Digital Mapping and Image Understanding

David M. McKeown, Jr.
Department of Computer Science,
Carnegie-Mellon University,
Pittsburgh, Pennsylvania 15213, U.S.A.

George E. Lukes
Center for Artificial Intelligence,
Research Institute,
U.S. Army Engineer Topographic Laboratories,
Fort Belvoir, Virginia 22060, U.S.A.

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Abstract

Emerging requirements associated with digital mapping pose a broad set of challenging problems in image understanding research. Currently several leading research centers are pursuing the development of new techniques for automated feature extraction; for example, road tracking, urban scene generation, and edge-based stereo compilation. Concepts for map-guided scene analysis are being defined which will lead to further work in automated techniques for spatial database validation, revision and intensification.

This paper seeks to describe on-going activity in this field and suggest areas for future research. Research problems range from the organization of large-scale digital image/map databases for tasks such as screening and assessment, to structuring spatial knowledge for image analysis tasks, and the development of specialized "expert" analysis components and their integration into automated systems. Significantly, prototype image analysis workstations have been configured for both film-based and digital image exploitation which interface conventional image analysts and extracted spatial data in computer-assisted systems. However, the state-of-the-art research capabilities are fragile, and successful concept demonstrations require thoughtful analysis from both the mapping and image understanding communities.

1. Introduction

The goal of this paper is to give a broad description of current research and development in the areas of digital mapping and image understanding. This paper should be viewed as as position paper, reflecting the authors opinions and observations on directions for current research and prospects for the future.

There are many research and development opportunities at the interface between digital mapping and image understanding. This paper identifies several tasks that we believe require cooperative efforts, both in the precise identification of the problem and in designing and evaluating particular concept demonstrations. In Sections 2 and 3 we present a brief overview of Digital Mapping and Image Understanding. Section 4 describes three prototype research systems developed by the authors. Section 5 suggests several mapping and feature extraction tasks that could benefit from cooperative research efforts. In summary, Section 6 outlines some prospects for the future and the possible impact of image understanding on digital mapping.

2. Digital Mapping

Conventional mapping, based on processing aerial photography with analog and analytical instrumentation, requires film input. Much of the contemporary mapping research, however, addresses issues of processing digital imagery with digital systems to produce digital map products. The objective of this section is to provide a frame of reference for current initiatives in digital mapping research.

2.1. Conventional Data Extraction Processes

Reconstruction of a three-dimensional stereomodel, recorded by overlapping aerial photography, represents a fundamental photogrammetric objective which is addressed by a variety of well-known instrumentation. Classically, elevation data have been compiled manually from metric stereomodels using analog stereoplotters and recorded as contour lines in orthographic manuscripts. Such equipment and procedures have dominated photogrammetric practice and continue to serve as the workhorses of modern commercial practice.

The advent of the digital computer led to the analytical characterization of photogrammetric imaging geometry and to the subsequent development of the real-time analytical stereoplotter. Rigorous solutions have been implemented for metric camera systems, panoramic camera systems [12] and non-optical systems such as synthetic aperture radar [27]. Analytical plotters were designed to generate gridded elevation data directly with interactive profiling capabilities. Automated stereoplotters based on real-time area correlation have been developed building on this analytical photogrammetric foundation.

The compilation of feature data generally starts with the identification and delineation of map features in the stereomodel by human photo interpreters skilled in a relevant discipline such as cartography, forestry, or geology. Then, delineated features are transferred from the annotated photos or photo overlays to an orthographic manuscript using rigorous photogrammetric procedures or less precise feature transfer methods. Finally, analog maps and map overlays are produced from these orthographic manuscripts using conventional cartographic methods.

The major thrust of digital cartography has been to produce machine readable representations of spatial data from existing orthographic manuscripts and map sheets. The initial approach, based on interactive use of a digitizing tablet to manually trace and digitally encode individual features, was relatively successful and dominates current practice despite labor intensive requirements. Recently, capital intensive raster scanning systems have emerged as effective products in high volume applications while other developments pursue automated and semi-automated line-following techniques.

2.2. Transition from Film to Digital Media

Much of the mapping research community has transitioned from film-based to digital media. There are several reasons for this trend. First, there is an increase in digital electro-optical and non-optical sensors such as multi-spectral scanners and synthetic aperture radars. Second, there is the expectation of automated image analysis and feature extraction using digital image processing technology. Finally, requirements are growing for digital products in the military and civilian communities, such as digital elevation models (DEM), orthophoto maps, and geographic information systems. Major problems include the maintenance of traditional measurement accuracy, storage requirements for digital images at the resolution necessary for digital mapping, as well as the transfer of photogrammetric tools to digital image processing environments.

