A DECADE OF EXPERIENCE WITH DIGITAL STEREO COMPILATIONS SYSTEMS

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ABSTRACT

In the early 1970's the Surveys and Mapping Branch pioneered the development and implementation of an integrated system for the digitisation of topographic information directly from aerial photography using stereo plotters for the creation of a digital topographic data base. The operational procedures, methodology and experience gained in digital data acquisition, interactive (on-line) and batch (off-line) data editing for the capture of error-free data are described. The basic elements of the digital topographic data model and the digital topographic data base are given. Future developments and implications of digital mapping on the generation of spatial geo-coded information systems are discussed.
ISPRS: INTERNATIONAL SYMPOSIUM ON MAPPING FROM MODERN IMAGERY

PAPER: TITLE: TOWARDS A GEOGRAPHICAL INFORMATION SYSTEM FOR NORTHERN IRELAND

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Northern Ireland, geographically compact and with a relatively simple administrative structure is in a unique position to reap the benefits from the creation of a Geographic Information System for the proper management of its various public sector functions. Work has already begun on the Topographical part of the database, which will underpin this Information System, as well as pilot schemes to extend it - initially into the Public Utilities and Land Registration.

This paper outlines the system from concept through organisational development to initial implementation. In particular it describes the part that photogrammetry is playing in an integrated data capture and digital conversion programme which will be completed in 6-10 years. The setting up of Northern Ireland's new Regional Remote Sensing Processing Centre, located at the Ordnance Survey with the Topographical digital database, is discussed together with the plans to ultimately interface it directly with Remote Sensed data, to assist in a number of applications.
CONCEPT

With the rapid growth in both the requirements for and techniques of information technology during the past decade, the Ordnance Survey of Northern Ireland (OSNI), in common with many other organisations, began to look at the possibility of replacing its conventional map production (using largely manual techniques) with a computerised system. The concept involved the conversion of geographical data into digital form, their storage in computer systems and their subsequent manipulation and display. In late 1981 a feasibility study on the provision of a digital mapping and topographical database and its implications was begun. The study concluded that the current topographic archive should be digitised over a ten-year period using a commercially available 'turnkey' system. This would provide a complete topographical database for Northern Ireland in digital form and establish the basis of a single integrated Geographical Information System.

Geographical information may be defined as all information that can be spatially referenced using a common system of geographic co-ordinates. All information, whether it be about a water stand pipe, a traffic incident or an unemployment record has one thing in common - it has a location. All Ordnance Survey of Northern Ireland mapping is based on the Irish Grid (as is the modern mapping for the whole of Ireland), using a Universal Transverse Mercator Projection. The geographic position (co-ordinates) of any feature of the map is therefore the unique 'hook' to which all other data sets can be tied and so provides the common link between them. Thus the Geographical Information System would hold digital geographic data for, say, housing in any chosen areas, and a whole plethora of information - population, age structure, valuation, services networks, etc - would be related to the positional data. Many organisations already require positional data in digital form and as the system develops demand for this will grow. The possibilities that are provided by a properly constructed and managed Geographical Information System are almost limitless.

INTEGRATED APPROACH

The single most important feature in our thinking is that the system should produce a DATABASE - not simply a cartographic databank. Such cartographic databanks are fine for producing cartographic maps or digital 'backdrops' but are quite unsuitable for manipulation for other purposes. Our ultimate goal is a true Geographic Information System. Herein lies the essential difference in our approach from that taken by many organisations in other parts of the world.

To assist in achieving this goal Liaison Committees were set up bringing together the many public services concentrated in Northern Ireland government departments as well as other major organisations in the public sector. These included those bodies responsible for land registration, valuation, water and sewage, roads, planning and electricity services as well as police, housing, tele-communications, agriculture, forestry, economic development and health and social security. The function of these committees was and still is to advise on the structure and form of the topographical database and on the programmed population of it. They also carry out a vital role in the spread of information amongst members regarding the requirements of data exchange and the progress of computerisation within each organisation; and they have an increasing co-ordinating function.
This establishment of user needs was and is fundamental to our approach. From the beginning the objective was the systematic introduction of an information system - and perhaps Northern Ireland is in a unique position to benefit from computer-based spatial data: it is a geographically compact area of some 14,000 square kilometres, with a population of approximately 1,500,000. Thus the database will be of a size that is relatively easy to manage. However, to put the size of the project into perspective, it is estimated that the topographical part of database alone will be about 20 gigabytes in volume. This emphasises the problems to be experienced elsewhere.

Northern Ireland also has a comparatively simple administrative structure, where most of the local government and utility-type services are run directly and centrally by government departments. This leads to little or no geographical conflict in demand between requirements from different user sources. Thus we have a compact and simple environment within which to operate to assist in the production of a single integrated system, with no duplication of effort in data capture and a ready sharing of data - providing an early start was made.

This latter point is vital because in Northern Ireland until recently most of the organisations concerned had not introduced computer technology except for financial and administrative purposes, eg, pay, invoicing, customer records, etc. Therefore we have a clean page, so to speak, upon which to write without having the constraints of previous system procurement decisions and of data conversion. Large computer files of statistical information and cabinets and plan presses bulging with maps and written records are of limited use if accessing them is a clumsy business and they are difficult to relate to the real world. This is especially so if they are prone to damage and costly to maintain.

Public utilities and other bodies base many of their administrative and service records on maps. The availability of suitably structured digital databases containing both graphic and non-graphic linked information will provide them with fast and flexible means of storing, retrieving and manipulating this information. Northern Ireland is determined that users of topographical information do not experience the incompatibility problems in utilising digital data now being encountered in many other places. For this reason it is important that all user organisations' systems are capable of linking into an integrated geographic information system. Compatibility is therefore the essential element.

Political support for this integrated approach has been forthcoming because the wisdom of avoiding duplication of the digitisation of topographic information by public sector bodies has been realised. This thinking extends even to other information used by public sector bodies where, in parts, 80% of that required for the proper management of municipal and utility functions and for the efficient provision of services to their customers is common to more than one organisation. Information should only be collected or converted to digital form once, by the appropriate authority and to the proper standards, so that it may be used by all. It is thought that in Northern Ireland the Ordnance Survey is the natural originator of standards for production for digital maps, such standards being essential.
BENEFITS

Availability of a digital topographical database provides many already well-known benefits: Gone are the constraints of map sheet lines and of conventional content and output specifications; and there is the luxury of scale-free data that can be extracted selectively or used in conjunction with data from other sources.

The financial benefits are much more difficult to quantify - particularly as many of them accrue to other organisations, and not in the immediate future. We are in essence making a necessary investment in the infrastructure of the nation for the future. However, the fact that many organisations worldwide (and an ever increasing number of them) have both the requirement and the justification to computerise their own graphical records for some applications, which in turn need a topographic base for full utility, indicates that these benefits are real. The main stumbling block or constraint for many is the non-availability of the topographical data and the cost of its provision not only in financial terms but in other resources including time.

In Northern Ireland the financial justification is soundly based on non-duplication of data conversion and on the realisation and acceptance that additional and larger benefits accrue when the information systems of the entire Public Sector are linked, thus allowing the free exchange of information between those that require it. It is interesting to note that it has been conservatively estimated that the savings on the topographical data only could amount to some ten times the investment within the Ordnance Survey.

SYSTEM PROCUREMENT

The Ordnance Survey of Northern Ireland sought a computer-based system with the following broad objectives:-

- Capture and maintenance of the map archive in scale-free digital form over an initial ten-year period;
- Use of this digital archive for all map production;
- Creation of a fully structured topographic database to allow flexible extraction and manipulation of archive information by the Ordnance Survey and various other public sector organisations;
- Integration of the topographic database with other organisations' databases at their sites for convenient exploitation by them;
- Provision and development of all these services into the indefinite future.

Following evaluation of the output from a comprehensive series of Benchmark Tests designed to identify suitable 'turnkey' systems, equipment was bought. The system configuration operates within a VAX environment, and as the database grows additional data storage will be acquired as necessary to hold the estimated 20 gigabytes of topographic information for Northern Ireland.
DATABASE

The design of the topographical part of the database is crucial. From the outset it was realised that ultimately a fully relational-type database would be required. Although there are a number of these presently available the full development of this type of database is still in its infancy. As a result it was decided initially to simulate a relational one to facilitate the eventual translation of data.

