4-10-1986

Computer vision of a moving square using a two-level data hierarchy

David Zokaites

Recommended Citation

Zokaites, David, "Computer vision of a moving square using a two-level data hierarchy" (1986). Thesis. Rochester Institute of Technology. Accessed from

COMPUTER VISION OF A MOVING SQUARE USING A TWO-LEVEL DATA HIERARCHY

David Zokaites

April 1986

A Research Thesis submitted in partial
fulfillment of the requirements for
a Bachelor of Science Degree from
the Center for Imaging Science at the
Rochester Institute of Technology

Signature of the Author David Z. Zokaites 10-Apr-86
Imaging and Photographic Science

Certified by Willem Brouwer
Thesis Advisor

Accepted by Ronald Francis
Coordinator of Undergraduate Research

Abstract

An investigation of the relative speed and effectiveness of two computer vision algorithms has been conducted. One algorithm incorporates a two-level data hierarchy. The other incorporates a one-level hierarchy and serves as a relatively conventional basis for comparison. The computer vision algorithms, programmed in Fortran, detect and recognize a moving square. Both computer vision algorithms could readily be implemented in existing hardware. The two-level algorithm was found to be up to 90% faster than the one-level algorithm.

An analysis was made of elapsed CPU time variance as a function of time of day and user load. This was done to minimize the variance of results in comparing the above two algorithms. The mean and standard deviation of elapsed CPU time were both found to increase with system load, and system load was found to exhibit a midday peak.

Thesis Release

ROCHESTER INSTITUTE OF TECHNOLOGY

COLLEGE OF GRAPHIC ARTS AND PHOTOGRAPHY

PERMISSION FORM

Title of Thesis: Computer Vision of a Moving Square using a Two-Level Data Hierarchy

I David Zokaites hereby grant permission to Wallace Memorial Library of RIT to reproduce my thesis in whole or part. Any reproduction will not be for commercial use of profit.

Date: 10-Apr-86

Acknowledgements

With their assistance and encouragement, many people helped bring this thesis to completion. The author wishes to thank the following people for their part in this endeavor: first and foremost, my wife Coni for her continued understanding, love, and encouragement; the members of this thesis committee (Dr. Willem Brouwer, Alexander Martens, and Paul Conlon) for their technical expertise and assistance; my parents for their love; and the many others who assisted me in any way.

Table of Contents

Abstract ii

Thesis Release iii

Acknowledgements iv

Table of Contents v

List of Tables vi

List of Figures vii

I. Introduction 1

II. Experimental 13

III. Results 37

IV. Conclusions 46

V. References 47

VI. Appendix One: Program Listings ... 49

VII. Appendix Two: Sample Output 84

VIII. Vita 92

List of Tables

Table	Title	Page
1	Square Specification Variables	21
2	Standard Deviation and Mean CPU Time	38
3	Predicted CPU Time Savings	43
4	Average CPU Time Required for Two Algorithms	44
5	Comparison of Actual To Predicted Time Saved	45

List of Figures

Figure Title Page

Data Hierarchies

1 Illustration of Data Hierarchies 5

Edge and Corner Detection

2 Number of Points Defining Edges of a Square 22
3 Clipping of Square at Scene Boundary 23
4 First Collinearity Test 26

5 Second Collinearity Test 27
6 Splitting Line Segments 28

7 Merge Check 29
8 Setting the Number of Test Points 33

CPU Variability Analysis

9 Log Standard Deviation Vs. Log Mean CPU Time ... 39
10 Mean CPU Time Vs. Load 40
11 Standard Deviation Vs. Load 41

12 System Load Vs. Time of Day 42
13 Mean Vs. Time of Day 42
14 Standard Deviation Vs. Time of Day 42

Conclusions

15 Time Saved Vs. Width 44

Contents

A. Relation to Previous Work 2
  1. Overview 2
  2. CPU Time Variability Analysis 2
  3. Edge Detection 4
  4. Data Hierarchies 5
  5. Corner Detection 6
  6. Pattern Recognition 7
B. Applications 8
C. Implementation 9
  1. General 9
  2. Data Hierarchies 10
  3. Object and Scene 11

A) Relation to Previous Work

1) Overview

This research presents a new approach to the implementation of data hierarchies. The difference in number of pixels (by area) of the various levels of data hierarchies is commonly four. The author arbitrarily chose a factor of sixteen. This data hierarchy was applied to the analysis of a moving square generated in software. Polygonal scenes (as analyzed here) were formerly popular subjects for analysis [Aggarwal and Duda 1975; Mitiche and Bouthemy 1985]. Generating images or scenes is rare in computer vision, but is quite common in computer graphics. As a preliminary to pattern recognition, a suboptimal corner detection algorithm was implemented [Pavlidis 1982]. The accuracy of this algorithm was improved considerably with three minor revisions. A pattern recognition algorithm was implemented which recognized a square given information derived from the location of its four corners.

2) CPU Time Variability Analysis

Accounting data measures the amounts of computer resources a user consumed. Some types of accounting data are elapsed CPU time, duration of user sessions, and amount of memory used [Knudson 1985; O'Neill and O'Neill 1980].

The demands users place upon a computer vary from installation to installation. For example, one computer may be used mostly for many small programs, while another may be used mostly for text processing and larger programs. The configurations of large computers is often adjusted or "tuned" to peak performance under a given set of conditions [Ferrari, Serazzi, and Zeigner 1983]. For example, the page size of virtual memory systems may be adjusted, or a high speed printer may be added to a system to reduce the load on low speed printers.

The above-described field of computer performance evaluation and tuning is somewhat concerned with variability in accounting data. Davies' 1979 study examined elapsed CPU time for the same program under various conditions. He reported that elapsed CPU time increased with the load placed upon a computer [Davies 1979].

The author repeated this study using a VAX/VMS instead of a Decsystem 10/50. The author's results generally concur with those of Davies. The parameters of system load analyzed show a system and installation dependence.

3) Edge Detection

Edges of shapes usually correspond to intensity discontinuities in a digital image. Edge detection algorithms locate small spatial regions of large intensity change. Most edge detection algorithms locate boundary points which must be grouped together to form shape boundaries. A few techniques reduce the extent of this grouping by locating edges in terms of lines instead of points [Suk and Hong 1982].

Intensity discontinuities are found through the use of computational operators. A large variety of these operators are currently in use. Some of the most popular are templates [Kittler, Illingworth, and Paler 1983], Laplacian [Wiejak, Buxton, and Buxton 1985], and Hough Transforms [Brown 1983]. For a general discussion of these and other operators, see Ballard and Brown 1983.

The author implemented an edge operator which detected grey-level discontinuities. The digital images under analysis were binary, so detecting dincontinuities was a fairly simple problem. The changes detected were from zero to one, and from one to zero [Capson 1984].

4) Data Hierarchies

Data hierarchies are also known as pyramid data structures. They contain N versions of an image, each at a different resolution level and pixel size. To create a data hierarchy, pixels of a high resolution view may be grouped together and averaged in software, resulting in a lower resolution view of the same scene.

One-Level Hierarchy Two-Level Hierarchy

Figure 1: Illustration of Data Hierarchies

To increase speed and accuracy, data hierarchies may be incorporated into edge detection algorithms [Tanimoto and Klinger 1980; Spann and Wilson 1985; Harlow and Eisenbeis 1973]. For example, one level of a data hierarchy might be 512 pixels square (high resolution), and another level might be 64 pixels square (low resolution). The low resolution level could be useful for rapidly finding the outline of an apple, and the high resolution level for resolving this shape in greater detail.

Quadtrees are perhaps the most popular form of data hierarchy. In a quadtree, the high resolution image has four times as many pixels as the low resolution image. The author differed from this convention in choosing a high resolution image with sixteen times as many pixels.

5) Corner Detection

Numerous types of methods are currently employed to represent boundaries of shapes. One of the simplest is a region occupancy array. This is a array of the same size as the digital image. If a pixel is within the shape of interest, then the corresponding pixel in the occupancy array is given a value of one, otherwise is is given a zero.

A more common class of techniques is polygonal curve fitting. This method divides a boundary into sections, and fits a polynomial to these sections. Linear polynomials are perhaps most frequently used [Bezdek and Anderson 1986]. The endpoints of these boundary sections are called break points, polygon vertices, or feature points. (For an overview of these techniques, see Fischler and Bolles 1986.)

It is possible to optimize the locations of the break points [Dunham 1986]. Optimization minimizes both the number of break points and the error of polygonal approximations.

The disadvantage of optimization is higher computational cost. Some algorithms include optimization, and some do not.

The author implemented a suboptimal algorithm based on the description found in Pavlidis 1982. The performance of this algorithm was improved considerably by implementing a few minor revisions. For the extent of these revisions, see Corner Detection on page 29.

6) Pattern Recognition

Moving squares are relatively simple shapes to recognize, requiring neither a complicated model nor a complicated algorithm. There exist a wide variety of complex algorithms for pattern recognition. For an introductory discussion, see Ballard and Brown 1983.

The pattern recognition algorithm analyzed the following parameters of "squareness" which were calculated from the corner locations: the number of corners, lengths of the sides, and interior angles [Mitiche and Bouthemy 1985].

B) Applications

A possible application of the principles employed is tracking and identifying missiles. Other possible applications are: watching traffic to determine flow characteristics; tracking products on an assembly line to verify dimensional accuracy as well as presence or absence; identifying the region of text in a letter for automatic sorting; locating alignment marks for silicon wafer production; aligning and inserting components in printed circuit assembly; tracking motions of animals and people; measuring the flow of liquids; etc..

C) Implementation

1) General

This thesis presents a study of software techniques, particularly data hierarchies. These hierarchies were implemented in computer vision algorithms (software). This software implementation demonstrates the feasibility of hardware implementation.

The difficulties of hardware implemented were avoided to concentrate on the new aspects of the work done here. In keeping with this concentration, the software equivalent of a moving square was created. This was thought to be a speedier and more flexible approach than having a physical shape move. In addition, a square generated in software offered the advantage of a more controlled test ground.

Fortran was chosen as the language for the software because it is a popular language for scientific uses, it compiles efficiently, and it is the author's favorite language. The version of Fortran used was VAX-11 Fortran V4.3, a structured extension to Fortran-77. The machine used was VAXB of the Rochester Institute of Technology's VAXcluster. This is a Digital Equipment Corporation VAX/VMS model 11/785 computer.

The computer vision algorithms implemented consisted of the following major sections: scene generation, edge detection, corner detection, and pattern recognition. The scene was a moving square on a stationary square background. The edge detection, corner detection, and pattern recognition algorithms were much more generalized than the scene was. These algorithms did not "know" a priori that the object being analyzed was a square. The edge and corner detection algorithms could find the edges and corners of almost any closed figure. The pattern recognition algorithm could determine if the shape found was a regular polygon with the specified number of sides. While these algorithms were designed to be very general, their utility was only tested with squares.

2) Data Hierarchies

A two-level data hierarchy was created. It contained two digital images, or arrays of pixels. These images correspond to the same scene, and differ in resolution. Digital images are usually 512 X 512 pixels. For the high resolution level of the data hierarchy, it was decided that a relatively small array (128 by 128) would most readily illustrate the computer vision algorithms implemented. For the low resolution level of the data hierarchy, an even smaller array (32 by 32) was chosen.

To implement a two-level data hierarchy, the scene was examined first in low resolution, then in high resolution. To implement a one-level data hierarchy, the scene was examined only in high resolution.

3) Object and Scene

The software equivalent of a moving square was created. The square had a constant brightness of one, while the background had a constant value of zero. (This square is described in more detail in the Object and Scene section of the Experimental on page 20.)

The creation of the moving square took into account the size of the digital image which mapped onto the scene. A high resolution view of the scene was created by mapping the scene onto a large digital image. A low resolution view resulted from mapping the scene onto a small digital image. As a result of the above procedure, it was not necessary to average the high resolution view to result in a low resolution view of the scene.

Initially, the square was allowed to move while the scene was being scanned. This resulted in motion blur. To eliminate the problem of motion blur, the square was allowed motion only between examinations of the scene. This condition could be achieved in hardware by synchronizing a strobe with the digitizing scan rate.

The image digitizing system modeled here created two data files, one of which was the scene in low resolution, the other being the scene in high resolution.

Contents

A. CPU Time Variability Analysis 14

  1. Background 14

  2. Statistical Analysis 16

B. Modeling of CPU Time Saved 17

C. Coordinate System 19

D. Object and Scene 20

  1. Choice of Object and Scene 20

  2. Implementation 20

E. Edge Detection 22

  1. Background 22

  2. Implementation 23

F. Corner Detection 25

  1. Introduction 25

  2. First Collinearity Test 26

  3. Second Collinearity Test 26

  4. Split and Merge Aspects 27

  5. Implementation 29

  6. Enhancements 29

G. Pattern Recognition 34

H. Data Hierarchies 35

I. Statistical Analysis 36

A) CPU Time Variability Analysis

1) Background

Two general criteria are currently used to determine how much time a computer requires to complete a task. The first is elapsed time, as could be measured with a stop watch. The second is elapsed CPU time, or the amount of CPU time utilized. Note that in a timesharing environment (as occurred here), CPU time may readily be orders of magnitude lower than elapsed time.

The elapsed time required to replicate a task is known to vary greatly, being longest when the system load is the highest. One might expect that the CPU time needed to replicate a task would not vary at all. During the course of his experimentation, the author discovered that the CPU time required to replicate a task varied.

To characterize the relative speed of two algorithms, elapsed CPU time for both algorithms was measured. If this research had been done in an environment where CPU time showed great variation, then little faith could be placed in the results gathered.

The simplest method to reduce CPU variability would be to use a single-user machine. Another possibility would be to analyze CPU variability to isolate a low variability time for processing. Due to the unavailability of a single-user machine with sufficient power, the latter option was chosen. CPU variability was found to be very low between midnight and 6:00 AM; consequently all data from the computer vision algorithms was collected during this time.

To analyze CPU variability, a program was written to utilize processor time in computing transcendental functions (sine, logarithm, etc.). Various amounts of processor time were used, ranging from 1 to 400 ms.. The use of processor time was replicated 35 times. The program which used processor time in this manner was called CPU.FOR (a copy of which appears in Appendix One).

It was hypothesized that relationships existed among time of day, system load, and processor time. These hypothesized relationships appear in the Results section on page 38. To characterize these relationships, a command file (CPU.COM) was submitted to batch. This command file ran the above program (CPU.FOR) approximately once every hour and a half. Just before the program was run, the system load was determined by calling the local "nodeshow userload" utility. System load was defined as the average number of processes waiting for time or memory resources over the last fifteen minutes.

2) Statistical Analysis

A statistical analysis of the CPU time data was undertaken. A program ([.CPU]STATS.FOR) was written to calculate mean and standard deviation using the following formulas. The results of this statistical analysis can be found in the Results section of this report on page 38.

$$\bar{X} = \frac{\sum_{I=1}^{N} Xi}{N} \qquad Sx = \sqrt{\frac{N \sum_{I=1}^{N} Xi^{2} - \left[\sum_{I=1}^{N} Xi \right]^{2}}{N * (N - 1)}}$$

Where $\bar{X}$ = Mean
Sx = Standard Deviation
N = Number of Data Points
Xi = ith Data Point

B) Modeling of CPU Time Saved

A mathematical model was developed to predict the relative speed of the two computer vision algorithms implemented.

