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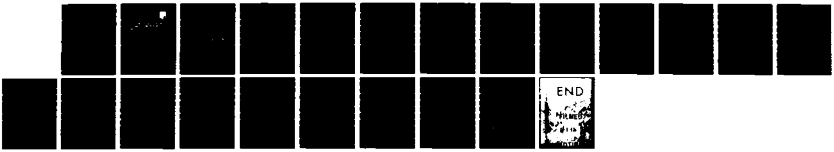

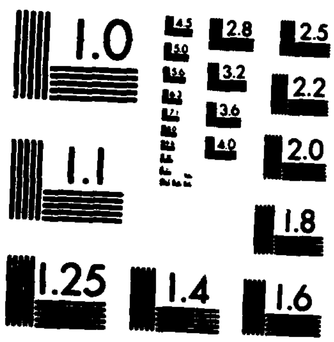


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RADC-TR-83-33
Final Technical Report
February 1983



# EVALUATION OF FOURIER DESCRIPTORS FOR TARGET RECOGNITION IN DIGITAL IMAGERY

**Purdue University**

**O. R. Mitchell and T. A. Grogan**

This effort was funded totally by the Laboratory Directors' Fund

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| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER<br>RADC-TR-83-33 | 2. GOVT ACCESSION NO.<br>AD-A130182 | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle)<br>EVALUATION OF FOURIER DESCRIPTORS FOR TARGET RECOGNITION IN DIGITAL IMAGERY | | 5. TYPE OF REPORT & PERIOD COVERED<br>Final Technical Report |
| | | 6. PERFORMING ORG. REPORT NUMBER<br>N/A |
| 7. AUTHOR(s)<br>O. R. Mitchell<br>T. A. Grogen | | 8. CONTRACT OR GRANT NUMBER(s)<br>F30602-78-C-0148 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Purdue University<br>School of Electrical Engineering<br>W. Lafayette IN 47907 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS<br>61101F<br>LDFP18P1 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>Rome Air Development Center (IRRE)<br>Griffiss AFB NY 13441 | | 12. REPORT DATE<br>February 1983 |
| | | 13. NUMBER OF PAGES<br>22 |
| 14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)<br>Same | | 15. SECURITY CLASS. (of this report)<br>UNCLASSIFIED |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE<br>N/A |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

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

Same

18. SUPPLEMENTARY NOTES

RADC Project Engineer: Donald A. Bush (IRRE)

This effort was funded totally by the Laboratory Directors' Fund.

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

Fast Fourier Transform
Shape Analysis

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

This report describes the mathematical processes involved in generating co-efficients from a binary image of an object. It includes fourier descriptor theory, the normalized fourier descriptor, description of system implementation with library generation, chain code format, normalized fourier descriptor calculation, feature vector format, feature reduction, unknown feature vector extraction, feature vector classification and results applied to target recognition.

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## EVALUATION

This report describes the theory for using fourier descriptors to perform target identification in a digital image. The theory includes a normalization of the co-efficients so that the identification is both scale and rotationally invarient. The report also identifies the library generation and chain encoding algorithms for working with digital imagery and provides a summary "Results of Fourier Descriptors Applied to Target Recognition."

DONALD A. BUSH
Project Engineer

## I. Introduction

The purpose of this project was to determine false alrarm rates and probability of detection for the use of Fourier descriptors in recognition of targets in aerial imagery. Another goal was to develop the software package for Fourier descriptor analysis so that it could be installed on a VAX11/780 computer running the UNIX operating system at Rome Air Development Center.

## II. Fourier Descriptor Theory

The Fourier descriptor is a method using basis functions to decompose or characterize the shape of an object. The basis functions of the Fourier series have nice properties. All the rigid motions in the plane and dilations can be performed by simple operations in the representation space. By tracing the boundary of the silhouette, a complex function of time is obtained. This function is periodic and can be expanded in a Fourier series. Several authors have extended the list of known properties and methods of normalization and recognition [GRAN72], [RICH74], [PERS77], [WALL80].