The major element of any investment into any such project is not the capital hardware or software part of the system but in the data itself. With a data capture period of up to ten years (a workload well in excess of 600 man years), the database structure must be very carefully designed to allow for portability and currency. In essence we are planning for a year 2000 system in the year 2000. Thus the design must be flexible enough to allow for the as yet unknown requirements of the future.

It is only on a project like this, when one dissects a map with its mass of information both specific and implied, that its value as a vehicle for the storage and transmission of information is fully appreciated. The topographical part of the data will have in excess of 140 main families of data, but it is intended that much of this structuring and its further breakdown will be done automatically using computer files held by other organisations. For example, buildings could be classified by their usage or other attributes from information held in valuation records, eg, private or government; dwelling or commercial; retail outlet or office, etc.

THE ROLE OF PHOTOGRAMMETRY

OSNI has been fully committed to the use of photogrammetry in the creation and maintenance of the national topographic archive of Northern Ireland since it acquired its first stereoplotting instrument (A Wild AB) in the early 1960s. Since then its photogrammetric department has grown steadily in size and importance reflecting the requirements of a modern forward-looking organisation with wide commitments as the Northern Ireland Government official survey, cartographic and reprographic organisation. Now equipped with 3 Wild AB, 1 Wild B8, 1 Wild AMH and 1 Kern DSR 11, a Wild RC10 camera and ancillary equipment, OSNI is capable of meeting the increasing demands being placed upon it. Moreover, in 1982 OSNI set up the Northern Ireland Register of Aerial Photography containing details of all aerial survey photography held by both public and private sectors. Thus interested parties throughout Northern Ireland, and beyond, can quickly establish the type and extent of aerial photography available, and this avoids costly duplication of effort.

OSNI has pioneered a number of procedures reflecting the advantages of its relatively small scale operations, flexibility, and the particular requirements of Northern Ireland government departments. These include:

(a) Acquisition of photography using its own camera, operators and navigators through an arrangement with a local air taxi firm for fitting out an aircraft at "short notice" booking.
(b) Aerial triangulation of small blocks (approx 50 models) using airline strip formation techniques developed in-house and controlled by micro-computer.

(c) Quick-response surveys to meet the high priority needs of certain sister government departments such as Roads and Water Service Divisions of the Department of the Environment (NI).

Our concept of the digital system embodies full system integration and this has been fully reflected in the systems acquired and the operating procedures developed. OSNI's photogrammetric department now has computer access to equipment (eg, flatbed plotters, digital workstations) elsewhere in the organisation.

The greatest impact of the new technology occurs with the necessity to adopt new techniques for data capture. With data captured in a structured manner an entirely new set of requirements makes fresh demands on the operator. Using conventional methods of plotting, the emphasis is on highly skilled control of the floating mark and interpretation of model features. Digital data capture now adds as further requirements: familiarity with logic codes, logic levels, and skillful manipulation of digitising modes. Additional foot pedals to control data input and the need to have some knowledge of the basic command language combine with the new data capture techniques to make for more demanding work practices.

The full range of data codes as required for the Ordnance Survey's Topographical database structure is not employed. There are three principal reasons for this:

(a) the operator lacks sufficient information to accurately classify all data in the model;

(b) during the field completion stage changes in position and classification will occur, as well as deletion of some data;

(c) field recorded alterations require subsequent input as amendments to the original data files and this is the stage where all necessary information is at hand to fully structure data.

A subset of the structure is used for input, sufficient only to provide essential information to assist field completion.

Raster-based check plots are used at the edit stage to detect errors not detected immediately after perpetuation. Unless these are significant it is more economical to annotate the document plots and thus highlight them for appropriate action later. A content plot is produced on the conventional plotting table and provides the operator with evidence of features actually digitised.

Already the impact on efficiency of the digital procedures can be detected and indications are that the potential exists to achieve savings in the order of 40% on large-scale survey input time. This in addition to the other advantages of increased precision (information captured and stored digitally) and, of course, the availability of information in digital form.
NORTHERN IRELAND REGIONAL PROCESSING CENTRE FOR REMOTELY SENSED DATA

Early this year a Regional Processing Centre was established after agreement between the DOE (NI) and the Department of Trade and Industry, the latter acting through the National Centre at Farnborough. The CEMS based system is located at the Ordnance Survey of Northern Ireland and follows on from the very successful SPOT Simulation exercise of 1984-5. In late 1986 it is planned to start interfacing the system directly with the topographical database system - operating in the same clustered DEC VAX configuration, thus considerably enhancing both the facilities of the centre and the effectiveness of the database.

Northern Ireland will be responsible for the acquisition of most of the remotely-sensed data of the Province for the National archive. Airborne campaigns to capture data at 5 metre resolution of selected parts of Northern Ireland as well as data from SPOT Image and the Thematic Mapper are underway. This will lead to a series of project-orientated investigations and studies of a number of disciplines including soil, forestry, agricultural crop census and disease identification, pollution control, etc.

IMMEDIATE FUTURE

Compatibility between all co-operating user organisations' systems is vital in achieving full benefit from their co-operation. For this reason a number of pilot schemes to be conducted (at OSNI) with our colleagues in the Land Registry, and the Water and Roads Services will begin this year. These schemes will help users to define and refine their ideas on (i) their own database designs, and (ii) the exploitation of those databases in conjunction with OSNI's digital database as well as other external databases.

In addition to these pilot schemes, a project bringing together the Ordnance Survey, Water Service and the Institute of Hydrology is progressing. This contains topographic information, which includes relief, in the form of a DTM and river systems with the output of river telemetry stations. This will enable a series of graphical outputs of water quality, flows, etc, and all their derivatives to be produced, and also provides the opportunity to undertake computer modelling exercises. Other plans include a soil survey of Northern Ireland which will be 'digital', and studies leading to incorporation of Geographical information to the system.

When several users are connected to the system, each of them will be able to extract data not only from the Ordnance Survey system but also from other systems (subject to access privileges) and to manipulate the total data as necessary. As the number of users sharing information in this way increases, the system will constitute a continually improving Geographic Information System for the benefit of all.
DIGITAL CARTOGRAPHIC DATA BASES: ADVANCED ANALYSIS AND DISPLAY TECHNOLOGIES

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ABSTRACT

The Defense Mapping Agency produces digital data bases that describe the physical appearance of the surface of the earth. Using state-of-the-art display and analysis concepts in conjunction with sophisticated interactive computer graphics systems, a variety of geographic simulation and analysis displays are available. Applications include visual and electro-optical sensor simulations to support aircrew training simulators, mission and land use planning displays, trafficability analysis based upon terrain and surface cover, threat and survivability displays, airport radar installation analysis, and advanced convolution and digital Fourier analysis for quality control of the digital data bases.

BACKGROUND

The Defense Mapping Agency (DMA) produces digital data bases that describe the physical appearance of the surface of the earth. These data bases include, but are not limited to, terrain elevation, culture including landscape characteristics, and vertical features. This data is collected from digitized source maps, from optically or digitally correlated stereo-pairs of photographic imagery, and from digital multi-spectral sensor data. A dramatic impact has been made in the ability to analyze these digital data bases by applying state-of-the-art digital image technology processing and display concepts. These include a variety of color and/or black and white displays of not only intensity/color coded matrix data, but also image processed data using specialized convolution filters, texture discrimination, digital Fourier analysis, and special color representation techniques. In addition, computer generated visual and electro-optical imagery from these data bases serves as a final analysis tool.

For purposes of quality control and data base applicability investigations, DMA has developed the Sensor Image Simulator (SIS), a very high speed data base edit station and static scene simulator that allows for interactive
query and manipulation of individual features in the data base displays and/or simulated sensor scenes to determine the corresponding data base elements responsible for the simulated features. The SIS was installed at DMA in 1981, and plays a key role in determining the applicability of existing and prototype data bases for use in a variety of applications, as well as to ensure the quality of, and coherence between the various digital data bases prior to new data insertion into the master cartographic data base files.

