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KANDIDATS IMAGE PROCESSING SYSTEM[†]

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ABSTRACT

KANDIDATS is a comprehensive digital image processing system that interacts with the user at a command string level. It includes prompting for parameter input and checks user input for errors. Image analyses available in KANDIDATS consist of utility functions, image transform operations, spatial clustering, and Bayesian classification. The versatility and capabilities of KANDIDATS arise from a modular programming structure and file structure. These attributes allow processing of images that are a few thousand rows by a few thousand columns in a minicomputer system with only 32 K words of main memory.

1.0 IMAGE PROCESSING

1.1 Introduction

Image processing encompasses all the various operations which can be applied to photographic or image data. These include, but are not limited to, image compression, image restoration, image enhancement, preprocessing, quantization, spatial filtering and other image pattern recognition techniques. Interactive image processing refers to the use of an operator or analyst at a console with a means of assessing, preprocessing, feature extracting, classifying, identifying and displaying the original imagery or the processed imagery for his subjective evaluation and further interaction.

Image data are collected in the course of scientific experiments, medical tests, surveillance operations, and satellite and telescopic photography. To an increasing extent, these data must be processed by computer before they can be used by human interpreters. Computer processing has evolved over the last decade from the use of specialized machines to more flexible program packages using digital computers to sophisticated full scale computer systems. This move toward computer processing of images has been necessitated by the large volume of image data being produced at the present. One example of this production is the Earth Resources Technology Satellite which produces 782 images each day.

As a result, image processing software must resolve some of the most difficult problems confronting programmed systems: handling large amounts of data and heavy and varied computational loads. These problems require sophis-

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ticated and complex software for even the simplest image processing tasks. In this paper we discuss an image processing perspective and then describe the image processing system developed at The University of Kansas.

1.2 Image Processing Systems

Image processing is the manipulation of image data. This manipulation generally includes all processes which remove degradation from, provide feature enhancement of, or extract information about the image data. At various points in this process it may be necessary to provide information about the progress made during the course of the processing. Despite wide variation in applications, the specific tasks that constitute image processing are common to many applications and can be found in most image processing systems. These basic functions form a set of utility operations which are necessary for any image processing system. This set includes image retrieval routines, image access routines and the various number crunching and processing routines.

1.2.1 Image Creation.
Once introduced to a computer, an image is ordinarily a two-dimensional sampling of grey tone intensities. This two-dimensionality reflects both the physical characteristics of most images and the rectangular nature of most scanning techniques. In all cases, the digitized version of the image represents only a portion of the information found in the original scene. This loss of information occurs first in the acquisition of the data and then in the digitization of this data. The digital image produced by the scanning process and A/D conversion then takes the form of a finite two-dimensional array of small uniformly shaped regions called resolution cells. Each resolution cell has an associated grey level. When more than one sensor is scanning the scene to be imaged, a set of images is created. Multispectral LANDSAT data for example is a multi-image with four bands.

Both the size of image data sets and the diversity of processing techniques present problems when organizing the format of the image data sets. Large, high resolution image data sets are too large to be contained in main memory during processing and, therefore, they must be maintained instead in some manner on peripheral devices. By their nature, these devices require more time to access data than main memory. Once the decision has been made to store image data on some peripheral device, the question of data format arises. The format required is not necessarily obvious since the data structures themselves may restrict the types of image processing techniques which are easily implemented.

In addition, image data must ordinarily be compacted when placed on auxiliary storage devices to make maximum use of storage space. Such compaction makes the data unwieldy for use in computational purposes and, therefore, requires additional software to provide the ability to unpack the data and bring it into core in a more readily usable form.

1.2.2 Image Characteristics. Besides the actual grey levels associated with the digital image, there are various general attributes about the image that must be maintained. These include the area over which the imagery was taken, the sensor creating the image, various processing routines previously applied to the data along with their parameters as well as the more mundane parameters which allow the system to keep track of the image. These parameters include the image size, the number of images in the image set, the type of the data format, etc.

One possibility is for the user to supply these attributes as input parameters. The problems facing the operator with respect to keeping track of these parameters are not trivial. He must either know the parameters or where to find them. However, the nature of these attributes is such that they are fixed for any given image or set of images. Therefore, once they have been introduced to the system, they should be automatically maintained by the system. If this mechanism is an integral part of the system, significant information such as image size, etc., may be easily remembered and transported between processing steps to provide necessary parameters and minimize repetitive user I/O. Additional information on the entire image processing history may be saved for documentation purposes.

1.2.3 Software System Design Perspective. The software of an image processing system includes processing packages and a monitor section that directs the flow of control and information between the various subsystems. The processing of an image is a series of discrete steps, each yielding an image product that may be used later in the sequence. The monitor initiates each step by calling it into action and providing the necessary information for it to run to completion.

The monitor is the point at which the operator and the image processing system are interfaced. The monitor and its subsystems should assume responsibility for as much bookkeeping as possible in order to free the operator from routine tasks. However, it should be flexible enough to allow the operator to control these tasks if necessary. The monitor must also examine all operator input to insure to the largest extent possible that all his entries are free of error and inform him clearly of any that are not.

