All-aspect Ship Recognition in Infrared Images

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Abstract

The paper describes an investigation of the problem of identifying objects, in particular ships at sea, in infrared images obtained at a variety of angles and scales.

The paper covers theoretical and experimental work relating to the choice of feature vectors to describe the images and the application of the this work to the development of a demonstration system.

1 Introduction

The paper describes an investigation of the problem of identifying objects, in particular ships at sea, in infrared images obtained at a variety of angles and scales.

The following sections describe the problem and the approach adopted in the investigation; the method used to simulate images for the creation of feature vectors; the various types of moments that were used as features; the way in which the geometry of the moments was investigated; the metrics used in subsequent recognition experiments; the results of these experiments; the construction of the demonstration system and a summary of its performance.

2 Problem Statement

The project was concerned with the identification of ships at sea from images obtained from airborne infrared imaging systems. (Similar considerations apply to images obtained using light in the visible part of the electromagnetic spectrum.)

The appearance of a ship in such an image will depend on the distance between the ship and the imaging system, which we will term the *range*, and the aspect angle of the ship relative to the imaging system.

It will be convenient to describe the aspect angle in terms of two other angles: the *angle of lookdown*, which

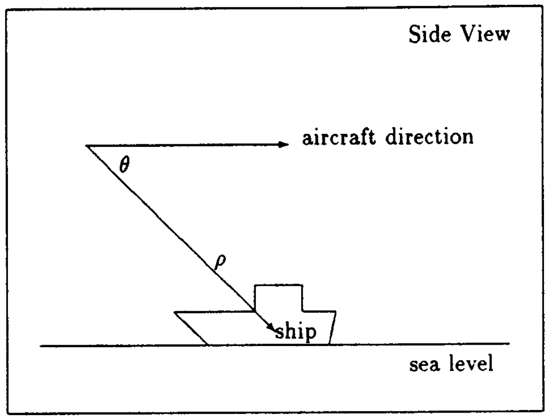

Figure 1: Definition of the range (ρ) and lookdown (θ) parameters.

is the angle between the horizontal and the position of the ship, and the *relative heading*, which is the angle between the direction to the ship (assumed to be directly ahead of the aircraft) and the direction in which the ship is moving. Figures 1 and 2 give a diagrammatic explanation of these parameters, which we will denote by ρ, θ, and ϕ, respectively.

The appearance of a ship will vary greatly as these three parameters vary, growing smaller as the range increases. and presenting a variety of profiles as the angle of lookdown and relative heading change. The fundamental problem to be addressed in this project is concerned with the identification of a ship from an image of it. regardless of these variations in appearance. (For the purposes of the project, identification relates to the class of ship — for example, patrol boat, frigate, or submarine — rather than the naming of a particular ship.)

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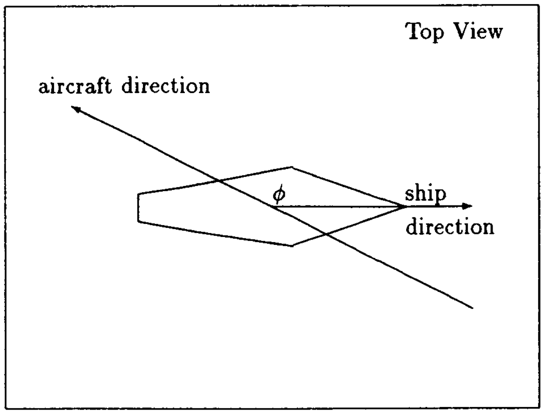

Figure 2: Definition of the relative heading parameter (ϕ).

3 Approach Adopted

The approach adopted was to use simulated data to study how various sets of feature vectors behaved as the parameters ρ, θ, ϕ varied. Wireframe models of ships were constructed and their profiles at various ranges and aspect angles generated. These profiles were used to construct various sorts of feature vectors.

Projections of the set of feature vectors from higher-dimensional space on the two-dimensional screen of a computer monitor were studied in order to gain an understanding of the geometry of the set. This study led to a number of hypotheses about effective ways of discriminating between the various ship classes, which were tested on the simulated data. Consideration was also given to ways in which the discriminating algorithms might be implemented as ANN architectures.

A set of realistic infrared images was supplied for the purpose of testing the ideas that were developed during the project. These were used to develop a demonstration system.

4 Image Simulation

Three sets of images were constructed using the simulation software developed at the beginning of the project. These images were derived from wireframe models of an aircraft carrier, a submarine and a tanker. The models consisted of a set of cubic splines which outlined the hull, deck and superstructure of these ships. The more detailed features such as radio masts and life boats were not included in the wireframe models in order to keep the models as simple as possible.

A projection program was written which created profiles of the simulated ships as they would appear at various ranges and from various aspect angles. These profiles were displayed as binary images. The images were used as the data from which the feature vectors were computed.

Using the simulated data, a large number of feature vectors were generated. This made it possible to study in detail the geometry of the set of feature vectors and the way in which they depended on the range, lookdown and relative heading parameters.