Given the silhouette of the object, trace the boundary counterclockwise at a uniform velocity. After one complete circuit around the boundary the function repeats. Let,

$$\gamma(t) \triangleq (x(t)\,,y(t)) = x(t) + i\,y(t) \subset R \times R\ .$$

$$v(t) \triangleq velocity = \frac{\partial \gamma(t)}{\partial t}.$$

So,

$$|v(t)|^2 = \frac{\partial \gamma(t)}{\partial t} \frac{\partial \gamma^*(t)}{\partial t}.$$

A uniform tracing velocity implies that

$$|v(t)| = \sqrt{\dot{x}(t)^2 + \dot{y}(t)^2} = Constant.$$

Since $\gamma(t)$ is periodic

$$\gamma(t) = \gamma(t+T),$$

where $T =$ period and $vT = L =$ arc-length. For simplicity let $v = 1$ space unit / time unit. Since $\gamma(t)$ is periodic, we can expand in its Fourier series

$$\gamma(t) = \sum_{n=-\infty}^{+\infty} c_n\, e^{i\frac{2\pi n}{T}t}$$

where

$$c_n = \frac{1}{T}\int_{t_0}^{t_0+T} \gamma(t)\, e^{-i\frac{2\pi n}{T}t}\,dt.$$

All the well known properties of Fourier series analysis are now at our disposal in investigating the properties of this representation.

1) *Convergence:* First, the basis functions $e^{i\frac{2\pi n}{T}t}$ forms an orthonormal basis complete in $L_2$. So, for any curve that is connected and rectifiable, the series converges.

2) *Continuity:* $\gamma(t)$ is everywhere continuous. So, $c_n \sim O(\frac{1}{n^2})$.

3) *Translation:*

$$\gamma'(t) = \gamma(t) + Z_0 \rightarrow c'_0 = c_0 + Z_0$$

4) *Rotation:* Rotation of the shape through an angle $\alpha$

$$\gamma'(t) = \gamma(t)e^{i\alpha} \rightarrow c'_n = c_n\, e^{i\alpha}.$$

5) *Dilation (Scale):*

$$\gamma'(t) = \lambda\gamma(t) \rightarrow c'_n = \lambda\, c_n.$$

6) *Starting point:* For a shift in starting point,

$$\gamma'(t) = \gamma(t - t_0) \rightarrow c'_n = c_n\, e^{-i\frac{2\pi n}{T}t_0}.$$

7) *N-fold symmetry:* For a shape having N-fold rotational symmetry,

$$\gamma(t)e^{i\frac{2\pi}{N}} = \gamma(t + \frac{T}{N}) \rightarrow c_n e^{i\frac{2\pi}{N}} = c_n e^{i\frac{2\pi n}{T}\frac{T}{N}}.$$

We have

$$c_n(1 - e^{i\frac{2\pi}{N}(n-1)}) = 0\,.$$

So, for each $n$ either $c_n = 0$ or

$$(1 - e^{i\frac{2\pi}{N}(n-1)}) = 0 .$$

This means that $(n-1)$ must be a multiple of $N$.

Hence, for an object to have N-fold rotational symmetry, the only non-zero coefficients, $c_n$, are those such that $n = pN+1$, for some integer $p$.

8) *Axial symmetry:* For a shape which is symmetric through its centroid,

$$\gamma(t) = -\gamma(t+\frac{T}{2}) .$$

So,

$$c_n = \frac{1}{T}\int_{t_0}^{t_0+T} \gamma(t) e^{-i\frac{2\pi n}{T}t} dt$$

$$= \frac{1}{T}\int_{t_0}^{t_0+T} \gamma(t) e^{-i\frac{2\pi n}{T}t} dt + \frac{1}{T}\int_{t_0+\frac{T}{2}}^{t_0+T} \gamma(t) e^{-i\frac{2\pi n}{T}t} dt$$

Let $\lambda = t - \frac{T}{2}$,

$$c_n = \frac{1}{T}\int_{t_0}^{t_0+\frac{T}{2}} \gamma(t) e^{-i\frac{2\pi n}{T}t} dt + \frac{1}{T}\int_{t_0+\frac{T}{2}}^{t_0+T} \gamma(\lambda+\frac{T}{2}) e^{-i\frac{2\pi n}{T}(\lambda+\frac{T}{2})} d\lambda$$

$$= \frac{1}{T}\int_{t_0}^{t_0+\frac{T}{2}} \gamma(t) \left[e^{-i\frac{2\pi n}{T}t} - e^{-i\frac{2\pi n}{T}(t+\frac{T}{2})}\right] dt$$

$$= \frac{1}{T}\int_{t_0}^{t_0+\frac{T}{2}} \gamma(t) e^{-i\frac{2\pi n}{T}t} \left[1 - e^{-in\pi}\right] dt .$$

Now,

$(1 - e^{-in\pi}) = 2$, $n$ *odd.*

$= 0$, $n$ *even.*

Hence,

$$c_n = \frac{2}{T}\int_{t_0}^{t_0+\frac{T}{2}} \gamma(t)e^{-i\frac{2\pi n}{T}t}dt \text{ , } n \text{ odd.}$$

$$= 0 \text{ , } n \text{ even.}$$

Thus, a shape exhibiting axial symmetry has only odd non-zero coefficients.

