional computer time. The tradeoff between detail and accuracy on one hand and computer time on the other will be discussed critically in the next paper of this series.

3. Preliminary results

The algorithm was tested with two shapes: a square, and an irregular region. The corresponding results are presented. At the initial time ($t = 0$), 10000 particles were assigned to each boundary pixel for each of the two cases. In the case of the square, the number of particles for each pixel of the image has been computed for times 10, 50, and 100. (See Figures 1a, b, and c, respectively.) For the three cases a value of $K = 0.01$ was used.

9923	9158	9090	9158	9923
9158	1682	949	1682	9158
9090	949	157	949	9090
9158	1682	949	1682	9158
9923	9158	9090	9158	9923

Figure 1(a). Number of particles in each pixel for the square region, with $k = 0.01$. (a) $t = 10$.

8940	7605	7106	7605	8940
7605	4654	3541	4654	7605
7106	3541	2197	3541	7106
7605	4654	3541	4654	7605
8940	7605	7106	7605	8940

Figure 1(b). $t = 50$.

6406	6402	6399	6402	6406
6402	6398	6395	6398	6402
6399	6395	6393	6395	6399
6402	6398	6395	6398	6402
6406	6402	6399	6402	6406

Figure 1(c). $t = 500$.

Let us assume that we establish an order on the boundary of those squares by labeling the pixels with consecutive natural numbers following a clockwise direction, starting at the left uppermost. In Figures 2a, b and c the number of particles on the boundary pixels has been expressed as a function of the number utilized as labels for the pixels, for each of the corresponding cases of Figure 1.

In the case of the irregular shape, only the number of particles of each pixel on the boundary has been shown for times 3 and 10 in Figures 3a and b.

For such irregular shapes the boundary pixels are labeled with consecutive integers, again proceeding clockwise from the left uppermost pixel. Graphics of the same kind as Figure 2 appear as Figure 4 for the irregular shape.

Both for the case of the regular shape (the square) and the irregular one, it can be seen immediately that the number of particles per pixel – the concentration – is higher in concavities than in convexities.

If human shape perception does rely heavily on detection of curvature maxima (Attneave, 1954), then the (positive- and negative-going) peaks in a plot of pixel content-vs.-boundary location (corresponding, respectively, to segments of high con-

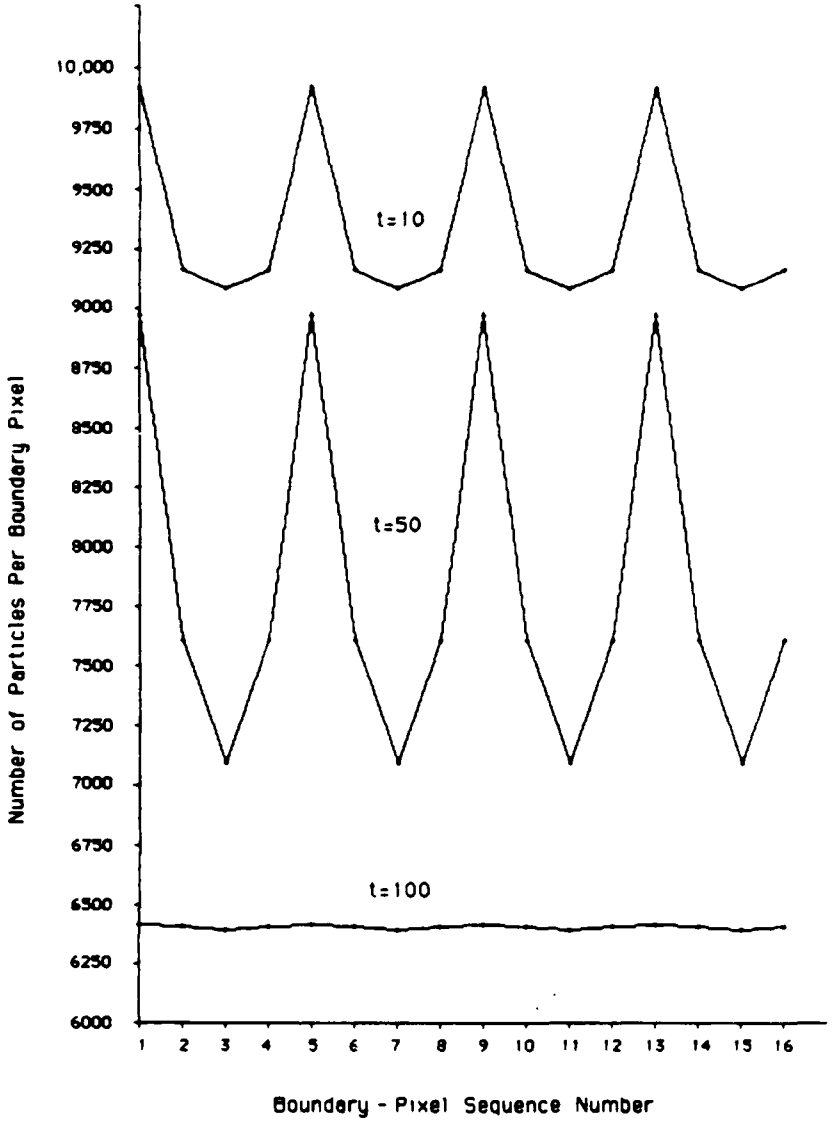


Figure 2. Number of particles for consecutive boundary pixels of the three cases of Figure 3, beginning at the left uppermost. (a) $t = 10$; (b) $t = 50$; (c) $t = 500$.

cavity and convexity) are likely to be useful in identifying those important regions.

4. Conclusions and perspectives

We have presented a new method for describing the shape of a region. The region must be simply-connected, but need not be convex. The descriptor is invariant under translation, rotations by multiples of 90°, and, it appears, under scale changes. It is almost invariant - in a sense that will be made precise in the next paper - under rotations of non-multiples of 90°. It can be implemented easily in hardware (especially on future parallel processors), is as effective in higher dimensions as in two, and will lend itself easily to image-processing and pattern-recognition applications. The method appears to be relatively insensitive to noise (cf. the medial-axis transform, in which very

	7780	7570	7550	7550	7550	7550	7550	7550	7550	7550	7550	7550	7580	8000	9250	
7780															8000	
7570															7600	
7550															7780	
7760												5990	7360	7770		
	6020										4450					
		5990										5990				
			4450										6020	7540		
	7560	6010													6050	
7780																7780
7600								6010	7130	6010						7800
8000					6020	7360	7750				7760	7570	7550	7570	7790	
9250	8000	7580	7570	7760												

Figure 3(a). Number of particles in each boundary pixel for the irregular region (interior pixels' values omitted for clarity), with $k = 0.01$, $t = 3$.

large changes in the axis are produced by very small changes in the boundary (Nevatia, 1982)), does not pose problems with the definition of slope (Rosenfeld and Johnston, 1973) as occurs in the $\psi - s$ curve computation, and appears to be capable of dealing with the matching of partially-occluded shapes (e.g., in the robot vision case), since the diffusion-produced boundary descriptors are likely to be less affected far from the occluding boundary and thus can provide the basis for a partial match to a pre-stored description of a complete boundary. The effects of noise and of occlusion will be studied together in a forthcoming paper.

The effect of changes in the diffusion constant, K, and the time at which the process is stopped will be examined in detail in future papers. A method and its proof are needed that will allow for invariance of the measure under scale changes; these results are expected soon. The present stopping criterion, which terminates the process when the difference between maximum and minimum values along the boundary is maximized, has great intuitive appeal, since we are interested in distinguishing concavities from convexities and can think of this as a sensitivity measure.

Alternatives for the characterization of the results of the diffusion-type process also will be considered in the future. Particle-count plotted against boundary position is not necessarily the most effective representation. Other possibilities are: (1) to normalize the count by subtracting the mean and dividing by the standard deviation, thus providing for the possibility of establishing data-independent criteria for detecting extrema; and (2)

	6006	5235	5116	5114	5113	5114	5113	5114	5116	5126	5171	5326	5782	6711	7682	
6019															6780	
5610															6130	
5494															6148	
5660												3775	4982	5849		
	4099										2406					
		3571										3550				
			2423										4045	4996		
	5284	4039													4664	
6083																6156
6100								3863	4083	3898						6333
6776					4138	4843	5410				5619	5421	5395	5684	6167	
7684	6721	5843	5549	5652												

Figure 3(b). Number of particles in each boundary for the irregular region (interior pixels' values omitted for clarity), with $k = 0.01$, $t = 10$.

to use the first difference along the boundary to detect regions of small and of large change.

Acknowledgements

We appreciate the computer simulation work of Mr. Jean-Fernand Duc, the figures drawn by Ms. Nevine El-leithy, and financial support provided by the U.S. Office of Naval Research under Contract No. N00014-83-K-0578 and by the Center for Devices and Radiological Health, U.S. Food and Drug Administration under Purchase Order FDA-204358-01-4-F100.

References

Attneave, F. (1954). Some informational aspects of visual perception. *Psychol. Rev.* 61, 183-193.

Ballard, D. and C. Brown (1982). *Computer Vision*. Prentice-Hall, Englewood Cliffs, NJ.

Danielsson, P.-E. (1978). A new shape factor. *Computer Graphics and Image Processing* 7, 292-299.

Nevatia, R. (1982). *Machine Perception*. Prentice-Hall, Englewood Cliffs, NJ.

Pavlidis, T. (1978). A review of algorithms for shape analysis *Computer Graphics and Image Processing* 7, 243-258.

Rosenfeld, A. and E. Johnston (1973). Angle detection on digital curves. *IEEE Trans. Comput.* 22, 875-878.