The amount of operator direction required by a system varies with the type of image processing being done. A system that is processing a large number of images in a well-defined manner requires only minimal operator interaction. In contrast, when image processing is being done in a research environment where the goal is to determine the above mentioned "well-defined manner", the operator should be able to guide the program much more closely and readily. At this point, image processing enters the area known as interactive image processing. In this situation, the operator is the person who measures the results directly. He is in charge of the design and evaluation process and it is the function of the system to assist him as fully and as easily as possible with automation in an interactive-hands-on environment.

The goal of an interactive image processing system is a quick flexible way of analyzing and manipulating image data and trying out various tools from a versatile tool kit to determine which algorithm should be selected for a given application. This evaluation of various tools is enhanced by interactive automation of known procedures so they can be applied in a routine fashion with immediate availability of the results to the operator.

The language by which the system is guided must be appropriate to the operator and the task. The operator should be required to provide only the minimum amount of information necessary to invoke his task and be given immediate feedback if his entry is in error. In addition, information should be available to prompt him on how to use the system. Of course, this information should be as concise, explanatory, and up to date as possible. Such an implementation should enable a new operator to receive necessary help but should not stand in the way of an experienced operator. The system must allow the operator to retrieve information directly, simply and in an easily recognizable format.

The above mentioned constraints force a structure on the image processing system. The many programs necessary for implementing the various options cannot all be stored in main memory at once. This generally leads to some form of overlay system where the monitor calls various subsystems into main memory as they are needed and overlays systems no longer necessary. The following sections discuss how we designed an image processing system to meet the needs of a user of remotely sensed image data.

2.0 KANDIDATS

KANDIDATS is an interactive/batch-mode digital multi-image pattern recognition system designed to facilitate the man-machine interface between the user and the computer complex. It is intended to allow users with an interest in image processing and varied degrees of sophistication with computer hardware and software an easy access to the image processing facilities available. KANDIDATS provides a great deal of flexibility and degree of freedom to the operator. It is designed primarily as a tool to be used in a research environment. The type of image processing it provides is the flexible, easily changed image processing tasks necessary in formulating and evaluating algorithms which will later be applied to large amounts of image data. KANDIDATS runs on the PDP-15 computer system and uses the IDECS as an image acquisition and display device. Digital image data may be introduced through magnetic tape units on an IBM 7094 interfaced to the PDP-15.

The entire system is guided by an operator at a console directing the system either by initiating commands or by directing input to be taken from a command file. KANDIDATS then manipulates the particular image data accordingly.

Once image data is entered into the system, KANDIDATS automatically maintains and processes multiple digital images in a standard format which provides a complete processing history for the image from the time it enters the system until the time it is no longer needed.

Image processing capabilities currently implemented in the KANDIDATS system include:
1. Equal interval and equal probability quantizing
2. Sub-image cutting, pasting, and mosaicing
3. Gradient and edge enhancement operations

4. Spatial and measurement space clustering
5. Computing textural feature images
6. Category histogram and scattergram
7. Category mean and covariance estimation
8. Feature selection
9. Table look-up decision rule determination and image classification
10. Image display
11. Image transformation (FHT, FFT, DCT, DLB, KL)
12. Image convolution
13. Image expansion, compression, and general rubber sheeting
14. Reformatting of images
15. Creation of bar or checkerboard test images or even simulated scenes
16. Addition of ground truth information or maps to images
17. Spatial operations on symbolic images

Appendix I gives a more complete outline of image processing capabilities in KANDIDATS.

2.1   KANDIDATS/User Interaction

To be of any use a system must be available to the people who wish to use it. The interface between the user and the system can make the difference between people having applications for the system using it or requiring a special operator as an intermediary. Therefore, a KANDI-DATS user does not need to know how to program. He needs to know very little about the system. KANDIDATS accepts free format command strings entered at a terminal or items selected from a menu by the user. The command string consists of a command name, output image, input image(s) and flags or options. Typical commands are:

<u>#:</u> QUANT IMAGE OUT ← IMAGE INP

<u>#:</u> TID ← IMAGE QNT

<u>#:</u> CMBIN TEST IMG ← INPUT1 IMG, INPUT2 IMG (CD)

(Note that we have underlined computer output.)
As shown above, image names consist of 1-6 characters for a first name, a blank, and a 3 character last name.

Prompting is performed for additional parameters that are required by a command. For example, the QUANT-ize request above would prompt the user for the desired number of levels in the following manner.

<u>ENTER NUMBER OF QUANTIZED LEVELS (>0) -- 16</u>

Note that the user does not need to know the internal name of the parameters required and the system does not have to scan a parameter list. Each user input is checked for errors. The QUANT routine will only accept numbers greater than 0 in the above example. If a bad number was entered the system would prompt the user again. Prompting messages usually come in two forms, a long message as shown above and short messages. Short messages are for use with a slow terminal device or by an experienced user.