2.3. Expectations and Capabilities

The growing interest in digital map data involves far more than demands for increased production quantity and higher metric accuracy. Critical applications such as advanced computer image generation [7, 8, 28]for flight and sensor simulation can effectively exploit far more detailed feature data and higher resolution elevation data than currently produced. Expanding capabilities in digital terrain and environmental analysis suggest similar needs. To date, expectations for significant increases in productivity based on digital data extraction remain largely unfulfilled. A major thrust has been to develop digital system components that perform the function of traditional analog instruments: digital rectifiers; digital correlators of elevation compilation; digital light tables for photo interpretation. These systems and subsystems are largely experimental, and many significant obstacles must be overcome to realize adequate throughput for operational use.

We believe that the numerous experimental and commercial initiatives to develop computer-assisted systems, including less expensive analytical plotters, tailored to the production of digital map data are highly significant. In the long term, highly integrated digital map production operations based on interactive systems and subsystems should offer numerous opportunities for the introduction of advanced automated modules leading to evolutionary increases in throughput and productivity.

3. Image Understanding

There are several partially overlapping disciplines that have historically had application to feature extraction from aerial imagery. These disciplines can be grouped loosely into two groups: pattern recognition and image processing, and computer vision and image understanding. One major difference is that pattern recognition has had its roots in the interpretation of 2 dimensional shapes in a 2d image, whereas image understanding explicitly performs interpretation of 2d images as projection of 3d world [1, 4]. The research goal in image understanding is to ultimately build general vision systems that approach human level performance in a wide variety of application domains. On the way to that goal, various application areas such as natural scene analysis, robotics and manufacturing assembly, vehicle navigation, and cartography have been used to evaluate the strengths and limitations of various research approaches. Most research in pattern recognition and image processing is performed on monocular views of the world, whereas a relatively large body of work has been done in the area of computational stereo within image understanding. Computational stereo, the recovery of the three-dimensional characteristics of a scene from multiple images taken from different points of view [2], has been used in most of the application areas previously mentioned.

3.1. Model Based Systems

A second thrust in image understanding research is the application of domain knowledge to guide scene interpretation. This knowledge can be represented in terms of 3 dimensional models. Recognition and interpretation requires the extraction and matching of features in the image to the model. Image features include edges, lines, line junctions, surfaces, and regions with particular shape, spectral, and texture properties. In order to perform feature extraction and model building, we must have adequate spatial resolution in the image, probably higher than is needed by a human to identify the same feature. In addition to the feature extraction and model building, we must have adequate constraints on the scene in order to interpret it. Some common constraints that have been used in several systems [31, 22, 5, 11, 20, 21]are camera geometry, knowledge about the scene such as urban environment vs. countryside or forested area, and spectral properties of generic features such as buildings, roads, water, etc. Once a general model is constructed, more specific knowledge such as agricultural and farming styles and building construction methods and patterns can be used. Broad applications have included linear feature extraction [23, 14], road detection and tracking [26, 10, 13], symbolic registration and change detection [25], recursive region segmentation [24, 30]. A good survey and evaluation of model based vision systems can be found in Binford [3].

3.2. Spatial Knowledge

If a world model is represented explicitly in 3 dimensional geodetic coordinates, specific *spatial knowledge* can be applied to the extraction of cartographic features. For example, it is possible to represent what a geographic area looked like the last time we updated the map and to predict where to attempt to extract new information. The application of spatial knowledge, when applied using *map-based* models projected using a known camera model, is a relatively new result in image understanding. Previous work in pattern recognition and image processing has relied on the generation of *image-based* descriptions of particular scene features. These descriptions were generally not robust across images showing differences in scale, camera orientation, and sensor response. The integration of digital spatial databases with photogrammetry and image processing tools and techniques is a promising area for research and development in digital mapping.

4. Systems At the Interface

In this section we briefly describe three systems whose research goals and capabilities overlap between digital mapping and image understanding. A common link among these systems is the interaction between image analysis and spatial databases. The explosive increase in the availability of digital imagery and image related information makes finding some small piece of relevant information increasingly difficult. On-line storage of tens of thousands of images does not help unless the user can quickly locate a feature or landmark of interest in many different images simultaneously. The same underlying problem exists from an automated image interpretation standpoint. Symbolic indexing and addressing of images for *a priori* knowledge in automated analysis requires many of the same techniques as in interactive analysis, except that the human image analyst provides the guidance.