The bulk of the CPU time utilized by the edge detection algorithms was thought to be spent examining the requisite number of pixels. A much smaller fraction of CPU time was thought to be used by the overhead portions (initializing variables, error trapping, etc.) of these algorithms.

The model analyzed the number of pixels each algorithm examined, the resultant relative savings of CPU time, and neglected the above-described overhead. Because the overhead was not included in the model, the model represents a best-case analysis, and the actual results are expected to be slightly less favorable.

The one-level algorithm analyzed only the high resolution view. This view is 128 pixels square, for a total of 16384 pixels. This was compared to the number of pixels examined by the two-level algorithm. The two-level algorithm first analyzed the entire low resolution view (32 pixels square) for 1024 pixels. The region of the shape in low resolution was isolated, then analyzed in high resolution for a variable number of pixels. This number of pixels depended on the width of the shape found.

A short computer program, MODEL.FOR, was written to implement this model. For more details on the modeling, see the Modeling of CPU Time Saved section of Appendix One on page 55. The results appear in the Results section on page 43.

C) Coordinate System

A coordinate system was arbitrarily chosen for the scene. The scene had a width of one, centered on the origin (0,0). The coordinates of top-right corner of the scene were (.5,.5); the bottom-left was denoted by (-.5,-.5).

A short subroutine called COORD (included in Appendix One under Coordinate System) implemented the above coordinate system. Arrays are accessed in terms of array indices, I and J for example. This routine translates from array indices to the above scene coordinate system. I and J, the array indices to be transformed, are passed to the routine and shifted so that they are centered about 0, then they are scaled so that they range from -.5 to +.5. X and Y in scene coordinates are returned.

D) Object and Scene

1) Choice of Object and Scene

The object and scene were chosen to be relatively simple: closed regular polygons; squares. This was done to eliminate unnecessary complications from the computer vision algorithms. Note that a more complex scene is not likely to change the relative performance of the two algorithms, but it would certainly make it much more difficult to achieve conclusive results.

The object and the scene it moves through were chosen to be coplanar squares. The moving square had a constant brightness of one, and the stationary background had a constant brightness of zero. The square was allowed to travel in a straight line at constant velocity. The direction of the square's travel and its starting point were variable. The square may rotate about its center while it is translating. The direction and rate of rotation were variable. For an example of the generated square, see page 88 of Appendix Two.

2) Implementation

A function subprogram named SQUARE was written to implement the above choice of object and scene. It created the moving square during run-time. Input to this function were the following variables to specify the movement of the square:

Table 1: Square Specification Variables

Variable	Description	Units
Speedr	speed of rotation	degrees/time
Speedt	speed of translation	scene widths/time
Width	width of square	scene width
Angleo	initial offset angle	degrees
Anglet	direction of translation	degrees
Xi, Yi	initial coordinates of square's center	scene units

To let the square rotate, the square's angle from the horizontal was incremented. To let the square translate, the square's definition stayed constant, and the coordinate system of the scene was moved in the opposite direction. This resulted in apparent motion in the desired direction.

The square was defined in polar coordinates to simplify letting the square rotate. The square's angle from the horizontal was simply incremented to let the square rotate. To create the scene, the array indices corresponding to each pixel were passed to the subroutine SQUARE. The array indices were transformed first into scene cartesian coordinates, then into polar coordinates. If the coordinates of the pixel's center lie within the square, then a one was returned. Otherwise, a zero was returned.

E) Edge Detection

1) Background

The edge detection algorithm was designed to be slightly more general than necessary to examine the scene. Even though only moving squares were analyzed, the edge detection algorithm was given the capacity to accurately find the edges of nearly any single convex polygon. As a result, it was not necessary to give this algorithm a priori knowledge of the shape it was analyzing.

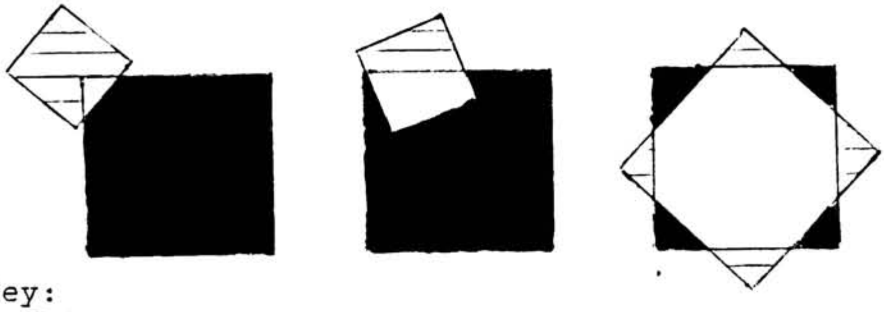
To detect the edges of the as-yet unidentified shape, the scene was scanned horizontally, one row at a time. For most of the shape two points per line are sufficient to define the edges. However, on the top and bottom edges of the shape, a variable number of points are needed. See the figure below.

The Square	Number of Boundary Points Per Row
+++++++++	8
+XXXXXXX+	2
+XXXXXXX+	2
+XXXXXXX+	2
+XXXXXXX+	2
+XXXXXXX+	2
+XXXXXXX+	2
+++++++++	8

Key:
X Interior Point
\+ Boundary Point

Figure 2: Number of Points Defining Edges of a Square

As the square moved, sometimes parts of the square were clipped at the scene boundary. When this occurred, the edge detection algorithm found the edges of the unclipped portion of the square. Depending on how the square was clipped, the resulting shape could have anywhere from three to eight sides. See the below figure.



Key:
■ Scene
□ Square Inside Scene
☰ Square Outside Scene

Figure 3: Clipping of Square at Scene Boundary

2) Implementation

A subroutine, EDGE, was written to implement the above edge detection algorithm. The output from this subroutine includes two arrays containing the coordinates of the edge points, and a flag to note whether or not a shape was found. This subroutine calls the above-mentioned square generating function, creating the moving square during program execution.

To locate the square, the first and last pixel on each row with a value of one is found. In addition, a boundary condition may occur at the right-hand edge of the scene: If the edge of the square extends beyond the edge of the scene, then a one followed by a zero will not be found. This condition was trapped accordingly.

F) Corner Detection

1) Introduction

As a preliminary to pattern recognition, the corners of the square were found via a split-and-merge polygon fitting algorithm. Polygon fitting algorithms draw a polygon to approximate the boundary of closed figure. Split-and-merge algorithms split data into successively smaller segments when necessary, and new segments identified are merged when possible.

Due to quantization error, a theoretically smooth edge may become ragged or saw-toothed. As the width of a square becomes small in terms of pixels, the raggedness of theoretically smooth edges increases. (See page 89 for an example of a very ragged edge.) This phenomenon made it difficult to find the four corners of a square in the low resolution view of the scene. This problem occurred rarely in high resolution.

A significant portion of the polygon fitting algorithm are two collinearity tests. These tests determine whether a given set of points lie on the same line to within a given tolerance. The line is drawn directly from the first point to the last point. This line is probably not the optimal fit to the data, but it is relatively easy to calculate.

2) First Collinearity Test

The first collinearity test checks for a relatively rare occurrence which is illustrated below. Note that points B, C, and D are nearly collinear. Note also, that when viewed as an ordered sequence, these points are not collinear. The first collinearity test checks for this condition by computing and summing the length of the lines from point to point (AB, BC, CD, and DE). This sum is compared to the overall length (AE). If the sum divided by AE is less than 1.1, then the points are declared to be collinear; if the quotient is greater than 1.5, the points are not collinear.

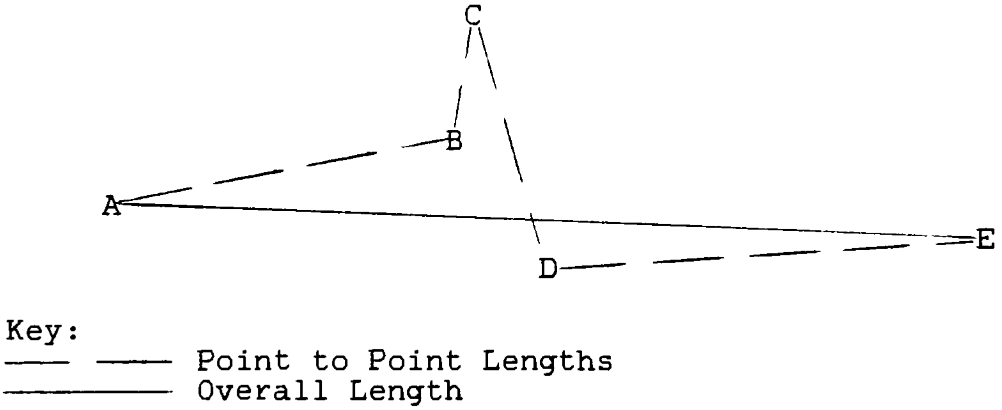


Figure 4: First Collinearity Test

3) Second Collinearity Test

Ideally, every point under test will lie exactly on the line drawn, but this is rarely the case. The more perpendicularly distant points are away from the line drawn, the less the points are collinear. To evaluate this measure of collinearity, the second collinearity test calculates the distance from the line drawn to each point under test. The point furthest away from the line drawn is identified. By the above definition, this is also the least collinear point.

The largest perpendicular distance was scaled by the length of the line. If the result is less than a specified tolerance, the points are declared to be collinear. If not, then the number of points under test is reduced: the test points are divided into two groups at the most distant point.

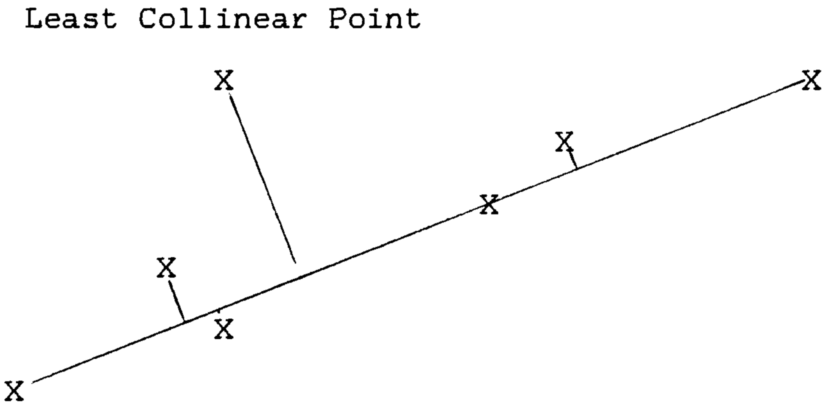


Figure 5: Second Collinearity Test

4) Split and Merge Aspects

Using the above two tests, a selectable number of the edge points were grouped together and tested for collinearity. If these points were found to be collinear to within a tolerance, they formed a line segment. If these points were not collinear, then the number of points under test was reduced. The new endpoint was chosen to be the point furthest away from the original line segment. The new line was tested for collinearity and split further as necessary.

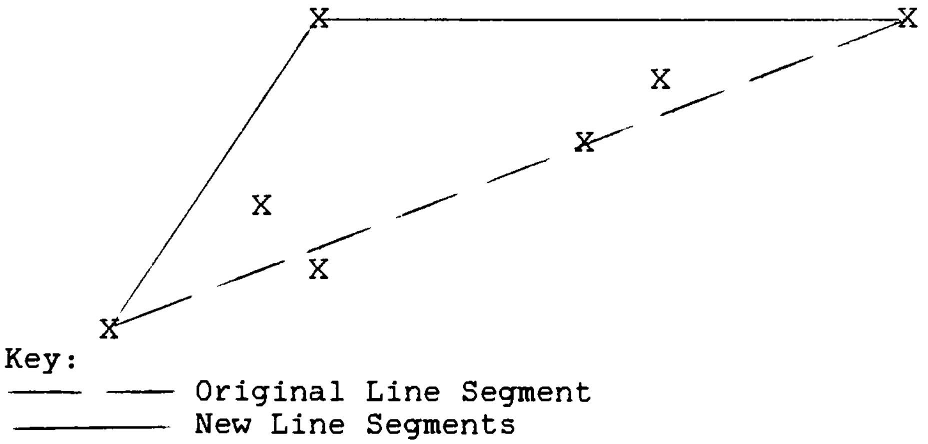
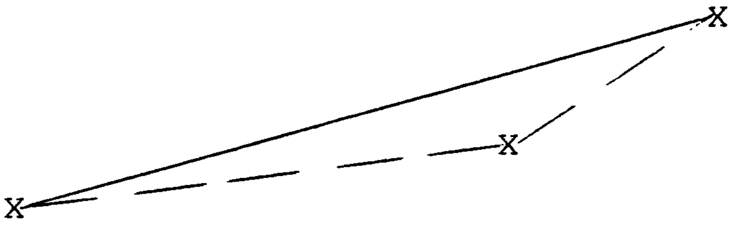


Figure 6: Splitting Line Segments

The above procedure identified a set of collinear points. Starting from the last element of the above set, the next group of collinear points was found as above. These two sets of collinear points form two line segments, which in turn form an interior angle. If this angle was equal to 180 degrees to within the specified tolerance, then the two line segments were merged.



Key:
—— —— Original Line Segments
———— Merged New Line Segment

Note that only for clarity, only the endpoints of the above line segments are shown.

Figure 7: Merge Check

The indices to the points under test were then incremented, and the next group of points analyzed. This process continued until all the points describing the edges of the square were analyzed.

5) Implementation

The main subroutine for polygon fitting was named POLY, the subroutine which tests points for collinearity was named COLINE. Three other associated routines appear listed with the above in the Corner Detection section of Appendix One on page 76.

6) Enhancements

The polygon fitting algorithm was modified slightly in three ways to optimize its performance: 1) a merge check between the first and last corners found was added, 2) the collinearity tolerances were adjusted, and 3) the number of test points was adjusted to be slightly larger than the expected width of the moving square.

The first edge point of the square was the starting point for corner detection. As a result, the first edge point was a default polygon vertex. The first edge point may have unnecessarily (and incorrectly) been declared a polygon vertex. This potential error was trapped by applying a merge check between the first and last polygon vertices: the second collinearity test was applied to the line segments bounded by the last, first, and second vertices.

There are two tolerances input to the polygon fitting algorithm: the first tolerance is the maximum separation of a point from the line it is thought to be collinear with; the second tolerance applies to the interior angle formed by two lines. If this angle equals 180 degrees within the second tolerance, then the two line segments are merged.

These two tolerances have a pronounced affect on the number of polygon vertices declared. If the above tolerances are set to low values, then a large number of polygon vertices will generally be found. If these tolerances are set high, then a small number of vertices will be declared. These tolerances were adjusted just to the point where four corners were found for a square in low resolution with a width equal to 40% of the scene width. Note that this square was only 12 pixels wide. The tolerance for distance was set to 2.5 pixels, and the tolerance for angles was set to 45 degrees.