Some processes may provide several options for the user to choose from. These options typically select more complex processing than the default case. For example, in combining two images by overlapping one on top of the other the default case is to register the upper left corners of both images and extend the smaller image to the size of the larger image. The user can select the options for truncation of the larger image, for registration offsets and/or image band selection from the input images. Options are selected by typing appropriate character flags contained within

parentheses and appended to the end of the command string. These flags indicate to the command string interpreter that the user desires additional prompting questions so that he can input further parameters. Corresponding to the 26 alphabetic characters there is a maximum of 26 options for any one command.

KANDIDATS is designed to be able to instruct a user with minimum knowledge of the system. Once an operator has entered KANDIDATS there exists five commands to instruct him on usage of the system. They are:
(1) MESG - This command provides a message indicating current system status. It also explains in detail the format of the command strings and the various device mnemonics. File naming considerations, run file techniques, and methods for gracefully interrupting processing are included as well.
(2) SVOC - This command provides a list of all the valid system commands.
(3) VOCA - Once the operator thinks he understands a command name but he wants to check if his memory is correct, he can use this command to receive a short 30 character description of the command.
(4) EXPL - This command provides all the information about a command in the following format

ACTION	Describes the primary function of the command
DEST	tells the legal device types that may appear in the destination device field of the command and the use to be made of that device. If it is a disc file, it explains the type or format of the file that is produced.
SOURCE	tells the legal device types that may appear in the source device field of the command and the use to be made of that device. If it is a disc device, the number of filenames required (maximum of three) is given along with the format or type of each file.
FLAGS	tells the alphabetic flags recognized by the particular command process subsystem and the action taken for each.
CTRLT	tells the action taken if the user types a 'CTRL T' on the keyboard during the execution of the command. The default action for all commands is to return to the '#:' level. If a run file is in operation, the operator is asked if he wishes to abort it or continue.
COMMENTS	this section gives any remarks which might be helpful in using the command as well as references to external documentation on the command. If the command makes use of special equipment additional instruction will be given here.

(5) MENU - The menu function begins a process whereby the user selects a command from a list of commands presented by the system. The system presents commands in functional groups, e.g., MESG, SVOC, VOCA and EXPL are in the group of Information Operations. The user chooses the function group from a list of groups in the system.

KANDIDATS has a facility for reading command strings from a disc file rather than an interactive terminal device. This allows a user to write a sequence of image processing operations as a command string program and then have the computer execute them at a later time. Such batch input can be used when interaction with the system is not required.

2.2 KANDIDATS Digital Images

KANDIDATS maintains digital image information in a form known by the acronym-SIF- (Standard Image Format). This standard form of digital image representation establishes a data base that digital image-processing routines can interact with on an independent basis. SIF allows multi-digital-images containing both numerous grey tone and symbol map information as well as processing history information to be maintained via KANDIDATS system routines. The system routines permit the creation of image files in a manner that gives the user easy access to image data and minimizes storage space. Files may be maintained in all four data modes supported by FORTRAN. These data modes are integer, floating point, double integer, and double precision. Files may be manipulated in the two ways allowed by FORTRAN-IV I/O statements: sequential and direct access input/output. Sequential file manipulation directs information to and from the file in the sequence in which the information is physically recorded on the storage device. Direct access file manipulation allows access of image information in a random fashion.

The format of a KANDIDATS standard image file has several nice features. The file structure allows easy access to any single band of a multi-band image without accessing any other bands. Alternatively several bands can be accessed at one time without much physical movement of the disc access arm. Allowing the image to be blocked in a variety of ways reduces the memory requirements when spatial neighborhoods such as 64 rows by 64 columns need to be in main memory at the same time.

The SIF multi-image file exists on the various storage devices as a binary file with fixed length records. The length of the record is determined by the amount of image data to be stored in a logical record and the length of the variable length byte in which grey tone intensity is encoded. Logical records are separated into three basic categories. They are:
1. The identification record. This record contains information with respect to file size, data mode, and format in which the image data is recorded.
2. The descriptor records. These records:
   (a) provide a history of image processing that has led to the creation of the current image file, and
   (b) information about the image or file that cannot be stored within the other two types.
3. The image data.

2.2.1 The Identification Record. The identification record contains twenty 18-bit words of pertinent information about the SIF file. This places a lower bound on the logical record size of the file. These twenty words of information are ordinarily stored in an array during the period when a particular SIF file is being manipulated. The contents of the IDENT array is as follows:

IDENT(1)   left coordinate of the image on the display screen
IDENT(2)   right coordinate of the image on the display screen
IDENT(3)   top coordinate of the image on the display screen
IDENT(4)   bottom coordinate of the image on the display screen
IDENT(5)   number of bits used to represent the digitized grey tone
IDENT(6)   number of resolution cells per line in the image

