Considerations in the Design of a System for the Rapid Acquisition of Geographic Information

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ABSTRACT: In response to a need for a capability for more timely creation and revision of digital topographic map data, MacDonald Dettwiler, in cooperation with the Canada Centre for Mapping, has undertaken the development of a Topographic Data Base Revision System (TDBRS). The objective of the system is to create and update digital topographic map data using remotely sensed imagery. Utilizing SPOT satellite imagery and aerial frame photographs as input data sources, the system provides the capabilities for geocorrection, radiometric correction, orthoimage generation, image enhancement, and epipolar pair production of images from those sources. The system provides a high-resolution stereoscopic display and allows graphical superimposition of vector data in stereo. Automatic transformations for DEM extraction, linear feature extraction, and change detection are provided. The system is implemented using the C++ object-oriented programming language and includes an object-oriented database management system. Considerations in the design of the TDBRS are described, particularly in relation to improving the overall production time for map creation and revision.

INTRODUCTION

PRODUCERS OF GEOGRAPHIC INFORMATION are feeling the pressures of increased demands for accurate and up to date geographic information for a growing variety of applications. Whereas paper topographic maps have been the media for the general provision of geographic information for many years, the need for more diverse and specialized forms of this information is growing, and there is increasing demand for this information in digital forms. Many agencies mandated with the provision of geographic information are going through the process of restructuring their operations to accommodate the needs for digital versions of their geographic information products. As well, as this information is playing a larger role in planning and decision making, there is an increased pressure to provide more complete geographic information coverage at a variety of scales, and to ensure the information provided is up to date.

In response to these needs, the Canada Centre for Mapping (CCM) has embarked upon a program to produce a National Digital Topographic Data Base. In conjunction with this effort, CCM and MacDonald Dettwiler are proceeding with a cooperative development effort to produce the Topographic Data Base Revision System (TDBRS). This program, which brings together the capabilities of CCM and MacDonald Dettwiler as well as expertise from the Canada Centre for Remote Sensing, the Canadian Department of National Defence, and the National Research Council of Canada, is focused upon developing a system which can provide the capability to create and revise digital topographic map data from remotely sensed imagery. The goal is to improve the end-to-end production time for newly created or revised maps.

Existing analog approaches to the stereo-compilation process for geographic information capture still provide a very powerful means for the visualization of geography, and the devices provide very precise and accurate mechanisms for geometric mensuration. However, the capture of semantic information about the geographic entities relies on the human operator's interpretative skills. While the human is very good at doing the deductive and heuristic reasoning needed to determine that, for example, the linear feature evident in the image is a railway line rather than a road, the overall collection process is constrained by both the reliability and consistency of this approach as well as by the labor intensive nature of it. It is clearly hard to achieve significant throughput improvements when the process is so heavily dependent on human interpretation.

The digital domain can offer benefits to the process of deriving geographic information from image data. Recent advances in display resolution and digital stereoscopic display are providing analogous visualization and mensuration capabilities to the stereoplotter. In addition, the digital domain is better suited to integrate and exploit the benefits of image data recorded digitally such as images acquired from satellites or airborne digital scanner devices. These types of data sources usually provide improved spectral resolution over photographic images, thus providing more data to aid in the semantic information extraction. Considerable research has been done in utilizing spectral information through classification algorithms to extract higher level semantic information in an automated fashion. The digital domain begins to offer some automated alternatives to the process of capturing and modeling the higher-valued semantic entities required in the geographic information acquisition process.

The goal of the TDBRS system is to derive a model of geographic information from a set of measurements of geographic phenomena—most namely satellite images and aerial photographs. The objective is to reduce the end-to-end production time for collecting this information.

This paper will outline the operational requirements for doing topographic map creation and revision from remotely sensed imagery in the context of the needs of the Canada Centre for Mapping. An overview of the design of the TDBRS will be provided as it applies to meeting the operational requirements outlined. Key design features of the TDBRS will be described and future enhancements to the system will be outlined.

OPERATIONAL REQUIREMENTS

As noted previously, the fundamental requirement on the TDBRS is to reduce the overall time for the production and revision of topographic maps. To further understand the likely operational usage of the TDBRS, an operational task analysis was performed.