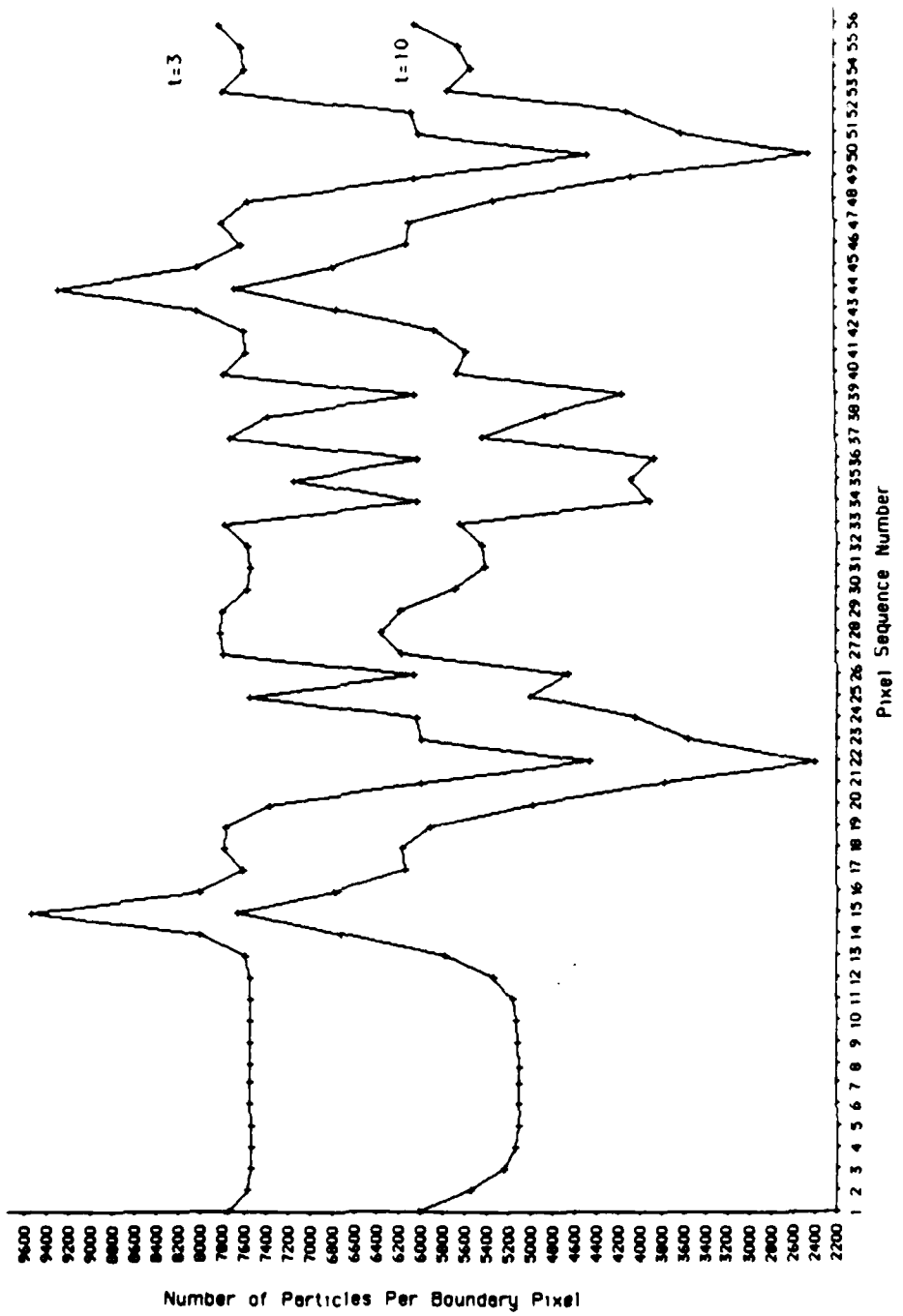


Fig. 4. Number of particles for consecutive boundary pixels of the two cases of Figure 5, beginning at the left uppermost. (a) $t = 3$. (b) $t = 10$.

THE QUADCODE AND ITS ARITHMETIC

Shu-Xiang Li* and Murray H. Loew**

*Dept. of Automatic Control, Changsha Institute of Technology
Changsha City, Hunan Province, China
**Dept. of Electrical Engineering and Computer Science
George Washington University, Washington, D.C. 20052, USA

INTRODUCTION

The quadcode is a hierarchical data structure for describing digital images. It has the following properties:

- Straightforward representation of dimension, size, and the relationship between an image and its subsets.

- Explicit description of geometric properties, such as location, distance, and adjacency.

- Ease of conversion from and to raster representation.

The quadcode has applications to computer graphics and image processing because of its ability to focus on seleted subsets of the data and to allow utilization of multiple resolutions in different parts of the image. A related approach is the quadtree. Samet recently presented a thorough survey of the literature in that field [1]. Gargantini [2] and Abel [3] presented linear quadtrees and linear locational keys which are efficient labeling techniques for quadtrees. In those papers, the geometric concepts of the image are discussed by using the tree as an

interpretive medium, and the approaches and procedures are based on traversal of the nodes in the tree. In this paper we present the quadcode system which is a direct description of the image, and discuss the geometric concepts in terms of the coded images.

1. QUADCODE

1.1 QUADCODE

The quadcode is a quaternary (base 4) code. A quadcode of length n is of the form

$$Q = q_1 q_2 \cdots q_n$$

where $q_i = 0,1,2,3$ for $i = 1,2,\ldots,n$.

When the quadcode is used in describing an image, each character represents one operation of subdividing the image or its subimage into quadrants, as shown and labeled in Fig. 1.

Fig. 1

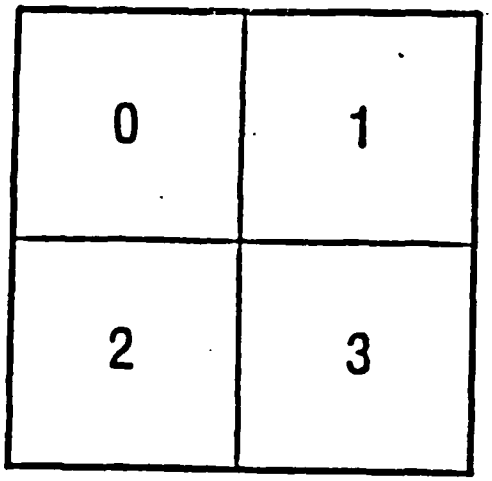


Fig. 1 Quadcodes and Quadrants

In many applications (e.g., smoothing, edge detection, shape description) an image is usually subdivided into much smaller units, so the subdividing operation can be repeated recursively many times, until there is no further subdividing needed. Fig. 2 shows the subdividing process and the corresponding quadcodes. A particular quadrant is represented by one of 0, 1, 2, or 3, concatenated to the quadcode of its predecessor, and after each subdividing operation the length of the quadcode increases by one. As shown in the figure, the quadcode length signifies how many subdividing operations have been done.

Fig. 2

1.2 PROPERTIES OF THE QUADCODE

Property 1 (qc length)

The quadcode length of individual pixels in a 2^n by 2^n image is n.

Property 2 (dimension)

The side length of a subimage with quadcode length m in a 2^n by 2^n image is 2^{n-m}.