DATA BASE CONTENT

The current DMA standard production data bases (Level I) contain large area cultural information, and digital terrain data sampled at a three arc second interval. The cultural data consists of point, linear, and areal features described by characteristics such as surface material category, generic identification, predominant height, structure density, and percentages of roof and tree cover. The cultural data is in lineal (planimetric boundary) format and, although feature sizes may vary depending upon local circumstances, reflects a resolution on the order of 500 feet. Smaller features are aggregated into homogeneous features described by predominant characteristics. The current high resolution (Level II) data bases contain small area cultural information, and limited digital terrain elevation data sampled at a one arc second interval. This translates to a resolution of about 100 feet, with smaller features aggregated. With the exception of some special products, DMA does not produce digital terrain elevation data sampled at one arc second intervals. The majority of Level II data produced contains Level II digital feature analysis data and Level I digital terrain elevation data.

The terrain elevation data is produced by contour digitization from charts or directly from stereo pairs of photographs using advanced analytical stereoplotters. The cultural data is produced from both charts and photographs with a much higher level of manual effort required in order to perform the complex feature analysis.

SIS CONCEPT

The natural evolution of sensor simulation at DMA led to the design and fabrication of the Sensor Image Simulator (SIS), a dedicated mini-computer-based image processing system capable of performing simulations in an interactive mode.
The Sensor Image Simulator performs five major functions:

1. Digital Data Base File Input and Output.
4. Interactive Data Base Editing.
5. Software Development and Maintenance.

The SIS brings together, in a self-contained integrated hardware/software facility, a significant capability to evaluate the digital data bases. All operations are conducted under interactive control. Both the software structure and operations sequence reflect a top-down implementation philosophy wherein principal control functions are resident at the top of the hierarchy and functions concerned with processing individual data elements are at the lowest. The system is implemented in such a fashion that future changes in processing can be accomplished at the highest level of system software support. Detailed information on SIS operations, hardware, and software has been previously published.

GENERAL LAND USE AND RESOURCE MANAGEMENT

Maps are perhaps the single most important tool for the solutions of the problems confronting the land use and resource manager. The proper map, viewed in the proper manner, can sometimes convey all that is needed. Yet, frequently, the maps that must be used are too general — they cannot address themselves directly to the problem at hand. It is the ability to quickly customize presentations of digital cartographic data through interactive selections that give computer generated maps their advantage over conventional maps. The basic information contained in digital terrain and feature data bases can be manipulated in hundreds of different ways to produce the one electronic map or image necessary to address a specific problem.

Sometimes, a land use solution lies solely with terrain evaluation. One of the most common means of terrain analysis is through the use of a contour map. With digital terrain on an interactive system, contour vectors can be generated at the analyst's discretion. The analyst simply chooses the upper and lower limits of evaluation along with an interval
for the contours. Perspective profiles are another type of vector display that can be easily generated. To increase the analyst's comprehension of profile displays, the vectors can be color coded with a color spectrum scale. Using this technique, progressions of elevations from the lowest to the highest value correspond with vectors that are colored from violet to red. Color coding dramatically increases the analyst's understanding of a profile display by eliminating any ambiguity about relative vector heights. Matrix analysis of digital terrain is available by using displays of shaded relief, color elevations, and gradient magnitude.

The gradient magnitude operator is a useful function for producing a nonconventional type of terrain matrix image. The gradient magnitude image becomes a very useful method if identifying areas of steep slope is part of the solution to a land use manager's problem. The gradient is a vector function \( \nabla f(x,y) \) that points in the direction of maximum slope and is defined by:

\[
\nabla f(x,y) = \frac{\partial f}{\partial x} \hat{i} + \frac{\partial f}{\partial y} \hat{j},
\]

where \( \hat{i} \) and \( \hat{j} \) are unit vectors.

Its magnitude is defined by:

\[
| \nabla f(x,y) | = \sqrt{\left( \frac{\partial f}{\partial x} \right)^2 + \left( \frac{\partial f}{\partial y} \right)^2},
\]

and represents the steepness of slope at every point. One of the specific applications in which a gradient magnitude image could be used is in the determination of drainage patterns in terrain of high spatial frequencies. Finding these same patterns using contours or shaded relief images is much more difficult.

If surface feature information is the primary concern in a land use problem, then feature boundary plots can be produced that use vectors to identify the outlines of feature data in geographic region. These displays are highly interactive and allow for the analyst to create displays of color coded vectors based on the surface material categories (i.e., metal, soil, etc.) of the feature data. If desired, the analyst can also display only certain features specified by combinations of surface material category, the feature type (i.e., residential, processing industry, commercial buildings), feature identification number, and feature length, width, height, and orientation.
If the combination of feature and terrain information is important, then the two data types can be displayed simultaneously in an image using color. Color is perceptually defined in three-dimensional space by its intensity, hue and saturation attributes. Each of these attributes can be independently controlled by a multi-dimensional data structure to generate representative colors. A raster geographic data base can be displayed in color such that for each cell, the feature component determines the hue, while the terrain data, through slope shading, determines the intensity. The result, when using conventional hues in association with general landcover classes, is a natural appearing color image clearly displaying the character of the landscape. Saturation may also be used in addition to hue and intensity to reveal a third data class, such as data accuracy levels or climatic conditions.

The computer generated intensity, hue, and saturation (IHS) display allows a great deal of flexibility to achieve a variety of capabilities through the manipulation of the digital data. The terrain shading condition of the image can be controlled to vary the direction and intensity of the slope illumination. This is used to create displays with optimum illumination conditions to enhance terrain characteristics or to provide desired aesthetic effects without changing the information presented by hue or saturation.

The digital feature data base may consist of a variety of descriptors which can be selected for display. Normally, the basic surface material is used to determine hue, resulting in general land-use displays. Such information as predominate heights or tree types can be portrayed using hue to create thematic IHS images. The ability to relate various types of data to terrain in a single image makes the IHS display particularly useful to the analysis of the landscape. In addition, the rapid generation speeds for interactive computer generated map displays allows the user to quickly generate a variety of unique images to fully exploit the information available in the data base.

The IHS display contains the realism of aerial photography, the planimetric control and generalization of a map, and the flexibility of a computer generated image. It can thus be used in place of, or to supplement, aerial imagery, conventional maps and less advanced computer graphics. Applications include the interpretation of geologic formations for mineral exploration, hydrology studies, civil land use assessment and planning, environmental research, route planning, inventory of natural resources such as timber or water, and a variety
of other uses which can benefit from advanced digital geographic data displays.

**MISSION PLANNING ANALYSIS**

Digital terrain and feature data displays are particularly useful for mission planning analysis due to the realism, efficiency, and flexibility possible with advanced processing and display technology. The geographic data can be rapidly processed into a variety of graphic forms best suited for specific needs.

Various data base displays have been demonstrated to be very effective for ground operation mission planning. During the planning process for a mountain climbing expedition, several computer generated displays, including shaded terrain, color height, gradient magnitude, feature and surface material, IHS, were used to determine the optimal route to the top of Mt. Powell in central Colorado by visual inspection of the displays. Such images proved to be superior to conventional maps using contour coding by providing a variety of graphics which made it possible to better comprehend the actual landscape. When particular terrain conditions required greater clarification, the digital data displays were quickly manipulated to more appropriate images by changing the area, resolution, color, shading conditions, or the type of display. Color hardcopy was created of the most useful images for navigation and planning in the field. Since the digital data displays lacked symbology, conventional maps were required. However, this information can be added to digital images using graphics overlays. The climbing route selected from the digital data followed one recommended by the Colorado Mountain Club.

Perspective visual simulation is perhaps one of the most effective display methods since it creates a natural appearing image, allowing the user to closely associate geographic data with the real world. It is especially useful for airborne operation planning by providing a pilot's eye view of the landscape which will be encountered in an actual mission.

Perspective simulation employs the same IHS techniques used for surface material color coded shaded terrain raster map displays and thus may include similar flexibility. Surface material codes are used to determine associated conventional hues for natural color, general purpose simulations. This provides highly realistic out-of-the-window scenes with viewer position, attitude, and optics controlled.
by the simulation producer. Atmospheric effects such as haze or fog can be created using the saturation component of color. This is significant in indicating to the simulation user the possible visibility conditions as opposed to the theoretical scene based solely on feature and terrain data.

In certain situations it may be desirable to vertically exaggerate a perspective simulation to enhance the portrayal of terrain. This is often necessary for areas of low relief in which the vertical dimension is very small proportional to the horizontal dimension. Earth curvature may also be accounted for as a significant factor in visual simulation to produce a scene correctly portraying what can actually be seen by the observer.