9) *Reflections:* Let $\gamma'$ be the reflection of $\gamma$ about the vertical axis through the centroid. Hence, we have

$$\gamma'(t) = -x(-t + \frac{T}{2}) + iy(-t + \frac{T}{2}).$$

Writing

$$x(t) = \sum \alpha_n e^{i\frac{2\pi n}{T}t}$$

$$y(t) = \sum \beta_n e^{i\frac{2\pi n}{T}t}.$$

From our previous definition of $c_n$,

$$c_n = \alpha_n + i\beta_n \rightarrow c'_{-n} = \alpha_n e^{i(n+1)\pi} + i\beta_n e^{in\pi}.$$

This gives us the following relationship between $\gamma$ and $\gamma'$:

$$|c'_{-n}| = |c_n| \quad \text{and} \angle c'_{-n} = (n+1)\pi - \angle c_n \text{ .}$$

11) *Area:* For a simple closed curve (not necessarily traced at an uniform velocity),

$$Area = \frac{1}{2}\int_\gamma xdy - \frac{1}{2}\int_\gamma ydx \text{ .}$$

$$Area = \frac{1}{2}\int_{t_0}^{t_0+T}\left[x\dot{y} - \dot{x}y\right]dt$$

$$Area = \frac{1}{T}\sum_{n=-\infty}^{+\infty} \pi n \ |c_n|^2$$

When the curve is traced at a constant speed,

$$Area = \frac{v}{L} \sum_{n=-\infty}^{+\infty} \pi n \ |c_n|^2$$

12) *Line shape:* For a line shape, i.e. one with no interior $\gamma(t) = \gamma(T-t)$.

$$c_n = \frac{1}{T}\int_0^T \gamma(t) e^{i\frac{2\pi n}{T}t} dt$$

$$= \frac{1}{T}\int_0^{\frac{T}{2}} \gamma(t) e^{i\frac{2\pi n}{T}t} dt + \frac{1}{T}\int_{\frac{T}{2}}^{T} \gamma(t) e^{i\frac{2\pi n}{T}t} dt \ .$$

Let $\lambda = T-t$ in second integral and substitute $\gamma(\lambda)$ for $\gamma(t-\lambda)$ to obtain

$$c_n = \frac{2}{T}\int_0^{\frac{T}{2}} \gamma(t) \cos(\frac{2\pi n}{T}t) dt \ \rightarrow \ c_n = c_{-n} \ \rightarrow \ Area = 0.$$

- An equivalent Fourier series representation of $\gamma(t)$ is the following [KUHL]:

$$x(t) = \sum_{n=0}^{\infty} \left[ A_n \cos(\frac{2\pi n}{T}t) + B_n \sin(\frac{2\pi n}{T}t) \right]$$

$$y(t) = \sum_{n=0}^{\infty} \left[ C_n \cos(\frac{2\pi n}{T}t) + D_n \sin(\frac{2\pi n}{T}t) \right]$$

Now, $\gamma(t) = x(t) + iy(t)$. So, substituting the above for $x$ and $y$

$$\gamma(t) = \sum_{n=0}^{\infty} \left\{ \left[ A_n \cos(\frac{2\pi n}{T}t) + B_n \sin(\frac{2\pi n}{T}t) \right] \right.$$

$$\left. + i \left[ C_n \cos(\frac{2\pi n}{T}t) + D_n \sin(\frac{2\pi n}{T}T) \right] \right\} .$$

$$= \sum_{n=0}^{\infty} \left\{ A_n \left[ \frac{e^{i\frac{2\pi n}{T}t} + e^{-i\frac{2\pi n}{T}t}}{2} \right] + B_n \left[ \frac{e^{i\frac{2\pi n}{T}t} - e^{-i\frac{2\pi n}{T}t}}{2i} \right] \right.$$

$$\left. + iC_n \left[ \frac{e^{i\frac{2\pi n}{T}t} + e^{-i\frac{2\pi n}{T}t}}{2} \right] + iD_n \left[ \frac{e^{i\frac{2\pi n}{T}t} - e^{-i\frac{2\pi n}{T}t}}{2i} \right] \right\}$$