IDENT(7)   number of lines in the image
IDENT(8)   relative size of the resolution cell in the horizontal dimension
IDENT(9)   relative size of the resolution cell in the vertical dimension
IDENT(10) number of descriptor records in the file
IDENT(11) number of quantized levels (the number of discrete levels from the minimum to the maximum grey tone - significant only with respect to integer files)
IDENT(12) number of 36-bit words per logical record
IDENT(13) number of columns contained in each sub-image or logical record
IDENT(14) number of rows contained in each subimage or logical record
IDENT(15) minimum grey tone over all bands on the image (significant only with respect to integer images)
IDENT(16) maximum grey tone over all bands on the image (significant only with respect to integer images)
IDENT(17) total number of image bands in the multi-image set
IDENT(18) number of symbolic or "map" image bands in the multi-image set. Symbolic images are the last images to occur on the image.
IDENT(19) data mode indicator
   = 0 absolute binary representation (positive integers only)
   = 1 two's complement representation (negative as well as positive integers)
   = 2 floating point representation
   = 3 double integer representation
   = 4 double precision representation
IDENT(20) unused at present

2.3 The Descriptor Records

Descriptor records, if any, follow the identification record. Descriptor records tell the entire processing history of the image: which commands were executed, when they were executed, who they were executed on, and with what parameters they were executed. The number of descriptor records is determined by IDENT(10). Each descriptor record contains a maximum of twenty words of actual information. This insures that as descriptor records are copied from file to file, no information is lost as IDENT(12) changes. Descriptor records provide general information about the image as well as a detailed history of the processing steps performed on the image data. Thus there are two distinct classes of descriptor records:
   (a) Processing history descriptor records, and
   (b) Free format information descriptor records.

2.3.1 Processing History Descriptor Records. Processing history records provide a detailed account of the action performed by one processing routine on the file. These records are arranged so that they indicate the name of the processing routine, the date of the processing, and the name(s) of the input file(s).

2.3.2 Ancillary Data Descriptor Records. Information pertinent to the image is also stored in descriptor records. Routines record the parameters used when processing an input image to an output image. Data gathered by the routine, e.g., a mean vector and covariance matrix for each category in an image, can also be placed in descriptor records.

2.3.3 Free Format Records - (Optional). Free format records are ASCII records beginning with the 5 character

string '*□□□□'. The remaining 45 characters (18 words) of the record contain general information about the -SIF- image file. Free format records can be placed anywhere within the entire descriptor record set as long as they do not interfere with the structure of the processing history descriptor records. There is currently one free format record of special interest. It is organized as shown below:

Ground truth descriptor records consist only of ASCII characters and can occur anywhere in the string of descriptor records. Each record describes the ground truth category assigned to a specified rectangular region. To facilitate multiple training and test sets, each record is labeled by set number.

The records must be in the following format:
Characters

1-10	*□□□□GT□□□	This is the designation for a ground truth descriptor record
11-15	GTSTN	Ground truth set number
16-20 .	CATNM	Category name for the descriptor record
21-25	CATST	Numeric category symbol for category name (CATST must be positive)
26-30	IMCAT	Image band number on which the numeric category symbol referenced by this descriptor record appears (zero, if none)
31-35	IFR	First row
36-40	ILR	Last row
41-45	IFC	First column
46-50	ILC	Last column

2.4 The Image Data

Image data records make up the third section of the -SIF- file. The digital multi-image is divided into mutually exclusive rectangular regions called blocks and each logical record contains one block. This allows the flexibility of having the logical records correspond to image rows, image columns or perhaps 20 row by 50 column areas. The data that is stored in each subimage block is encoded in one of the five modes indicated by IDENT(19): absolute binary, two's complement binary, floating point, double integer, and double precision.   The byte length for the absolute binary and two's complement binary is given in IDENT(5). The bytes are packed into 36 bit double words.

2.4.1 SIF File Organization.

1. Data points within a SIF subimage block are ordered sequentially in a row by row manner as shown in Figure 1. This array (compacted if possible) is written as one logical record.
2. These blocks cover the entire image in a column-wise fashion as shown in Figure 2.
3. Figure 3 illustrates how the entire SIF multi-image file appears on the storage device. Each record is -K- words long. -K- is determined by the block size, the data mode and the number of bits/point if the data mode is integer. The identification record is first, followed by IDENT (10) descriptor records and then the image data. If the entire image is viewed as a four-dimensional array (L, M, N, O) where:
   L - number of image bands
   M - number of blocks

N - number of rows per block
O - number of columns per block
then the subscripts would vary from fastest to slowest in the following order:

	O columns	(1 to IDENT(13))
then	N rows	(1 to IDENT(14))
then	L bands	(1 to IDENT(17))
then	M blocks	(1 to [IDENT(7), IDENT(14)] · [IDENT(6), IDENT(13)]

where [a,b] is the smallest integer greater than or equal to a/b.

3.0 KANDIDATS UTILITY PACKAGE

Every digital image processing system requires a set of basic operations used to shape and mold images, gather information about the images, move images around the system and display information about images and the system. In KANDIDATS these operations are in the utility package and are divided into the following command groups:
   (1) information operations
   (2) transfer operations
   (3) spatial domain operations
   (4) greytone operations
   (5) operations to compute statistics
   (6) control operations
   (7) ground truth operations
   (8) image generation operations
The first thing that strikes a user of a digital image processing system is the need for precise spot checking of image content in order to verify correct A/D conversion of the image or to verify the result of an image processing operation. Precise spot checking of image content requires the capability to examine any resolution cell or groups of resolution cells and determine the numerical grey tone values there. Since the grey tones are stored as bit patterns on magnetic tape or disc, they are not immediately available. Converting them to an image on a display screen allows a qualitative comparison but not a quantitative evalution. Therefore, the first utility operation the system must have is one which can create a grey tone or color image display for qualitative evaluation and which prints out in any desired format the numerical values of any specified part of an image for quantitative evaluation.