In addition to surface material codes, other information significant to planning analysis may be portrayed using hue. One method is to code terrain elevation levels in the simulation using a spectral arrangement of hues such that higher elevations appear in hues towards the red end of the spectrum. This is useful in allowing the pilot to accurately determine ground elevations in perspective view for terrain avoidance planning or landing assistance. The predominate heights of only the feature data can also be displayed using the same technique to indicate vertical obstructions or structures which will cause shadowing and high returns of radar. Radar and electro-optical sensor potential reflectance can be calculated from feature data and portrayed in the visual simulation using a similar arrangement of hues. Such displays are significant for the planning of missions in which sensors will be used in navigation by indicating the various strengths and positions of sensor returns which will be encountered. The numerous types of data which can be portrayed using hue in perspective scenes can also be displayed in raster map images.

Specific radar and electro-optical sensors may be digitally modeled to produce sensor simulations using digital terrain and feature data. All aspects of the simulation, including radar parameters and aircraft position and attitude, can be controlled by the operator to produce scenes simulating various circumstances. Sensor simulations are valuable to navigation planning and may serve as enroute navigation check points.

In hostile tactical military environments, the ability to predict threats, such as surface-to-air missiles, is an extremely valuable tool. Techniques have been developed
to place models of multiple threat acquisition parameters into the simulation data base to provide safe "pathways in the sky" displays for mission planning.

The capability to simulate electro-optical displays from the digital data led to a pilot study to support the Department of Transportation in planning the location of airport radar systems. Of primary concern was the shadowing of ground vehicles by airport buildings. The flexibility of easily changing radar location and altitude with the resultant computer generated radar shadow mask proved the viability of this technique.

**TRAFFICABILITY ANALYSIS**

Trafficability analysis is concerned with the determining of movement costs and optimum routings over a selected set of data. By using digital terrain and/or feature data as inputs to imagery processes, it is possible to create cost of movement displays that can aid in this analysis. These cost of movement displays are created by using a cost matrix concept.

Cost matrices are arrays whose elemental values indicate the cost associated with moving through each particular element. These cost values can be considered in many different ways. For example, the costs could be in terms of speed of movement, danger of movement, combinations of the two, or in any other conceivable manner. These cost matrices consist of 256 levels. The terrain costs are produced by computing the gradient magnitude of the terrain data and using the value to assign a terrain cost of 0 to 127. The terrain cost, \( T_c \), can be varied for different scenarios by changing a terrain cost multiplicative factor \( \alpha \),

where:

\[
T_c (x,y) = \nabla \text{Terrain} (x,y);
\]

\[
0 \leq \alpha T_c (x,y) \leq 127.
\]

The feature costs, \( F_c \), are produced using the thirteen different surface material categories present in the feature data (i.e., water, trees, soil). An entry cost value between 0 and 127 must first be selected for each surface material category. In the special case that a no entry condition is desired for any particular surface material category, a value of 255 is assigned,
where:
\[ 0 \leq F_c (x,y) \leq 127; \]
no entry: \( F_c (x,y) = 255. \)

The feature data is then used by examining the surface material category at each location and assigning the cost matrix a feature cost value. By summing the terrain and feature cost values together at each location, a cost matrix is produced and can be displayed using a color spectrum intensity mapping,

\[
\sum_{x=0}^{m} \sum_{y=0}^{n} C_m (x,y) = \sum_{x=0}^{m} \sum_{y=0}^{n} T_c (x,y) + \sum_{x=0}^{m} \sum_{y=0}^{n} F_c (x,y);
\]
\[ 0 \leq C_m (x,y) \leq 255. \]

This use of a visual cost matrix technique on digital terrain and feature data, along with the ability to interactively change cost structures, gives an analyst the power to quickly solve many problems relating to trafficability. The cost matrix format could also readily lend itself to manipulation by software that would automatically select optimum routes based on the analyst's decision of cost structures for a given scenario.

**DATA BASE QUALITY CONTROL**

In order to perform interactive analysis of the digital files, digital terrain elevation data may be used to generate color coded contour plots and line profile displays. An alternative is to color code the matrix terrain data directly. While analysis of these matrix image displays is superior to trying to perform analysis by visual inspection of the data in printed numerical matrix format, they only provide for a low spatial resolution analysis capability. Shaded relief display with variable illumination adds additional information for analysis of all types of matrix data and is particularly meaningful for cartographic data because of the relationship to the physical world. Higher spatial resolution analysis of the shaded relief display may be gained by applying photogrammetric models to generate pseudo-stereo-pairs of images in which spike points are apparent under stereoscopic analysis. These techniques, used singly or in combination, allow for data base analysis far superior to techniques of a decade ago, but they are not enough.

In order to perform high resolution anomaly analysis of data bases for the purpose of either quality control
or information gathering, advanced techniques are required. These techniques include convolution filtering, specialized color representation, digital Fourier analysis, and computer generated sensor simulation.

Convolution filters have been used very effectively to enhance matrix data to show processing anomalies as well as where data has been merged from different production equipment, different stereo models, different production methods, variable requirement specifications, and even from different analysts. These types of filters are used extensively by the image processing community to detect edge differences, and then to reapply the differences to sharpen the original image. They also have been shown to be a powerful tool for the analysis of cartographic data bases.

For the purpose of determining compatibility between data types, such as between digital terrain and culture data, simple color coding and overlay in Red-Green-Blue (RGB) space may not be sufficient. A more powerful technique employs coding each data type along an Intensive-Hue-Saturation (IHS) axis and then converting from the IHS space to RGB space prior to display. Since the visual perception process can distinguish variation between IHS, the data types can be overlayed without a merging of colors, and therefore, without an information loss. Various cultural thematic displays may be overlayed on variably illuminated terrain displays.

The DMA is beginning to explore the potential of using digital Fourier analysis for filtering of the terrain data. The digital generation and interactive display of two-dimensional Fourier transformations of the terrain data in conventional frequency vs azimuth as well as profile displays have highlighted and isolated data anomalies that were previously extremely difficult to describe. A variety of digital pass and rejection filters have been applied to these transforms for anomaly removal.

Finally, and probably unique to cartographic data bases, is the technique of computer generating landform scenes as seen by various visual and electro-optical sensors. This allows for a final quality control analysis of information content, and also has been very valuable in the definition of data base requirement specification.
IMPACT

The impact of this interactive system and application technique development has been enormous. Not only is there a greatly increased capability for the degree and sophistication of quality control of the digital data bases, but also there is now a highly flexible and interactive tool for data base application studies which allows users to investigate potential methods for topographic information display to meet a wide variety of requirements.

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Using Landsat Data with a Geographic Information System

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ABSTRACT

Remote sensing has great potential as a primary data source for geographic information systems. This paper describes the use of Landsat data in BASIS, a GIS covering the San Francisco Bay Area. A specific application involving air pollution models is described.

INTRODUCTION

In large metropolitan regions like the San Francisco Bay Area, where rapid population growth occurs in a complex natural environment, there is a great demand for information about land and the human activities on it. Planning and regulatory activities require detailed and current data about physiographic features, land use, transportation facilities, natural and manmade hazards, population distribution, and economic activity. Further, the spatial component of this information is important—knowing where is often as important as knowing what and how much.

The geographic information system (GIS) is one solution to this demand for data. Building on rapidly-changing hardware and software technology, the automated handling of spatial data has become a widely used tool in both government and the private sector. At the same time, and often in a separate organizational setting, airborne and space remote sensing activities have moved from the realm of research into a common set of practical tools.

This paper will examine the integration of remote sensing technology with that of the GIS. It will use the experience of BASIS, a GIS that has existed in the San Francisco Bay Area for over ten years. We will first look at the background of BASIS, and then discuss an application using remote sensing. Finally, some conclusions about the integration of these technologies are presented.

BASIS AS THE REGIONAL GIS

BASIS is a large geographic information system covering the 7000-square mile San Francisco Bay region (Figure 1). It was created by the Association of Bay Area Governments (ABAG) in 1974, and was designed to support regional and local planning applications.
The system, which is currently maintained and operated by GeoGroup Corporation, is used to provide services to both governmental and private organizations.

A major objective in the design of BASIS was the ability to support a broad range of mapping and analytical applications. Since ABAG’s scope was very broad, ranging from land use planning to environmental management and hazard mitigation, the system would potentially be called on to provide many different types of products. These requirements demand a large and diverse data base. A listing of data contents (Figure 2) indicates the range of data types that have been used.