$$= \sum_{n=0}^{\infty} \left\{ \left[ \frac{A_n}{2} + \frac{B_n}{2i} + i\frac{C_n}{2} + i\frac{D_n}{2i} \right] e^{i\frac{2\pi n}{T}t} \right.$$

$$\left. + \left[ \frac{A_n}{2} - \frac{B_n}{2i} + i\frac{C_n}{2} - i\frac{D_n}{2i} \right] e^{-i\frac{2\pi n}{T}t} \right\}$$

$$= \sum_{n=-\infty}^{1} \frac{1}{2} \left[ A_{-n} + iB_{-n} + iC_{-n} - D_{-n} \right] e^{+i\frac{2\pi n}{T}t}$$

$$+ (A_0 + iC_0)$$

$$+ \sum_{n=1}^{\infty} \frac{1}{2} \left[ A_n - iB_n + iC_n + D_n \right] e^{i\frac{2\pi n}{T}t}$$

Thus, we have the following relationship between the two representations:

$$c_0 = A_0 + iC_0$$

$$c_n = \frac{1}{2} \left[ (A_n + D_n) - i(B_n - C_n) \right]$$

$$c_{-n} = \frac{1}{2}\left[(A_n - D_n) + i(B_n + C_n)\right], n = 1,2, \cdots$$

**The Normalized Fourier Descriptor**

In this section we will discuss the procedure used to normalize the characterization of the shape to a standard orientation, size, and starting point. To compare two Fourier descriptors (FD's) for shape recognition we need to scale, rotate, and shift the starting point of the unknown object boundary curve to that of the template curve.

Persoon & Fu [PERS77] describe a method that is "optimum" in that it minimizes the mean-squared error between the unknown and the template shape. Given two shapes $\gamma$ and $\gamma'$ having coefficients $c_n$ and $c'_n$, respectively, minimize the distance

$$d(\gamma,\gamma') = \left[\sum_n |c_n - c'_n|^2\right]^{\frac{1}{2}}.$$

In practice, only N coefficients of the FD for the shape are retained. We want to scale, rotate, and shift the starting pint by introducing the parameters $s$, $\alpha$, $\varphi$ , respectively. Hence, we want to minimize the quantity

$$\sum_{n=-N/2,\, n\neq 0}^{N/2} \left[c_n - se^{i(n\varphi+\alpha)}c'_n\right]^2$$

Letting

$$c_n^* c'_n = \rho_n e^{i\psi_n}$$

we have

$$\sum c_n c_n^* + s^2 \sum c'_n c'^*_n - 2s \sum \rho_n \cos(\psi_n + n\varphi + \alpha) .$$

To minimize this expression with respect to $s$, $\alpha$, $\varphi$ take partial derivatives and set them equal to zero.

$$\frac{\partial}{\partial s} = 2s \sum c'_n c'^*_n - 2\sum \rho_n \cos(\psi_n + n\varphi + \alpha)$$

$$\frac{\partial}{\partial \varphi} = 2s \sum \rho_n sin(\psi_n + n\varphi + \alpha)$$

$$\frac{\partial}{\partial \alpha} = 2s \sum \rho_n n sin(\psi_n + n\varphi + \alpha) .$$

By setting the partials equal to zero the following equations are obtained

$$s = \frac{\sum \rho_n cos(\psi_n + n\varphi + \alpha)}{\sum c'_n c'^*_n} \quad (1)$$

$$tan(\varphi) = - \frac{\sum \rho_n sin(\psi_n + n\varphi)}{\sum \rho_n cos(\psi_n + n\varphi)} \quad (2)$$

$$tan(\varphi) = - \frac{\sum \rho_n n \; sin(\psi_n + n\varphi)}{\rho_n n \; cos(\psi_n + n\varphi)} . \quad (3)$$

Combining (1) and (2) into one equation in $\varphi$

$$f(\varphi) = \sum \rho_n sin(\psi_n + n\varphi) \sum n \rho_n cos(\psi_n + n\varphi)$$

$$- \sum \rho_n cos(\psi_n + n\varphi)_n \rho_n sin(\psi_n + n\varphi) .$$

The optimum value for $\varphi$ is obtained when $f(\varphi)$ is zero. The corresponding values of $s$ and $\alpha$ can be obtained from equations (1) and (2).