There are two ways to specify a part of an image: specify spatial position and get grey values, or specify grey values and get spatial position. Both of these possibilities are permitted under the examine image command of KANDIDATS. Other options allow a user to change the grey tone values in specified resolution cells or change all occurrences of one grey value to another.

The user obtains information about images or the system by using commands from the information operations group. Commands to list an identification block, list descriptor records, list system commands and explanations are in this group. Images are moved to and from system peripherals via transfer operation commands. Transfer include reading ERTS, Skylab and LARSYS magnetic tapes to disc and displaying images from disc to a television monitor.

The control operation group controls the KANDIDATS interactive prompting by selecting long or short messages, and controls the KANDIDATS mode of operation: interactive or batch.

One category of necessary image utility operations is concerned with operations on the spatial domain of an

Note: □ indicates a blank

image. There are commands to separate out pieces of an image or put pieces of an image together. Combining images has two modes, one is overlaying or registering different images of the same area and the second is to join two images together in the way mosaics are done. If the mosaic has overlapping areas a grey tone mapping is applied to calibrate the grey tones of one image to the other. Other operations exist to change the image scale in the horizontal and/or vertical direction, flip an image about a horizontal, vertical or diagonal axis, rotate an image 180°, or perform a general rubber sheeting geometrical transformation.

Grey tone operations are concerned with functions on the grey tones of a resolution cell and those in a neighborhood around it. Included here are quantizing (contrast stretching), linear combinations of bands, arithmetic operators on bands, masking, rectangular convolution (low pass filtering), and contour mapping. Quantizing can be equal interval, equal probability or a general non-linear quantizing. Image arithmetic operations include addition, subtraction, multiplication, and division of any specified bands of two images.

The user can direct KANDIDATS to compute several different types of statistics from an image. Histograms by band, scattergrams by band pairs, range plots by band and category, second order marginals, RMS error between band pairs, mean vectors and covariance matrices for the entire image or by category can be obtained. These data are typically stored in the descriptor records and hence are available to other processes.

The user can input mean and covariance statistics as well as his own symbolic image to generate simulated images by using commands in the image generate group.

The ground truth specification operations are necessary for the supervised discrimination processes. Ground truth can be entered by specifying rectangular areas on the display screen with a frame, specifying first and last, row and column coordinates or entering a symbolic image. The data obtained is stored on descriptor records or as symbolic bands of an image.

4.0 KANDIDATS PATTERN DISCRIMINATION PACKAGE

Pattern discrimination processing on multi-image data generates maps indicating a landuse or category type for each resolution cell. Operations in the pattern discrimination package are divided into the following command groups:
   (1) feature selecting
   (2) decision rule creating
   (3) classifying image

The first step of this process involves selecting a training data set and labeling it with the appropriate ground truth labels. This may be done with the ground truth input command. Ground truth can be taken by framing areas on a TV display or by looking at a grey tone overprint output and specifying the row and column coordinates for each ground truth region.

Once the training data has been determined, the best bands must be feature selected. KANDIDATS feature selectors are designed to select those bands yielding lowest classification error. There are two options available. Feature selecting can be done based on a Gaussian assumption for the category probability distribution and Bhattacharyya coefficients, or feature selecting can be done in a non-

parametric way. Once the best bands are selected and second order marginal probability distributions estimated, the distribution must be smoothed and normalized according to the user specified prior category probabilities.

For each category second order marginal probability distribution, a Bayes rule is determined and stored as a table. The image is then classified by a table look-up of all the Bayes rules in the low order spaces. Category assignments can be made on the basis of majority vote or unanimous consent of those low order rules. Any resolution cell having reserved decisions made by the Bayes rule can be assigned a category by a spatial fill operation which relabels any reserved decisions resolution cell to the category of its spatially nearest assigned neighbor.

The identification accuracy of the classified image or images can be computed by asking for a contingency table or confusion matrix whose $(i,j)^{th}$ entry shows the number of resolution cells in category c_i of a specified ground truth image whose category assignment on the classified image is category c_j.

By combining the classified image with the original multispectral image, letting the feature selector use it as a numeric data band, and running the feature selector and classification operations again, a table look-up sequential decision tree rule can be created.

5.0 KANDIDATS SPATIAL AND MEASUREMENT SPACE CLUSTER PACKAGE

Spatial clustering processes multi-image data into maps which delineate the homogenous regions of the image. The spatial clustering package consists of image operations to do this task. Thus, for a satellite image, which may cover hundreds of square miles, it is possible by spatial clustering, to generate a map of that area, showing the different landuse classes. The algorithms for these operations constitute unsupervised clustering. In this mode no prior information such as ground truth data, is needed.