The system was designed to provide data for many users and for a wide range of applications, not just one regional planning agency or one narrow subject area. Since the data base structure supports hierarchical access, a broad regional overview and a detailed local study can exist within the same spatial framework. Further, the variety of existing data makes the system a valuable tool for many types of resource management applications.

**BASIS Data Structure**

The primary unit of data representation in BASIS was originally the one-hectare grid cell (100 meters square). Coverage of the region (nine counties, the Bay, and small areas of the ocean which contain data of interest) requires over two million of these hectare cells. This structure was selected as a compromise between level of detail and ease of implementation. It was clear that a larger cell (perhaps a quarter square kilometer, which would divide the region into about 84,000 units) would support any project that was regional in scope. A cell smaller than a hectare would allow for more detailed local studies, but would greatly increase the costs of implementing and maintaining the system. Other data structures, such as polygons, seemed to have conceptual advantages but were much more complex to implement. The hectare cell was chosen as a structure that maximized the number of potential applications but did not increase cost and complexity past the point where the system could not be implemented.

Since ABAG also provided technical assistance to local governments, another system design goal for BASIS was the ability to handle small areas with a greater level of detail. It was clear that the hectare cell structure would be adequate for many subregional studies and a few local applications, but could not support sufficient detail for site-specific projects. There was no immediate method (or need) for attaining the capability for more detail; however, all original data encoding and digitizing was designed to be retained so that conversion to a smaller cell or to other structures could be accomplished later (if supported by the scale and quality of the source maps).
FIGURE 2 – BASIS Data Base Overview (August 1983)

NATURAL ENVIRONMENT
- Bay Water Depths
- Elevation, Slope / Aspect (Digital Elevation Models)
- Geologic Materials
- Hydrography (Bay and Ocean Coastline, Lakes, Marshes)
- Precipitation
- Soil Associations
- Wind Speed

POLITICAL / ADMINISTRATIVE UNITS
- City and County Boundaries
- Sewage Districts
- Solid Waste Collection Areas
- Transportation Zones
- Water Districts
- ZIP Codes

TRANSPORTATION
- Electric Power Lines
- Gas Pipelines
- Highways, Bridges / Overpasses
- Petroleum Pipelines
- Street Network (DIME) Files
- Water Aqueducts

LAND USE
- Airports and Airport Runways
- Hazardous Waste Sites
- Industrial Sites
- Land Use
- LANDSAT Land Cover
- Regional Parks
- Seaports
- Sewage Treatment Plants
- Urbanized Area Boundaries

HAZARDS
- Air Pollutants (six categories)
- Airport Noise Zones
- Dam Failure Inundation Areas
- Earthquake Intensity, Maximum
- Earthquake Risk (three building types)
- Fault Study Zones and Fault Traces
- Flood Plains (FEMA-NFIP and USGS)
- Liquefaction Susceptibility (Earthquake-Induced, Rainfall-Induced)
- Landslides
- Liquefaction Potential
- Liquefaction Susceptibility
- Tsunami Inundation Areas
This capacity to maintain a regional overview, while capturing local detail where appropriate, is very important in this type of system. It adds the ability to support applications at both regional and local scale, and insures some consistency of data used for decisionmaking at several levels of government. The impact of these needs on data structures is contradictory, however. One end of the spectrum, the regional perspective, calls for a data base which can cover a large area at a relatively low cost. The other requires detail, and extensive area of coverage is a secondary consideration.

Both of these factors act to demand flexibility in data structures. Having many different types of data makes it less likely that any single data structure will provide a satisfactory representation. The need to vary the level of detail means that no fixed-size unit can be used, and that a mode which is adequate at one scale may be too gross or too detailed at another scale.

BASIS combines data from many different sources: conventional maps have been supplemented by digital data sources such as USGS Digital Elevation Models and Census DIME files. All of these data sources are transformed into a common spatial framework so comparative analyses can be performed.

Remote sensing data fits well into this framework. The level of detail provided by Landsat MSS technology is appropriate for the regional level study, and often can be used for local work as well.
Applications

BASIS has been utilized for many applications at both the regional and local scale. These include the location of sites for hazardous solid wastes, several studies of earthquake hazards, industrial site data, airport noise analysis, market feasibility studies, and mapping of socioeconomic data.

Many projects require the use of multiple data sets. An example of a project which called for extensive data integration was an analysis of the impact of earthquakes on lifelines. For this project, lifelines were defined to include public or private facilities that are important in maintaining public safety and economic activity. They include facilities such as electric power substations, which can be represented as a point. Others (highways, railways, rapid transit lines, bridges, power lines, pipelines) are most naturally stored as vectors.

The objective of this project was to overlay these lifelines on maps (data sets) containing projections of ground shaking intensity. The intensity data, which was derived from a series of models incorporating fault locations and geology, was stored in the hectare grid cell base. The lifelines were represented as points and vectors and then overlayed on the cell data. This procedure was used to determine both an average level of risk for each entity (such as a freeway segment) and to pinpoint specific parts of a network most vulnerable to damage.

AIR POLLUTION AS A SPATIAL ISSUE

Growth and concentration of population in urban areas has had many undesirable effects. One is a rapid increase in air pollution. This problem has been studied in the San Francisco Bay Area for many years. It is clearly a nonlocal problem, since the transport of airborne pollutants does not conform to political boundaries. In the San Francisco Bay Area, several agencies share responsibility for air quality.

While most air pollution is clearly caused by the industrial and transportation activities which abound in any urban area, there are also natural sources. Some types of vegetation, under certain climatic conditions, produce a significant amount of hydrocarbons. These in turn combine with nitrogen oxides to form ozone, which is a major component of smog. These natural sources of pollution are called biogenic to distinguish them from the more common anthropogenic (manmade) sources.

Although these effects have been recognized for many years, studies have concentrated on a very local scale (often measuring the emissions from a single tree) or global scale. For studying the issue of natural sources in the San Francisco Bay Area, a methodology operating at the regional level was needed. Much of
the necessary background research had been completed. There was a fair understanding of the emission rates from each category of vegetation, but no comprehensive source of data about vegetation patterns within the Bay Area. Therefore, it was difficult to estimate a total amount of biogenic contribution or -- equally important -- see any spatial variation in the results.

The desired output of such a study was a data set containing emissions amounts under a defined set of time/temperature conditions. The data were to be represented spatially as one-kilometer grid cells for input into an existing regional air quality model (LIRAO). Within the framework of this model (which already contained extensive information about man-made sources of air pollution), comparisons could be made to actual monitored levels and adjustments made.

Methodology

Landsat imagery was an obvious candidate for filling this need for vegetation coverage. The lack of comparable data on conventional maps led to a search for other sources, and imagery had the advantages of being timely, detailed, and available. As an added benefit, Landsat data was already in machine-readable form, so there was no need to undertake an expensive map compilation and digitizing project.

The existence of classified Landsat data for the Bay Area was a major advantage for the project. A NASA-sponsored program called CIRS (California Integrated Remote Sensing System) had developed a statewide land use / land cover file from imagery in 1979. Some additional processing was needed to tailor the statewide file to this application. Since the major requirement was to identify distinct types of vegetation, the file was reclassified to derive 22 land cover classes.

The existence of BASIS helped in this reclassification work. The original classification resulted in some confusion in urban fringe areas because of similar spectral responses in certain types of urban structures and areas of vegetation; BASIS land use data was used to generate an urban mask, which helped refine those categories in marginal areas.

Addition of the Landsat file to the BASIS data base was a relatively straightforward procedure. The statewide file was in an 80-meter cell format using the Lambert Conic Conformal projection; resampling produced a regional file in the one-hectare UTM structure used by BASIS. Actual transfer of the data from NASA was by magnetic tape, with each input file representing the classified data for a one-degree block.

It is important to emphasize that the existence of BASIS made both the reclassification and registration steps easier. The existence of other data sets, such as hydrography, provided a way
to check the fit of the registration procedures. Corallary data such as the urban area boundary was used to further refine the classified data and remove confusion between urban and nonurban classes with similar spectral responses.

As this work was going on, another group was developing sets of emission factors for the land cover classes. This process consisted of adjusting rates for distinct species into levels which fit the broader vegetation categories identifiable through Landsat.