Because only N coefficients are usually retained to characterize each shape, the roots of $f(\varphi)$ can be obtained. This will be a very expensive computation however.

To reduce the expense in normalization several authors ([WALL80], [KUHL], [GRAN72]) have used a "suboptimal" method which normalizes each shape to a standard orientation independently. Because the fundamental or $c_1$ component has been observed always to be the largest for a closed curve traced CCW, this component is used for scale normalization. This is performed by scaling the shape so that $c'_1 = 1$, i.e. $c'_n = \frac{c_n}{|c_1|}$. Most of the variation between normalization methods comes in normalizing with respect to rotation and starting point. The simplest method is to rotate and shift so that the phase of the transformed coefficients $c_1$ and $c_{-1}$ are zero. This is equivalent to assuming the shape is an ellipse and rotating and shifting the starting point so that the major axis of the ellipse coincides with the x-axis.

There are two basic problems with this method of normalization. For many shapes, including all that have N-fold symmetry for $N>2$, we have that $|c_{-1}| = 0$, except for representation errors.

Secondly, there are two possible rotations of the object that will satisfy the above requirements. A 180° rotation and $T/2$ shift of starting point also places the major axis of the fundamental ellipse along the x-axis.

Wallace[WALL80] addresses both of these problems. Wallace's normalization method is as follows:

1) Set $c_0 = 0$.

2) Scale the object so that $|c_1| = 1$.

3) Find k such that $|c_k|$ is a maximum for all $k \neq 0, 1$.

4) Rotate the object so that $\angle c'_1 = 0$ and $\angle c'_k = 0$, i.e. $c'_n = e^{i\left[(n-k)\angle c_1 + (1-n)\angle c_k\right]/(k-1)}$

5) There are $m[k] - 1 = |k-1| - 1$, possible normalizations such that 4) is true. So, choose the normalization such that $\sum \mathrm{Re}\left[c'_n\right] |\mathrm{Re}\left[c'_n\right]|$ is a maximum. This is the normalization that places the starting point and the lobe of the m[k]-fold fundamental shape on the x-axis such that the curve is farthest from the centroid.

## III. Description of System Implementation

### A. Library Generation

The first order of business in implementing a shape recognition system is to generate the libraries for the different shapes. To accomplish this a set of parameters for an airplane are provided to the program *planen2* This program takes a parametric or "blueprint" description of the airplane and generates planar patches covering the skin of the airplane. The parameters needed for *planen2* are such things as: the number of engines, where the engines are on the airplane, the length and width of the fuselage, the position of the wings on the fuselage, the position of the wing tip edges, the width of the wings at the fuselage and at the wings tips, the same data for the tail wings, and tail is needed. The fuselage and engine bodies are approximated by a cylindrical prism. The nose cone and tail cone on the fuselage are approximated by a prismatic cone. Coordinates for the vertices of the planar patches are output from the program.

For each aspect desired in the library for each airplane, the program *mdgen* generates a chain-code. The chain-code for the desired aspect angle is obtain as follows:

a) Rotate each vertex of each planar patch by the aspect angle ($\varphi_{xy}$ , $\varphi_{yz}$)

b) Project the rotated patch onto the image plane (set z coordinate to zero).

c) The object is traced and the chain-code is generated by detecting if a point in a NxN grid in the image plane lies within at least one of the projected planar patches. This part of the algorithm is sped up by sorting the planar patches by the upper left hand corner coordinate of the patch and its lower right hand corner coordinate. An initial edge point on the contour is found by beginning at the center of the grid and scanning to find an object edge transition. Once a starting-point on the edge is found, then the nearest patches in the image plane are searched first to indicate if that grid point lies within one of the patches. From this edge following, the object contour is traced and its corresponding chain-code is produced.

Once chain-code descriptions have been determined for all the desired aspects for each airplane, the normalized Fourier descriptor is calculated.