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Table 1 describes the tasks required for the first operational scenario: update of a feature data set corresponding to an existing 1:50,000-scale mapsheet using SPOT satellite images and sets of stereo airphotos. Operational Scenario #1 assumes that a DEM exists for the map area and can be ingested via magnetic tape. Figure 1 shows the dependency graph for the tasks involved in Operational Scenario #1. The highlighted line through the graph indicates the critical path for the complete activity.

Operational Scenario #2 corresponds to the update of a 1:50,000-scale feature data set using SPOT images and aerial photographs, where the DEM has to be generated from the image data provided. Table 2 and Figure 2 correspond to the list of operational tasks and to the dependency graph for the scenario, respectively.

Table 3 illustrates the typical data volumes expected for the source data. It is assumed that the SPOT data will be provided in Level 1A format. Airphotos are assumed to be at the 1:50,000-scale and typically monochrome, and approximately 30 to 40 are required for complete coverage of the mapsheet extent. It is assumed that each airphoto would need to be scanned at a

TABLE 1. OPERATIONAL SCENARIO #1. UPDATE OF AN EXISTING FEATURE DATA SET USING SPOT AND AIRPHOTO IMAGES AND AN EXISTING DEM.

Precedence	Task	Interaction	Duration
(1)	Import SPOT image(s)	L	Medium
(1)	Scan airphotos	L	Long
(1)	Import DEM	L	Short
(1)	Import existing feature data set into topographic model	L	Medium
(2)	Mark GCPs and create geometric models • SPOT image • airphotos	H	Medium/ Long
(3)	Create orthoimages • SPOT • airphoto	L	Long
(4)	Create false stereo pairs • SPOT • airphoto	L	Long
(5)	Topographic model update		
	• manual update using geographic editor – 2D with topographic model feature data overlaid on orthoimages in monoscopic window – 3D with topographic model feature data overlaid on false stereo image pair in stereoscopic window	H	Long
	• Planimetric feature extraction	L/H	Medium
	• Change detection	M	Medium
(6)	Topographic model export	L	Medium /Long

Duration: Short <10 min, Medium 10 to 60 min, Long >60 min
Interaction: indicates low, medium, or high amount of operator interaction required

TABLE 2. OPERATIONAL SCENARIO #2. UPDATE OF AN EXISTING FEATURE DATA SET USING SPOT AND AIRPHOTO IMAGES, INCLUDING GENERATION OF A DEM.

Precedence	Task	Interaction	Duration
(1)	Import SPOT image(s)	L	Medium
(1)	Scan airphotos	L	Long
(1)	Import existing feature data into a topographic model	L	Medium
(2)	Mark GCPs and create geometric models • SPOT image • airphotos	H	Medium/ Long
(3)	Create epipolar image pairs • SPOT stereopair • airphoto stereopairs	L	Long
(4)	Create DEM	L/H	Long
(5)	Create orthoimages • SPOT • airphoto	L	Long
(6)	Topographic model update		
	• manual update using geographic editor – 2D with topographic model feature data overlaid on orthoimages in monoscopic window – 3D with topographic model feature data overlaid on epipolar pairs in stereoscopic window	H	Long
	• Planimetric feature extraction	L/H	Medium
	• Change detection	M	Medium
(7)	Topographic model export	L	Medium /Long

Duration: Short <10 min, Medium 10 to 60 min, Long >60 min
Interaction: indicates low, medium, or high amount of operator interaction required

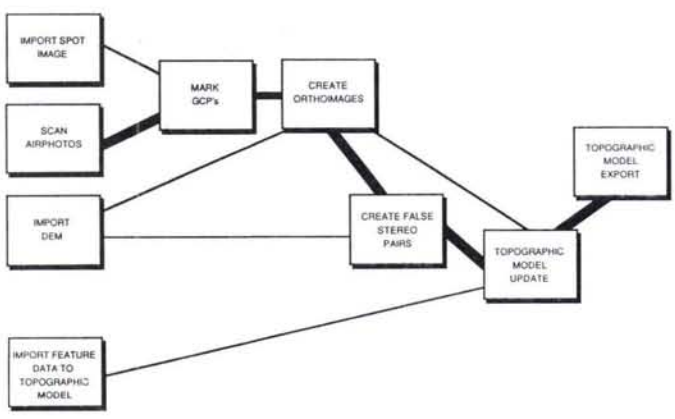

FIG. 1. Operational Scenario #1 critical path.