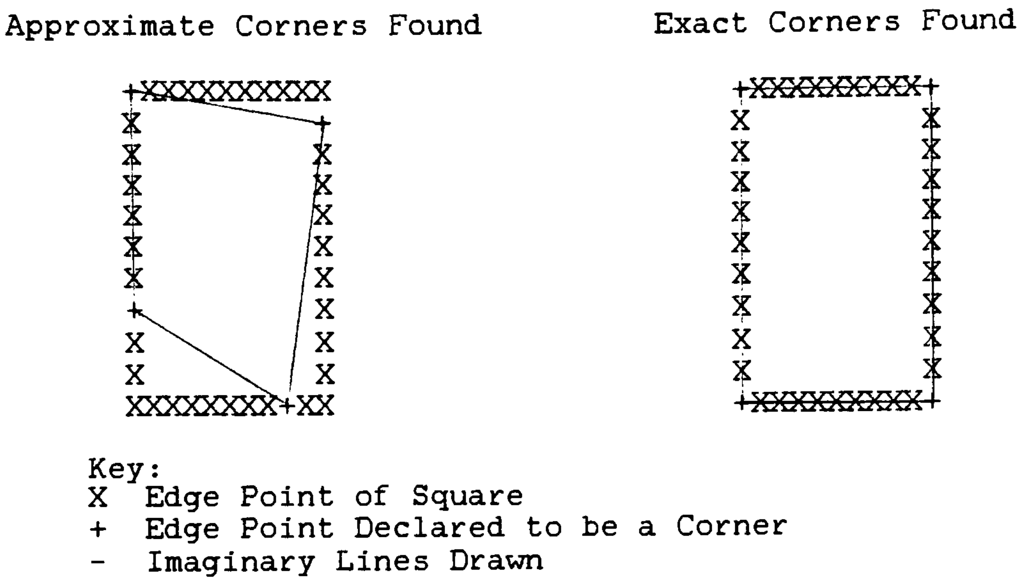
Corner detection was much easier to perform in high resolution than in low resolution. This is because quantization error and the raggedness of the squares' edges increased as the number of pixels representing a shape decreased. Enabling the corner detection algorithm to find four corners on a square with ragged edges required setting the two above tolerances to high values.

The corner detection algorithm started its analysis at the first edge point. Let us assume for the sake of discussion that the first edge point corresponded to the first corner of the square. Starting from the first edge point, a variable number of data points were grouped together and tested for collinearity. Let the number of points grouped together be denoted by "N". The value of N affected which edge points were declared to be corners. In the field, common values for N range from five to ten [Pavlidis 1982].

An imaginary line was drawn from the first corner to an edge point. The value of N determined which edge point formed the second endpoint of this line. For some values of N, the line was drawn from the first corner to a point near the second corner. This line potentially could have passed the collinearity test with the tolerances specified.

A second line was drawn from the last endpoint of the above line to a new point. These two lines would not be collinear in this example, so the common endpoint of both lines would be declared to be a new polygon vertex. For small values of N (ten for example), the author discovered that this endpoint could be up to four pixels away from the true corner of the square. See the below figure.

To more accurately find the square's corners, the value of N was adjusted to be at least six pixels greater than the width of the largest square expected. N was set equal to the number of pixels on one row of the digital image. With this setting of N, edge points from more than one side of the square were grouped together to form the first line tested for collinearity. These points did not pass the collinearity test. The point furthest away from this line was found, and corresponded to an exact corner of the square. This line was then split at the exact corner of the square, and this corner declared a polygon vertex. This procedure, due to the adjustment of N, resulted in locating the corners of the square more precisely.


Approximate Corners Found

Exact Corners Found

Key:
X Edge Point of Square
+ Edge Point Declared to be a Corner
- Imaginary Lines Drawn

Figure 8: Setting the Number of Test Points

Setting N to the above value required that another small change be made. After each polygon vertex was found, the indices to the points under test were incremented by N. The corner detection algorithm continued until the above indices were greater than the number of edge points. If the number of edge points was not an integer multiple of N, then some edge points would not have been analyzed using the above technique. This error was trapped by setting one of the above indices to the last edge point for the last pass through the algorithm.

G) Pattern Recognition

In most applications of computer vision, pattern recognition is a very important task. How can one track moving squares without first being certain that there are squares to track?

Three criteria were chosen to measure "squareness": the number of corners was tested for equality with four; the lengths of the sides were tested for being the same within a specified tolerance; and the interior angles were tested for being equal to ninety degrees within a tolerance. The number of corners, the lengths of the sides, and the interior angles were calculated as an integral part of the polygon fitting routine. The function subprogram written to implement pattern recognition was named RECOGN. Its text is listed in Appendix One on page 79.

H) Data Hierarchies

Taken as a whole, the above-described software implemented a one-level data hierarchy. The entire scene was scanned at low resolution to find the edges of the moving shape. From the edge data, the corners were found. From the corners, it was determined whether or not a square was found.

To implement a two-level data hierarchy, the author used the low resolution edge data to find the region of the moving shape. This region was then enlarged by a few pixels in all directions to allow for quantization error, then examined again in high resolution.

For the two-level data hierarchy, the corner detection could occur in either of three options: low resolution only, high resolution only, or combined low and high resolution.

I) Statistical Analysis

The two vision algorithms reported elapsed CPU time. To characterize the mean and standard deviation of elapsed CPU time, a program named [.VISION]STATS.FOR was written. Note that a different program was written to do similar statistical analysis for a different set of elapsed CPU time data (see CPU Time Variability). It was necessary to write a new program due to the variations in file format.

Contents

A. CPU Time Variability Analysis 38
  1. Introduction 38
  2. Standard Deviation Vs. Mean CPU Time .. 38
  3. Mean CPU Time Vs. Load 39
  4. Standard Deviation Vs. Load 40
  5. System Load, Mean, and Standard Deviation Vs. Time 41
B. Modeling of CPU Time Saved 43
C. Actual Time Saved 44

A) CPU Time Variability Analysis

1) Introduction

To analyze elapsed CPU time variability as functions of user load and time of day, system load was determined throughout one day at approximately one and a half hour intervals. Immediately following this, elapsed CPU time data was collected for replicates of various processes. These processes were designed to utilize various amounts of CPU time, from 1 to 400 ms.

2) Standard Deviation Vs. Mean CPU Time

For many processes, the standard deviation increases with the mean. The author expected the standard deviation of CPU time to increase with the mean, as it does. Note that the rate of increase changed throughout the day. See the below figure and table.

Table 2: Standard Deviation and Mean CPU Time

3:00 AM		3:00 PM	
Standard Deviation (ms)	Mean (ms)	Standard Deviation (ms)	Mean (ms)
.406	1.200	.632	1.200
.490	4.371	.781	4.086
.471	17.314	1.435	18.000
.725	75.657	5.371	75.829
1.132	183.314	6.638	186.000
1.721	432.743	7.699	439.314

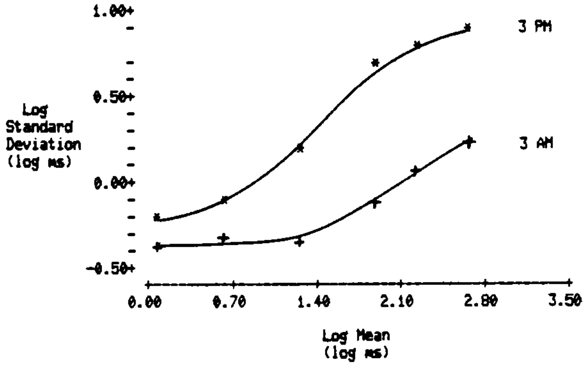


Figure 9: Log Standard Deviation Vs. Log Mean CPU Time

3) Mean CPU Time Vs. Load

This research was run in a timesharing environment. As the user load increased, the length of the slice of CPU time allotted to each user is hypothesized to have decreased. This resulted in each process being shuffled in and out of the CPU at an increasing rate. Moving a process in and out of the CPU requires CPU time. In other words, as the system load increases, the amount of CPU time spent in overhead increases. Considering the above, one might expect mean CPU time to increase with the system load, as it did indeed.

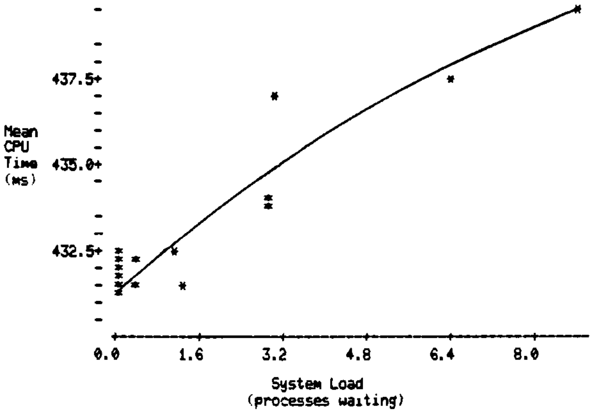


Figure 10: Mean CPU Time Vs. Load

4) Standard Deviation Vs. Load

User load in a timesharing environment is subject to large variations over small intervals of time. Processes heavily dependent on CPU resources are begun and ended at random intervals, resulting in variable demand upon CPU resources and large fluctuations in system load over the short term.

If the system load varies greatly, then the mean CPU time to replicate a task varies. This results in a high standard deviation. Using the above logic, the author expected the standard deviation to increase with the load, as did occur.

The CPU time data plotted below had a mean of approximately 76 ms.. Note that this is a different group of data then plotted elsewhere in this section. This was necessary because the other data set was very noisy and did not exhibit a very clear relationship between standard deviation and load.

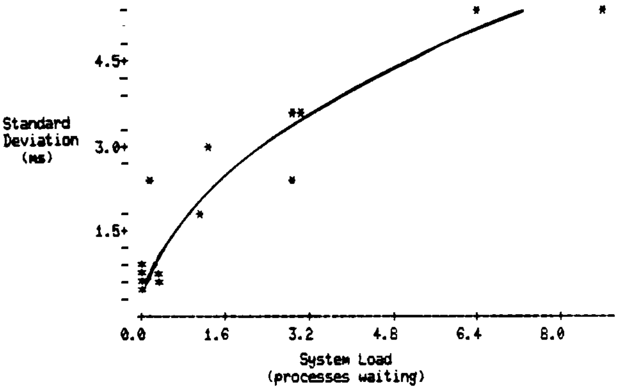


Figure 11: Standard Deviation Vs. Load

5) System Load, Mean, and Standard Deviation Vs. Time

The computer centers for the system used are open from 8:00 AM to 11:00 PM daily. During the day when the computer centers are open, the system load is relatively high. As a consequence of high load, the mean CPU time and standard deviation are also relative high. At night, the computer centers close and the system load is very low. Mean and standard deviation are consequently also very low. See the following three graphs.

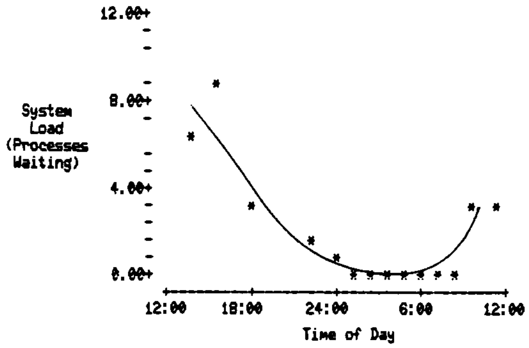


Figure 12: System Load Vs. Time of Day

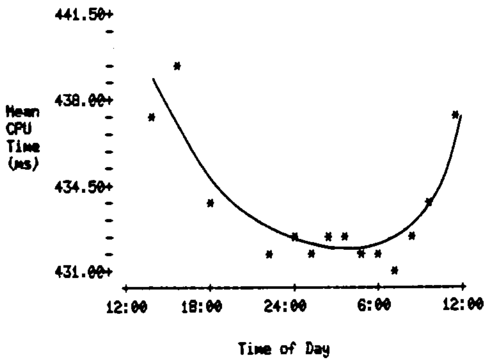


Figure 13: Mean Vs. Time of Day

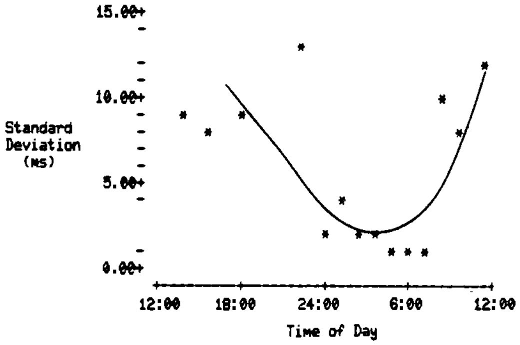


Figure 14: Standard Deviation Vs. Time of Day

B) Modeling of CPU Time Saved

The relative CPU time required by both algorithms was modeled. The two-level algorithm, as modeled, was much faster than the one-level algorithm.

Table 3: Predicted CPU Time Savings

Width of the Square (% of Scene Width)	Predicted CPU Time Saved (%)
3.5	93.1
10	91.6
25	85.0
40	73.8
65	45.2
70	38.0
85	13.3
100	-6.3

C) Actual Time Saved

The two-level edge detection algorithm was experimentally shown to be much faster than the one-level algorithm. The predicted results are quite close to the actual results. See the below figure and tables for more details.

Table 4: Average CPU Time Required for Two Algorithms

Width of Square (% of Scene Width)	One-Level (ms)	Two-Level (ms)	Savings (%)
3.5	263	36	86
10	262	41	84
25	265	62	77
40	263	86	68
65	265	154	42
70	266	178	33
85	268	255	5
100	268	288	-8

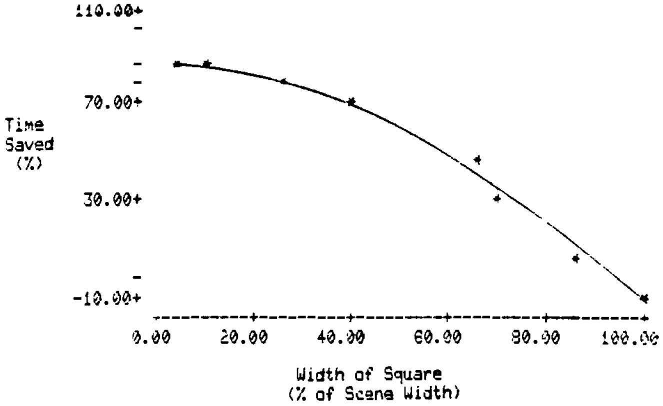


Figure 15: Time Saved Vs. Width

Table 5: Comparison of Actual To Predicted Time Saved

Width of Square (% of Scene Width)	Actual Savings (%)	Predicted Savings (%)	Error in Prediction (%)
3.5	86	93	7
10	84	92	8
25	77	85	8
40	68	74	6
65	42	45	3
70	33	38	5
85	5	13	6
100	-8	-6	-2

In the two-level data hierarchy, the low resolution level located the region of the moving square. This region was then examined in high resolution. Note that the region of the moving square was often much smaller then the entire field. This is to be compared to the one-level data hierarchy in which the entire field was examined in high resolution to find the square.

With small shapes, a small section of the high resolution level was analyzed in the two-level hierarchy. This resulted in significant savings of time. If the shape was the same size as the scene (or nearly so), then the entire high resolution level was analyzed. In this case, the time spent analyzing the low resolution level was effectively wasted. The result is that the two-level data hierarchy implemented actually required more CPU time than the corresponding one-level hierarchy.

A comparison of actual to predicted time savings shows that there is a close correlation (see Table 4 on page 44). The author expected the predicted savings to be slightly higher than the actual savings. Note that this is the case, except for a square with a width of 100%.