As a final step, these factors were applied to the land cover file and emissions were calculated for each hectare cell. These numbers were then aggregated for kilometer cells and transferred via tape to the mainframe which supported the elaborate LIRAP model. Results of the process were very encouraging. By adding the previously-ignored biogenic contribution to the model, most of the unexplained difference between model and measurement were explained. From a planning perspective, this study gave the appropriate agencies a way of comparing the effects of natural and manmade sources, and then adjusting control programs accordingly.
CONCLUSIONS

Our experience with BASIS has shown that it is possible, and very desirable, to incorporate remote sensing imagery into a regional data base. Imagery is an invaluable source, particularly in those cases -- such as the application described here -- where there is no alternative short of a massive data collection effort. Further, the fact that much remote sensing data is already in machine-readable form can significantly undercut the time and costs of alternative methods.

The framework of an existing GIS is an essential component in making imagery work for this type of application. As noted above, the classification of satellite data is often aided by existing data sets in the GIS. Perhaps the best conceptual framework is to simply view imagery as an element or layer in the data base, equivalent to other layers derived from more conventional sources.

Much of the value of Landsat data has derived from its fairly high level of detail and its timeliness. Newer sensor technology such as the Thematic Mapper add even more detail; advances in processor and memory size, as well as more sophisticated software, should maintain our ability to handle the larger volumes of data. Timeliness is a more difficult issue. Changes in the management and support of the U.S. remote sensing satellites have raised questions about continuity of data, and the availability of imagery from foreign sources has gained acceptance only slowly.

REFERENCES

Reports describing this project are available from Geogroup Corporation or from the Association of Bay Area Governments. For information on other BASIS applications, a series of ABAG reports on earthquake mitigation planning are good illustrations of GIS techniques being used with different data types and data structures.

A study of data integration issues (with a major focus on California state government, but covering many other types of users) was conducted by the California Integrated Remote Sensing System in 1979-1982. This effort, sponsored by NASA Ames Research Center, identified the barriers to data integration and tested institutional forms to overcome them.
A GEOCODED DATA BASE FOR THE REGION OF TUNIS

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ABSTRACT

The objective of this study is to realise a geographic information system where Remote Sensing data are combined with ancillary data and digitised data from map documents. The region of Tunis is chosen as an example of the system use. Various data are integrated in the system. Some of these data are unchanging such as topographic or geological data, others are changing in time such as soil or meteorological data. Remote Sensing data, generally, are digital, multitemporal and multispectral images. These images are constituting both the geographic reference and the mean to bring up to date the data.

The system can handle operations such as: data management, display of the data, interrogation of the data base, processing, restitution of information both in cartographic and statistical way.

In addition of the data base aspect, the one of data processing including some interpretation aid is the originality of the system. Its modularity permit to include, in further steps, some other spatial or non-spatial informations ending in a geographic information system.
KNOWLEDGE-BASED SEGMENTATION OF REMOTELY-SENSED IMAGES

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Abstract

The paper describes progress on a U.K. Alvey Information Technology project to develop a system for the knowledge-based segmentation and interpretation of remotely-sensed images. The knowledge used may be about the types of structures to be expected within the scene and their relationships, and other datasets such as existing map data or previous classifications. A major objective is to increase substantially the accuracy to which the images can be classified. A further use could be to update the existing map data as a result of the segmentation.

1. Introduction

Remote sensing platforms are one of the most prolific sources of data in the field of image analysis. Further, sensor spatial and spectral resolutions are continuing to increase, resulting in increased data volumes per unit area on the ground. As data sizes grow, so does the need for efficient machine-implemented analysis of these data. Unfortunately, the improved image generation techniques have been far more successful in producing increased data sizes than developments in image analysis have been in producing increased classification accuracies, even though the latter have advanced significantly since the launch of the first LANDSAT.

Much current machine analysis of remotely-sensed data relies solely on the spectral analysis of pixels on an individual basis. The per-pixel spectral classifiers originally found favour because of the wealth of information that could be obtained from the spectral domain at relatively low computational cost. However, if these techniques are compared with those used by a trained photointerpreter, their limitations become apparent. The photointerpreter may use several other types of information, such as size and shape; contextual information, such as the interrelationships between pixels and/or regions; topographic information, such as the height of a region; and temporal information, such as the previous classification of a region.

There have been a number of attempts at incorporating spatial and temporal information into the classification process (see section 2). These methods have certainly achieved improvements in overcoming the shortcomings of the basic per-pixel classifiers. However, the statistical classification methods have a limitation in that they show, in essence, to which category each point in a picture belongs. Their most serious shortcoming is their inability to incorporate the concept of 'object' into the processing; they do not use the available knowledge about the various properties of objects, such as size, shape, location, syntactic

and semantic relationships with other objects, and so on.

It is natural to introduce image understanding techniques to overcome the limitations of the statistical classifiers. Image understanding aims to detect objects in a scene and to describe their structures and mutual relationships, rather than simply label each pixel with a category name. The processes of detecting objects and describing the scene require knowledge from various external sources. This external knowledge may be in the form of models of the imaging process; knowledge and/or models of the types of structures to be expected within the scene, and their relationships; other data sets such as previous interpretations or map data, perhaps resident within a geographic information system; or the analyst's own expertise.

The present project is a U.K. Alvey Information Technology Man-Machine Interface project involving a collaboration between Systems Designers Ltd., Sussex University, and the N.E.R.C. The project aims to produce a demonstrator system for the knowledge-based segmentation of remotely sensed terrain images of the type used in the environmental sciences.

It is envisaged that the project will involve segmentation-by-recognition. Segmentation involves the decomposition of an image into its constituent parts. For simple images with high contrast between their constituent regions, a number of segmentation techniques exist which will produce accurate segmentations. These include region forming techniques, such as simple thresholding, region growing (e.g. Landgrebe 1980), spatial clustering (e.g. Narendra and Goldberg 1980) and split-and-merge (e.g. Chen and Pavlidis 1979); and edge detection techniques (e.g. Nevatia and Babu 1979). None of these techniques is adequate for segmentation of complex images of land from aircraft or satellite. Even if the technique performs to the best of its ability, segmentation errors and ambiguities still occur, whether they are due to the image, its representation, or the assumptions made by the technique. As an example of the latter, a split-and-merge procedure searching for regions of homogeneous tone and texture will not succeed in segmenting, say, fields, correctly, because few real fields are completely homogeneous. To overcome this, Tenenbaum and Barrow (1977), and others, have proposed a more intimate integration of segmentation with interpretation, in which an initial segmentation by a standard procedure is partially interpreted, and successively modified to allow the interpretation to evolve into one which is complete and consistent. Thus the correct segmentation emerges alongside an interpretation of the given image.

It is proposed to use two main types of knowledge in the analysis - (i) knowledge about the type of structures to be expected in the scene and their relationships (e.g. fields often have straight edges, hedgerows border fields), (ii) knowledge contained in other data sets of the area, such as existing maps, or previous classifications.

As the project has commenced only recently, this paper confines itself to a description of the project, a discussion of previous relevant work, some of the problems to be expected, and some possible solutions. It is hoped to present a more up-to-date statement of progress in the presented paper. The project involves 7 man-years of effort being expended over a 2-year period. However, due to the breadth of the subject, it is likely that the treatment will be illustrative rather than exhaustive.

2. Knowledge-based image interpretation techniques

A review of knowledge-based image interpretation methods relevant to remote sensing has been completed (Tailor et al. 1986). The review brings together the various ways in which knowledge has been incorporated into image segmentation and classification. It is useful to summarise this
review in order to highlight the ways in which various existing approaches have tackled some of the problems to be expected, and the possibilities for incorporating various techniques used in per-pixel classification into segmentation.

Most of the standard pattern-recognition techniques use in some form, albeit implicitly, knowledge of the Gestalt principles of the human visual system for grouping i.e. proximity, similarity and connectivity. This low-level domain-independent knowledge has been used to incorporate spatial information into the per-pixel spectral classification schemes in order to improve them, in several ways. These include segmenting the scene into homogeneous regions before classification, then classifying each region as a single entity (e.g. Landgrebe 1980), or using local texture in the neighbourhood of a pixel (e.g. Weszka et al. 1976).