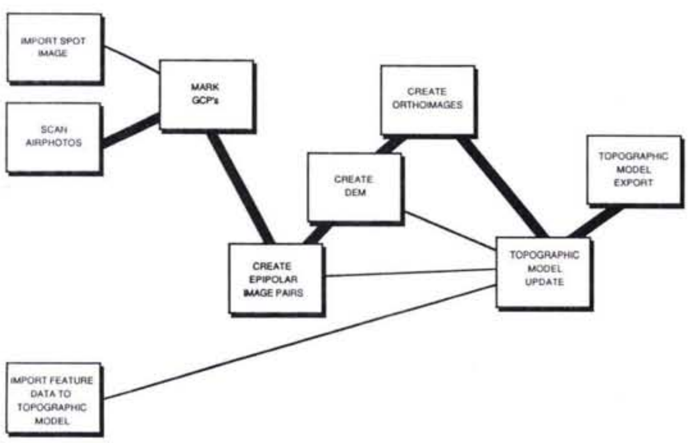

FIG. 2. Operational Scenario #2 critical path.

25-micrometre resolution to provide sufficient pointing accuracy.

The operational scenarios illustrate some of the fundamental difficulties in utilizing digital imagery—data volumes can quickly become overwhelming. The total amount of disk storage required over the complete map update operation can easily total a number of gigabytes, primarily due to the volume of aerial photograph data. As well, the scanning and resampling operations required for production of orthoimages, epipolar images, and stereomates can involve significant computation.

The operational task analysis leads to a number of requirements on the TDBRS:

- allow parallelization of the scanning and resampling tasks with the topographic model update task, so that update can be done as images become available;
- provide on-line disk storage of at least 5 Gbytes;
- optimize and accelerate the resampling operations;
- provide tools that allow preview of the available data and planning of the image production pipeline; and
- provide the capability to scan selected portions of airphoto images, at a variety of resolutions.

DESIGN CONSIDERATIONS

The process of acquiring geographic information from remotely sensed image data involves a significant transformation of the source data entities to the data entities that model the information required by the end user. The fundamental input data entity is a pixel: typically an *n*-tuple representing measurements of the spectral exitance of an area on the Earth's surface. Compared with the type of data entity required in the information domain (cultural features, hydrography, etc.), the difference in semantic content from the input domain to output domain is enormous. The derivation of the geographic information often involves the application of deductive and heuristic reasoning to large collections of these input pixels. The human is very good at doing this type of reasoning, while techniques for doing these types of operations in the computer domain are still evolving.

There are fundamentally two aspects to the type of information that must be acquired in the transition from input data to output information: knowledge of "where" the data entity is, and the knowledge of "what" the entity represents. The "where" aspect involves establishing the geometric transformation from the image coordinate system to a geographic coordinate system as well as providing precise and accurate means of measurement in the image domain. In the traditional analog approaches, much effort has been expended in this area and the current methods are generally very good. In the digital domain there has been much effort in attempting to achieve the same degree of geometric fidelity as in the analog approach, and current systems have improved dramatically in this regard.

The second aspect of information capture – "what" the entity represents, or semantic information capture – is the harder problem. Once again, the traditional approaches almost exclusively utilize the human to deduce this information. While the human is good at this, there can be problems with consistency and reliability in applying this knowledge. Furthermore, it is hard to envisage any significant improvements in the overall throughput in this aspect of the information capture process while it remains a manual effort. In this area, digital methods can provide some aid. Utilization of spectral information can be enhanced, and image analysis and computer vision techniques can provide tools to the operator in extracting higher-level semantic information from images.

These observations have lead to the following design considerations in the development of the TDBRS:

- geometric transformations must be accurate, precise, and reliable. There must be precise methods for pointing and measurement in the image domain;
- human skills for interpretation must be augmented with tools that can improve productivity, consistency, and reliability; and
- automated tools for information extraction should be provided where possible to ensure consistent, reliable results.