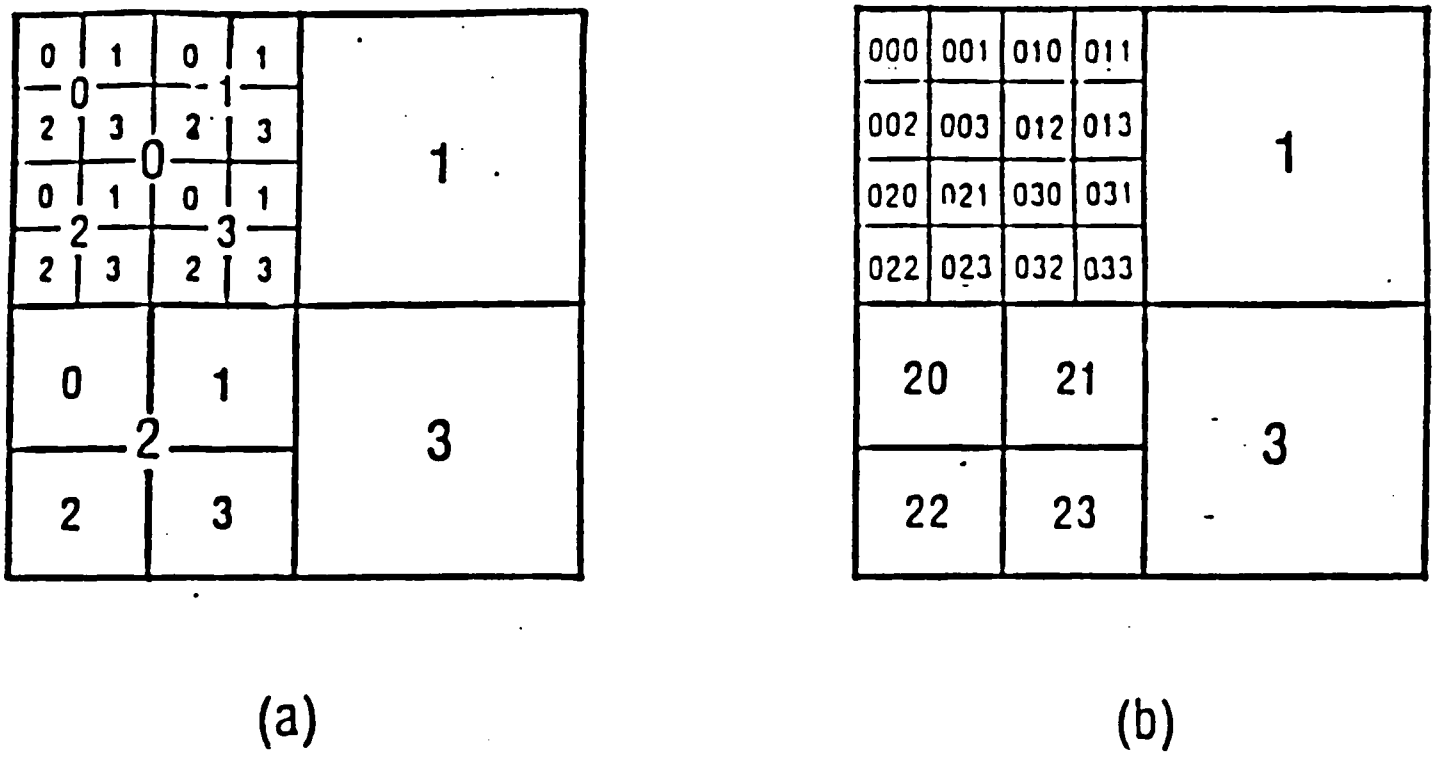


Fig. 2 Subdividing and Quadcode Representation

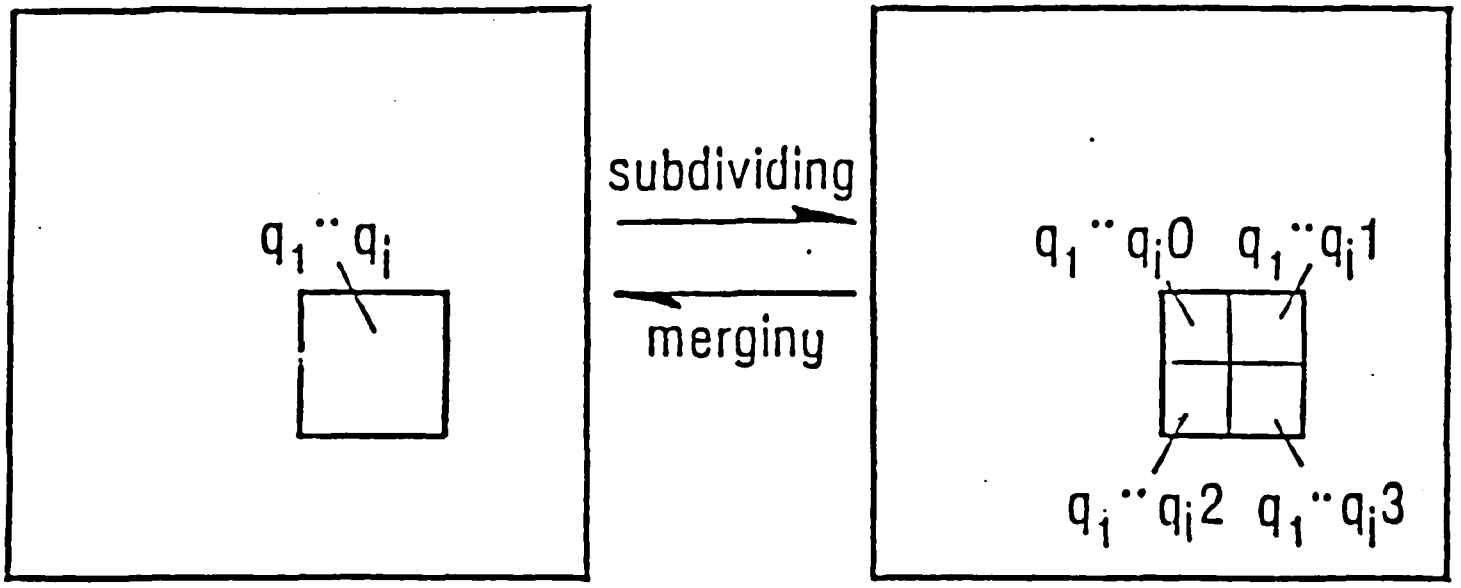


Fig. 3 Subdividing and Merging

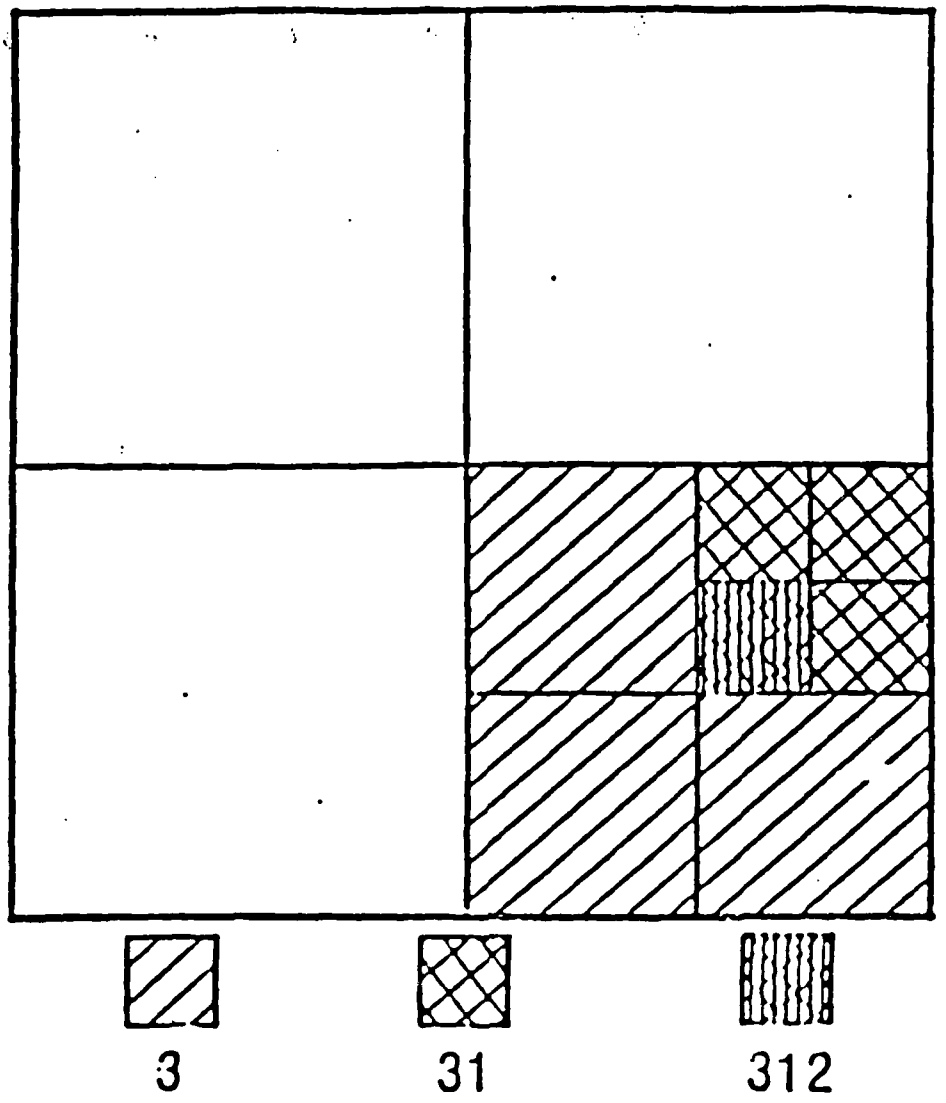


Fig. 4 Locating A Subimage Using Quadcode

Property 3 (area)

The area of a subimage with quadcode length m in an image of area A_0 is $4^{-m}A_0$.

Property 4 (subdividing)

Adding one character to a given quadcode subdivides the given subimage into its quadrants (see Fig. 3).

Fig. 3

Property 5 (merging)

If four quadcodes of length i have the first i-1 positions the same, they represent the four quadrants of the same subimage which is represented by the (i-1)-position quadcode (Fig. 3).

Property 6 (locating)

A subimage can be located in an image according to each position of its quadcode, which is equivalent to subdivision of the initial image (see Fig. 4).

Fig. 4

Property 7 (conversion)

Write the quadcode and array labels i,j of a pixel in a 2^n by 2^n image (i,j are supposed to be from 0 to 2^n-1) all into binary form, it can be proved [4] that

$$q_1 q_2 \cdots q_n = i_1 j_1 i_2 j_2 \cdots i_n j_n \qquad (1)$$

or

$$\left.\begin{aligned} i &= \sum_{k=1}^{n} (q_k \text{ DIV } 2) * 2^{n-k} \\ j &= \sum_{k=1}^{n} (q_k \text{ MOD } 2) * 2^{n-k} \end{aligned}\right\} \qquad (2)$$

$$Q = \sum_{k=1}^{n} (2i_k + j_k) * 4^{n-k} \qquad (3)$$

In equations (1), (2), and (3), q_k, i_k, j_k (k=1,...,n) represent the k-th position of the quadcode and array labels i,j, respectively. The equations show that the array labels i,j are the same as the two binary numbers which compose the odd and even bits of the quadcode when written in binary. This is represented in Table 1 where the two axes are array labels (or coordinates) i,j; the entries give the corresponding quadcodes in both binary and quaternary forms.

Table 1

i_1i_2 \ j_1j_2 / $i_1j_1i_1i_2$ / q_1q_2	00	01	10	11
00	0000	0001	0100	0101
01	0010	0011	0110	0111
10	1000	1001	1100	1101
11	1010	1011	1110	1111

2. ANALYSIS OF ELEMENTARY SQUARES

2.1 ELEMENTARY SQUARES

When a quadcode can represent a subset of an image, we call the subset an *elementary square.*

For example, in Fig. 5 there are two elementary squares and their quadcodes are A = 12 and B = 221. In general, an elementary square in a 2^n by 2^n image can be represented by $q_1 \ldots q_m$ where $m \leq n$.

The size of an elementary square with quadcode length m is 2^{n-m} by 2^{n-m}. For instance, in Fig. 5 the size of elementary square A is 2^{3-2} by 2^{3-2}, i.e., 2 by 2, and the size of B is 2^{3-3} by 2^{3-3}, i.e., 1 by 1.

Fig. 5

2.2 LOCATION

If we know the size of a given elementary square, we can locate it by the coordinates of one of the characteristic points in the square. We choose the upper left corner point as the characteristic point. Then, from Eq. (2),

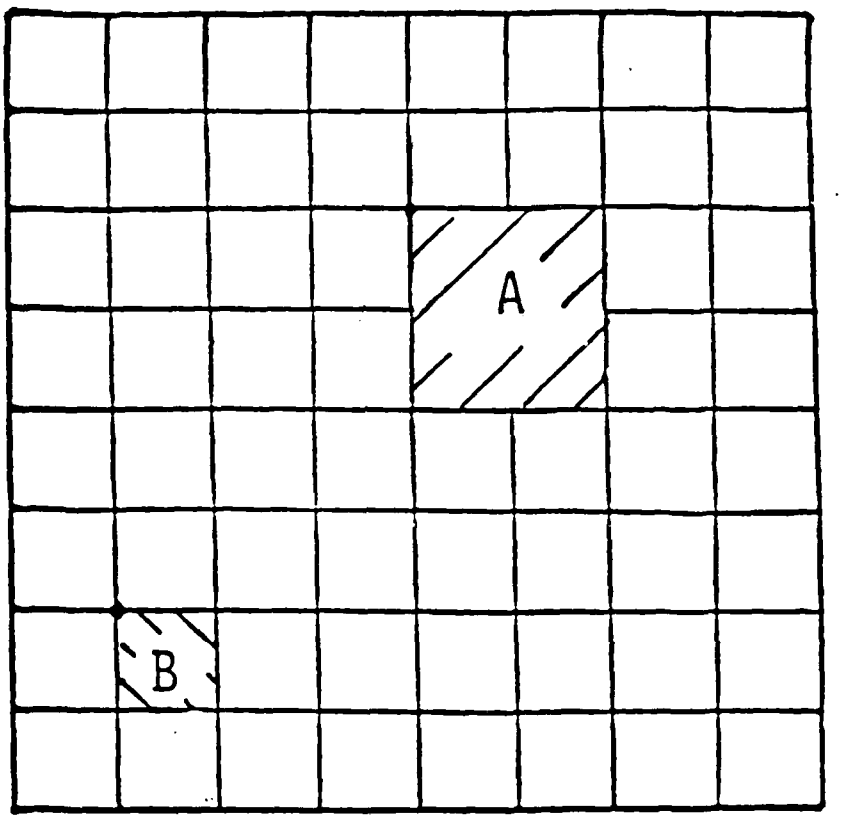
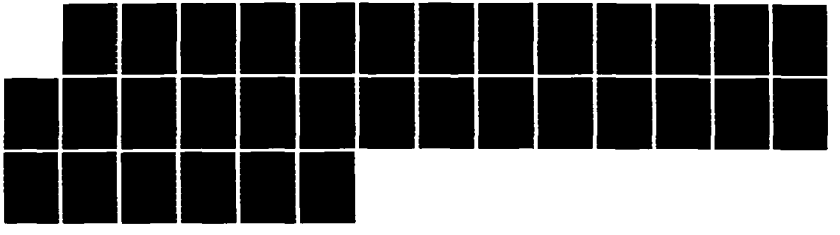
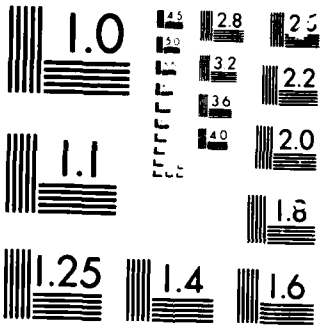