The operations in the clustering package are divided into the following command groups:
   (1) edge and texture feature extraction
   (2) spatial clustering operation
   (3) measurement clustering operation
   (4) symbolic image operations

The first process of image clustering consists of partitioning the image into spectrally homogenous areas. First a gradient image is generated from the original image. Two operators are available for this process. The Roberts gradient operator for distances 1 and 2, and the Laplacian operator. As the term implies, a gradient operator measures the change in grey tone in the neighborhood of each resolution cell. It assigns a relatively high value for a cell across which there is a large variation in grey tone. This corresponds to a cell on the boundary between spectrally homogenous areas. Resolution cells in the interior of such areas, are assigned low values as they have little or no variation in the grey tones in their neighborhood.

To separate the different homogenous areas then, we need to threshold the gradient image. Those resolution cells having grey tones above an adaptively computed cutoff, constitute the boundary, while those falling below, belong to homogenous regions. A level slicing operation, which computes the cutoff can be based on the running means of

rows above and below a cell, is one quick and efficient algorithm. It works well on most images. However, for images which contain large homogenous areas in which the boundaries are few or localized to a few areas, different thresholding schemes in which the cutoff for a cell is sensitive to its local neighborhood only and not a function of cells which lie far away from it are more effective. One processing approach is to rectangular convolute the gradient image, and then compare the convoluted gradient image to the gradient image.

The thresholded image usually has to be cleaned to remove noise. The noise is a consequence of fuzzy boundaries which occur even if we use the best of gradient operators. The process involves checking the immediate neighborhood of homogenous resolution cells to see how many homogenous neighbors it has. If not enough neighbors are homogenous the resolution cell boundary is relabeled. Each maximally connected region in the cleaned image is then given a unique label to identify it. If some of these regions are not homogenous enough, they are broken further into sub-regions by a splitting operator. This splitting is done using the grey tone values of the original image, which is usually a multiband image.

The second part of the clustering procedure involves the grouping of the homogenous regions. This clustering is done in the measurement space, defined by the grey tone n-tuples of the original multiband image. It is an interactive process which acts on the average spectral signature in measurement space, for each spatial region. In each iteration the closest measurement space neighbor for each cluster is found. The metric used is the Euclidean distance in measurement space. Then, if the neighboring cluster is close enough, they are put together in the same group. The degree of "closeness" is based on some parameters specified by the user. The process is repeated until the number of clusters is reduced to what is desirable. These then make up the different categories in the image.

In addition to the operations mentioned above, there are others that can increase the effectiveness of the spatial clustering. While these are not integral to the process, their use under certain situations greatly increases the accuracy of the product. The enhance operation sharpens boundaries in the original image by increasing the contrast. This results in a better gradient image. The fill and shrink operators allow for the spatial growing and shrinking of categories. They are especially useful in the assignment of boundary cells neighboring the determined spatial clusters. They help smooth out the clustered image, giving it a map-like appearance. This last process can be considered analogous to the spatial generalizations cartographers often make.

6.0 IMAGE TRANSFORM OPERATIONS

One important class of image processing operations consists of enhancement operations done by filtering and of image data compression operations done by transform coding. Both of these kinds of processing are done by performing an image transform, operating in the transform domain, and then taking the inverse transform. This package is used to study techniques applicable to reducing the amount of data required to transmit or store an image.

Available image transforms include:
(1) Karhunen Loeve
(2) Fast Karhunen Loeve
(3) Hadamard
(4) Fourier
(5) Slant
(6) Discrete Linear Basis
(7) Discrete Cosine

The transform operations work on n x k subimage blocks of the image. Once an image has been transformed, various processes can be used in the transform domain. Filters can be applied to enhance certain features of the image, or for compression, eliminate low energy components. The transformed image can be coded and compressed using an optimal bit allocation algorithm. The modified transformed image can then be reconstructed by taking the inverse transform.

APPENDIX 1
OUTLINE OF KANDIDATS OPERATIONS

PACKAGES

A. UTILITY
B. CLUSTER
C. PATTERN DISCRIMINATION
D. BANDWITH COMPRESSION

A. UTILITY

1. Information Operations
2. Transfer Operations
3. Spatial Domain Operations
4. Greytone Operations
5. Operations to Compute Statistics
6. Control Operations
7. Ground Truth Operations
8. Magnetic Tape Operations
9. Image Generation

   1. Information Operations
      (a) Examine Image (Image Editor Subsystem)
      (b) Explain
      (c) Short Vocabulary
      (d) Vocabulary
      (e) Add Descriptor Record(s)
      (f) Delete Descriptor Record(s)
      (g) Transfer Identification Block
      (h) List Descriptor Records

   2. Transfer Operations
      (a) Transfer Image To/From Display
      (b) Transfer Symbolic Image to Line Printer
      (c) Transfer ERTS Tape to Disc
      (d) Transfer Skylab (Universal) Tape to Disc
      (e) Transfer LARS Tape to Disc