TABLE 3. TOTAL SOURCE DATA VOLUME

Data Source	No. Items	Size Per Item (MB)	Total Size
SPOT Multispectral	1	27	27
SPOT Panchromatic (stereopair)	2	36	72
Aerial Photos (25 micrometre scan resolution)	35	85	2975
Feature Data Set	1	50	50
DTED	1	7	7
			3131 MB

DESIGN OVERVIEW

Figure 3 gives the context diagram for the TDBRS. The TDBRS accepts SPOT satellite images and aerial photographs as input images. Digital Terrain Elevation Data (DTED) format elevation information can also be input. Feature data can be both imported and exported using the Canada Council on Geomatics Interface (CCOGIF) format. This format can provide an exchange mechanism for the feature data with other digital geographic information users. Scanned airphoto image data can be imported and exported via magnetic tape. The TDBRS maintains an integrated spatial database of both imagery and feature data.

Figure 4 depicts the ultimate hardware configuration for the TDBRS. The system is based on the Sun-4/UNIX platform and utilizes accelerator boards to improve throughput. The system has an integrated Vexcel VX3000 photo-scanner subsystem for scanning aerial photographs. An integrated map scanning subsystem can be provided for converting existing paper maps. A mass storage subsystem provides additional magnetic disk storage as well as optical disks to add a further 21 Gigabytes of online storage.

TDBRS provides support for interactive feature capture through a high-resolution stereoscopic display and geographic editor as well as through a control point marking facility and geometric

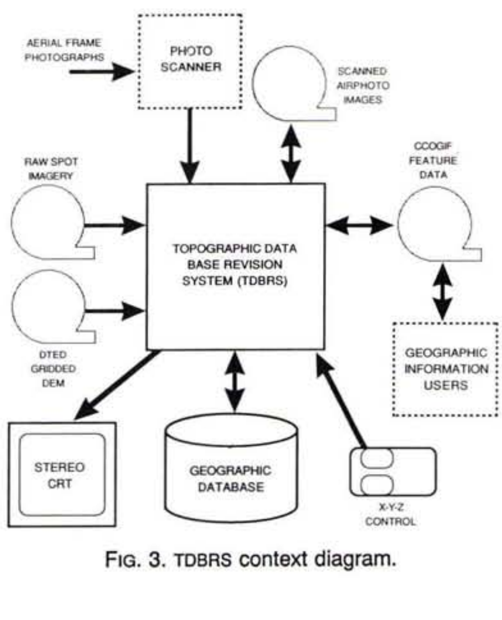

FIG. 3. TDBRS context diagram.

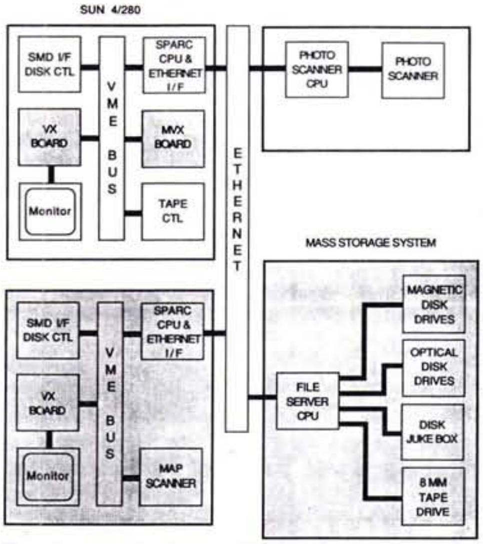

FIG. 4. TDBRS hardware diagram. Shaded areas indicate optional hardware items.

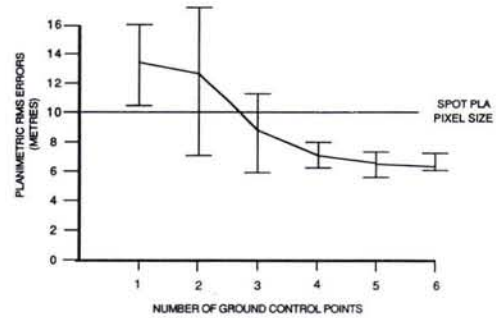

FIG. 5. RMS planimetric errors as a function of the number of GCPs used.

modeler. Automated transforms include geometric and radiometric correction, orthoimage production, epipolar pair generation, image enhancement and analysis transforms, automatic DEM extraction, automatic linear feature extraction, and change detection transforms.