Fig. 5 Location and Distance

AD-A168 197 DEVELOPMENT OF ALGORITHMS AND HARDWARE FOR STRUCTURED-LIGHT VISION(U) GEORGE WASHINGTON UNIV WASHINGTON DC DEPT OF ELECTRICAL ENGIN.. 4/4

UNCLASSIFIED M H LOEW ET AL. 1986 N00014-83-K-0578 F/G 20/6 NL




1.0
1.1
1.25
1.4
1.6
2.8
3.2
3.6
4.0
2.2
2.0
1.8

A and B, and S_U is the vertical side length of the uppermost of the elementary square. Because the quadcodes of A, B give their dimensions and their horizontal and vertical locations, both S_L and S_U can be obtained from their quadcodes.

For example, in Fig. 5 A = 12, B = 221; the leftmost elementary square is B, and the uppermost is A.

Then,

$$x(A) = 4 \qquad y(A) = 2$$

$$x(B) = 1 \qquad y(B) = 6$$

$$S_L = S_B = 2^{3-3} = 1 \qquad S_U = S_A = 2^{3-2} = 2$$

Hence, the distance between A, B is

$$D_x(A,B) = |1-4| - 1 = 2$$

$$D_y(A,B) = |6-2| - 2 = 2$$

as shown in Fig. 5.

2.4 ADJACENCY

The detection of connectivity is a basic and important subject in image analysis. The general condition of adjacency for elementary squares is the following:

$$D_x(A,B) \cdot D_y(A,B) = 0$$
$$D_y(A,B) + D_y(A,B) \leq 0 \qquad (6)$$

$$\left.\begin{aligned} x &= \sum_{k=1}^{m} (q_k \text{ MOD } 2) * 2^{n-k} \\ y &= \sum_{k=1}^{m} (q_k \text{ DIV } 2) * 2^{n-k} \end{aligned}\right\} \qquad (4)$$

For example, the locations of the squares A = 12, B = 221 in Fig. 5 are

$$x(A) = \sum_{k=1}^{2} (q_{Ak} \text{ MOD } 2) * 2^{3-k} = 4$$

$$y(A) = \sum_{k=1}^{2} (q_{Ak} \text{ DIV } 2) * 2^{3-k} = 2$$

and

$$x(B) = \sum_{k=1}^{3} (q_{Bk} \text{ MOD } 2) * 2^{3-k} = 1$$

$$y(B) = \sum_{k=1}^{3} (q_{Bk} \text{ DIV } 2) * 2^{3-k} = 6$$

2.3 DISTANCE

The distance between two elementary squares A and B is composed of the smallest distances between any points on the boundaries of the two elementary squares in both horizontal and vertical directions, and they are calculated by

$$\begin{aligned} D_x (A,B) &= |x(B) - x(A)| - S_L \\ D_y (A,B) &= |y(B) - y(A)| - S_U \end{aligned} \qquad (5)$$

where S_L is the horizontal side length of the leftmost of the two elementary squares

Proof

If $D_x(A,B) = 0$, then $D_y(A,B) \leq 0$.

According to the first equation of (5), $D_x(A,B) = 0$ means that the right side of the far left square is co-linear with the left side of the far right square. And according to the second equation of (5) $D_y(A,B) \leq 0$ means that either the upper left corner of the far right square is on the right side of the far left square (see Fig. 6(a)), or the upper right corner of the far left square is on the left side of the far right square (see Fig. 6(b)). If $D_y(A,B) = 0$, then $D_x(A,B) \leq 0$ and the proof is the same.

In Fig. 7 there are three elementary squares A = 1, B = 221, C = 310. According to equation (5), the distances among them are

$$D_x(A,B) = 2 \qquad D_x(A,C) = -2 \qquad D_x(B,C) = 4$$

$$D_y(A,B) = 2 \qquad D_y(A,C) = 0 \qquad D_y(B,C) = 1$$

so, $D_x(A,B) \cdot D_y(A,B) = 4$, $D_x(B,C) \cdot D_y(B,C) = 4$

and $D_x(A,C) \cdot D_y(A,C) = 0$, $D_x(A,C) + D_y(A,C) = -2$

In view of Eqs (6), we observe that elementary squares A, C are adjacent, but A, B and B, C are not, as shown in Fig. 7.

Equation (6) is the general adjacency condition for elementary squares of any size. For the connectivity detection of pixels, $S_L = S_U = 1$, the distance equation (5) becomes

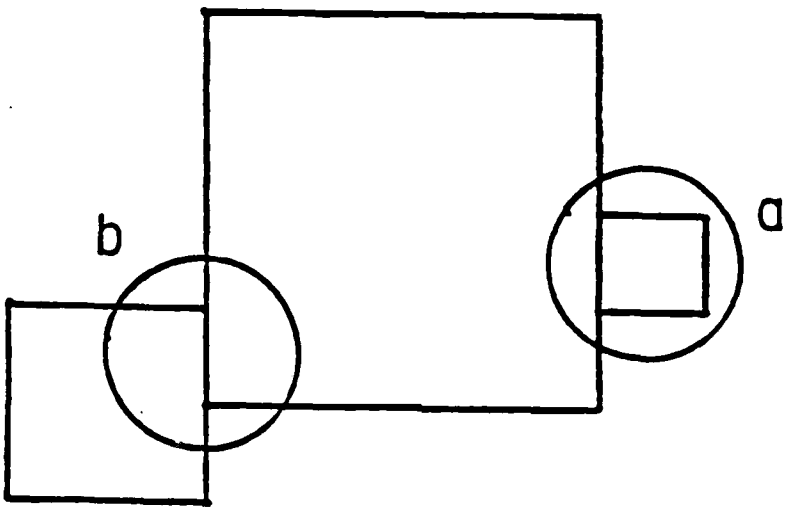


Fig. 6

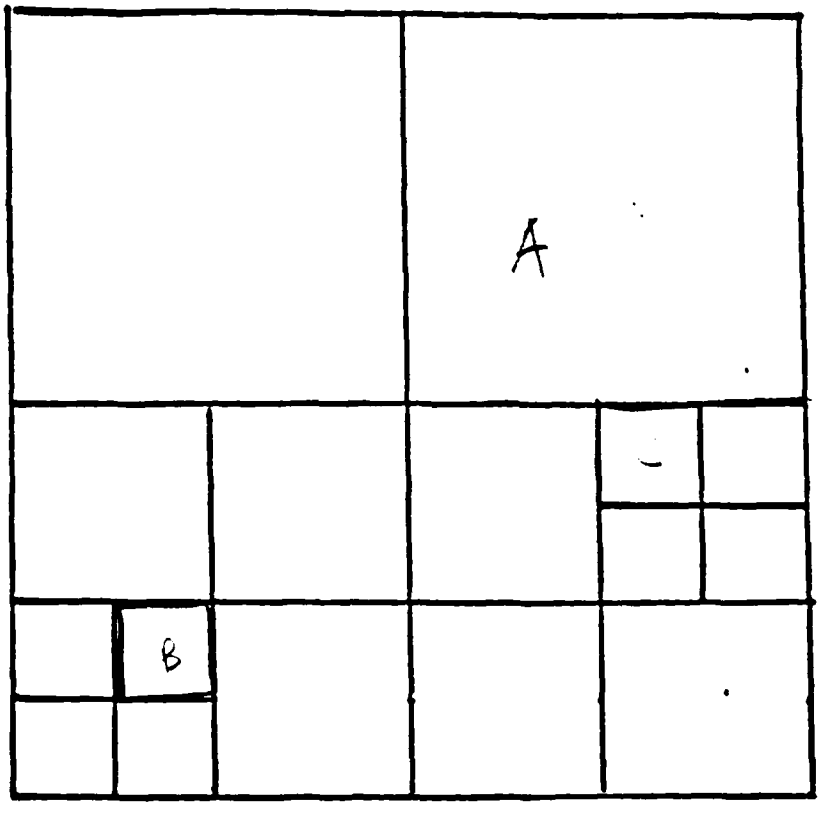


Fig. 7 Adjacency

$$D_x(p_1,p_2) = |x(p_2) - x(p_1)| - 1 \qquad (7)$$
$$D_y(p_1,p_2) = |y(p_2) - y(p_1)| - 1$$

and adjacency condition (6) becomes

$$\max(|x(p_2) - x(p_1)|, |y(p_2) - y(p_1)|) = 1 \qquad (8)$$
$$\text{or} \quad |x(p_2) - x(p_1)| + |y(p_2) - y(p_1)| = 1$$

Equations (5) and (6) can be extended to detect the connectivity of elongated regions, if we know their locations (still represented by the coordinates of their upper left corner points) and the lengths of their sides.

Fig. 7

3. REGION REPRESENTATION AND ANALYSIS

3.1 REGION REPRESENTATION

In quadcode representation, a region is represented as a set of quadcodes

$$R = \{Q_n\} \qquad n = 1,\ldots,N \qquad (9)$$

where each element represents an elementary square in region R, and N is the total number of those elementary squares in region R.