Facilities such as on-line image/map databases, signal and symbolic indexing of natural and man-made features, and spatial reasoning can be viewed in the short term as a semi-automated tool for increasing productivity of human photo interpreters and analysts, and in the long term, as the knowledge base for automated rule-based systems capable of detailed analysis including change detection and the update of map descriptions. We feel that research in building spatial databases has immediate payoff for both cartographic production environments and as a component of an automated feature extraction system. The CAPIR system applies rigorous photogrammetric principles for the generation of spatial data using film-based media with computer generated superposition. MAPS is a digital system, with a less rigorous photogrammetric front-end, providing detailed descriptive and display capabilities for extracted spatial data. It is also an interface to image analysis tools that use the spatial data to provide knowledge and constraints for feature extraction.

4.1. CAPIR

A program in Computer Assisted Photo Interpretation Research (CAPIR), underway at the U.S. Army Engineer Topographic Laboratories [15], reflects operational mapping considerations. A testbed CAPIR system has been developed using an APPS-IV analytical plotter as a computer-interfaced stereoscope to support interactive feature extraction. Computer graphic displays have been introduced into the optical train of the instrument to provide direct display of encoded spatial data in the stereomodel. This capability for stereoscopic graphic superposition provides, for the first time, a closed-loop system for the compilation and management of digital spatial data using high resolution, stereo mapping and reconnaissance imagery. Initial studies have focused on terrain analysis [6] and management of previously compiled digital map data [9].

The CAPIR system has demonstrated the implementation of rigorous metric procedures to interface a photo interpreter to a geographic information system. In one sense, it represents a prototypical digital mapping system. The system serves a second role as a research testbed available for the introduction of other forms of computer-assistance to support spatial data extraction and management tasks.

4.2. MAPS: An Image/Map Database

Over the past three years we have developed the MAPS system (Map Assisted Photo-interpretation System) as part of an Image Understanding Systems project at Carnegie-Mellon University. MAPS [16, 17, 18] is a large-scale image/map database system for the Washington D.C. area which contains approximately 100 high resolution aerial mapping images, a digital terrain (elevation) database, and map databases from USGS and Defense Mapping Agency (DMA). The current database covers approximately a 150 square mile area centered over the District of Columbia. This system is the first to deal with a complex urban environment, integrating digital image, terrain, and map databases, using large-scale imagery with high ground resolution. Users are able to interact with a high resolution image display and query the database for the names, descriptions, and spatial relationships between natural and man-made map entities. Current research involves the evaluation of a hierarchical spatial representation to constrain search in large databases, the application of spatial knowledge to navigate through a map database, and support for complex geometric and factual queries that arise in cartography. Dynamic symbolic and signal access to the image/map database, detailed semantic descriptions of man-made and natural features, generalized geometric computations of map feature relationships, and an intelligent window-based image display manager distinguish MAPS from other work in this area.

MAPS represents a step toward the goal of an integrated spatial database, since a 3D world model is represented from multiple images using camera models. Information in this model may then be used to interpret new images of the area. An important aspect of the system is that the world model need not be complete in order to be useful; it is usable as it is developed. Three-dimensional information can be extracted by monocular analysis (shadow, contour, texture, shading), by stereo analysis and through the combination of information from these sources into a coherent description. Since, the shape information we can obtain from images is partial, noisy, and imprecise, having a variety of representations, 3D image analysis requires versatile and robust geometric reasoning methods. The image/map database provides a framework in which various three-dimensional shape-extraction techniques can be developed, evaluated, and integrated.

4.3. SPAM: A Rule-Based System

Current knowledge-based systems typically exhibit a rather narrow character -- often described as *shallow.* Though substantial knowledge is collected in the rules, capable of being applied appropriately to perform a task, there is no ability to reason further with that knowledge. The basic semantics of the task domain is not understood by the system. New rules are not learned from experience nor does behavior with the existing rules become automatically tuned. To point out such limitations is not to be hypercritical of the current state-of-the-art. Indeed, the important scientific discovery behind the success of artificial intelligence knowledge-based expert systems is precisely that sufficient bodies of such shallow knowledge could be assembled, without any of the supporting reasoning and understanding ability, and still prove adequate to perform real consultation tasks in the medical and industrial world.