J. Aggarwal and O. Duda, "Computer Analysis of Moving Polygonal Images", IEEE Trans. Computers, 24, 966-976 (1975).

D. Ballard and C. Brown, Computer Vision, Prentice-Hall, Englewood Cliffs, NJ (1983).

C. Brown, "Inherent Bias and Noise in the Hough Transform", IEEE Trans. Pattern Analysis and Machine Intelligence, 5, 493-505 (1983).

J. Bezdek and I. Anderson, "An Application of C-Varieties Clustering Algorithms to Polygonal Curve Fitting", IEEE Trans. Systems Man and Cybernetics, 15, 637-641 (1985).

D. Capson, "An Improved Algorithm for the Sequential Extraction of Boundaries from a Raster Scan", Computer Vision, Graphics, and Image Processing, 28, 109-125 (1984).

D. Davies, "Analysis of Variability in System Accounting Data", Fourteenth Meeting of the Computer Performance Evaluation Users Group, National Bureau of Standards, Washington, DC (1979).

J. Dunham, "Optimum Uniform Piecewise Linear Approximation of Planar Curves", IEEE Trans. Pattern Analysis and Machine Intelligence, 8, 67-75 (1986).

D. Ferrari, G. Serazzi, and A. Zeigner, Measurement and Tuning of Computer Systems, Prentice-Hall, Inc., Englewood Cliffs, NJ (1983).

M. Fischler and R. Bolles, "Perceptual Organization and Curve Partitioning", IEEE Trans. Pattern Analysis and Machine Intelligence, 8, 100-105 (1986).

C. Harlow and S. Eisenbeis, "The Analysis of Radiographic Images", IEEE Trans. Computers, 22, 678-688 (1973).

J. Kittler, J. Illingworth, and K. Paler, "The Magnitude Accuracy of the Template Edge Detector", Pattern Recognition, 16, 607-613 (1983).

M. Knudson, "A Performance Measurement and System Evaluation Project Plan Proposal", ACM Sigmetrics: Performance Evaluation Review, 13, 20-31 (1985).

A. Mitiche and P. Bouthemy, "Tracking Modeled Objects Using Binocular Images", Computer Vision, Graphics, and Image Processing, 32, 384-396 (1985).

P. O'Neill and A. O'Neill, "Performance Statistics of a Time Sharing Network at a Small University", Communications of the ACM, 23, 10-13 (1980).

T. Pavlidis, Algorithms for Graphics and Image Processing, Computer Science Press, Rockville, MD (1982).

M. Spann and R. Wilson, "A Quad-Tree Approach to Image Segmentation which Combines Statistical and Spatial Information", Pattern Recognition, 18, 257-269 (1985).

M. Suk and S. Hong, "An Edge Extraction Technique for Noisy Images", Computer Vision, Graphics, and Image Processing, 25, 24-45 (1984).

S. Tanimoto and A. Klinger (Eds.), Structured Computer Vision, Academic Press, New York (1980).

J. Wiejak, H. Buxton, and B. Buxton, "Convolution with Separable Masks for Early Image Processing", Computer Vision, Graphics, and Image Processing, 32, 279-290 (1985).

Contents

A. CPU Time Variability Analysis 50

1. Command Files 50
2. Program 50
3. Statistical Analysis 52

B. Main Vision Algorithm 55

1. Modeling of CPU Time Saved 55
2. Command Files 56
3. Program 56

C. Coordinate System 64

D. Object and Scene 65

E. Edge Detection 67

F. Corner Detection 72

1. Main Routine 72
2. Collinearity Tests 75
3. Associated Subroutines 76

G. Pattern Recognition 79

H. Statistical Analysis 81

A) CPU Time Variability Analysis

1) Command Files

```
$! file name is BATCH.COM
$! it submits CPU.COM to batch
$! written by David Zokaites Dec-85 to Jan-86
$ SUBMIT/RESTART/NOTIFY/QUE=VAXB$LARGE/LOG_FILE= -
 [DMZ5436.THESIS.DEVELOP.CPU]CPU.LOG -
 [DMZ5436.THESIS.DEVELOP.CPU]CPU

$!file name is CPU.COM
$!Written by David Zokaites 16-Dec-85, 12-Jan-85
$!This file executes a series of commands to test cpu time
$!variability.  These commands are repeated after a certain
$!delta time.
$!
$!initialize
$  SET NOON   !ignore all errors
$  WSO :== WRITE SYS$OUTPUT
$  SET DEF [DMZ5436.THESIS.DEVELOP.CPU]
$  COUNT = 0
$ LOOP:
$  WSO "count = ", COUNT
$  NODESHOW USERLOAD VAXB
$  RUN CPU
$  RENAME CPUA.DAT 'COUNT'A
$  RENAME CPUB.DAT 'COUNT'B
$  COUNT = COUNT + 1
$  WAIT 01:00        !HH:MM:SS.CC
$  IF COUNT .LT. 24 THEN GOTO LOOP
```

2) Program

```
!Program name is CPU.FOR
!Written by David Zokaites
!8-Dec-85 to 13-Dec-85, revised 12-Jan-86
!It determines elapsed CPU time for both computation and I/O.
!Note that the elapsed time is determined repeatedly.  This is
!to get an estimate of variability.

!initialize
  !declare variables
      INTEGER*4 TIME,  !elapsed cpu time
   +  MS,              !limit on do loop, roughly = CPU
   +  REPS             !number of times cpu time is found
```

```
         REAL ARG,              !argument to math functions
      +  COMP, IO,              !scales MS for computation or i/o
      +  COUNTER1, COUNTER2  !counters, could be integer

         !LIB$INIT_TIMER and LIB$STAT_TIMER  are part of system's
         !run time library.  The former initializes the count of
         !elapsed CPU time, the latter determines elapsed time.

     !open files
         OPEN (NAME ='CPUIN.DAT', TYPE = 'OLD', UNIT = 1)
         OPEN (NAME = 'CPUA.DAT', TYPE = 'NEW', UNIT = 2)
         OPEN (NAME = 'CPUB.DAT', TYPE = 'NEW', UNIT = 3)

     !read and write
          READ (1,*) REPS, COMP, IO
         WRITE (2,*) 'Computation CPU time '
         WRITE (3,*) 'I/O CPU time  '
         WRITE (2,5) REPS
         WRITE (3,5) REPS
   5     FORMAT (' in ms for repetitions of same thing '/
      +  ' Number of repetitions = ', / I3/ )

   !start of loop to read and compute
   10     READ (1,*, END = 20) MS

     !use cpu time in computation
       !repeat this section to get an indication of variability
       DO I = 1, REPS
         CALL LIB$INIT_TIMER    !initializes timer

       !use some time
         DO COUNTER1 = 1, (MS * COMP)
         DO COUNTER2 = 1, 1000
         VARIABLE =SIN(COUNTER1)*COUNTER1**COUNTER1-LOG(COUNTER1)
         END DO
         END DO

       !determine elapsed time
         CALL LIB$STAT_TIMER (2, TIME)
         WRITE (2,*) TIME

         END DO
       WRITE (2,*) !skip a line

     !use cpu time in I/O
       !repeat this section to get an indication of variability
       DO I = 1, REPS
         CALL LIB$INIT_TIMER    !initializes timer

       !use some time
         OPEN (NAME = 'JUNK.DAT', TYPE = 'NEW', UNIT=20)
```

```
      DO J = 1, (MS * IO)
      WRITE (20,*) J
      END DO
      CLOSE (UNIT =20)

    !determine elapsed time
      CALL LIB$STAT_TIMER (2, TIME)
      WRITE (3,*) TIME

      END DO
    WRITE (3,*) !skip a line

!end of loop to read and compute
      GO TO 10

!end program
20    STOP ' NORMAL END OF CPU.FOR'
    END
```

3) Statistical Analysis

```
! Program name is [.CPU]STATS.FOR
! Written by David Zokaites 20-Dec-85, 12-Jan, 13-Jan-86
! This program characterizes mean, standard deviation, range.
! The input is the output from CPU.COM and CPU.FOR

!initialize
      CHARACTER*7 FILE    !cpu input data file to be opened
  !initialize output file
      OPEN (UNIT=4, NAME ='STATS.DAT', TYPE = 'NEW')
      WRITE (4,10)
10    FORMAT (' ELAPSED CPU TIME VARIABILITY ANALYSIS DATA '/
+   ' time = time the data was collected '/
+   ' users = number of users on the system, excluding batch '/
+   ' load = avg sys load in last minute, # processes waiting'/
+   ' process = process using cpu time, computation or I/O '/
+   ' The statistical parameters calculated follow: '/
+   ' mean (mean), standard deviation (sdev); range, from'/
+   ' minimum (min) to maximum (max), for POINTS points. '/
+   ' file = file containing elapsed cpu time '//
+         TIME        USERS  LOAD PROCESS   MEAN '
+   '  SDEV RANGE  MIN  MAX POINTS  FILE  SDEV/MEAN '/)

!call stats for two groups of file names
     FILE(4:7) = '.DAT'
       FILE (3:3) = 'A'
      CALL STATS (FILE)
       FILE (3:3) = 'B'
      CALL STATS (FILE)
```

```
!end calling routine
        STOP 'NORMAL END OF STATS.FOR'
          END


!subroutine to do all the work
          SUBROUTINE STATS (FILE)
!initialize
  !declare variables
          INTEGER
      +   POINTS,       !number of numbers
      +   DATA,         !input data
      +   MIN, MAX,     !minimum and maximum values of the data
      +   RANGE,        !max - min
      +   SUM,          !sum of data
      +   SUMSQ,        !sum of data * data
      +   COUNTER,      !counter on which file was opened
      +   LSDIGIT,      !least significant digit
      +   MSDIGIT       !most

          REAL
      +   MEAN,         !mean of the input data
      +   SDEV,         !standard deviation
      +   SCALED        !scaled sdev = sdev / mean

           CHARACTER*4 PROCESS,     !process that used cpu time
       +   USERS,   !number of users on sys (excludes batch jobs)
       +   LOAD     !system load in terms of jobs waiting
          CHARACTER*7 FILE      !cpu input data file to be opened
          CHARACTER*26 TIME      !TIME of data collection

          OPEN (UNIT=1, NAME = 'CPU.LOG', TYPE = 'OLD') !input
          OPEN (UNIT=4, NAME ='STATS.DAT', TYPE = 'OLD')!output

!open loop to read files numbered 0, 1, 2, ...
          COUNTER = -1
12        CONTINUE
          COUNTER = COUNTER + 1
  !read descriptive data from cpu.log
          READ (1,15, END=40, ERR=40) TIME, USERS, LOAD
15        FORMAT ( / T27, A26, 5X, A3, 74X, A4 //)
  !open CPU time input file
          !compute lsdigit, msdigit
          MSDIGIT = 10 * INT( COUNTER/10)
          LSDIGIT = COUNTER - MSDIGIT
          MSDIGIT = MSDIGIT/10
        !compute FILE
          FILE (2:2) = CHAR (LSDIGIT + 48)
          IF (COUNTER .GE. 10) THEN
            FILE(1:1) = CHAR (MSDIGIT + 48)
            ELSE
```

```
          FILE(1:1) = ' '
        END IF
        !open
          OPEN (UNIT=2, NAME= FILE, TYPE = 'OLD')
    !read initial data from file
        READ (2,20) PROCESS, POINTS
  20    FORMAT ( ' 'A3,///, I3 /)
    !open loop to examine new sets of data in file
        DO I = 1, 6
      !initialize variables
        MIN = 1000000
        MAX = 0
        SUM = 0
        SUMSQ = 0
      !compute statistics
        DO J = 1, POINTS
          READ (2,*,END=50) DATA
          IF (DATA .LT. MIN) MIN = DATA
          IF (DATA .GT. MAX) MAX = DATA
          SUM = SUM + DATA
          SUMSQ = SUMSQ + DATA * DATA
        END DO
        READ (2,*) !skip over a blank line in a file

        RANGE = MAX - MIN
        MEAN = FLOAT (SUM) / POINTS
        SDEV = POINTS * SUMSQ - SUM * SUM
        SDEV = SDEV / ( POINTS * (POINTS - 1) )
        SDEV = SQRT ( ABS (SDEV))
        SCALED = SDEV / MEAN
      !output data
        WRITE (4, 30)TIME,USERS,LOAD,PROCESS,MEAN, SDEV, RANGE,
     +        MIN, MAX, POINTS, FILE, SCALED
  30      FORMAT ( ' ', A26, 3(4X, A4), 2F8.3, 4I7, A8, F8.3)
    !close loop to examine new sets of data in file
        END DO
        WRITE (4,*) !skip line in output file
  !close loop that read files
        CLOSE (UNIT = 2)
        GOTO 12
  40     CLOSE (UNIT = 1)
  !finalize
        RETURN
  50    STOP 'END OF FILE IN STATS.FOR'
        END
```

B) Main Vision Algorithm

1) Modeling of CPU Time Saved

```
!Program name is MODEL.FOR
!Written by David Zokaites 4-Feb-86

!This program models the CPU time saved by a two-level data
!hierarchy as compared to a one-level data hierarchy.  More
!specifically, the % savings of number of pixels examined is
!computed.


!initialize
        REAL
     +  LEVEL1, !number of pixels examined one-level hierarchy
     +  LEVEL2, ! ...                             two
     +  WIDTH,  !width of the square in % of scene width
     +  WIDTHt  !transformed width
     +  SAVED   !% time saved

        INTEGER
     +  PIX1,   !number of pixels per row in low resolution
     +  PIX2    !...                             high

        PARAMETER (PIX1 = 32, PIX2 = 128)

        OPEN (UNIT=1, NAME='MODELIN.DAT', TYPE='OLD')
        OPEN (UNIT=2, NAME='MODELOUT.DAT', TYPE='NEW')

        WRITE (2,*) '% time saved with 2-level data hierarchy'
        WRITE (2,*)     WIDTH   % TIME '
!compute
    !read while not end of file
20      READ (1,*, END=100) WIDTH

    !transform width
        WIDTHt = WIDTH/100      !converts from % to decimal
       !Detected square in low res could be 0 to 2 (avg of 1)
       !pixels smaller than actual due to quantization error
       !in generating the square.  To correct for this, the
       !region of interest was expanded by 2.5 pixels.  Net
       !avg expansion = 1.5 pixels.
        WIDTHt = WIDTHt + 1.5/PIX1
        IF (WIDTHt .GT. 1) WIDTHt = 1

    !number of pixels examined
        LEVEL1 = PIX2 * PIX2    !high resolution
        LEVEL2 = PIX1 * PIX1    !low res
```

```
        LEVEL2 = LEVEL2 + (WIDTHt * PIX2) ** 2

    !time saved
        SAVED = (LEVEL1 - LEVEL2) / LEVEL1
        SAVED = SAVED * 100     !converts to %

    !output results
        WRITE (2,40) WIDTH, SAVED
40      FORMAT (' ',2F9.3)

!end compute
        GOTO 20

!end
100     STOP 'NORMAL END OF MODEL.FOR'
        END
```