For example, the region in Fig. 8 can be represented as

$$R = \{03,120,121,21,230,231,300,301,320,321\}$$

Fig. 8

3.2 SET ARITHMETIC FOR QUADCODES

Suppose A, B are the quadcodes of two elementary squares

$$A = a_1,\ldots,a_k$$

$$B = b_1,\ldots,b_m$$

and $k \leq m$

THEOREM 1

The intersection of two such quadcodes is either empty or the longer quadcode:

$$a_1,\ldots,a_k \underset{k\leq m}{\cap} b_1,\ldots,b_m = \begin{cases} b_1,\ldots,b_m & \text{if } a_1,\ldots,a_k = b_1,\ldots,b_k \\ 0 & \text{otherwise} \end{cases} \qquad (10)$$

Proof

(1) $a_1,\ldots,a_k = b_1,\ldots,b_k$

$B = b_1,\ldots,b_m = a_1,\ldots,a_k b_{k+1},\ldots,b_m \subset a_1,\ldots,a_k = A$

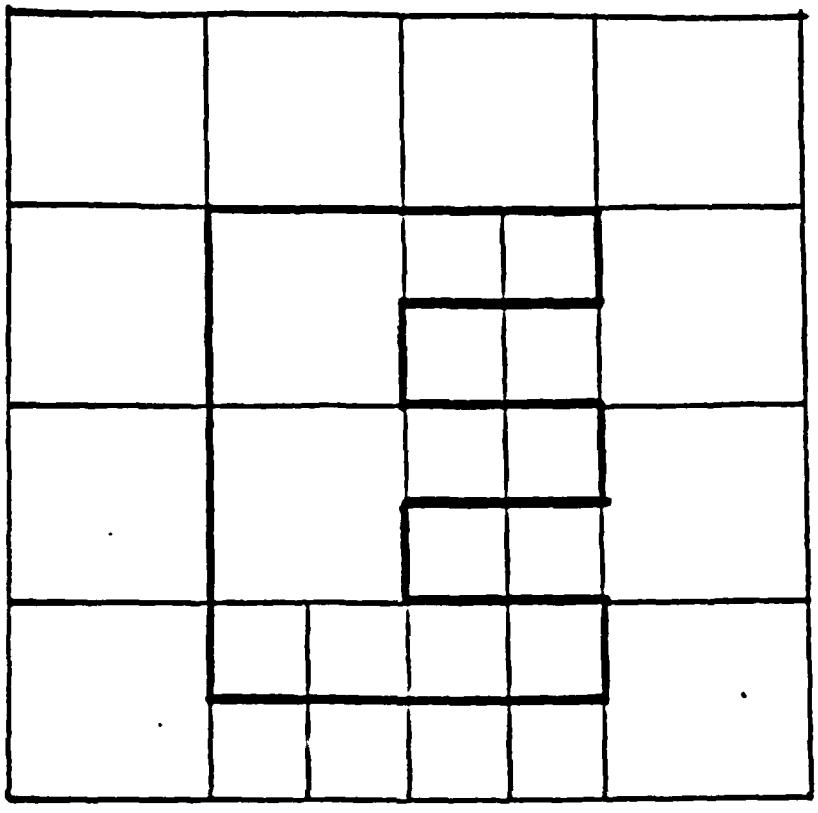


Fig. 8 Quadcode Set of a Region

(2) $a_1,\ldots,a_k \neq b_1,\ldots,b_k$

According to the definition of the quadcode,

$a_1,\ldots,a_k \cap b_1,\ldots,b_k = 0$ and $b_1,\ldots,b_m \subset b_1,\ldots,b_k$ Q.E.D.

THEOREM 2

The union of two such quadcodes is either then concatenation or the shorter quadcode:

$$a_1,\ldots,a_k \underset{k\leq m}{\cup} b_1,\ldots,b_m = \begin{cases} a_1,\ldots,a_k & \text{if } a_1,\ldots,a_k = b_1,\ldots,b_k \\ \{a_1,\ldots,a_k,b_1,\ldots,b_m\} & \text{otherwise} \end{cases}$$

The proof is as the above.

The laws of set arithmetic are true for quadcode sets too, and they include the commutative, associative, and distributive laws, as well as de Morgan's law.

3.3 UNION AND INTERSECTION

DEFINITION

The UNION of two regions is represented by the union of the sets of the two regions.

For example, in Fig. 9 there are two regions

A = {12, 211, 3} and B = {03, 1, 21, 310}

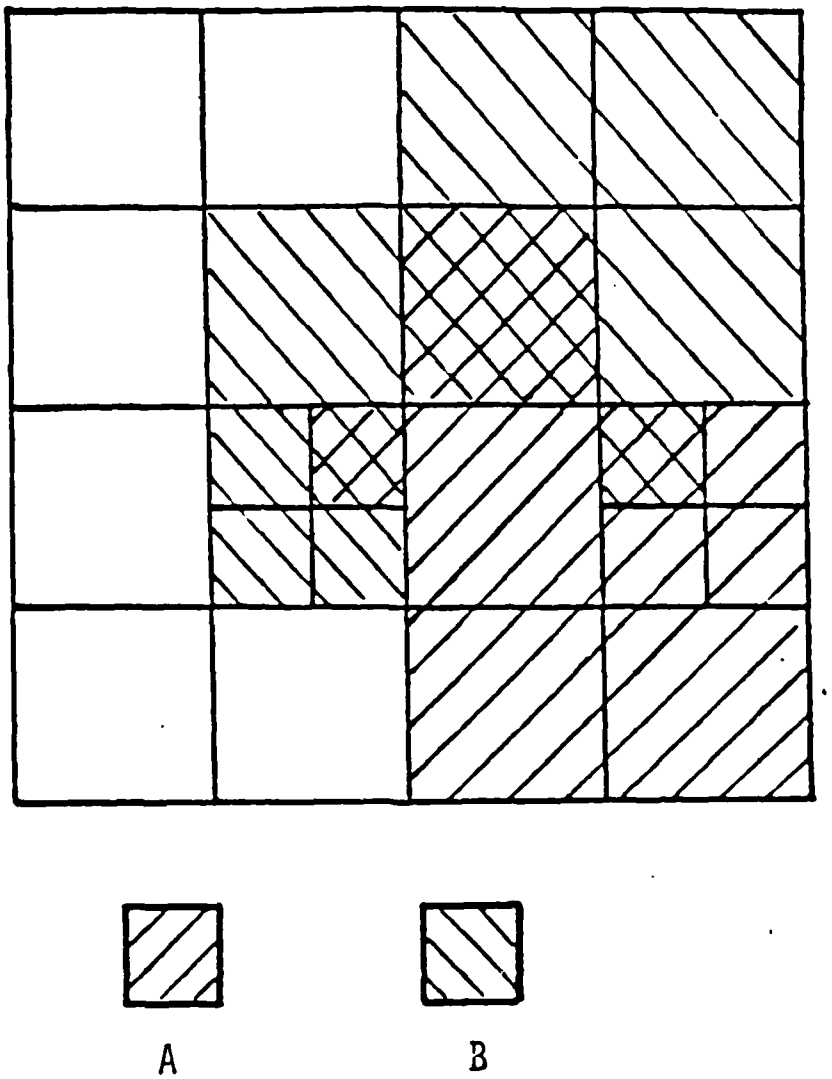


Fig. 9 Union and Intersection

The union of A, B, according to (10) is

$$A \cup B = \{12, 211, 3\} \cup \{03, 1, 21, 310\}$$
$$= \{03, 1 \cup 12, 21 \cup 211, 3 \cup 310\}$$
$$= \{03, 1, 21, 3\}$$

DEFINITION

The INTERSECTION of two regions is represented by the intersection of the sets of the two regions.

According to (9),

$$A \cap B = \{12, 211, 3\} \cap \{03, 1, 21, 310\}$$
$$= \{1 \cap 12, 21 \cap 211, 3 \cap 310\}$$
$$= \{12, 211, 310\}$$

as shown in Fig. 9.

Fig. 9

CONCLUSIONS

In the paper we introduced the quadcode system, discussed its geometric properties, analyzed the geometric concepts of elementary squares, and presented the quadcode set representation of regions. From the discussion we see that the information-compact and intrinsic hierarchical characteristics of the quadcode benefits the representations and analysis by making them more intuitive and more easily computed. The quadcode can also be used in a tree-structured representation. In earlier work [5] and [6] we discussed the quadcode-labeled tree (the qc-tree), discussed the storage efficiency [5], and the applications of the qc-tree, such as boundary search [6]. Instead of using a tree as the interpretive medium, transferring a image into the tree, performing the processing by traverse and search of the tree, and then transferring back to the image, this paper discussed opportunities and methods for analysis directly on the coded image. In a companion paper [7], we discuss adjacency detection and perform all the computation in terms of quadcodes.

The properties and the results presented here for 2-D images can be extended to 3-D images, where the octcode combines the coordinates of three dimensions into one code. In binary form, each position of the octcode is composed of, respectively, z, y, and x coordinate

$$O_i = z_i y_i x_i$$

and the so-constructed octcode is also an intrinsically hierarchical coding system.

REFERENCES

[1] H. Samet, "The quadtree and related hierarchical data structure", Computing Surveys, Vol. 16, No. 2, June 1984.

[2] I. Gargantini, "An effective way to represent quadtrees", Comm. ACM, Vol. 25, No. 12, Dec. 1982.

[3] D.J. Abel and J.L. Smith, "A data structure and algorithm based on a linear key for a rectangle retrival problem", CGIP, Vol. 24, No. 1, Oct. 1983.

[4] S.X. Li and M.H. Loew, "Quadcodes and their application in image processing", George Washington University, Dept. of EECS, GWU/IIST Rept. No. 83-15, Oct. 1983.

[5] S.X. Li and M.H. Loew, "The quadcode and its application", Proc. Seventh ICPR Conf., Montreal, Canada, July 1984.

[6] S.X. Li and M.H. Loew, "Boundary chain codes from quadcode trees", Proc. IEEE 1984 Computer Vision Conf., Annapolis, MD, May 1984.

[7] S.X. Li and M.H. Loew, "Adjacency detection using quadcodes", George Washington University, Dept. of EECS, GWU/IIST Rept. No. 84-52, Dec. 1984.

ADJACENCY DETECTION USING QUADCODES

Shu-Xiang Li* and Murray H. Loew**
*Dept. of Automatic Control, Changsha Institute of Technology
Changsha City, Hunan Province, China
**Dept. of Electrical Engineering and Computer Science
George Washington University, Washington, D.C. 20052 U.S.A.