5 Moments as Features

The use of moments is an established method for the construction of feature vectors from image data. The computation of moments is robust against various sorts of noise, and it is possible to combine moments to produce features which have desirable invariance properties. It was therefore decided to limit the investigation to various types of moment-based features. The theoretical and experimental work related to symmetrized central moments and moment invariants. The demonstration system uses symmetrized central moments and Zernike moments.

Central moments are invariant with respect to translation. The second-order central moments can be used to construct a natural coordinate system for an object. This coordinate system can then be used to construct third-order moments that are invariant with respect to scale and orientation in the plane. It is also possible to find algebraic combinations of central moments which have similar invariance properties.

5.1 Moment Invariants

Hu [3] proposed using algebraic combinations of second and third-order moments to construct features that are invariant with respect to translation, rotation and scaling. These *moment invariants* were used by Dudani *et al.* [2] for the recognition of aircraft profiles, and in a previous project on infrared image recognition (deSilva, [1]). Formulae for the computation of these moment invariants can be found in Dudani *et al.* [2].

The use of moment invariants, as an alternative to the symmetrized central moments, was investigated experimentally.

5.2 Zernike Moments

An alternative approach to the construction of invariant moments was proposed by Zernike [5]. These moments are derived from a family of orthogonal polynomials defined on the unit disk in the complex plane. Formulae for the Zernike moments can be found in Khotanzad and Lu [4].

The geometric characteristics of these moments were not investigated, but they have been used in the demonstration system.

6 The Geometry of the Moments

It was hypothesized that the set of feature vectors for a particular ship would form a three-dimensional submanifold of the moment space as the three parameters ρ, θ, ϕ, were varied.

The geometric structure of this submanifold was investigated by projecting the data down from the multidimensional moment space onto the two-dimensional screen of the computer monitor. Projecting along various directions gives a variety of views of the submanifold, which give some indication of its overall shape, in much the same way that we can gain an impression of an unfamiliar object by walking around it and looking at it from many angles.

The *fview1.2* package was used as a visualization tool to inspect the distribution of vectors within the feature space. *fview* was originally designed for viewing speech feature trajectories embedded in high dimensional spaces and is therefore well suited to displaying data of this form. It allows a range of linear projections to be made of the trajectories, for animated sequences to be made of the trajectories as they are rotated through feature space and for three-dimensional views into the feature space. The projections that *fview* provides allow the two-dimensional screen of a workstation to provide glimpses into the feature space.

As indicated above, three different feature representations were investigated: the second-order central moments in a three-dimensional feature space, the third-order symmetrized central moments in a four-dimensional feature space, and the moment invariants in a seven-dimensional feature space.

We were interested in ascertaining the degree of curvature of the manifolds and whether their structure could be described in a simple parametric fashion. With this in mind a variety of *tours* were constructed in which one or more of the parameters ρ, θ, ϕ were fixed whilst the others were varied in discrete steps across their ranges. In each case this gave rise to a trajectory passing through the feature space.

The inspection of these trajectories projected down onto the computer screen from the higher-dimensional feature space suggested that the set of feature vectors did have a well-defined geometric structure parametrized by the parameters ρ, θ, ϕ, and that this structure did resemble a three-dimensional submanifold of the feature space.

On the basis of these experiments it was decided to proceed with some quantitative tests, which will be described in section 7.

7 Recognition experiments

A simple minimum distance classification scheme was decided upon for testing. It had been found that the manifold formed within the third-order moment space was fairly flat. It therefore seemed appropriate to form a subspace for each of the ship classes using eigenvector analysis. The eigenvectors would then form a basis for defining metrics with which new points could be compared to the three classes.

It had also become clear that the separability between the three wireframe classes diminished considerably as the lookdown angle dropped below a certain threshold and so it was decided to restrict the range of lookdowns encountered to values above a certain limit during testing. The limit could then be varied to see what effect this had on the error rate. During the tests the relative headings were unconstrained and the range was varied between 300 and 1000 units.

Five hundred training examples were randomly generated for each ship class and used in the computation of an $N \times N$ covariance matrix (denoted Σ), from which an eigenbasis was constructed spanning the N-dimensional space. In the case of the third-order moments used in the initial tests, $N = 4$.

We will denote the mean value for the feature space cluster corresponding to ship class c by μ_c. The analysis generates N unit eigenvectors, denoted $b_{c1}, \ldots, b_{cN}$, associated with the monotonically decreasing eigenvalues $e_{c1}, \ldots, e_{cN}$.

Three metrics were developed based on the eigenvectors of the covariance matrix. Each metric was tested on 3000 randomly generated feature examples and a percentage error rate derived. The metrics were based on the *least significant eigenvector*, the *least significant eigenvector pair*, and the *Mahalanobis distance*.

7.1 Least Significant Eigenvector

Assuming that the subspaces formed by the three ship clusters are three-dimensional and embedded within the four-dimensional moment space, the least significant eigenvector (the one having the smallest eigenvalue) will be orthogonal to the subspace.