2) Command Files

```
$! file name is BATCH.COM
$! it submits VISION.COM to batch
$! written by David Zokaites Jan-86
$ SUBMIT/NOTIFY/QUE=VAXB$LATE/AFTER=TOMORROW/LOG_FILE= -
 [DMZ5436.DEVELOP]VISION.LOG [DMZ5436.DEVELOP]VISION

$! file name is VISION.COM
$! it collects data for my thesis
$!
$ set noon !ignore errors
$ set def [dmz5436.thesis.develop]
$ assign input.dat sys$input
$ assign sysout.dat sys$output
$ nodeshow userload 2
$ run vision
$ nodeshow userload 2
$ deassign sys$input
$ deassign sys$output
```

3) Program

```
*************************************************************
* INTRODUCTORY COMMENTS
*************************************************************
! Written by David Zokaites
! 11/19/85 - 1/86
! Program name is VISION.FOR
! This program implements the two computer vision algorithms
```

```
! described in the author's research thesis, "Computer Vision
! of a Moving Square using a Two-Level Data Hierarchy."
***************************************************************
* INITIALIZE
***************************************************************
!declare variables
    !View1 is a low res view of the scene PIX1 pixels square,
    !View2   high                          PIX2

   BYTE         !integer data type, 1 byte of memory
+  SQUARE       !below function to create moving square

  INTEGER
+  PIX1,        !number of pixels per row of VIEW1
+  PIX2,        !number of pixels per row of VIEW2
+  TIME,        !time
+  NSCANS,      !# of times scene is scanned
+  CPU,         !elapsed CPU time in milliseconds
+  SCANT,       !cpu time for calling EDGE in 2-level hierarchy
+  OVERALL,     !overall cpu time
+  OVERALL1, OVERALL2,      !overall cpu time for view1 or view2
+  XEDGE(512), YEDGE(512), !boundary of shape 512 = 4 * pix2
+  Ncorners,        !number of corners of the shape found in POLY
+  CORNERS(10,2), !X,Y locations of the corners
+  Nedge,           !# of points on boundary of shape
+  NTEST1, NTEST2,!# of points tested for collinearity see POLY
          !for VIEW1 and VIEW2
  !boundary values for square location, VIEW1
+  HIJ, LOWJ, HII, LOWI,
+  IA, IB, JA, JB           !do loop indices in examining VIEW2

  REAL
+  CONST1(2), CONST2(2), !constants used in COORD
+  LOCATE1, LOCATE2,     !find search location for high res view
+  EXPAND,         !expand area of moving square in high res
+  IANGLES(10), !interior angles of the polygon
+  LINET,          !tolerance for two lines being collinear
+  POINTT,         !tolerance for points on a line being collinear
+  TOLL,           !tolerance for lengths of sides in % from avg
 !parameters of moving square, see line 50
+  SPEEDR, SPEEDT, XI, YI, WIDTH, ANGLE0, ANGLET,
+  SIDES (10)     !lengths of the sides of the polygon fitted

  LOGICAL
+  FLAG,       !T if a shape has been found
+  MEDIUM,     !T if medium length output was chosen
+  LONG,       !     long
+  RECOGN,     !below pattern recognition function
+  RECKON      !T if a square was recognized

 CHARACTER*1    OUTPUT    !used to input length of output
```

```
 !LIB$INIT_TIMER and LIB$STAT_TIMER  are part of the system's
 !run time library. The former initializes the count
 !of elapsed CPU time, the latter determines elapsed time.

!miscellaneous initialization
  !common blocks
    COMMON /SQUAR/ SPEEDR, SPEEDT, Xi, Yi, !for SQUARE
    +     ANGLET, ANGLEO, WIDTH, TIME
    COMMON /CORD/ CONST1, CONST2    !COORD subprogram
      COMMON /SCN/ Nedge        !EDGE
      COMMON /POLY/ LINET, POINTT    !POLY and COLINE
      COMMON /LINE/ XEDGE, YEDGE    !POLY, LINE, EDGE
      COMMON /REC/ TOLL        !RECOGN
      COMMON /OUTPUT/ MEDIUM, LONG    !output in POLY, EDGE

!*** OPEN LOOP TO READ WHILE NOT END OF FILE
  !input length of output
    WRITE (6,20)
20    FORMAT (/
    +  ' Input B for brief output, M for med, and L for long.')
      READ (5,30, ERR=200, END=200) OUTPUT
30    FORMAT (A1)
      IF (OUTPUT .EQ. 'L' .OR. OUTPUT .EQ. 'l') THEN
        MEDIUM = .FALSE.
        LONG = .TRUE.
      ELSE
        IF (OUTPUT .EQ. 'M' .OR. OUTPUT .EQ. 'm') THEN
          MEDIUM = .TRUE.
          LONG = .FALSE.
        ELSE
          MEDIUM = .FALSE.
          LONG = .FALSE.
        END IF
    END IF
  !open output files
    OPEN (UNIT = 1, NAME = 'OUTPUTA.DAT', TYPE = 'NEW')
      IF (LONG) THEN
    OPEN (UNIT = 3, NAME = 'OUTPUTC.DAT', TYPE = 'NEW')
    OPEN (UNIT = 4, NAME = 'OUTPUTD.DAT', TYPE = 'NEW')
      END IF
    OPEN (UNIT = 11,NAME = 'OUTPUTT.DAT', TYPE = 'NEW')
  !output length of output
      WRITE (1,110) OUTPUT
110    FORMAT (' Chosen length of output was ', A1 )
    IF (LONG) WRITE(1,112)
112    FORMAT (' (B = brief, M = medium, L = long) '/)
  !open loop to read
10    CONTINUE

!initialize global variables
```

```
      DATA  PIX1, PIX2 /32, 128/
      LOCATE1 = PIX2 / PIX1
      LOCATE2 = LOCATE1 / 2 - .5
      EXPAND = 1.001 + 1/ LOCATE1
      HII = 0   !variables for square location in VIEW1
      HIJ = 0
      LOWI = PIX1 + 1
    LOWJ = PIX1 + 1
      CONST1(1) = PIX1/2 + .5    !used in COORD
      CONST1(2) = PIX2/2 + .5
    CONST2(1) = PIX1    !used in COORD to scale coordinates
    CONST2(2) = PIX2
      OVERALL = 0
!read variables from screen
  !initial description
    IF (LONG) WRITE (6,40)
40    FORMAT (/
+  ' One unit of time is needed to examine the scene. Scene'/
+  ' has a width of one scene width, is centered about the '/
+  ' origin. Please input the following variables in '/
+  ' these units to define the squares motion.'//)
  !table of variable identification
      IF (LONG) WRITE (6,50)
50    FORMAT (
+  ' VARIABLE DESCRIPTION                  UNITS '/
+  ' SPEEDR  speed of rotation             degrees/time '/
+  ' SPEEDT  speed of translation          scene width/time'/
+  ' NSCANS  # of times scene is examined  counts '/
+  ' Xi, Yi  initial coordinates           scene width '/
+  ' WIDTH   width                         scene width '/
+  ' ANGLEO  initial offset angle          degrees '/
+  ' ANGLET  direction of translation      degrees '//
+  ' ANGLET is measured counter clockwise from horizontal X'/
+  ' axis. ANGLEO is measured counter clockwise from Y axis.'/
+  ' Positive SPEEDR results in counter clockwise rotation,'/
+  ' negative values result in clockwise rotation. Only '/
+  ' Xi, Yi, and SPEEDR are allowed to be negative. NSCANS '/
+  ' must be >= 1 '/)
    READ (5,*, ERR = 220, END = 220) SPEEDR, SPEEDT, NSCANS,
+  Xi, Yi, WIDTH, ANGLEO, ANGLET
!correct for bad input
      SPEEDT = ABS (SPEEDT)
        IF (NSCANS .LT. 1) NSCANS = 1
      WIDTH = ABS (WIDTH)
      ANGLEO = ABS (ANGLEO)
      ANGLET = ABS (ANGLET)
  !echo print input
      IF (LONG)  WRITE (6,60) SPEEDR, SPEEDT, NSCANS,
    +  Xi, Yi, WIDTH, ANGLEO, ANGLET
60    FORMAT (' INPUT ' /
    +  ' SPEEDR SPEEDT NSCANS   Xi   Yi  WIDTH '
```

```
    +  ' ANGLE0 ANGLET'/
    +  2F8.3, I8, 5F8.3/)
  !input polygon fitting, variables
      IF (LONG)   WRITE (6,70)
70    FORMAT (
+  ' Input the following variables which '/
+  ' affect the polygon fitting done here:'/
+  ' LINET, collinearity tolerance in degrees >=1 for 2lines'/
+  ' POINTT, collinearity tolerance in pixel units >=.3 for'
+  ' points on a line'/
+  ' NTEST1, number of points >=3 grouped together for VIEW1'/
+  ' NTEST2, number of points >=3 grouped together for VIEW2'/)
    READ (5,*, ERR = 230, END=230)LINET,POINTT,NTEST1,NTEST2
      !correct for bad input
        IF (LINET .LT. 1) LINET = 1
        IF (POINTT .LT. .3 ) POINTT = .3
        IF (NTEST1 .LT. 3) NTEST1 = 3
        IF (NTEST2 .LT. 3) NTEST2 = 3

 !echo print input
      IF (LONG) WRITE (6,80) LINET, POINTT, NTEST1, NTEST2
80    FORMAT (' INPUT '/
    +  '  LINET POINTT NTEST1 NTEST2', /2F8.3, 2I8/)

 !input pattern recognition variable
      IF (LONG)   WRITE (6,90)
90    FORMAT (' Input the following variable which '/
  +   ' affect the pattern recognition done here: '/
  +   ' TOLL, tolerance for lengths of sides in pixel units'
  +   ' change from the average '/
  +   ' tolerance for interior angles is calculated from TOLL'/)
    READ (5,*, ERR = 240, END=240) TOLL
    !correct for bad input
      TOLL = ABS (TOLL)
  !echo input
      IF (LONG)   WRITE (6,100) TOLL
100    FORMAT (' INPUT '/
    +  '  TOLL', /F8.3/)

!initialize output files
  !square generation variables
    IF (LONG)   THEN
        WRITE (1,40)
        WRITE (1,50)
      END IF
      WRITE (1,60) SPEEDR, SPEEDT, NSCANS,
    +  Xi, Yi, WIDTH, ANGLE0, ANGLET
  !polygon fitting vars
      IF (LONG)  WRITE (1,70)
      WRITE (1,80) LINET, POINTT, NTEST1, NTEST2
  !pattern recognition vars
```

```
      IF (LONG)  WRITE (1,90)
      WRITE (1,100) TOLL
    !elapsed cpu time
        WRITE (11,115)
115       FORMAT (/
      +   ' Elapsed CPU time for executing major routine calls '/
      +   ' Subroutine Called   View    CPU Time (ms) '/)

      !reverse direction of rotation for a given input SPEEDR
        SPEEDR = - SPEEDR
************************************************************
* MAIN SECTION OF PROGRAM
*************************************************************
!repeat the below NSCANS times to allow the shape to move
        DO TIME = 0, (NSCANS -1)

!examine VIEW1 to find a moving shape
  !call edge detection algorithm (scan scene)
    CALL EDGE (1, PIX1, 1, PIX1, 1, PIX1, FLAG, NTEST1, CPU)
    !determine elapsed CPU time
        OVERALL1 = CPU
        SCANT = CPU
        WRITE (11,120) 'edge', '1', CPU
120       FORMAT (2 A14, I14)

  !if a shape was not found, go to end of this section
    IF ( .NOT. FLAG) THEN
      WRITE (1,*)
      WRITE (1,*) ' A SHAPE WAS NOT FOUND IN VIEW1 '
      WRITE (1,*) ' VIEW2 OMITTED '
        OVERALL = OVERALL + OVERALL1
    ELSE

  !call corner detection (polygon fitting) algorithm
    CALL LIB$INIT_TIMER !initializes CPU time
    CALL POLY (PIX1,Nedge, Ncorners, CORNERS, IANGLES,
    +  NTEST1, SIDES, 1)
    !determine elapsed CPU time
        CALL LIB$STAT_TIMER (2,CPU)
        OVERALL1 = OVERALL1 + CPU
        WRITE (11,120) 'poly','1', CPU

  !call pattern recognition algorithm
    CALL LIB$INIT_TIMER !initializes CPU time
    RECKON = RECOGN (NCORNERS, SIDES, IANGLES)
    !determine elapsed CPU time
        CALL LIB$STAT_TIMER (2,CPU)
        OVERALL1 = OVERALL1 + CPU
        WRITE (11,120) 'recogn', '1', CPU

  !find region of the moving shape in VIEW1
```

```
      !find hi and low values for I and J
          CALL LIB$INIT_TIMER
        DO I = 1,Nedge
          IF ( YEDGE(I) .GT. HII)    HII = YEDGE(I)
          IF ( YEDGE(I) .LT. LOWI)  LOWI = YEDGE(I)
          IF ( XEDGE(I) .GT. HIJ)     HIJ = XEDGE(I)
          IF ( XEDGE(I) .LT. LOWJ)      LOWJ = XEDGE(I)
        END DO
        !output results
        IF (LONG) WRITE (1,150) LOWI, HII, LOWJ, HIJ
150       FORMAT (' The region of moving square in VIEW1 is ' /
        +   ' I = ', I2, ' to ', I2, /
        +   ' J = ', I2, ' to ', I2, /)

      !convert from VIEW1 array index to VIEW2 array index
      !EXPAND expands VIEW1 locations by EXPAND pixels
        IA = LOCATE1 * (LOWI - EXPAND) -LOCATE2
        IB = LOCATE1 * (HII + EXPAND) -LOCATE2
        JA = LOCATE1 * (LOWJ - EXPAND) -LOCATE2
        JB = LOCATE1 * (HIJ + EXPAND) -LOCATE2
        !check for and correct out of bounds errors
          IF (IA .LT. 1) THEN
            IA = 1
            END IF
          IF (IB .GT. PIX2) THEN
            IB = PIX2
            END IF
          IF (JA .LT. 1) THEN
            JA = 1
            END IF
          IF (JB .GT. PIX2) THEN
            JB = PIX2
            END IF
        !output results
          IF (LONG)  WRITE (1,160) IA, IB, JA, JB
160       FORMAT (' The region under analysis in VIEW2 is ' /
        +   ' I = ', I3, ' to ', I3, /
        +   ' J = ', I3, ' to ', I3, /)

      !determine elapsed CPU time
          CALL LIB$STAT_TIMER (2,CPU)
          OVERALL1 = OVERALL1 + CPU
        OVERALL = OVERALL + OVERALL1
          WRITE (11,120) 'view1 total', '1', OVERALL1

    !Examine VIEW2 to resolve square
      !edge detection
          CALL EDGE (2, PIX2, IA, IB, JA, JB, FLAG, NTEST2, CPU)
          !elapsed cpu time
          OVERALL2 = CPU
            SCANT = SCANT + CPU
```

```
        WRITE (11,120) 'edge', '2', CPU
    !corner detection
        CALL LIB$INIT_TIMER
        CALL POLY (PIX2, Nedge, Ncorners, CORNERS, IANGLES,
      +  NTEST2, SIDES, 2)
        !elapsed cpu time
          CALL LIB$STAT_TIMER (2,CPU)
          OVERALL2 = OVERALL2 + CPU
          WRITE (11,120) 'poly','2', CPU
    !pattern recognition
        CALL LIB$INIT_TIMER
        RECKON = RECOGN (NCORNERS, SIDES, IANGLES)
      !determine elapsed CPU time
          CALL LIB$STAT_TIMER (2,CPU)
          OVERALL2 = OVERALL2 + CPU
          WRITE (11,120) 'recogn','2', CPU
          WRITE (11,120) 'view2 total','2', OVERALL2
          OVERALL = OVERALL + OVERALL2
    !repeat edge detection, for a one-level data hierarchy
    !instead of two-level
      CALL EDGE (2, PIX2, 1, PIX2, 1, PIX2, FLAG, NTEST2, CPU)
        !elapsed cpu time
        OVERALL2 = CPU
        OVERALL = OVERALL + CPU
        WRITE (11,120) '1 level scan','2', CPU
          WRITE (11,120) '2 level scan','1&2', SCANT
          WRITE (11,120) 'delta time ','1&2', (CPU - SCANT)
          WRITE (11,*)
  !end of this major section
        END IF
        END DO
        WRITE (11,120) 'TOTAL','1&2',OVERALL


  !END PROGRAM, end loop to read data
        WRITE (1,180)
        IF (LONG) THEN
        WRITE (3,180)
        WRITE (4,180)
        END IF
        WRITE (11,180)
  180    FORMAT (/ ' ',80('*')/ ' end of one data set '/  )
        GOTO 10

  200    STOP 'EOF while reading OUTPUT'
  220    STOP 'NORMAL END OF VISION.FOR (EOF reading square )'
  230    STOP 'EOF while reading polygon fitting '
  240    STOP 'EOF while reading TOLL'
         END
```