INTRODUCTION

A method is presented for determining whether two given regions are adjacent, and for finding all the neighbors of different sizes for a given region. Regions are defined as elementary squares of any size. In a previous paper [1] we introduced the quadcode and discussed its use in representing geometric concepts in the coded image, such as location, distance, and adjacency. In this paper we give a further discussion of adjacency in terms of quadcodes. Gargantini [2] discussed adjacency detection using linear quadtrees. Her discussion was applied to pixels and a procedure was given to find only a pixel's southern neighbor. This paper considers elementary squares of any size, and gives procedures for both aspects of the problem: to determine whether two given regions are adjacent, and also to find all the neighbors of different sizes for a given region.

1. ADJACENCY DETECTION

1.1 Adjacency for Elementary Squares of Same Size

An elementary square is a square region which can be represented by a quadcode. Suppose two elementary squares A, B in a 2^n by 2^n image are the same size and their quadcodes are of length m

$$A = a_1 \ldots a_m$$

$$B = b_1 \ldots b_m$$

and $m \leq n$.

We use bit operations and without loss of generality suppose d_k is the leftmost nonzero difference, i.e.,

$$b_i - a_i = 0 \quad \text{for} \quad i<k$$

$$b_k - a_k = d_k \neq 0$$

THEOREM

For A, B to be adjacent (4-neighbor), they should satisfy

$$b_i - a_i = -d_k \tag{1}$$

for all $k < i \leq m$ and $d = \pm 1$ or ± 2, and where the a_i and b_i are terms of the quadcode defined above.

PROOF

We give the proof in the case $m = n$; the proof for other cases will be similar. When $m = n$, A and B are pixels and the adjacency condition [1] is

$$|x(B) - x(A)| + |y(B) - y(A)| = 1 \tag{2}$$

i.e., (i) $x(B) - x(A) = \pm 1$ and $y(B) - y(A) = 0$

or (ii) $x(B) - x(A) = 0$ and $y(B) - y(A) = \pm 1$

In case (i), A, B are horizontally adjacent, $\Delta x(A,B) = \pm 1$, $\Delta y(A,B) = 0$ and $d_k = \pm 1$

$$b_1 \ldots b_n - a_1 \ldots a_n$$

$$= (b_k - a_k)2^{n-k} + \sum_{i=k+1}^{n} (b_i - a_i) \cdot 2^{n-i}$$

$$= d_k \cdot 2^{n-k} + \sum_{i=k+1}^{n} (b_i - a_i) \cdot 2^{n-i}$$

Because $b_1 \ldots b_n - a_1 \ldots a_n = \Delta x(A,B) = \pm 1$ and $d_k = \pm 1$

$$\sum_{i=k+1}^{n} \left(b_i - a_i\right) 2^{n-i} = -\left(d_k \cdot 2^{n-k} \mp 1\right)$$

$$= -\sum_{i=k+1}^{n} d_k \cdot 2^{n-i}$$

$$= \sum_{i=k+1}^{n} \left(-d_k\right) \cdot 2^{n-i}$$

Hence, $b_i - a_i = -d_k \qquad i = k+1, \ldots n$

In case (ii), A, B are vertically adjacent, $\Delta y(A,B) = \pm 1$, $\Delta x(A,B) = 0$. Because in the quadcode structure, coordinate y has weight of 2, $d_k = \pm 2$, then

let $d_k' = \frac{d_k}{2}$ and $d_k' = \pm 1$.

$$\Delta y(A,B) = b_1 \ldots b_n - a_1 \ldots a_n$$

$$= \left(\frac{b_k - a_k}{2}\right) \cdot 2^{n-k} + \sum_{i=k+1}^{n} \left(\frac{b_i - a_i}{2}\right) \cdot 2^{n-i}$$

$$= d_k' \cdot 2^{n-k} + \sum_{i=k+1}^{n} \left(\frac{b_i - a_i}{2}\right) \cdot 2^{n-i} = \pm 1$$

$$\sum_{i=k+1}^{n}\left(\frac{b_i-a_i}{2}\right)\cdot 2^{n-i} = -\left(d_k'\cdot 2^{n-k}\mp 1\right)$$

$$= -\sum_{i=k+1}^{n} d_k'\cdot 2^{n-i}$$

$$= \sum_{i=k+1}^{n}\left(-d_k'\right)\cdot 2^{n-i}$$

Hence, $b_i - a_i = 2\left(-d_k'\right) = -d_k$ Q.E.D.

For example, in Fig. 1(a) there is a pixel A = 123 in a 2^3 by 2^3 image.

Eastern neighbor E = 132 , $d_k = d_2 = 1$ and $d_3 = -1$

Western neighbor W = 122 , $d_k = d_3 = -1$

Southern neighbor S = 301 , $d_k = d_1 = 2$ and $d_2 = d_3 = -2$

Northern neighbor N = 121 , $d_k = d_3 = -2$

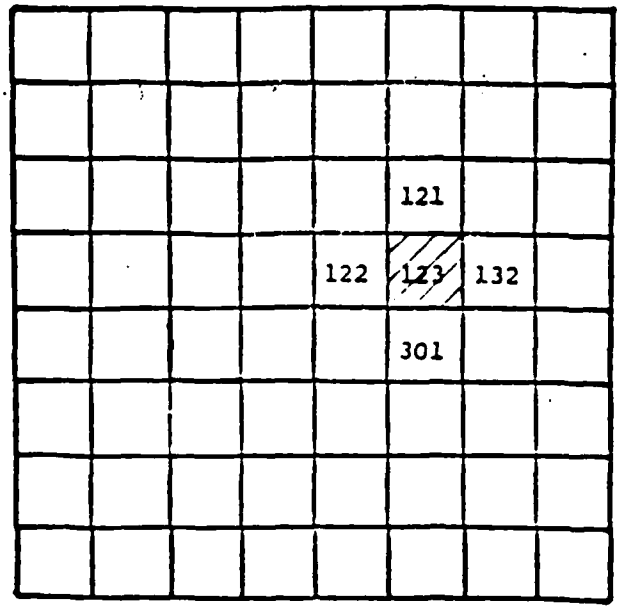
In Fig. 1(b) there is a pixel A = 2111 in a 2^4 by 2^4 image.

(1) E = 3000 , $d_k = d_1 = 1$ and $d_2 = d_3 = d_4 = -1$

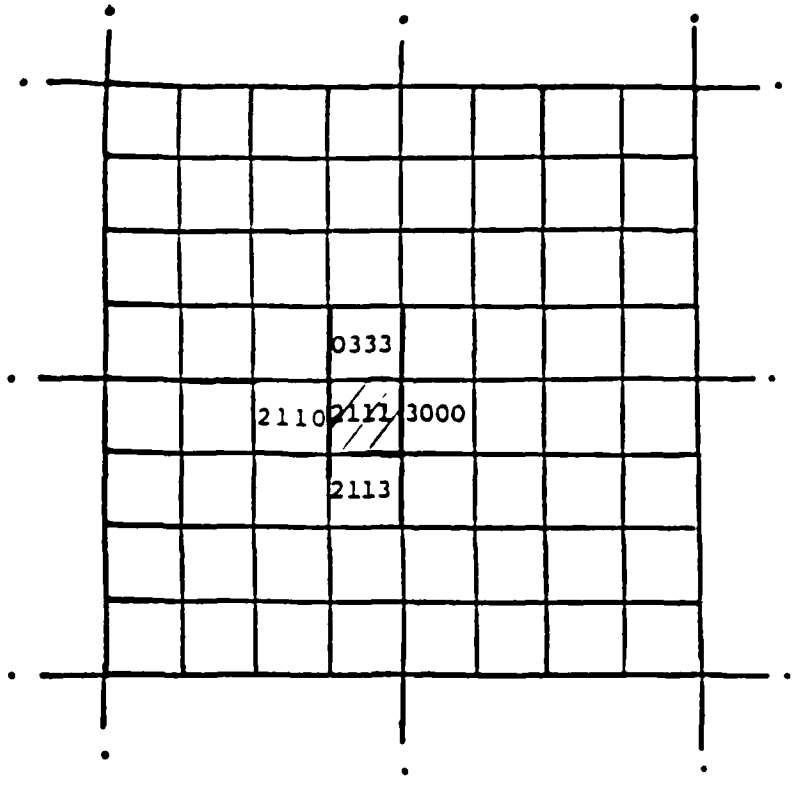
(2) W = 2110 , $d_k = d_4 = -1$

(3) S = 2113 , $d_k = d_4 = 2$

(4) N = 0333 , $d_k = d_1 = -2$ and $d_2 = d_3 = d_4 = 2$



(a)



(b)

Fig. 1

1.2 Adjacency for Elementary Squares of Different Sizes

Suppose two elementary squares are represented by quadcodes

$$A = a_1 \ldots a_m$$
$$B = b_1 \ldots b_r$$

where

$$m > r$$

THEOREM

If the two elementary squares are adjacent, they should satisfy the conditions

(i) $a_1 \ldots a_r$, $b_1 \ldots b_r$ satisfy condition (1)

(ii) if $d_k = b_k - a_k = 1$

then a_i MOD 2 = 1 for $i > r$

if $d_k = -1$

then a_i MOD 2 = 0 for $i > r$

if $d_k = 2$

then $a_i - 2 \geq 0$ (or a_i DIV 2 = 1) for $i > r$

if $d_k = -2$

then $a - 2 < 0$ (or a_i DIV 2 = 0) for $i > r$

(3)

We use Fig. 2 to explain what the conditions in (3) mean. The numbers in the middle grid represent the quadcode of the larger square B = $b_1 \ldots b_r$ which was supposed to be 0, 1, 2 or 3. The numbers around represent the quadcodes of the smaller square A = $a_1 \ldots a_m$, whose adjacency we wish to test. In Fig. 2, we suppose m - r = 3 and list the lower positions of the quadcodes of A, i.e., $a_{r+1} \ldots a_m$. For instance, elementary square 2 (or 3) has northern neighbors 0222, 0223, 0232, 0233, 0322, 0323, 0332, and 0333 (or 1222, 1223, 1232, 1233, 1322, 1323, 1332, and 1333), and elementary square 0 (or 2) has eastern neighbors 1000, 1002, 1020, 1022, 1200, 1202, 1220, and 1222 (or 3000, 3002, 3020, 3022, 3200, 3202, 3220, and 3222).

Fig. 2

2. FINDING NEIGHBORS

2.1 The Pixel Neighbors of a Pixel

Suppose a pixel in a 2^n by 2^n image has quadcode as A = $a_1 \ldots a_n$, and its eastern, western, southern and northern neighbor pixels have quadcodes E = $e_1 \ldots e_n$, W = $w_1 \ldots w_n$, S = $s_1 \ldots s_n$, and N = $n_1 \ldots n_n$, respectively.