We are mainly interested in this project in the addition of domain-dependent knowledge to the interpretation process. Some of the methods whereby this may be incorporated are discussed below. We consider methods exploiting contextual clues in the data, including relaxation labelling, and the combination of region-based and edge-based techniques (the latter not restricted to domain-dependent knowledge). Then methods using ancillary data are discussed. A section on model-based approaches follows. Then rule-based methods are considered. Finally, there is a discussion of some related issues.

2.1 Relaxation Labelling

Relaxation labelling is an iterative decision-making scheme incorporating contextual knowledge which can be used for image segmentation. Each pixel is initially assigned probabilities of belonging to each of a set of objects. These initial probabilities are iteratively revised based on the support, or lack of it, coming from the pixel's neighbours (this is embodied in compatibility coefficients) (Rosenfeld et al. 1976). Relaxation has been criticised as being too simple in both its method and its representation of knowledge (Matsuyama 1984). The iterative probability modification cannot cope with the variety of constraints in complex scenes which change locally, and the knowledge representation of just labels and compatibility coefficients is limiting. However, a number of authors have used relaxation techniques for segmentation of natural scenes with some success.

2.2 Combining region-finding and edge-finding techniques

Methods of segmentation tend to fall into two main classes, region-finding and edge-finding techniques. Nagao and Matsuyama (1980) argue that in complex aerial scenes, a region-based approach is preferable because regions can represent object properties such as colour and texture. In the edge-based analysis it is sometimes difficult to distinguish between boundaries of objects and texture edges. However, region-based techniques do not recover adequately the line segments in an image. It seems attractive to combine the two approaches, thereby bringing in context. There is no current theory which takes into account both regional and edge analysis of scenes. Practically, however, the improvement to be gained is evident throughout the literature. As an example, Medioni (1982) uses a combination of a region and an edge approach for segmentation of aircraft scenes.

2.3 Ancillary Data

2.3.1 Temporal Data

Temporal variation of the data may be viewed as ancillary information when segmenting or interpreting a scene and is treated as such below. Time sequences of images can aid in the improvement of image segmentations and classifications. One way to do this is to use the additional
information associated with each pixel as further features in an expanded feature vector. Another is to use as features parameters derived from a plot of object properties as a function of time (Badwhar 1982). Of more relevance here, is the registration of an image at time t + 1 with the result of analysis at time t, and the use of the former to update the result. There are various problems associated with this process, including finding an accurate registration algorithm, and coping with feature variations due to varying sensing conditions i.e. signature extension. Henderson (1976) developed signature extension methods to attain stable supervised spectral classification analyses from picture to picture. The latter problem may also be overcome by choosing features which are invariant to environmental influences such as differing illumination. Time sequences of images have proved their worth for improving per-pixel classification accuracy in several studies (e.g. Swain 1978), and it is likely that they can also improve the results of segmentations.

2.3.2 Maps

Map data, typically in the form of topographic maps, digital terrain models, geological maps, or soil maps, provide independent information about the scene. It must be noted that these maps may be inaccurate, incomplete, or insufficiently detailed. However, the information they contain serves as a crude model representing situations on the ground surface, and this should greatly facilitate segmentation. The result of analysing the image could in some instances then be used to update the 'old' map data to match the current situation. Problems with using map data include, again, how to register the image with the map sufficiently accurately, and how to store the map data in the computer.

The remote sensing literature highlights a number of uses for maps in single-pixel classification schemes. Classification improvement with map data has involved incorporating these data either before classification (stratification), during classification (classifier modification), or after modification (postclassifier sorting). All three methods could also be used in knowledge-based segmentation. Stratification is the use of ancillary map data prior to classification to divide a scene into smaller areas or strata based on some criterion, so that each stratum may be processed independently (Hutchinson 1982). Classifier modification involves modification of the a priori probabilities in the standard maximum likelihood classifier using the map data (Strahler 1980). Another approach in classifier modification is the use of ancillary data as another 'logical' channel in classification (Anuta 1976). Postclassification sorting involves the resolution of 'problem' spectral classes representing more than one information class. Pixels of the problem spectral class are assigned to the appropriate information class using ancillary data (Hutchinson 1982). Other uses of maps include the use of topographic land parcels to select training areas, and the use of a digital terrain model to correct pixel radiances for varying slope and aspect.

2.3.3 Multisensor data

This is a further form of ancillary data currently used to improve single-pixel classification accuracy, which again could be used to improve segmentation.

2.4 Computer Vision Modelling

Model-based approaches incorporate context much more formally by reasoning with the structural descriptions of objects (Binford 1982). They also aim for a much richer analysis of the data by directly exploiting the relationships between segmentation and interpretation of a
scene. Models are abstract descriptions of a set of objects for manipulation by a program. Objects are represented in terms of their parts and the inter-relationships between parts.

In the interpretation of aerial images, it would seem very difficult to build a cohesive world model capable of representing knowledge of all the possible types of object on the ground, and their myriad possible spatial relationships (Nagao and Matsuyama 1980). However, the presence of a map or previous classification means that at least a crude model is available, and thus model-based approaches are of interest.

2.4.1 2-D and 3-D models

The earliest users of geometric models in vision dealt exclusively with 2-D viewpoint-specific models. These are expressed in terms of the anticipated appearance of a visible object and relate in straightforward ways to observed features of an image. Perhaps the simplest kind of 2-D model is a grey-level template depicting a typical view of an object. An alternative is a features template which encodes 2-D dispositions of features (normally regions or curves) characterising particular views of an object. A more flexible approach involves representing the objects as a graph structure, with nodes representing uniform image regions corresponding to visible surfaces and arcs representing 2-D relationships between the regions, determined by the actual configuration of an object's visible surfaces.

3-D models are used for domains in which the viewpoint varies widely. These represent information about objects in a way which is independent of viewpoint, to avoid having to use a different 2-D model from each substantially different viewpoint. 3-D models have been explored extensively in several fields, especially computer graphics.

For the purpose of interpreting aerial images there may be advantages in maintaining a distinction between a 3-D terrain model (i.e. stored information about the anticipated layout of terrain structures), and the appearance of these terrain structures in images. This would aid in coping with variations in viewpoint. However, provided variations in the heights of surface objects are not too large, the scene depicted by the aerial image may be treated as planar. In this case, a 2-D planar model would provide the advantages of viewpoint independence whilst avoiding some of the difficulties encountered in using fully-fledged 3-D models.

2.4.2 Interpretation–matching

The standard analysis technique for model-based vision systems is firstly to preprocess images looking for as much structure as possible without invoking object-specific knowledge, and secondly to match the structure produced with stored object models. The balance between the two phases is controversial, though the broad approach is widely accepted. Generally, it may be said that the higher the level of description at which matching is attempted, the more likely the descriptions are to be invariant to imaging changes. However, the gain obtained using such descriptions (called observed features below) may be offset by the deficiencies of the techniques for computing the descriptions. Medioni and Nevatia (1984) have found that matching at the level of object boundaries is a suitable compromise. A symbolic description of each located boundary segment is constructed which is used for matching aerial images through use of a relaxation-like procedure.

Having produced a collection of observed features from an image the next task is to invoke and configure an appropriate model by assigning values to any parameters it has and by mapping observed features to model primitives. The straightforward method for discovering a consistent match involves searching methodically through all possible observed-features/model-primitive combinations for those which satisfy all of the
model constraints. A depth-first search is typically selected for this purpose. A number of methods exist to accelerate this search e.g. by discarding combinations which do not satisfy unary constraints associated with the model primitive in each case.

As an alternative to a rigidly structured exhaustive search, others have used more heuristic approaches. For example, McKeown et al. (1985) describe a method in which partial matches (cliques) involving several different groups of image regions are discovered in an initial phase and subsequently combined into a single consistent match i.e. their regions are parts of a deterministic feature. The idea is that it may be anticipated in advance that certain groups of regions will be found which have a fairly unambiguous interpretation. It therefore seems sensible to search for these solid foundations first and then to try and piece them together in the hope that they will be mutually consistent and further more that more ambiguous parts of the image will fall into place.

The matching methods above are deterministic e.g. constraints are either satisfied or they are not. Continuous relaxation labelling (see section 2.1) is a probabilistic method able to take account of the importance of individual constraints to allow constraints to be broken in the search for an optimal interpretation.