C) Coordinate System

```
**************************************************************
* subroutine:  translate from array indices (I,J)
* to scene coordinates (X,Y)
**************************************************************
! Arrays are accessed in terms of array indices, I and J for
! example. This routine translates from array indices to the
! coordinate system of the scene itself.  Scene coordinates
! are centered at 0,0 and have a width and height of one.

! This subroutine returns X and Y.

    SUBROUTINE COORD (I, J, N, X, Y)
    COMMON /CORD/ CONST1, CONST2  !constants
  !declare variables
      INTEGER
    +  I, J    !array indices
    +  N    !number of VIEW = 1 for low resolution, 2 for high
      REAL
    +  X, Y,  !position in terms of scene coordinates
    +  CONST1(2),  !used to shift coordinates
    +  CONST2(2)    !scales coordinates

  !shift axis
    X = J - CONST1(N)
    Y = CONST1(N) - I
  !scale axis
    X = X/CONST2(N)
    Y = Y/CONST2(N)

    END
```

D) Object and Scene

```
****************************************************************
* FUNCTION:  CREATE MOVING SQUARE
****************************************************************
! Written by David Zokaites 3/85
! Create the software equivalent of a square which can
! translate as well as rotate. The square has a brightness
! of 1 on a background of brightness 0. If the coordinates
! of the pixel lie within the square, then a 1 is returned.
! Otherwise, a 0 is returned.

!initialize
    BYTE FUNCTION SQUARE (I, J, N)

      INTEGER SCALE, TIME
    COMMON /SQUAR/ SPEEDR, SPEEDT, Xi, Yi,
    +     ANGLET, ANGLEO, WIDTH, TIME

!increment THETA
    !theta = the square's angle from horizontal
      !change in THETA results in rotation of square
      THETA = ANGLEO + SPEEDR * TIME

!to let the square translate, the square's definition is
!constant, the coordinate system of the scene is transformed

!transform array indices
  !convert from array indices (I,J) to scene coordinates (X,Y)
      CALL COORD (I, J, N, X, Y)
  !find change in scene coordinates: allow for square's motion
      R = TIME * SPEEDT
      DELTAX = R * COSD (ANGLET)
    DELTAY = R * SIND (ANGLET)
  !implement above change
      X = X - Xi - DELTAX
      Y = Y - Yi - DELTAY
  !convert scene coordinates to polar coordinates
    !phi = angle from center of square to center of pixel
    PHI = ATAND (Y/X)
    COSPHI = COSD( PHI )
    IF (COSPHI .NE. 0) THEN
      Rxy = X/COSPHI !may give division by zero error
      ELSE
      Rxy = Y/SIND( PHI ) !correction for error
      END IF
    !distance from center of square to center of pixel
    Rxy = ABS( Rxy )

!calculate square's location
```

```
      !compute effective angle, ANGLEE, note the below is a new
      !definition of phi.  draw a line from the square's center
      !to a corner. Phi = angle
      !between this line and a point on the edge of square
        ANGLEE = THETA + PHI
        TEMP = ABS( ANGLEE) + 45
        SCALE = INT( TEMP/90)
        ANGLEE = ABS( ANGLEE - 90*SCALE)
    !Rs = distance from square's center to edge
        Rs = 1/ (2* COSD(ANGLEE))
        Rs = ABS( Rs * WIDTH)         !scales square to width

  !determine if pixel is part of square: core of this subroutine
      IF (Rxy .LE. Rs) THEN
        SQUARE = 1    !pixel is part of square
        ELSE
        SQUARE = 0       !pixel not part of square
      END IF

      RETURN
      END
```

E) Edge Detection

```
************************************************************
* SUBROUTINE:  DETECT EDGES OF MOVING SHAPE
************************************************************
!written by David Zokaites 10/85 - 1/86
!This subroutine scans the scene in either low or high res and
!finds the edges of the moving shape. The top right corner of
!the square is the first point stored in X, Y. The rest of the
!edge points are stored in clockwise progression. This routine
!returns X, Y, FLAG3, and CPU.   CPU = the cpu time required
!to execute this routine. Note that the time required to call
!SQUARE is not included in CPU. This is done by storing the
!results of SQUARE in a temporary file, and reading this file.

!initialize
    SUBROUTINE EDGE (NVIEW, PIX, Ibegin, Iend, Jbegin, Jend,
    +  FLAG3, NTESTP, CPU)

      COMMON /SCN/ Nedge
      COMMON /LINE/ X,Y
      COMMON /OUTPUT/ MEDIUM, LONG  !controls length of output

  !declare variables
       BYTE
    +  SQUARE,              !below function to create moving square
    +  VIEW (128,128)       !a view of the scene

       INTEGER
    +  NVIEW,               !# of view, = 1 or 2
    +  Ibegin, Iend,        !area of VIEW under interest
    +  Jbegin, Jend,        !area of VIEW under interest
    +  X(512), Y(512),      !shape boundary in array indices
    +  Xfirst(128), Yfirst(128),!first part of shape boundary
    +  FIRSTj, LASTj,           !locate square terms of array index
    +  OLDFIRSTJ, OLDLASTJ, !locate square for old row of VIEW
    +  PIX,         !pixels in a row of VIEW
    +  PIX2,        !2 * PIX
    +  PIX2P1,      !PIX2 + 1
    +  Nedge,       !# of points on boundary of shape
    +  Nedge2,      !number of points in Xfirst
    +  NTESTP, !see POLY, # of points tested for collinearity
    +  ONE(150), !array with 1,2,3,4,5,6,7,8,9,0 for output
    +  DELTAJ,      !jend - jbegin + 1
    +  START,       !number of spaces skiped in output statement
    +  ITEN,        !number of I10 format specifier
    +  LSDIGIT,     !function: find least significant digit
    +  INPUT,       !input to statement function
    +  CPU,         !elapsed cpu time
    +  LINES        !number of lines to skip in read statement
```

```
      LOGICAL   !flags for locating shape
   +  FLAG1,    !T if first "1" on a row was found
   +  FLAG2,    !   last
   +  FLAG3,    !T if shape was found
   +  FLAG4,    !T if first row was found
   +  FLAG5,    !T if bottom of shape has been found
   +  WITHIN,   !T if bottom of shape found before end of field
   +  BEYOND,   !T if shape extends beyond bottom of field
   +  MEDIUM,   !T if medium length output chosen
   +  MEDLONG,  !sometimes T when medium is T
   +  LONG      !T if long length output was chosen

  !declare statement function to find least significant digit
       LSDIGIT (INPUT) = 10.0 * ( FLOAT(INPUT )/10.0 + .01 -
    +  INT (INPUT/10))

      !LIB$INIT_TIMER and LIB$STAT_TIMER  are part of system's
      !run time library. The former initializes the count of
      !elapsed CPU time, the latter determines elapsed time.

      OPEN (UNIT = 1, NAME = 'OUTPUTA.DAT', TYPE = 'OLD')
      OPEN (UNIT = 10, NAME = 'SQUARE.DAT', TYPE = 'NEW')

  !initialize VIEW
      DO I = 1, PIX
      DO J = 1, PIX
        VIEW (I,J) = SQUARE (I,J,NVIEW)
      END DO
        WRITE (10,20) (VIEW (I,K), K = 1, PIX)
20        FORMAT (' '<PIX>I1)
      END DO
      CLOSE (UNIT=10)

  !call routine to initialize cpu time
      CALL LIB$INIT_TIMER

  !set pointer to SQUARE.DAT
      OPEN (UNIT = 10, NAME = 'SQUARE.DAT', TYPE = 'OLD')
      LINES = IBEGIN - 2
      IF (LINES .EQ. 0)  READ (10,*)
      IF (LINES .GT. 0)  READ (10,30)
30    FORMAT ( <LINES> (/) )

  !initialize variables
      Nedge = 0
      Nedge2 = 0
      PIX2 = 2 * PIX
      PIX2P1 = PIX2 + 1
      FLAG3 = .FALSE.          !square not found yet
      FLAG4 = .FALSE.          !end of square not found yet
```

```
      FLAG5 = .FALSE.
      MEDLONG = LONG .OR. (MEDIUM .AND. (NVIEW .EQ. 1))
      !initialize one, start
      IF (MEDLONG) THEN
        DO I = 0, 14
          DO J = 1,9
          ONE(J + 10*I) = J
          END DO
          ONE(J + 10*I) = 0
        END DO
        START = 10 - LSDIGIT (JBEGIN)
        DELTAJ = JEND - JBEGIN + 1
      ITEN=(JEND-LSDIGIT(JEND))- (JBEGIN - LSDIGIT(JBEGIN))
      ITEN = ITEN/10 - 1
      END IF
  !initialize output
      !check for printer overflow error
    IF (MEDLONG .AND. Jend - Jbegin + 6 .GT. 130) WRITE (1,40)
40  FORMAT (' '80('*')/ ' More than 130 characters per record,'
    +    'requires special printer set up '/ ' ', 80('*') )
    !normal output
        IF (MEDLONG)  WRITE (1,60) NVIEW,
    +       ( ONE (I), I = (JBEGIN/10 +1), (JEND/10) ),
    +       ( ONE (I), I = JBEGIN, JEND )
60      FORMAT ( / ' This is the scene as the program saw'
    +       ' it for VIEW',I1 / ' ROW '
    +    I<START>, <ITEN>I10, /, 5X, <DELTAJ>I1 )
!Examine VIEW to find square
    DO I = Ibegin, Iend
    !initialize variables for VIEW
      !read VIEW
        READ (10,65) ( VIEW(I,J), J = JBEGIN, JEND)
65        FORMAT ( T<JBEGIN+1>, <JEND-JBEGIN+2> I1)
      !flags for locating square, square not found yet
        FLAG1 = .FALSE.
        FLAG2 = .FALSE.
     !vars for locating square, if square not found, vars=< 0
        OLDFIRSTJ = FIRSTJ
        OLDLASTJ = LASTJ
        FIRSTj = 0
        LASTj = 0
    !open do loop to examine one row of VIEW
      DO J = Jbegin, Jend

  !LOCATE SQUARE: find first and last pixel per row = 1
    !find first pixel by finding first "1"
      IF ((VIEW(I,J) .EQ. 1) .AND. .NOT. FLAG1 ) THEN
      FIRSTj = J  !first pixel = J
      FLAG1 = .TRUE.  !set flag to find only one first "1"
        FLAG3 = .TRUE.    !square has been found
      END IF
```

```
    !find last pixel by finding first "0" after first "1"
      IF ((VIEW(I,J).EQ.0).AND..NOT.FLAG2.AND.FLAG1)THEN
      LASTj = J - 1  !last pixel = ...
      FLAG2 = .TRUE.   !set flag to find only one last pixel
      END IF
    !last pixel: boundary at right edge
      IF ((VIEW(I,J) .EQ. 1) .AND. (J .EQ. Jend)) THEN
      LASTj = Jend   !last pixel = Jend
      END IF

  !finish examination of one row of VIEW
      END DO
    !fill array of shape's boundary
        !first row of moving shape
        IF ( FLAG1 .AND. .NOT. FLAG4 ) THEN
          DO K = LASTJ, (FIRSTJ+1), -1
              NEDGE2 = NEDGE2 + 1
            Xfirst(NEDGE2) = K
            Yfirst(NEDGE2) = I
          END DO
          FLAG4 = .TRUE.
        END IF
      !middle section of moving shape
        IF (FLAG1) THEN
          NEDGE = NEDGE + 1
          X(NEDGE) = LASTJ
          Y(NEDGE) = I
          NEDGE2 = NEDGE2 + 1
          XFIRST(NEDGE2) = FIRSTJ
          YFIRST(NEDGE2) = I
          END IF
        !last row of moving shape
          !see if shape extends beyond the bottom row of VIEW
          BEYOND = (LASTJ .NE. 0) .AND. (I .EQ. Iend)
          !see if bottom of shape has been found within VIEW
        WITHIN = FLAG4 .AND. (FIRSTJ .EQ. 0)
          WITHIN = WITHIN .AND. .NOT. FLAG5
        IF BEYOND I = I + 1
          IF (BEYOND .OR. WITHIN) THEN
            IMINUS1 = I - 1
              DO K = (OLDLASTJ -1), OLDFIRSTJ, -1
              NEDGE = NEDGE + 1
            X(NEDGE) = K
            Y(NEDGE) = IMINUS1
          END DO
          DO K = (NEDGE2 - 1), 2, -1
            NEDGE = NEDGE + 1
            X(NEDGE) = XFIRST(K)
            Y(NEDGE) = YFIRST(K)
          END DO
            FLAG5 = .TRUE.
```

```
          END IF
      !output data
          IF (MEDLONG)
      +    WRITE (1,70) I, (VIEW(I,K), K = Jbegin, Jend)
  70      FORMAT (' ', I3,' ', <PIX>I1 )
    !close outer do loop
      END DO
    !output data
   IF (LONG) WRITE (1,80) NEDGE, NVIEW, (K, X(K),Y(K),K=1,Nedge)
  80  FORMAT(/,I3,' points describe shape boundary in VIEW',I1, /
      +  ' Point #    X and Y in Array Indices '/
      +  1000(3I8/))
  !end subroutine
        CALL LIB$STAT_TIMER(2,CPU)
        CLOSE (UNIT=10)
        END
```