The following is an algorithm for finding the quadcodes of neighbors.

A. Eastern neighbor

Suppose $j = \max \{i\}$ such that $a_i = 0$ or 2.

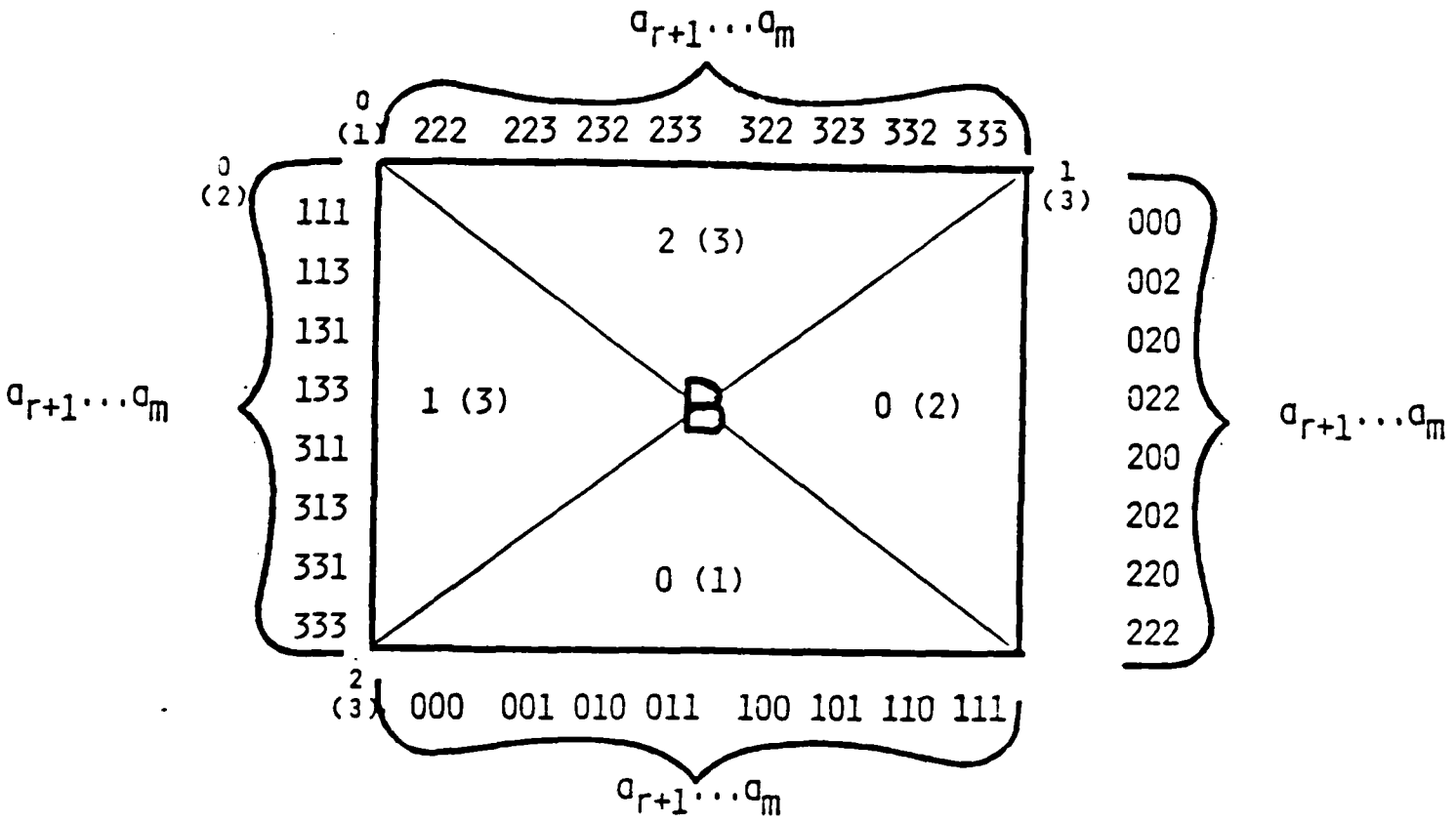

$a_{r+1}\cdots a_m$
0 (1)
222 223 232 233 322 323 332 333
0 (2)
111
113
131
133
311
313
331
333
1 (3)
000
002
020
022
200
202
220
222
2 (3)
0 (1)
B
$a_{r+1}\cdots a_m$
2 (3)
000 001 010 011 100 101 110 111
$a_{r+1}\cdots a_m$
$a_{r+1}\cdots a_m$

Fig. 2

If $j = 0$, then stop. It means that A does not have an eastern neighbor. Otherwise, we can construct the neighbor's quadcode, character by character, using

$$e_i = \begin{cases} a_i - 1 & i > j \\ a_i + 1 & i = j \\ a_i & i < j \end{cases} \qquad (4)$$

FOR $i = 1,\ldots,n$

Examples are shown in Table 1.

Table 1

A	012	023	213	113
E	013	032	302	none

B. Western neighbor

Suppose $k = \max\{i\}$ such that $a_i = 1$ or 3.

If $k = 0$, it means that A does not have a western neighbor.

Otherwise,

$$w_i = \begin{cases} a_i + 1 & i > k \\ a_i - 1 & i = k \\ a_i & i < k \end{cases} \qquad (5)$$

Examples are shown in Table 2.

Table 2

A	113	210	302	202
W	112	201	213	none

C. Southern neighbor

Suppose ℓ = max {i} such that a_i = 0 or 1.

If ℓ = 0, it means that A does not have a southern neighbor.

Otherwise,

$$s_i = \begin{cases} a_i - 2 & i > 1 \\ a_i + 2 & i = 1 \\ a_i & i < 1 \end{cases} \qquad (6)$$

Examples are shown in Table 3

Table 3

A	301	213	123	223
S	303	231	301	none

D. Northern neighbor

Suppose m = max {i} such that a_i = 2 or 3.

If m = 0, it means that A does not have a northern neighbor.

Otherwise,

$$n_i = \begin{cases} a_i + 2 & i > m \\ a_i - 2 & i = m \\ a_i & i < m \end{cases} \qquad (7)$$

Examples are shown in Table 4.

Table 4

A	213	230	311	101
N	211	212	133	none

E. The neighbors with the same size of an elementary square

The adjacency condition in A, B, C, D can be used to find the same-size neighbors of an elementary square $a = a_1 \ldots a_m$ ($m \leq n$), just by changing n to m.

2.2 The Neighbors with Smaller Size

To find the neighbors of an elementary square $A = a_1 \ldots a_m$ which are of smaller size than A, we use a two-step algorithm.

A. Using the algorithms in Sec. 2.1 to find the same-size neighbors of A, the results are represented as $e_1 \ldots e_m$, $w_1 \ldots w_m$, $s_1 \ldots s_m$, and $n_1 \ldots n_m$.

B. Add positions to each of those same-size neighbors starting from m + 1 until at most according to the following rules:

$$e_i = 0,2$$

$$w_i = 1,3$$

$$s_i = 0,1$$

$$n_i = 2,3$$

where $i = m + 1, \ldots r$ and $r \leq n$.

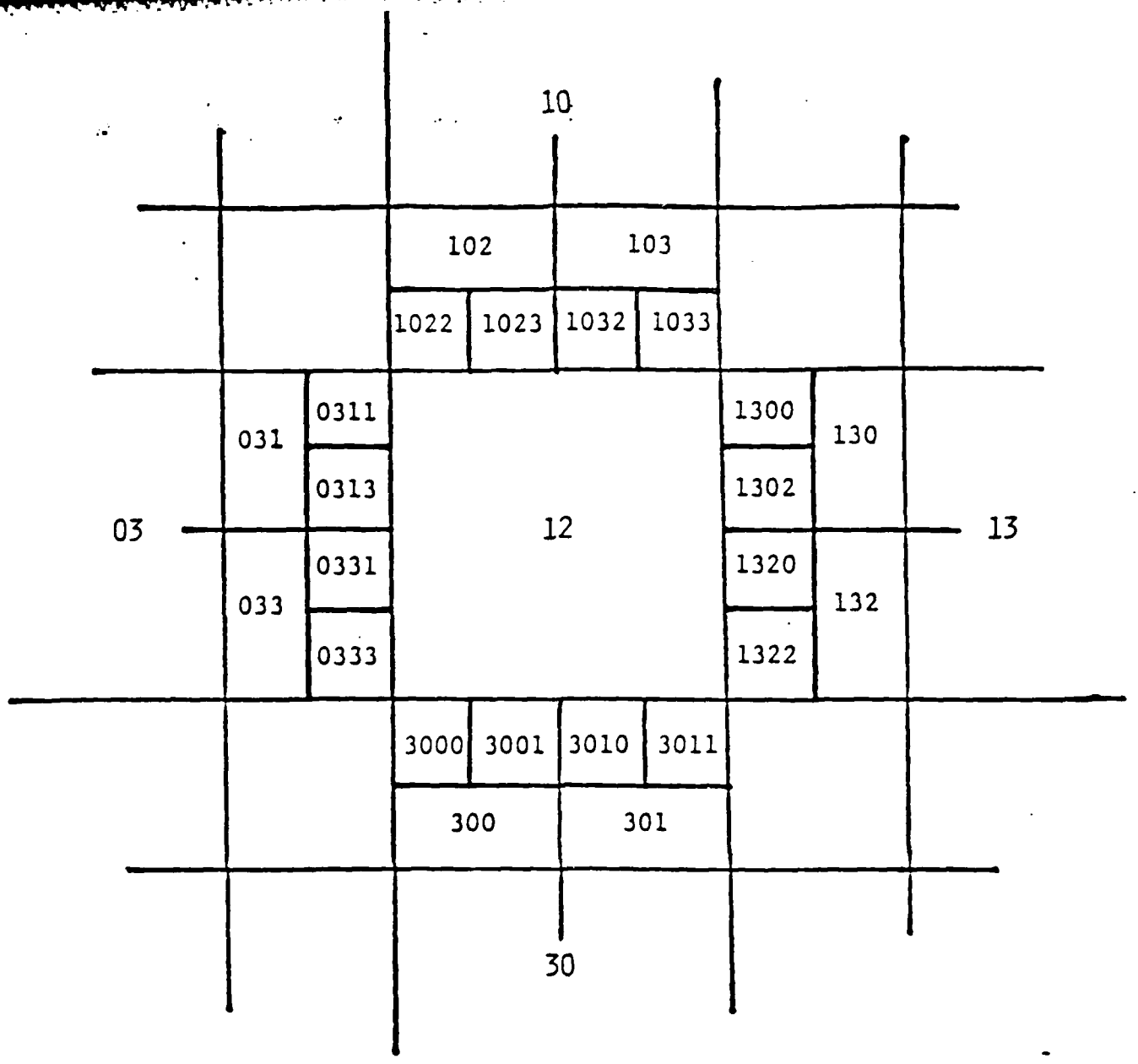


Fig. 3

NEIGHBORS OF EQUAL AND SMALLER SIZE

Example is shown in Fig. 3 and Table 5, which respectively show and list all the neighbors equal to or smaller than the elementary square A = 12 (n = 4).