The following sections provide details on some of the key system features.

GROUND CONTROL AND GEOMETRIC CORRECTION

The TDBRS is required to have extremely accurate geometric correction transformations to meet the requirements for 1:50,000-scale mapping. In addition, the user requires a precise pointing and marking capability for measurements in the image space. Because marking precision in the image space is a function of image resolution, there exists a design tradeoff between scanning at a higher resolution to improve marking precision, and reducing data volume for storage and throughput considerations. The requirement to maximize throughput implies that control point marking time be minimized, and that resampling time be minimized. The implications of all these factors is that accurate geometric modeling algorithms must be used. Warping functions, while simple and easy to use, would not provide the degree of accuracy required and would create a larger manual burden for marking additional control.

The utilization of satellite imagery provides a significant benefit in terms of having large geographic coverage (per scene) while requiring significantly less ground control. If the specific orbit and attitude data are retained from the imaging operation, the imaging geometry can be reconstructed and thus provide a strong condition on the image-to-Earth coordinate transformations. This minimizes the need for ground control. In general, sophisticated satellite image correction techniques need only four to six GCPs per scene for correction to sub-pixel accuracy (Sharpe *et al.*, 1988a), and GCP placement is not particularly critical (Welch *et al.*, 1985). Using correction methods based on spacecraft modeling, SPOT scenes have been corrected to sub-pixel accuracy using as few as three GCPs per scene (see Figure 5).

ORTHOIMAGE PRODUCTION

For the purpose of integrating image data that has been acquired such that its coordinate space is not consistent with the coordinate system of other existing data sources, it is necessary to resample the images to a projection consistent with a map projection. This often involves removing terrain induced distortions, particularly with satellites with an off-nadir viewing capacity such as SPOT. Clearly this requires the precise and accurate geometric models described previously as well as an existing DEM to remove the terrain induced distortions.

The process of resampling imagery to produce orthoimages is computationally intensive, and given the data volumes shown in Table 3, it is necessary to optimize the resampling approach for these operational requirements. The methods of Friedmann (1981) provide the basis for the orthoimage production facility of the TDBRS.

DIGITAL STEREO DISPLAY

One of the major sources of contextual information is the three-dimensional spatial relationships between feature components. The elevation dimension is very important for the identification and capture of hydrographic information as well as for providing the context for identifying a wide range of features. Conventional analog techniques have very powerful stereoscopic viewing capabilities that are heavily relied upon for image interpretation. A digital stereoscopic display capability is a requirement on the TDBRS to aid the operator in interactive feature capture.

The TDBRS provides a stereoscopic display capability using untethered active polarizing glasses worn by the operator (see Figure 6). A small emitter box resides on top of the display monitor which transmits synchronization signals to the glasses from the stereo controller. The user may view either monochrome or full color images in stereo, and with graphics superimposed. TDBRS has been designed using the X11 windowing system and supports multiple concurrent windows both in monoscopic and stereoscopic modes.

To date, digital stereoscopic displays using either active or passive polarizing techniques have suffered from an inability to utilize the full vertical resolution of the display monitor in stereoscopic mode. This leads to a "fuzzy" image which hinders the interpretation capabilities of the human expert as well as reduces the operator's pointing accuracy for feature capture. MacDonald Dettwiler has developed a means for a flicker-free full resolution stereoscopic display for the TDBRS.

DATA INTEGRATION

One of the distinct advantages of the digital approach is the ability to integrate data from a variety of different sources, and to maintain relationships between these data entities. For viewing purposes, this includes the ability to superimpose feature data in vector graphics form with image data. As well, there can be image data for the same area from a variety of sources and from different acquisition times. Providing the user with these different "views" can provide more contextual informa-