F) Corner Detection

1) Main Routine

```
**************************************************************
* SUBROUTINE: POLYGON FITTING
**************************************************************
! Written by David Zokaites 11/85
! This subroutine implements a polygon fitting or corner
! detection algorithm.  For more details, see the author's
! thesis, "Computer Vision of a Moving Square using a
! Two-Level Data Hierarchy".

! This subroutine returns Ncorners, CORNERS, IANGLES, and SIDES.

! initialize
   SUBROUTINE POLY (PIX, Nedge, Ncorners, CORNERS, IANGLES,
+  NtestP, SIDES, NVIEW)

  COMMON /POLY/ LINET, POINTT
  COMMON /LINE/ X,Y    !for LINE subroutine
  COMMON /OUTPUT/ MEDIUM, LONG    !controls output

   INTEGER
   !boundary of moving shape, coordinates of the data points
+  X(512), Y(512),
+  FIRSTp,  !index to first point of collinearity test group
+  LASTp,   !index of the last
+  NTESTP,  !number of points above group normally contains
    !usually 5 to 10, must be >3 here. bigger for VIEW2 than
    !VIEW1 because larger squares should be broken into bigger
    !segments for polygon fitting.
+  VERTEX(10),    !last polygon vertex declared
+  Ncorners,      !number of corners found in POLY
+  CORNERS(10,2),!vertices
+  LINEAR,        !true if points are collinear
+  MAXp,          !index of point where max error (MAXe) found
              !in a collinearity test
+  PIX,           !number of pixels in one row of VIEW
+  Nedge,          !# of points in X and Y boundary of shape
+  NVIEW         !# of view under test, = 1 or 2

  REAL
+  ANGLE,        !function to calculate angle between adjacent
            !sides of the fitted polygon
+  LENGTH,       !function to calculate length of polygon sides
+  IANGLES(10),!interior angle among adjacent edges of polygon
+  TESTA,        !interior angle under test for merging
+  SIDES(10),    !lengths of the sides of the polygon
```

```
+  LINET,        !collinearity tolerance between lines
       !ranges from 5 to 30?, minimum value here is 20?
+  POINTT        !used in COLINE not POLY

   LOGICAL
+  MEDIUM,       !true if medium length output was chosen
+  LONG          !true if long ...

!open output files
OPEN (UNIT = 1, NAME = 'OUTPUTA.DAT', TYPE = 'OLD')
  IF (LONG) THEN
OPEN (UNIT = 3, NAME = 'OUTPUTC.DAT', TYPE = 'OLD')
OPEN (UNIT = 4, NAME = 'OUTPUTD.DAT', TYPE = 'OLD')
  END IF
!initialize debugging output
  IF (LONG)  WRITE (3,10)  NVIEW
10    FORMAT (/ ' Variables in COLINE for VIEW' ,I1, /
+   '  FIRSTp  LASTp  MAXp  MAXe LINEAR ' )
  IF (LONG)  WRITE (4,20)  NVIEW
20    FORMAT (/
+   ' The angle between two lines as found in POLY for VIEW',I1/
+   ' The lines are described by three points.'/
+   '  ANGLE  POINT1  POINT2  POINT3 ')

!initialize variables
      VERTEX(1) = 1
      CORNERS(1,1) = X(1)
      CORNERS(1,2) = Y(1)
      Ncorners = 1
      FIRSTp = 1
      LASTp = NTESTP

!find vertices
      DO WHILE (LASTP .LE. NEDGE)

      CALL COLINE (FIRSTp,LASTp,MAXp,LINEAR)

      IF (LINEAR) THEN
          IF (VERTEX(Ncorners) .EQ. FIRSTp) THEN
            !line from VERTEX(Ncorners) to FIRSTP=
            !line from FIRSTP to LASTP
          ELSE
          !determine if line from VERTEX(Ncorners) to FIRSTP
          !can be merged with line from FIRSTP to LASTP
          !compute angles
            IANGLES(Ncorners + 1) = ANGLE (VERTEX (NCORNERS),
    +             FIRSTP, LASTP)
            IF (LONG)  WRITE (4,30) IANGLES(Ncorners + 1),
    +             VERTEX(Ncorners), FIRSTP, LASTP
30                FORMAT (F9.3, 3I9)
     !if lines can not be merged declare new polygon vertex
```

```
        TESTA = 180 - IANGLES (NCORNERS + 1)
      IF ( TESTA .LE. LINET ) THEN
       !merge line segments; line from VERTEX(Ncorners) to
       !FIRSTP = line from VERTEX(Ncorners) to LASTP
      ELSE
        Ncorners = Ncorners + 1
      VERTEX(Ncorners) = FIRSTp
          CORNERS(Ncorners,1) = X(VERTEX(Ncorners))
          CORNERS(Ncorners,2) = Y(VERTEX(Ncorners))
        END IF
     END IF
      !increment indices to points under test
      FIRSTp = LASTp        !step ten
      LASTp = LASTp + NTESTP
      !check for LASTP being too big
      IF ((LASTP .GT. NEDGE) .AND. ((NEDGE-FIRSTP) .GE. 1))
 +              LASTP = NEDGE
     !split last line into 2 segments at MAXp
    ELSE !continue if started
       LASTp = MAXp
     END IF
   END DO        !end do while started
!end of subroutine
!IANGLES(1) was not found yet
 IANGLES(1) = ANGLE (VERTEX( NCORNERS), VERTEX(1),VERTEX(2))
 IF (LONG)  WRITE (4,30) IANGLES(Ncorners + 1),
 +  VERTEX(Ncorners), FIRSTP, LASTP
!perform merge check on first and last corners
 TESTA = 180 - IANGLES (1)
 IF ( TESTA .LE. LINET ) THEN     !merge
   NCORNERS = NCORNERS - 1
   DO I = 1, NCORNERS
   DO J = 1, 2
     CORNERS (I,J) = CORNERS ( (I+1), J )
     VERTEX (I)  = VERTEX (I+1)
   END DO
   END DO
 !recompute interior angle
   IANGLES(1) = ANGLE (VERTEX( NCORNERS), VERTEX(1), VERTEX(2) )
   IF (LONG)  WRITE (4,30) IANGLES(Ncorners + 1),
 +    VERTEX(Ncorners), FIRSTP, LASTP
 END IF
!compute sides
   DO I = 1, (NCORNERS -1)
   SIDES(I) = LENGTH ( VERTEX(I), VERTEX(I+1) )
   END DO
   SIDES (NCORNERS) = LENGTH ( VERTEX( NCORNERS), 1)
!output data
 WRITE (1,40) Ncorners, NVIEW, (K, IANGLES(K), SIDES(K),
 +  (CORNERS (K,L), L=1,2), K=1,Ncorners)
40    FORMAT (' ', I1, ' Corners of the moving shape were found'
```

```
    +  ' in VIEW',I1,/
    +        Interior Side '/
    +  ' Corner #  Angle Length    X and Y in array indices '
    +  / 10(I9, 2F8.3, 2I8 /) / )

      END
```

2) Collinearity Tests

```
************************************************************
* SUBROUTINE: TEST POINTS FOR COLLINEARITY
************************************************************
! This subroutine returns MAXp and LINEAR.

!initialize
  SUBROUTINE COLINE (FIRSTp,LASTp,MAXp,LINEAR)

  COMMON /POLY/ LINET, POINTT
  COMMON /LINE/ X,Y
  COMMON /OUTPUT/ MEDIUM, LONG

   INTEGER
+  I,         !do loop index
+  X(512), Y(512), !coordinates of the data points
+  LINEa(2), !line from FIRSTp to LASTp, test collinearity
+  FIRSTp,    !index of first point of group tested
+  LASTp,     !index of the last point ...
+  LINEAR,    !true when points of LINEa are collinear
+  MAXp       !index of point where max error (MAXe) found
          !in a collinearity test

   REAL
+  DET,     !determinate of X and Y from firstp to lastp
+  LEN,     !length of LINEa
+  LENA,    !sum point(i) to point(i+1) lengths
+  ERROR,   !error at a point
+  POINTT, !collinearity tolerance for points on a line
       !minimum value here is 1?
+  LINET,   !used in POLY not COLINE
+  MAXe,    !error at MAXp, MAXp = point of max error
+  TEMP1, TEMP2    !intermediate variables

   LOGICAL
+  MEDIUM, !true if medium length output was chosen
+  LONG     !true if long

  IF (LONG) OPEN (UNIT = 3, NAME = 'OUTPUTC.DAT', TYPE='OLD')

!initialize variables
```

```
    MAXp = FIRSTp
    MAXe = 0.0
    LINEAR = .TRUE.
!evaluate LINEa
    DET = Y(LASTp)*X(FIRSTp) - Y(FIRSTp)*X(LASTp)
    CALL LINE (FIRSTP, LASTP, LINEA)
    LEN = LINEA(1) * LINEA(1) + LINEA(2) * LINEA(2)
    LEN = SQRT ( LEN )
!first collinearity test: compare LENA to LEN
  !compute LENA
    LENA = 0
    DO I = (FIRSTP + 1), LASTP
      TEMP1 = ( X(I) - X(I - 1) ) * ( X(I) - X(I - 1) )
      TEMP2 = ( Y(I) - Y(I - 1) ) * ( Y(I) - Y(I - 1) )
      LENA = LENA + SQRT ( TEMP1 + TEMP2 )
    END DO
      LENA = LENA / LEN
  !test collinearity
     IF ( LENA .LT. 1.1 ) THEN
     ! linear = .true.
     IF (LONG) WRITE (3, 65) FIRSTP, LASTP, MAXp, MAXe, LINEAR
     RETURN
     END IF
     IF ( LENA .GT. 1.5 ) LINEAR = .FALSE.
!find MAXe
    DO I = (FIRSTp+1), (LASTp-1)
      ERROR = DET- LINEa(2)*X(I) + LINEa(1)*Y(I)
      IF ( ABS(ERROR) .GT. MAXe) THEN
        MAXe = ABS(ERROR)
        MAXp = I
      END IF
    END DO
    MAXe = MAXe / LEN
!compute LINEAR
      IF (MAXe .GE. POINTT) LINEAR = .FALSE.
      ! if maxe > pointt  linear = .true.
!end of subroutine
  !output variables
    IF (LONG) WRITE (3, 65) FIRSTP, LASTP, MAXp, MAXe, LINEAR
65  FORMAT(' ', 3I8, F8.3, L8)
  !end
      END
```

3) Associated Subroutines

```
************************************************************
* MISC SUBROUTINES AND FUNCTIONS
************************************************************
```

```
!compute angle between adjacent edges of the fitted polygon
!using the law of cosines:   a*a =b*b + c*c -2*b*c* cos(A)
   REAL FUNCTION ANGLE (VERTEX, FIRSTP, LASTP)

    INTEGER   !pointers to X,Y endpoints of adjacent sides
 +  VERTEX, FIRSTP, LASTP

    REAL VTOF,         !distance from vertex to lastp,
 +  TEMP,              !intermediate variable
 +  FTOL, VTOL,        !distance firstp to lastp, vertex to lastp
 +  LENGTH,            !below function
 +  SMALL              !small correction for round off error

 PARAMETER (SMALL = .000003)

 VTOF = LENGTH (VERTEX, FIRSTP)
 FTOL = LENGTH (FIRSTP, LASTP )
 VTOL = LENGTH (VERTEX, LASTP )

    ANGLE = VTOL * VTOL - VTOF * VTOF - FTOL * FTOL
    TEMP = -2 * VTOF * FTOL
  !check for potential division by 0 error
     IF ( TEMP .EQ. 0 ) THEN
     ANGLE = 90
     RETURN
     END IF
     ANGLE = ANGLE / TEMP
  !check for abs(angle) > 1 due to round off error
    IF (ABS (ANGLE) .GT. 1) THEN
      ANGLE = ANGLE - SIGN (SMALL, ANGLE)
    END IF
    ANGLE = ACOSD (ANGLE)
    RETURN
    END

!compute the length of one side of the fitted polygon
!this function returns length
    REAL FUNCTION LENGTH (BEGIN, END)

      INTEGER
   +  BEGIN, END,  !pointers to X,Y endpoints of the line
   +  DELTA(2)

      CALL LINE (BEGIN, END, DELTA)
      LENGTH = DELTA(1) * DELTA(1) + DELTA(2) * DELTA(2)
      LENGTH = SQRT ( LENGTH )

    RETURN
    END

!compute delta X and delta y for the line from Xbegin, Ybegin
```

```
!to Xend, Yend.  This subroutine returns DELTA()

      SUBROUTINE LINE (BEGIN, END, DELTA)

       COMMON /LINE/ X,Y
       INTEGER
     +  BEGIN, END,       !indices to ends of the line
     +  X(512), Y(512), !boundary of shape
     +  DELTA(2)     !parameters of the line

      DELTA(1) = X(END) - X(BEGIN)     !delta x
      DELTA(2) = Y(END) - Y(BEGIN)     !delta y

      END
```

G) Pattern Recognition

```
*************************************************************
* FUNCTION: PATTERN RECOGNITION
*************************************************************
!Written by David Zokaites 11/85 - 12/85

!This function determines if a shape is square. If it is
!square, then a value of .TRUE. is returned. Otherwise, .FALSE.
!is returned.

!initialize
      LOGICAL FUNCTION RECOGN (NCORNERS, SIDES, IANGLES)

      COMMON / REC / TOLL

  !declare variables
       REAL
    +  IANGLES (10), !interior angles
    +  SIDES (10),   !lengths of the sides of the polygon
    +  AVERAGE,     !average of the sides
    +  ERROR,       !% deviation of one side from the average
    +  ANGLEREF,    !reference interior angle
    +  CHANGE,      !an interior angle - angleref
    +  TOLL,    !tolerance for lengths of sides change from avg
    +  TOLA,    !tolerance for interior angles in degrees
    +  TOLAIN !input tolerances

       INTEGER
    +  NCORNERS,     !number of corners found
    +  NSIDES         !number of sides the shape should have

      DATA NSIDES, ANGLEREF, AVERAGE /4, 90, 0/

      OPEN (UNIT=1, NAME = 'OUTPUTA.DAT', TYPE = 'OLD')

!determine if shape is a square
  !first criteria: number of corners
    IF (NCORNERS .NE. NSIDES) THEN
    RECOGN = .FALSE.
      WRITE (1,20) NCORNERS, NSIDES
20    FORMAT (' The shape has the wrong number of corners: ',
    +  I1, ' not ', I1 )
      WRITE (1,30)
30    FORMAT (' Therefore the shape is NOT a square. '/)
    RETURN
    END IF
  !second criteria: lengths of sides
    !compute AVERAGE
      AVERAGE = 0
```

```
      DO I = 1, NCORNERS
      AVERAGE = AVERAGE + SIDES(I)
      END DO
      AVERAGE = AVERAGE / NCORNERS
      !compare sides to average
    DO I = 1, NCORNERS
      ERROR = SIDES(I) - AVERAGE
      IF ((TOLL - ERROR) .LT. 0) THEN
        RECOGN = .FALSE.
        WRITE (1,40) I, SIDES(I), (ERROR - TOLL)
40        FORMAT (' Side # ', I1, ' of length ', F8.3,
    +       ' is out of tolerance by ', F8.3 , ' % ')
          WRITE (1,30)
        RETURN
      END IF
    END DO
  !third criteria: interior angles
      !compute TOLA from TOLL
        TOLA = ATAND( TOLL/ AVERAGE )
      !make the test
    DO I = 1, NCORNERS
      CHANGE = ABS(IANGLES(I) - ANGLEREF)
      IF (CHANGE .GT. TOLA ) THEN
      RECOGN = .FALSE.
      WRITE (1,50) I, IANGLES(I), (CHANGE - TOLA)
50      FORMAT (' Interior angle # ', I1, F8.3,
    +     ' is out of tolerance by ', F8.3, ' degrees.')
      WRITE (1,30)
      RETURN
      END IF
    END DO
  !if all criteria pass
     RECOGN = .TRUE.
     WRITE (1,60)
60    FORMAT (' The shape passes all criteria and '
    +  'therefore IS a square.'/)

    RETURN
    END
```