   3. Spatial Domain Operations
      (a) Combine Images
      (b) Select Sub-Image
      (c) Expand/Compress Image
      (d) Flip Image
      (e) Rotate Image 180°
      (f) Transpose Image
      (g) Mosaic Images
      (h) Rubber Sheet Image
      (i) Reblock Image

4.   Greytone Operations

   (a)   Equal Interval Quantize
   (b)   Equal Probability Quantize
   (c)   Rectangular Convolution
   (d)   Algebraic Operations
   (e)   Linearly Combine
   (f)   Contour Map
   (g)   Mode Change
   (h)   Principal Components Projec-
           tion
   (i)   Mask

5.   Operations to Compute Statistics

   (a)   Histogram by Band
   (b)   Scattergram by Band Pairs and
           Category
   (c)   Histogram and Range Plots by
           Band and Category
   (d)   Count Second Order Marginals
   (e)   RMS Error Between Bands of
           Two Images
   (f)   Generate Statistical Descriptor
           Records
   (g)   Compute Mean and Covariance
           by Category
   (h)   Compute Mean and Covariance
           of Entire Image

6.   Control Operations

   (a)   Brief Output Messages
   (b)   Long Output Messages
   (c)   Call External Routine
   (d)   Stop Execution
   (e)   Run Command File
   (f)   Build Command

7.   Ground Truth Operations

   (a)   Input Ground Truth Data
   (b)   Create Symbolic Image from
           Descriptor Records
   (c)   Create Symbolic Image from
           Binary Images
   (d)   Count Categories in Image
   (e)   Count Categories per Block

8.   Magnetic Tape Operations

   (a)   Card Transfer To/From Honey-
           well 635 Tape
   (b)   Card Transfer To/From PUFFT
           Tape
   (c)   Tape Dump
   (d)   Write End of File
   (e)   Forward Space Record
   (f)   Forward Space File
   (g)   Backspace Record
   (h)   Backspace File
   (i)   Rewind

9.   Image Generation

   (a)   Make Bar Image
   (b)   Make Checkerboard Image
   (c)   Simulate Image from Statistics

B.   CLUSTER

   1.   Edge and Texture Feature Extraction
   2.   Spatial Clustering Operations
   3.   Measurement Space Clustering Operation
   4.   Symbolic Image Operation

1.   Edge and Texture Feature Extraction

   (a)   Roberts Gradient
   (b)   Laplacian
   (c)   Replace by Local Minimum or
           Maximum
   (d)   Generate Textural Image Trans-
           form

2.   Spatial Clustering Operations

   (a)   Image Thresholding Operations
   (b)   Spatially Connect Homogenous
           Regions
   (c)   Clean Homogenous Regions
   (d)   Split Homogenous Regions

3.   Measurement Space Clustering Operation

   (a)   Find Mean of Regions
   (b)   Cluster Homogenous Regions
           Using Measurement Space
           Statistics

4.   Symbolic Image Operation

   (a)   Shrink Symbolic Regions Main-
           taining Connectivity
   (b)   Fill Symbolic Regions
   (c)   Shrink Symbolic Regions
   (d)   Symbolic Image Composition

C.   PATTERN DISCRIMINATION

   1.   Feature Selecting
   2.   Decision Rule Creating
   3.   Classify Image

   1.   Feature Selecting

   (a)   Non-Parametric Feature Select
           for Table Look-Up Rule
   (b)   Parametric Feature Select Using
           Bhattacharyya Coefficient

   2.   Decision Rule Creating

   (a)   Count Second Order Marginals
   (b)   Smooth Marginal Distributions
   (c)   Normalize Marginal Distributions
   (d)   Determine Non-Parametric Decision
           Rule
   (e)   Compute Contingency Table

   3.   Classify Image

   (a)   Classify Image by Existing Table
           Look-Up Rule
   (b)   Compute Table Look-Up Rule and
           Classify Image

D.   BANDWIDTH COMPRESSION

   1.   Transforms
   2.   Compressions
   3.   Pre/Post Processing

   1.   Transforms

   (a)   Hadamard
   (b)   Fast Fourier
   (c)   Discrete Linear Basis
   (d)   Discrete Cosine
   (e)   Slant
   (f)   Karhunen-Loeve
   (g)   Fast Karhunen-Loeve

2. Compressions

    (a) Band Pass
    (b) Energy
    (c) Optimal Bit Allocation

3. Pre/Post Processing

    (a) Add/Subtract Mean
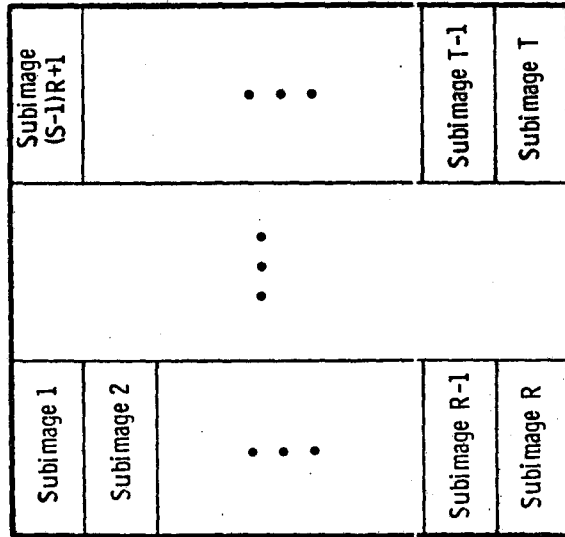   (b) Log/Anti Log