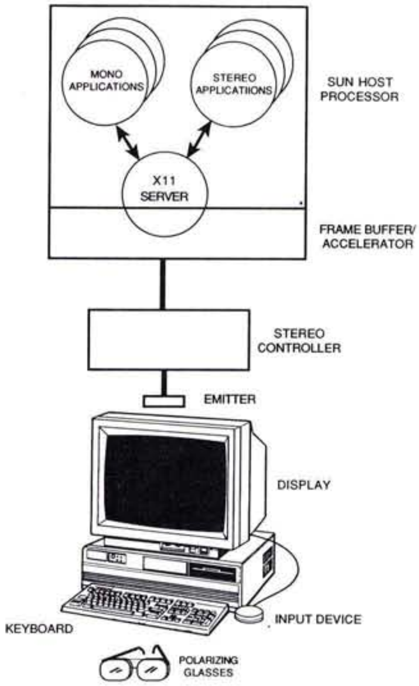

FIG. 6. TDBRS stereoscopic viewing configuration.

tion for his interpretation skills. In addition, the ability to integrate multispectral information adds another dimension of information available to the user. This information can be used both in an interactive manner, providing "color" cues that can help discern features. As well, multi-spectral classification techniques can be used for ground cover interpretation.

AUTOMATIC DEM EXTRACTION

DEM extraction is one of the most time-consuming aspects of the map production process. Automating this process can speed the overall map production process by a significant factor.

A number of authors have explored techniques for automatic DEM extraction (see Cooper *et al.*, 1987; Kauffman *et al.*, 1987; Wilson *et al.*, 1990). The TDBRS provides the capability for automatic DEM extraction both from aerial photographs and from SPOT. Tests of the accuracy of the DEM extraction capability from SPOT image pairs indicate RMS accuracies in derived elevation values at better than 6 m, which will allow contour mapping with a 20-m contour interval.

The TDBRS approach to DEM extraction involves first the generation of stereopairs of images in an epipolar projection. The result of this resampling is that all terrain induced parallax occurs only in the along-line direction. The next step involves applying matching techniques to derive parallax measurements. Matching can be done using an automated approach, or can be done manually utilizing the stereo editor capability. Once a set of parallax measurements has been produced, this set can be put through a transformation that converts the parallax measurements to elevation values.

The TDBRS supports elevation data represented as either regular grids, as Delauney Triangulated Irregular Networks (TINs), or as contours. The system supports transformations among those representations. As well, the TDBRS provides editing tools within the geographic editor to edit the elevation information within the geographic model. The system supports the notion of "surface-defining" features: features that define the surface of the Earth. Examples of surface-defining features might be rivers or ridge lines. Along these features one would expect the elevation model to remain true to the definition of the feature.

AUTOMATIC LINEAR FEATURE EXTRACTION

Extraction of linear features is often one of the more labor intensive operations for an operator. This also is an operation that could be automated, due to the fact that the heuristics used in determining linear features are relatively simple and well accepted, and because multi-spectral information can be used in supporting this approach. The TDBRS incorporates an automated approach to linear feature extraction, based on earlier prototypes (Yee, 1987; Zelek *et al.*, 1988).

An example of this approach might be in the extraction of road networks. Edges can be extracted from the imagery using segmentation operators, and potential road segments are inferred from parallel lines which are separated by an estimate of road width. Collinearity and connectivity rules are then applied to join road segments. Road sections can be extracted by optimally joining the road segments obtained by this approach using search techniques. This method can accurately extract the centerlines of roads, as required in topographic mapping. Bridges can be recognized by applying rules which relate road segments which cross rivers.

OBJECT-ORIENTED DESIGN

The TDBRS has been implemented using the C++ object-oriented programming language. Geographic information acquisition systems are characterized by a need to represent data entities that are quite disparate both in size and in meaning, and for which there exists a very rich interrelationship. This type of application is particularly well-suited to the benefits of the object-oriented paradigm. The TDBRS also utilizes an Object Data Base Management System (ODBMS).

A very important element of the TDBRS is its integrated geographic modeling capability. If the complex interrelationships among the geographic elements can be represented easily and efficiently, then this information can be used to aid in the interpretive aspects of the operator's task. This can potentially then provide assistance in the semantic information gathering process of geographic information capture.

For any DBMS used in the geographic information modeling application, however, a key issue is quite simply performance. Relational DBMSs are typically not well-suited to this type of application, and this manifests itself as performance degradation to the user. Recent benchmark results comparing RDBMSs and ODBMSs indicate that ODBMSs can provide significant performance improvements (Cattell, 1990) in these types of engineering applications.