H) Statistical Analysis

```
! Program name is [.VISION]STATS.FOR
! Written by David Zokaites 15-Jan-86
! This program characterizes mean, standard deviation, range.
! The input is OUTPUTT.DAT from VISION.FOR

!initialize
  !declare vars
      INTEGER
    +  POINTS,       !number of numbers
    +  DATA(3),       !input data
    +  MIN(3), MAX(3),!minimum and maximum values of the data
    +  RANGE(3),       !max - min
    +  SUM(3),       !sum of data
    +  SUMSQ(3)      !sum of data * data

      REAL
    +  MEAN(3),       !mean of the input data
    +  SDEV(3),      !standard deviation
    +  DELTA          !% change from mean(1) to mean(2)

      LOGICAL NEWSET      !T if read from new data set

      CHARACTER*5     TEST     !test string from input data file
      CHARACTER*7   LABEL(3)     !labels output

  !misc initialization
      !open files
      OPEN (UNIT=1, NAME = 'OUTPUTT.DAT', TYPE = 'OLD') !input
      OPEN (UNIT=3, NAME = 'STATSB.DAT', TYPE = 'NEW') !output
      OPEN (UNIT=4, NAME = 'STATSA.DAT', TYPE = 'NEW') !output
      !initialize output files
      WRITE (3,10)
      WRITE (4,20)
      !set LABEL
        DATA LABEL /'1 level','2 level','delta'/

!open loop to read and examine new sets of data while
!not end of file
30      CONTINUE
!  initialize vars
      NEWSET = .FALSE.
      POINTS = 0
      DO I = 1, 3
      MIN(I) = 1000000
      MAX(I) =-1000000
      SUM(I) = 0
      SUMSQ(I) = 0
      END DO
```

```
   !open loop to examine old data set
40    CONTINUE
    READ (1, 50, END = 100) TEST
      !increment sums if ...
         IF ( TEST .EQ. 'view2') THEN
      !increment sums
          READ (1,55) DATA
        POINTS = POINTS + 1
        DO I = 1, 3
          IF ( DATA(I) .LT. MIN(I) ) MIN(I) - DATA(I)
          IF ( DATA(I) .GT. MAX(I) ) MAX(I) = DATA(I)
          SUM (I) = SUM(I) + DATA(I)
          SUMSQ(I) = SUMSQ(I) + DATA(I) * DATA(I)
        END DO

      !if end of data set ..
      ELSE IF (TEST .EQ. '*****') THEN
      !compute statistics
        NEWSET = .TRUE.
        IF (POINTS .GE. 2) THEN
        DO I = 1, 3 !compute statistics
          RANGE (I) = MAX(I)   MIN(I)
          MEAN (I) = FLOAT ( SUM(I) ) / POINTS
          SDEV(I) = POINTS * SUMSQ(I) - SUM(I) * SUM(I)
          SDEV(I) = SDEV(I) / ( POINTS * (POINTS - 1) )
          SDEV(I) = SQRT ( ABS (SDEV(I)))
        END DO
          DELTA = 100 * MEAN(3) / MEAN(1)
      !output data
          WRITE (3, 70) MEAN, DELTA
        WRITE (4, 80) ( MEAN(I), SDEV(I), RANGE(I), MIN(I),
    +         MAX(I), LABEL(I), POINTS, I = 1,3)
        END IF

      END IF
  !close loop to examine new sets of data in file
      IF (NEWSET) THEN
        GOTO 30
        ELSE
        GOTO 40  !goto examine old data set
      END IF

!FORMAT STATEMENTS
!initialize output files
10    FORMAT (     mean '/
    +  '  ______________________________________'/
    +  '  1 level  2 level   delta  delta% ')
20    FORMAT (
+  ' Statistics calculated in [.VISION]STATS.FOR'
+  ' from data in OUTPUTT.DAT'/
```

```
+   ' mean (mean), standard deviation (sdev); range, from'/
+   ' minimum (min) to maximum (max), for POINTS points. '/
+   '   MEAN  SDEV RANGE  MIN  MAX  DATA TYPE  POINTS'/)
!read test
50          FORMAT (T4, A5)
!read data
55          FORMAT (3 (T35, I8, /) )
!output statistics
70          FORMAT (4 F10.3)
80          FORMAT ( 3(' ',2F8.3, 3I7, A10, I8/))


!finalize
100          STOP 'NORMAL END OF STATS.FOR'
110          STOP 'END OF FILE IN STATS'
              END
```

Contents

A. CPU Time Variability Analysis 85
  1. Output from BATCH.COM and CPU.COM ... 85
  2. Output from CPU.FOR 85
  3. Output from [.CPU]STATS.FOR 86
B. Main Vision Algorithm 87
  1. Modeling of CPU Time Saved 87
  2. Main Output 87
  3. Elapsed CPU Time Data 90
  4. Statistical Analysis 90
    a. First Output File 90
    b. Second Output File 91

A) CPU Time Variability Analysis

1) Output from BATCH.COM and CPU.COM

Note that the following output file was shortened to fit the available space.

```
count = 0
Userload on VAXB.
Tuesday, January 14, 1986  1:32 PM is: 43 users, 1 batch job,
Free memory is: 2686 pages, System load average is: 3.58  6.58

 NORMAL END OF CPU.FOR
count = 1
Userload on VAXB.
Tuesday, January 14, 1986  3:23 PM is: 46 users, 1 batch job,
Free memory is: 3144 pages, System load average is: 8.40  9.32

 NORMAL END OF CPU.FOR
count = 2
Userload on VAXB.
Tuesday, January 14, 1986  6:09 PM is: 30 users, 1 batch job,
Free memory is: 7094 pages, System load average is: 4.01  3.53
```

2) Output From CPU.FOR

Note that the following output file was shortened to fit the available space.

```
Computation CPU time
in ms for repetitions of same thing
Number of repetitions =
35

          1
          0
          2
          1
          1
          1
          2
          2
          2
          1
          2
          1
          2
```

3) Output from [.CPU]STATS.FOR

```
ELAPSED CPU TIME VARIABILITY ANALYSIS DATA
time = time the data was collected
users = number of users on the system, excluding batch
load = avg system over last minute in # processes waiting
process = process using cpu time, computation or I/O
The statistical parameters calculated follow:
mean (mean), standard deviation (sdev); range (range), from
minimum (min) to maximum (max), for POINTS points.
file = file containing elapsed cpu time

          TIME               USERS    LOAD  PROCESS     MEAN  -->

January 14, 1986  1:32 P      43      3.58    Com      1.257  -->
January 14, 1986  1:32 P      43      3.58    Com      4.829  -->
January 14, 1986  1:32 P      43      3.58    Com     18.314  -->
January 14, 1986  1:32 P      43      3.58    Com     76.829  -->
January 14, 1986  1:32 P      43      3.58    Com    185.886  -->
January 14, 1986  1:32 P      43      3.58    Com    437.629  -->

January 14, 1986  3:23 P      46      8.40    Com      1.200  -->
January 14, 1986  3:23 P      46      8.40    Com      4.086  -->
January 14, 1986  3:23 P      46      8.40    Com     18.000  -->
January 14, 1986  3:23 P      46      8.40    Com     75.829  -->
January 14, 1986  3:23 P      46      8.40    Com    186.000  -->
January 14, 1986  3:23 P      46      8.40    Com    439.314  -->

January 14, 1986  6:09 P      30      4.01    Com      1.200  -->
January 14, 1986  6:09 P      30      4.01    Com      3.886  -->
January 14, 1986  6:09 P      30      4.01    Com     17.371  -->
January 14, 1986  6:09 P      30      4.01    Com     76.400  -->
January 14, 1986  6:09 P      30      4.01    Com    185.571  -->
January 14, 1986  6:09 P      30      4.01    Com    433.914  -->

            |                 |       |        |        |
            |                 |       |        |        |
            V                 V       V        V        V
```

The above arrows note where the above file was shortened to fit on this page.

B) Main Vision Algorithm

1) Modeling of CPU Time Saved

```
% time saved with 2-level data hierarchy
    WIDTH    % TIME
    3.500    93.080
   10.000    91.593
   25.000    84.937
   40.000    73.780
   65.000    45.187
   70.000    37.968
   85.000    13.312
  100.000    -6.250
```

2) Main Output

Note that the following output file was shortened to fit the available space.

```
Chosen length of output was M
INPUT
SPEEDR   SPEEDT   NSCANS       Xi        Yi     WIDTH   ANGLEO   ANGLET
20.000    0.100        2    0.000     0.000     0.400    0.000    0.000


 INPUT
   LINET   POINTT   NTEST1   NTEST2
  45.000    2.500       16       32


 INPUT
    TOLL
   2.400


 This is the scene as the program saw it for VIEW1
 ROW            1         2         3
     12345678901234567890123456789012
   1 00000000000000000000000000000000
   2 00000000000000000000000000000000
   3 00000000000000000000000000000000
   4 00000000000000000000000000000000
   5 00000000000000000000000000000000
   6 00000000000000000000000000000000
   7 00000000000000000000000000000000
```

```
  8 00000000000000000000000000000000
  9 00000000000000000000000000000000
 10 00000000000000000000000000000000
 11 00000000001111111111110000000000
 12 00000000001111111111110000000000
 13 00000000001111111111110000000000
 14 00000000001111111111110000000000
 15 00000000001111111111110000000000
 16 00000000001111111111110000000000
 17 00000000001111111111110000000000
 18 00000000001111111111110000000000
 19 00000000001111111111110000000000
 20 00000000001111111111110000000000
 21 00000000001111111111110000000000
 22 00000000001111111111110000000000
 23 00000000000000000000000000000000
 24 00000000000000000000000000000000
 25 00000000000000000000000000000000
 26 00000000000000000000000000000000
 27 00000000000000000000000000000000
 28 00000000000000000000000000000000
 29 00000000000000000000000000000000
 30 00000000000000000000000000000000
 31 00000000000000000000000000000000
 32 00000000000000000000000000000000
4 Corners of the moving shape were found in VIEW1
           Interior Side
Corner #    Angle  Length      X  and  Y   in array indices
       1   90.000  11.000     22      11
       2   90.000  11.000     22      22
       3   90.000  11.000     11      22
       4   90.000  11.000     11      11

The shape passes all criteria and therefore IS a square.

4 Corners of the moving shape were found in VIEW2
           Interior Side
Corner #    Angle  Length      X  and  Y   in array indices
       1   90.000  51.000     90      39
       2   90.000  51.000     90      90
       3   90.000  51.000     39      90
       4   90.000  51.000     39      39

The shape passes all criteria and therefore IS a square.


This is the scene as the program saw it for VIEW1
ROW          1         2         3
    12345678901234567890123456789012
  1 00000000000000000000000000000000
  2 00000000000000000000000000000000
```

```
   3 00000000000000000000000000000000
   4 00000000000000000000000000000000
   5 00000000000000000000000000000000
   6 00000000000000000000000000000000
   7 00000000000000000000000000000000
   8 00000000000000000000000000000000
   9 00000000000000000000011000000000
  10 00000000000000000011111100000000
  11 00000000000000001111111100000000
  12 00000000000001111111111100000000
  13 00000000000111111111111110000000
  14 00000000000111111111111110000000
  15 00000000000011111111111110000000
  16 00000000000011111111111111000000
  17 00000000000001111111111111000000
  18 00000000000001111111111111100000
  19 00000000000001111111111111100000
  20 00000000000000111111111111100000
  21 00000000000000111111111111000000
  22 00000000000000111111111000000000
  23 00000000000000011111000000000000
  24 00000000000000011000000000000000
  25 00000000000000000000000000000000
  26 00000000000000000000000000000000
  27 00000000000000000000000000000000
  28 00000000000000000000000000000000
  29 00000000000000000000000000000000
  30 00000000000000000000000000000000
  31 00000000000000000000000000000000
  32 00000000000000000000000000000000
4 Corners of the moving shape were found in VIEW1
          Interior Side
Corner #   Angle  Length       X  and  Y  in array indices
       1  90.000  11.705      23        9
       2  90.000  11.705      27       20
       3  90.000  11.705      16       24
       4  91.818  11.705      12       13

The shape passes all criteria and therefore IS a square.

4 Corners of the moving shape were found in VIEW2
          Interior Side
Corner #   Angle  Length       X  and  Y  in array indices
       1  89.220  50.922      92       32
       2  90.383  49.980     109       80
       3  89.085  50.596      62       97
       4  91.975  49.041      46       49

The shape passes all criteria and therefore IS a square.
```

3) Elapsed Cpu Time Data

Note that the following output file was shortened to fit the available space.

```
Elapsed CPU time for executing major subroutine calls
Subroutine Called       View        CPU Time (ms)

           edge           1            17
           poly           1             3
         recogn           1             1
    view1 total           1            21
           edge           2            30
           poly           2             2
         recogn           2             4
    view2 total           2            36
   1 level scan           2           114
   2 level scan          1&2           47
   delta time            1&2           67

           edge           1            16
           poly           1             2
         recogn           1             2
    view1 total           1            20
           edge           2            41
           poly           2             2
         recogn           2             1
    view2 total           2            44
   1 level scan           2           116
   2 level scan          1&2           57
   delta time            1&2           59

          TOTAL          1&2          351
```

4) Statistical Analysis

a) First Output File

Note that the following output file was shortened to fit the available space.

```
Statistics calculated in [.VISION]STATS.FOR from OUTPUTT.DAT
mean (mean), standard deviation (sdev); range (range), from
minimum (min) to maximum (max), for POINTS points.
    MEAN     SDEV  RANGE     MIN     MAX    DATA TYPE    POINTS
```

```
262.667   1.496     5    260    265   1 level     15
 35.667   2.289     9     30     39   2 level     15
227.000   2.928    10    222    232   delta       15

261.933   1.624     6    259    265   1 level     15
 40.667   1.633     6     37     43   2 level     15
221.267   1.668     6    218    224   delta       15

265.133   3.067    12    262    274   1 level     15
 61.667   2.845    10     55     65   2 level     15
203.467   3.739    15    197    212   delta       15
```

b) Second Output File

```
mean

1 level    2 level      delta     delta%
262.667     35.667    227.000     86.421
261.933     40.667    221.267     84.474
265.133     61.667    203.467     76.741
263.267     85.533    177.733     67.511
264.867    153.667    111.200     41.983
266.400    177.667     88.733     33.308
267.733    254.600     13.133      4.905
268.000    288.467    -20.467     -7.637
263.133     40.600    222.533     84.571
262.800     66.400    196.400     74.734
262.533    128.600    133.933     51.016
264.933    253.067     11.867      4.479
265.000    284.000    -19.000     -7.170
267.000    290.800    -23.800     -8.914
266.600    290.467    -23.867     -8.952
```

David Zokaites was born and raised in Pittsburgh, PA. He attended North Catholic High School and is a graduating senior at Rochester Institute of Technology, majoring in Imaging and Photographic Science.

His interests include Aiki JuJutsu, camping, and carpentry. Mr. Zokaites is married and resides in Rochester, NY with his lovely wife, Coni, and their two cats, Jonathan and Harry.