P Columns where P = IDENT(13)
Q Rows   where Q = IDENT(14)
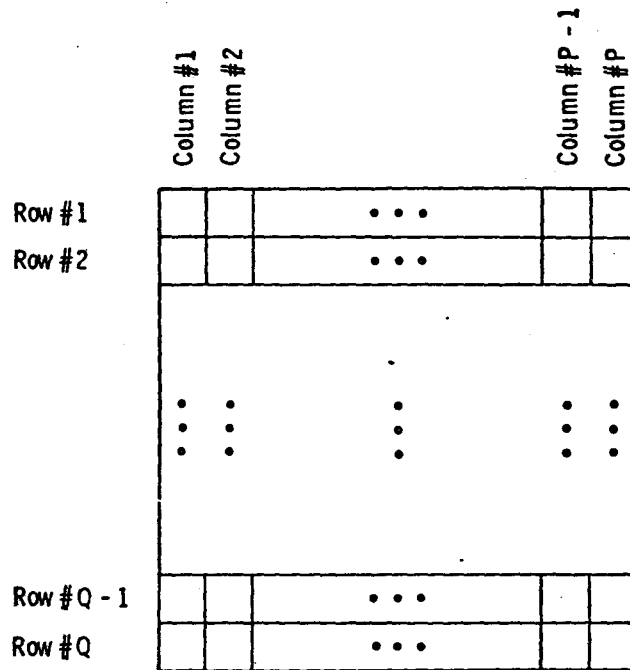
Each square represents one data point in the image.
The maximum value of the data point depends on
IDENT(5) -- the number of bits allowed to represent
one point. There are P x Q data points in each subimage.

Figure 1: Illustration of a Subimage(A Subimage is written
           as one logical record on the diskpack)

Number of words per record determined by IDENT(5), IDENT(13), and IDENT(14) -- equal to a constant -K- ($K \geq 20$)

Record #1 | 20 Words -- IDENT | 21 | 22 | ... | K-1 | K |
Word 1 / Word 2 ... Word K

Record #2

M Descriptor Records

Record #M+1 | Subimage 1 -- Image 1 |

Bit Compacted Image Data

Subimage 1 -- Image J
Subimage 2 -- Image 1
Subimage 2 -- Image J
Subimage N -- Image 1
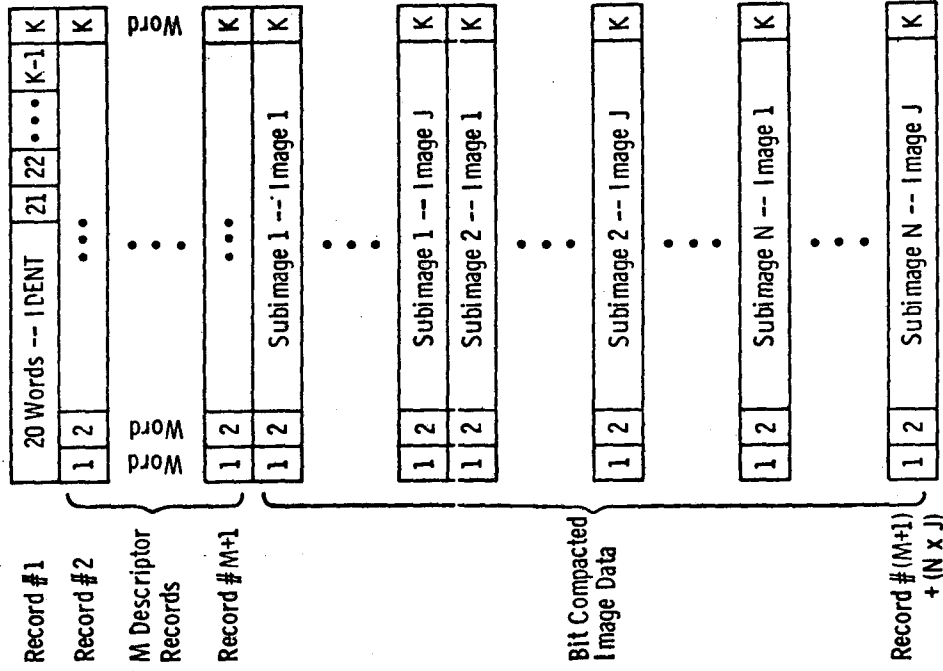
Record #(M+1) + (N x J) | Subimage N -- Image J |

Figure 3: Illustration of a Standard Image File on the Diskpack

S -- Columns of Subimages

Subimage 1
Subimage 2
Subimage R-1
Subimage R

Subimage (S-1)R+1
Subimage T-1
Subimage T

R -- Rows of Subimages

$R \times S = T$

Figure 2: Illustration of the manner in which an image is covered by subimages.