### B. Chain-Code Format

The chain-code output from ***mdgen*** has with it attributes that might be used later in processing the chain-code. Because of this a standard chain-code format was adopted having the following form:

```
short int   id              unique chain-code id number
short int   flags           flags
short int   code            image code
short int   xstart          x starting coordinate
short int   ystart          y starting coordinate
short int   zstart          z starting coordinate
short int   scale           object scale
short int   rotang          angle of rotation
short int   length          length of chain-code
char        chain[length]   chain-code
```

The chain-code itself is an eight-neighbor chain-code which indicates the direction to proceed to the next point along the contour. The chain-code directions are encoded as follows:

| | | |
|---|---|---|
| 3 | 2 | 1 |
| 4 | + | 0 |
| 5 | 6 | 7 |

### C. Normalized Fourier Descriptor Calculation

The normalized Fourier descriptor (NFD) of each chain-code is calculated (is calculated using the program *mrbld*).The normalized Fourier descriptor (NFD) of each chain-code is calculated by carrying out the following operations:

a) The chain-code is converted to a corresponding complex vector $\hat{z} = (x_j + i\ y_j)$.

b) The complex vector is smoothed by using a convolutional window as a function of arc-length. Possible windows are rectangular , triangular and Gaussian.

c) Next, if necessary, the contour complex vector is resampled to a power of two using linear interpolation (with respect to arc-length).

d) Once we have a complex vector,that is a power of two, we can perform a radix two FFT.

e) The result of the FFT is then normalized using the sub-optimal method of Wallace described above. Both the NFD , the starting-point rotation angle, and a normalization signature are output by this program. The normalization signature provides the information concerning the coefficient used in the normalization and which lobe was rotated to the x-axis.

### D. Feature Vector Format

Later, the output of the NFD generation program will be in a standard "feature vector " format. A standard feature format is desired so that competing shape methods can be analyzed using the same feature reduction and classification programs. This format is essentially the same as the chain-code format except in the PDS header information is provided to designate what method was used to create this feature vector and what is the arithmetic type of the data vector (i.e. character, integer, floating, or complex data). At the present, the NFDs is written in Fortran formatted ASCII I/O.

**E. Feature Reduction**

The features provided by the different shape methods is assumed to contain some redundant information, so some kind of feature vector transformation is desired to reduce the dimensionality of the feature vector. This is necessary to reduce the storage requirements for the libraries. This reduction is accomplished by performing an eigen-analysis (using the program *bldeig* ) on all the libraries. The feature vectors are eigen-analyzed by forming the matrix $A(i,j) = \mathbf{x}\,\mathbf{x}^T$ and averaging over all features in all the libraries. The resulting eigenvectors are sorted by there eigenvalues. The eigenvectors corresponding to the K largest eigenvalues are used to transform feature vectors.

The feature vectors in each library are transformed by the eigenvectors having the largest corresponding eigenvalues as described above using the program *bldint*. Each component is multiplied by 10,000 and the integer part retained in order to reduce the storage requirement for the libraries. The original feature vectors were $N \times 4$ bytes and the transformed feature vectors are $K \times 2$ bytes ($K < N$).

**F. Unknown Feature Vector Extraction**

To obtain the unknown feature vector, first the object must be extracted or segmented from the background. This is a very image class dependent problem and many methods exist to accomplish this. For the pan-chromatic video data provided, in order to segment the object from the background, a rather sophisticated image segmentation algorithm using both the grey-levels and edge inform tion was required. These operations are performed by the programs *sobel*, *postarg2*, *mean*, *mountain*, *trimptarg2*, and *radseg2*.

Once, the object is segmented from the background, the object boundary is traced and its corresponding chain-code output. The tracing is performed by the program *ctrace*. The chain-code is input to the same programs that generated the feature vectors for the library, except in this case it is often necessary to filter the contour more for noise removal.

### G. Feature Vector Classification.

Once the feature vector (i.e. the transformed NFD) has been computed. this unknown feature vector is compared to all the entries in each library. The unknown feature vector is then assigned to the airplane and to that aspect for which the distance between the unknown feature vector and the library feature vector is the smallest. In our classification program, the sum of the squared differences between the components of the feature vectors is used as the distance measure. This distance measure is used since it corresponds to the sum-of-squares distance measure in the space domain as well. The classification is performed by the program *clasfy*.

## IV. Results of Fourier Descriptors Applied to Target Recognition

The algorithms described above were used to perform recognition experiments on the data supplied by RADC. (This data is described in the final report for SCEE Contract PDP81-31.) The results indicate that when the target is sufficiently different in gray level from the background, the shape can be accurately extracted and very high (>97%) classification accuracies can be obtained. However under more commmon conditions, the lighting, shadows, and background variations cause difficulty with object segmentation, and the classifier must be adjusted to allow more variation in the expected contour (we allow 12% mean-square-error). In this case, classification accuracy drops to 90% for a four class problem and false alarms occur approximately once per 512x512 pixel image.

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# MISSION
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# *Rome Air Development Center*

[illegible] plans and executes research, development, test and [illegible]

END

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