Table 5

Equal-or-smaller Neighbors of A = 12 (n = 4)

Direction / Size	Eastern	Western	Southern	Northern
4x4	13	03	30	10
2x2	130	031	300	102
	132	033	301	103
1x1	1300	0311	3000	1022
	1302	0313	3001	1023
	1320	0331	3010	1032
	1322	0333	3011	1033

2.3 The Neighbors with Greater Size

To find the neighbors of an elementary square $A = a_1 \ldots a_m$ which are larger than A, the algorithm is as follows:

A. Using the algorithms in Sec. 2.1 to find the same-size neighbors of A, the results are represented as $e_1 \ldots e_m$, $w_1 \ldots w_m$, $s_1 \ldots s_m$, $n_1 \ldots n_m$.

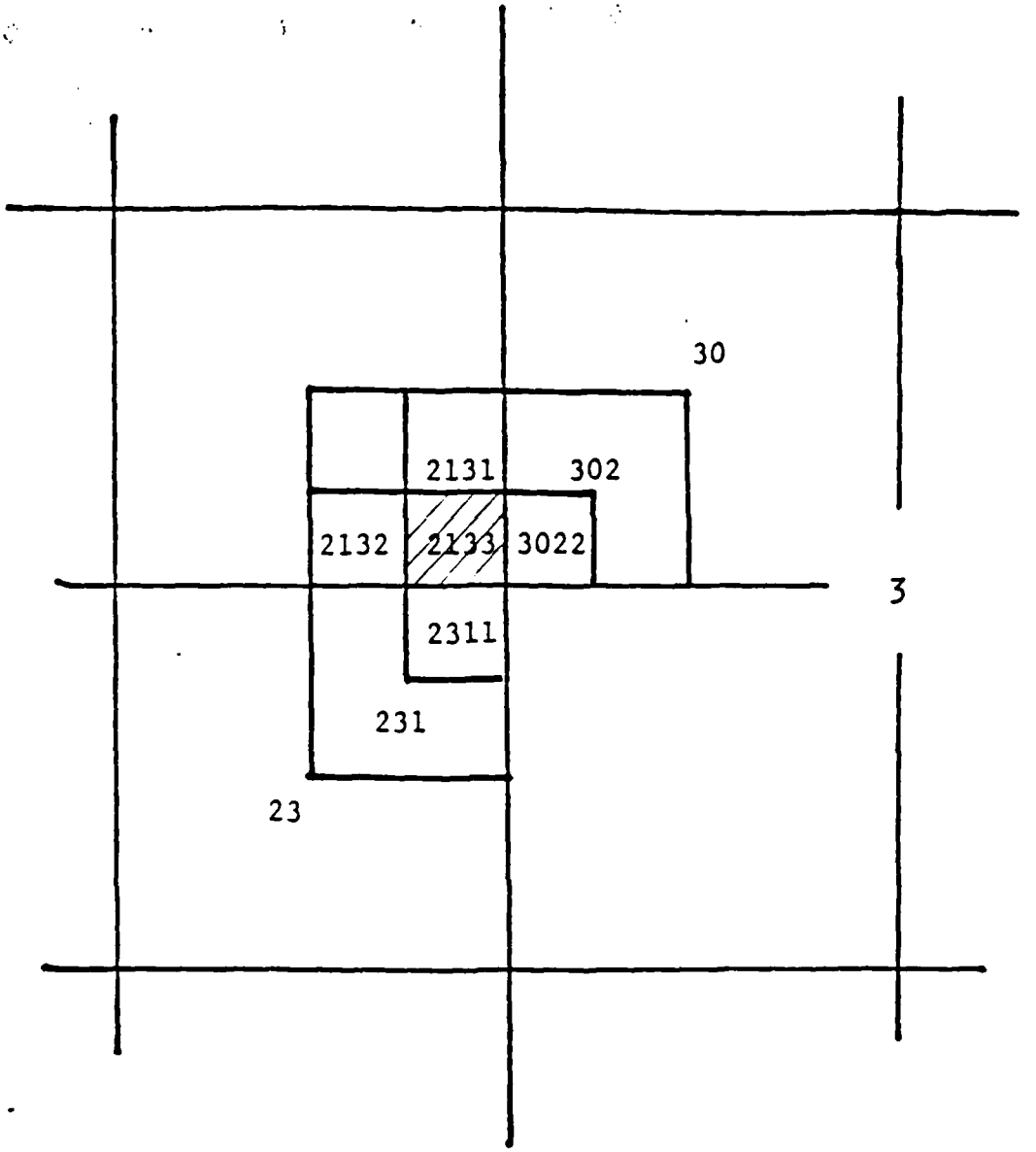


Fig. 4

B. Delete the positions from the rear one by one until meeting the position of the same value with a_i.

Example is shown in Fig. 4 and Table 6, which lists all the neighbors equal to or larger than the elementary square A = 2133 (n = 4).

Table 6

Equal-or-larger Neighbors of A = 2133 (n = 4)

Direction / Size	Eastern	Western	Southern	Northern
1x1	3022	2132	2311	2131
2x2	302		231	
4x4	30		23	
8x8	3			

As a general case, Table 7 and Fig. 5 show all the neighbors of elementary square A = 123 in a 2^4 by 2^4 image.

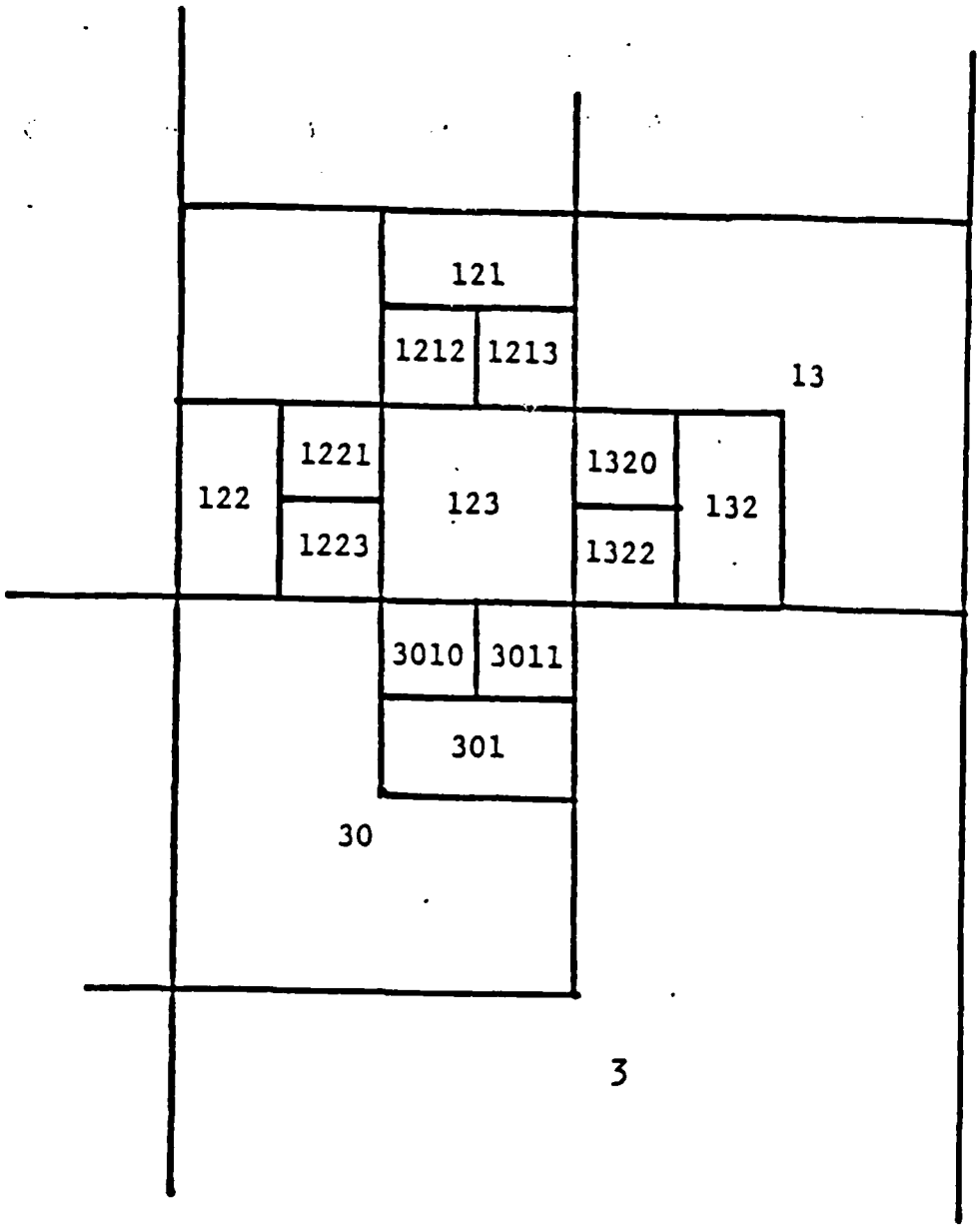

121
1212
1213
13
1221
1320
122
123
132
1223
1322
3010
3011
301
30
3

Fig. 5

Table 7

Direction / Size	Eastern	Western	Southern	Northern
8x8			3	
4x4	13		30	
2x2	132	122	301	121
1x1	1320 1322	1221 1223	3010 3011	1212 1213

Conclusions

Constructive methods are presented for finding neighbors of a region - regardless of size or direction - using quadcodes. The methods are straightforward and simple because they make efficient use of the position and size information implicit in the quadcode. The generality of the approach makes it a good candidate for parallel implementation.

REFERENCES

[1] S.X. Li and M.H. Loew, "The Quadcode and its arithmetic", George Washington University, Depart. of EECS, GWU/IIST Rept. No. 84-51, Dec. 1984.

[2] I. Gargantini, "An effective way to represent quadtrees", Comm. ACM, Vol. 25, No. 12, Dec. 1982.

END

DTIC

7-86