An entirely different method for discovering good matches is known as the Hough transform. This technique is suitable when the space of possible instantiations of a model has been parameterised. Given an n-dimensional parameter space, an n-dimensional accumulator array (initialised to zero) is constructed so that each cell corresponds to a small part of the space of possible model instances (represented by n-tuples of parameters values). Each cell will accumulate evidence (or votes) for its corresponding subset of model instantiations. For each combination of an observed feature and a model primitive, the accumulator cells containing n-tuples of model parameter values which could possibly have given rise to that pairing are computed and incremented by 1. Once all combinations have been considered, those cells in the accumulator array which exceed some threshold are taken to indicate the presence of a plausible model instance.

With regard to this project, it might be possible to combine these approaches in order to match edges in the image with those in the map or previous classification. This should produce a more accurate edge set in the image, and allow the image to be more accurately registered to the map than is possible using normal procedures involving the manual selection of ground control points. If a map edge is coincident with an image edge, and there is a high probability that these edges are correct. If a map edge exists without a corresponding image edge, the image edge may be weak or the map may be wrong. If an image edge exists without a map edge, the image edge may be spurious or the map wrong. A method such as that of Medioni and Nevatia (1984) might be used to match edges, after an initial approximate registration. Map edges without associated image edges might then be used to find weak image edges by defining a limited search area and edge direction. Perhaps a Hough transform in edge space could be used over this limited area to guarantee a high signal-to-noise ratio from straight or nearly-straight edges - this would exploit the fact that man-made features often have straight edges.

2.5 Rule-based Systems

This technique involves the construction of a rule-based 'expert system' for resolving ambiguities and misclassifications in an independent initial segmentation. Constraints are imposed on the segmentation in the form of explicit rules which capture the knowledge about regions and their relationships. Rules are condition-action pairs (i.e. if - then constructs) where the condition part represents a pattern match and the
action part consists of improving the current segmentation.

One of the first systems incorporating rule-based techniques into the analysis of aerial scenes was that of (Nagao and Matsuyama 1980). This system illustrates the concepts often employed in other later systems, and is discussed as a model of its type. The system utilizes knowledge about the intrinsic properties of objects such as size, shape, location, colour, and texture. Whenever possible the spatial characteristics of regions are used to determine objects, rather than their spectral properties, so that the system can give stable results despite changes in photographic conditions. The system also utilizes knowledge about locational constraints and spatial arrangement rules to recognize context-sensitive objects, so that it can recognize cars on roads and regularly-arranged houses. The authors point out that there are so many situations on the ground surface that it is very difficult to construct a model of the scene which represents all the possible mutual relationships amongst the objects. The variety of objects and their spatial arrangements also makes it difficult to fix the analysis process. They therefore adopted a rulebased production system as their software architecture. This allows a control mechanism whereby analysis programs can be activated adaptively according to a particular picture's structure. The knowledge sources in their system are a group of 'object-detection sub-systems' which individually search for specific objects, and communicate with each other via a common data base 'blackboard'. They use a focusing mechanism to save processing time, whereby knowledge is introduced in order of increasing computational effort. The system estimates approximate areas where specific objects are highly probable, then allows only the object-detection sub-systems for these objects to be activated, as these are computationally expensive. They show that the production system is a very valuable tool for organizing diverse aspects of knowledge when only sets of mutually independent partial knowledge of the world are available. Also, the system's modularity makes it easy to modify the knowledge stored in the system.

Amongst several other rule-based systems in this area must be mentioned that of Nazif and Levine (1984) who have produced a low-level segmentation system for an outdoor scene using domain independent knowledge, and the SPAM system of McKeown et al. (1985) which uses map and domain-specific knowledge to interpret airport scenes. The latter system is particularly interesting for the case where a map is available, as it incorporates a lower-level system for map-guided feature extraction from aerial imagery (McKeown and Denlinger 1984). The authors point out that map knowledge can be used to decide where in the image to look and what to look for, and that this may provide sufficient context for inherently weak methods of feature extraction to be effective. Rather than looking for 'perfect' segmentations, their approach extracts segments characterised as 'islands of reliability' for some particular class of object. These local regions can be further analysed by modules that bring to bear more object-specific knowledge to confirm or refute the initial hypothesis. They have developed a region-based segmentation scheme using constraints, which searches for prototype regions using as inputs primitive regions of homogeneous intensity and the edges separating these regions. They create new regions by merging the two regions sharing the weakest edge. Each time a new region is created, it is scored against a specified set of area, intensity, and shape criteria to determine if it is more similar to the prototype region than were the two original regions, and if so it is retained. The idea underlying the scheme is that, if a feature exists with the required characteristics, this feature will eventually be merged into a single region.

Other expert systems have been applied to the per-pixel image classification task, but contain concepts which may be taken over to the
segmentation task. Notable amongst these are the expert system of Goldberg et al. (1983) for analysing forested areas in multitemporal Landsat imagery, and the conceptual system of Erickson and Likens (1984) for producing a preliminary land cover identification from an unsupervised per-pixel classification of Landsat MSS imagery, using ancillary map data.

2.6 Related Issues

Whichever technique is chosen for a particular application, there are a number of issues to resolve before proceeding.

One issue is data representation. The image subsets produced and identified by the analysis can be represented in various ways for further processing. One simple way is to represent the image as a 2-dimensional raster array with each pixel having a value which is unique to the segment containing that pixel. This representation is likely to be too simple for higher-level processing. Shapiro (1979) describes four general representations: linear lists, hierarchic structures, graph structures, and recursive structures. A linear list is a finite, linearly ordered set of elements, and the best example is given by a chain encoding of planar curves. Hierarchic structures are tree representations of the data. An example which is gaining popularity is the quadtree, a tree in which the root node is the whole picture, each father node has four sons, and each terminal node is a square block of pixels of constant intensity. Graphical representations of interrelated segments have both the pros and cons of tree structures, but are more general in that the relationships between segments need not be hierarchical. Recursive structures include the symbolic data structures of artificial intelligence e.g. frames and semantic nets. These structures allow the representation of objects, their attributes, and the multiple relationships between objects.

A second issue is that of uncertainty. The ambiguity in image interpretations is one of the major problems using complex image data and it may be dealt with by introducing reliability (or uncertainty) values for the data and the knowledge. Matsuyama (1984) has discussed the various ways in which reliability may help in scene analysis. These include associating measures of reliability to a particular segmentation in order to decide on an optimum partition, and, in rule-based systems, associating 'probabilities of usefulness' to rules in order to help resolve scheduling problems.

A third issue is evaluation. Measuring the performance of the analysis is an important factor in directing the feedback and modification towards an optimum result. One way of evaluating a segmentation is to measure the 'distance' from a desired reference segmentation and then control the analysis so that the distance measure is minimised (Nazif and Levine 1984). Alternatively measures of the uniformity of segments may be used as optimisation criteria.

A final issue of great importance is computational complexity. The methods discussed are likely to be demanding computationally compared to the demands of per-pixel classifiers. A rule-based system, for example, can turn out to be extremely cumbersome and time-consuming. It is likely that special architectures will be needed to produce knowledge-based segmentations in a reasonable timescale. There is a great deal of activity in the development of special architectures for image processing at present (Duff 1983). It is not intended to develop or use such an architecture within the present project.

3. Discussion

It is proposed to segment high resolution imagery in the spatial resolution range 10-30 m, using the type of image used in environmental land use studies. Initially 10 m resolution multitemporal aerial MSS data
sets are being gathered, which include agricultural areas and areas of natural fenland. SPOT data of the same areas may also be used. The ancillary data proposed are land use maps based on 1:10000 O.S. maps, and previous classifications. The set of object types it is hoped to distinguish in these scenes includes fields, water bodies, woodland, urban areas, wetlands, and linear features including rivers, roads, hedgerows, and ditches.

A prime requirement of the segmentation procedure is that it should proceed automatically in an unsupervised mode with no collection of training sets necessary. Another desirable feature is that, as segmentation is a task-dependent process, it should be possible to allow the user to introduce further task-dependent rules to allow the basic segmentation to be refined, so that the segmenter could be enhanced without its structure requiring to be changed. It is also desirable that, in the case where a segmentation is being gradually refined using a sequence of images, the segmentation procedure be applicable to a single image, as in the 'start-up' case.

Candidate systems fulfilling these requirements are currently being devised.

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