By projecting feature vectors onto the least significant eigenvector, a distance away from this subspace may be computed. This distance may be usefully normalized by the eigenvalue of the eigenvector onto which it is projected. The distance of a feature vector f from class c is therefore:

$$d_1 = < (f - \mu_c), b_{cN} > / \sqrt{e_{cN}}. \quad (1)$$

7.2 Least Significant Eigenvector Pair

This metric operates on the same basis as that discussed previously but assumes that the ship clusters are two-dimensional, rather than three-dimensional. The two least significant eigenvectors then provide a means of measuring the distance from the sub-space.

Once again, the resolved distances are normalized by their respective eigenvalues since these quantify the variance along each of the basis vectors. The distance of a feature vector f from class c is therefore:

$$d_2 = \frac{< (f - \mu_c), b_{c(N-1)} >}{\sqrt{e_{c(N-1)}}} + \frac{< (f - \mu_c), b_{cN} >}{\sqrt{e_{cN}}}. \quad (2)$$

7.3 Mahalanobis Distance

The Mahalanobis distance from the cluster mean reflects the entire distribution of the cluster. The distance of a feature vector f from class c is:

$$d_3 = (f - \mu_c)^T \Sigma_c^{-1} (f - \mu_c), \quad (3)$$

Where Σ_c^{-1} denotes the inverse of the covariance matrix of class c.

8 Experimental Results

Two sets of experiments were conducted using different feature sets. The initial experiments concentrated on the third-order moments since these had been shown by *fview* to display better separability at small lookdown angles and were also defined within a four-dimensional feature space. The moment invariants were tested in an identical fashion, but with seven-dimensional feature vectors.

8.1 Symmetrized Central Third-order Moments

It was found that the Mahalanobis distance provided the best classification performance for small lookdown angles whilst the least significant eigenvector pair metric offered better performance as the lookdown increased. With no constraints on the lookdown angle the Mahalanobis distance produced an error rate of 5 per cent. Above 0.15π radians the error rate tended to zero.

8.2 Moment Invariants

An equivalent set of tests was conducted using moment invariants. In this case, the metrics were defined on a seven-dimensional space.

Again the Mahalanobis distance and least significant eigenvector pair metric were found to offer the best performance across the entire range of lookdowns. However, the classification errors were considerably greater in both cases. The lowest error achieved by the Mahalanobis distance was 2 per cent at the maximally constrained lookdown angle of 0.25π.

9 Summary of Experimental Work

The aim of the experimental work was to develop an understanding of the geometry of the manifold of feature vectors of each ship class. Features were assessed using the *fview* visualization tool. It was found that features based on symmetrized central moments derived from an array of pixels lack separability for certain values of the aspect angle.

This led to an investigation of the use of three different metrics for classification, on the basis that the feature vectors for a given ship class are likely to lie within a proper affine subspace of the feature space.

When classifying unconstrained projections of the three ship classes no metric achieved better than 95 per cent accuracy. To achieve total separability it is necessary to constrain the range of viewpoints from which the three ships are seen. Ensuring that the angle of lookdown is greater than 0.2π radians is sufficient to lift classification accuracy to almost 100 per cent.

The comparison of moment invariants with the more intuitive third-order central symmetrized moments has suggested that the latter, less conventional, features are better suited to this type of problem.

The work on the structure of the set of feature vectors has suggested that they do, in fact, form a set with a well-defined structure. It would be worthwhile to pursue the problem of the determination of this structure further from both the theoretical and experimental angles.

10 Demonstration System Development

A demonstration system that used the results of the experimental work described above was developed, using realistic infrared images of four warship classes (rather than wireframe models) as the data from which training and testing sets were constructed.

A simple thresholding scheme was devised to separate the ship from the background (sea and sky). Routines to compute the second-order central moments and the third-order symmetrized moments from the thresholded image and six Zernike moments from the greyscale values were implemented. The Mahalanobis distance was used to classify the images into one of four classes.

11 Performance of the Demonstration System

The following tables summarize the performance of the demonstration system on the training and testing sets. The system achieved 91.5 per cent correct identification on the training set and 77.5 per cent correct identification on the testing set.

Ship class	A	B	C	D
Class 1	55	2	0	0
Class 2	4	47	0	0
Class 3	4	10	62	0
Class 4	0	0	1	63

Table 1: Confusion matrix: training set

Ship class	A	B	C	D
Class 1	19	3	3	1
Class 2	1	11	2	0
Class 3	0	6	14	1
Class 4	0	0	1	18

Table 2: Confusion matrix: testing set

12 Conclusion

We have conducted an investigation into the use of features derived from various types of moments for the identification of ships in infrared images obtained at a variety of angles and scales.

We have found that the feature vectors vary with the range, angle of lookdown and relative heading parameters, to form a three-dimensional submanifold of the feature space. We have also found that the Mahalanobis distance is a useful metric for the classification problem.

These findings have been incorporated into a demonstration system.

13 References

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