Finally, the object-oriented approach provides benefits to the software engineering aspects of system development and maintenance. Object-oriented systems have been seen to require fewer lines of code to implement a system, and the code is more reusable. To the system user, this translates into a more reliable, maintainable, and more easily extensible system.

See Brownsword *et al.* (1991) for a more detailed description of the TDBRS internal system design.

FUTURE DEVELOPMENT

The TDBRS is expected to provide the framework for extended capabilities for rapid geographic image acquisition in future years. This section is intended to outline areas where the TDBRS will likely be expanded. The improvements are concerned with "pass processing," (a technique for processing a series of images as if they were a a single scene), interferometric radar, and the use of expert system techniques to aid in semantic information capture.

In pass processing, one can use the fact that the geometric model of a spacecraft's orbit and attitude stays relatively invariant over a segment of an individual orbit (assuming no thrusting or attitude correction takes place over that orbit). This means that the same model can be used for scenes that are relatively close on the same orbit. This results in a reduction in the number of GCPs required and gives more flexibility in their location. The technique can process a series of about ten scenes as if they were a single scene, so that the normal GCP requirement of about three to six GCPs per scene is averaged out to less than one GCP per scene. Also, the GCPs can be located anywhere in the pass. For example, in Australia GCPs can be located along the populated northern and southern coasts, and used to correct a pass of imagery including scenes of the center, for which control would be hard to establish.

Research results have shown that this technique could be applied to 15 Landsat TM scenes in a single pass, with good geometric correction results using only an average of one-half GCP per scene. Good accuracy is still possible with only four GCPs for the entire 15 scenes (see Friedmann *et al.*, 1983; Sharpe *et al.*, 1988b).

Interferometric radar is an evolving technique that uses Synthetic Aperture Radar (SAR) images for extracting geographic information. Radar has the advantage of not being constrained by cloud cover over terrain, thus allowing "all weather" mapping. Elevation models can be obtained by interpreting phase patterns from a second receiving channel corresponding to a second receiving antenna on the aircraft. Initial research indicates that accuracies conforming to 1:50,000-scale standards are possible (see Cumming *et al.*, 1990).

Expert system techniques for applying deductive reasoning and heuristic rules to a geographic knowledge base hold considerable hope for capturing the interpretive skills that human experts use for semantic information gathering in this application. Image analysis techniques for segmentation, texture analysis, shape analysis, and contextual recognition can be combined with heuristics which deduce higher level semantic information relating to the entities derived to build up models of geography. These types of techniques hold considerable promise for significant gains in geographic information capture capabilities.

CONCLUSIONS

Geographic information acquisition from image data can be characterized as having two component aspects: geometric modeling and semantic information capture. Precise and accurate geometric modeling is essential so that knowledge of "where" geographic features are can meet rigid mapping standards. Semantic information capture still remains largely an interpretive skill practiced by human experts, and remains a labor intensive task. For a computer system to aid in reducing the overall time for map creation or revision, both of these elements must be addressed.

Fundamentally, geographic information capture is difficult in the digital domain because the source data is composed of an extremely large number of data entities, each with very little semantic value. The geometric modeling transformations for these entities must be accurate. Marking and measuring in the image space must be precise.

The best means for adding semantic value to the derived entities remains the human operator. Thus, the digital system must provide powerful interactive aids to make that process as productive and reliable as possible. The TDBRS provides a powerful geographic editor that allows high-resolution stereoscopic display with feature data superimposition. Editing operations are extensive and designed with a convenient multi-window user interface.

Where possible, the TDBRS provides automated tools for information capture where consistent reliable results can be obtained. If the operator has to spend a great deal of time fixing the results of an automatic transform, then there is little advantage in using it. The TDBRS provides automated operations for DEM extraction, linear feature extraction, and change detection as well as for geometric and radiometric image corrections.

It is anticipated that the TDBRS will provide savings in the overall time to create or update a topographic map. The system will initially be used in a prototype environment for testing and training purposes, and over the course of this phase, it is expected to be enhanced and "tuned" towards operational needs. In addition, development will continue to occur in the areas described under future developments.

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