However, even without general problem solving capabilities, there is much to be gained by the development of "existence proof" rule-based interpretation systems. Current image processing systems are incapable of high-level description of the results of image interpretation. We believe that the combination of a map-based world model and rule-based systems which have "expert" level site-specific or task-specific knowledge, can be used to bridge the gap between users and current state-of-the-art image interpretation systems. The long-term goal of this research is to develop systems that can interact with a human photo-interpreter at a highly symbolic level, that maintain a world database of previous events, use expert level knowledge to predict areas for fruitful analysis, and integrate the results of the analysis into a coherent model. In the near-term, useful knowledge about the organization, strengths, and limitations of this approach will be gained.

One near-term task for rule-based systems in digital mapping is to provide constraints so that image analysis and interpretation tools can be used in spite of their inherently errorful performance. The goal, then, is to integrate rule-based systems with image analysis techniques to constrain the search space of possible scene interpretations using domain and general knowledge. These constraints can be characterized as *"what to look for"* and *"where to look for it".* SPAM is a an experimental system that is exploring these ideas in the context of airport scene analysis [19, 21]. For example, given an image segment that is tentatively labeled as "linear", particular rules are invoked for segment extension or evaluation against possible interpretations such as runway, taxiway, or access road. At any time during the interpretation there are a large number of different partial combinations of cues that can trigger continually more refined segmentation hypotheses. These partial interpretations interact with the image processing component by providing simple low-level segmentation goals. What forces the system to any interpretation is that although large numbers of hypotheses exist, only a small subset is consistent. Each rule recognizes inconsistency or is part of a reasoning chain that may identify an inconsistency. Inconsistencies can be detected by analysis of geometric relationships between local features and the application of world knowledge such as the typical length of runways, sizes of hangars and maintenance buildings, and their relative spatial organization within a general airport scene. SPAM makes use of the facilities provided by the MAPS system to tie feature descriptions to a geodetic coordinate system *<latitude, longitude, elevation>*, and to use camera models (image-to-map correspondence) to predict their location and appearance in the aerial photography. MAPS also provides facilities to compute geometric properties and relationships such as *containment*, *adjacency*, *subsumed by*, *intersection*, and *closest point.*

5. Tasks at the Interface

It is interesting to note differences in emphasis and maturity between aerial photogrammetry and image understanding. First, photogrammetry has 100 years of experience and refinement, while image understanding is in its early development. Photogrammetry uses rigorous camera models, both vertical and oblique. In the context of digital mapping, image understanding has mostly worked with images taken vertically with high scale, and without the benefit of camera models or ground control. In aerial photogrammetry, accurate 3D geodetic positions of ground control, which tie the model to the real world, are the *sine qua non.* Image understanding, however, makes use of many tools and techniques from rule-based systems, computer graphics, large-scale databases, the physics and geometry of image formation, and computer systems. We believe that these differences in emphasis point to opportunities at the interface. In the following sections we describe some mapping tasks that could benefit from cooperative research.

5.1. Road Tracking

Work on detecting and tracking roads has been performed using monocular views. Most techniques rely on image correlation along the road surface or finding significant points on the edges of the road. Due to a variety of factors such as shadows and occlusions, changes in road width, cars and trucks on the road, and the inherent noisiness in the image data, the success of such experimental systems is poor. However, another piece of information that we believe would greatly improve performance for detection, and especially tracking, is the use of elevation and slope information. If the grain of resolution for terrain elevation was fine enough, knowledge about constraints for changes in road slope, as well as road profiles, could be used as another source of information in an overall system. This requires either a detailed digital elevation database or the ability to recover elevation dynamically using digital stereo.

5.2. Shadow Geometry

The use of shadows has been a traditional tool in photogrammetry. Techniques in computer graphics for the generation of shadows and indirect illumination could be applied to predict and detect 3D discontinuities in an image. Ray casting, the projection of light from possibly multiple sources, has been used to produce realistic computer generated scenes and could be applied to prediction of shadows, and the inference of shapes from shadows [29].

5.3. Stereo Compilation

Area correlation has been the basis for most automated stereo compilation devices, and best performance is achieved in areas with smoothly changing terrain, having sufficient texture for correlation, and without large jumps in elevation. Emerging techniques in stereo compilation use a *feature-based* approach using epipolar constraints. The feature-based approach shows promise in areas with man-made structures, since these structures provide a variety of edges and 3D vertices that correspond to the corners, surface markings, or boundaries of cultural features. The combination of feature-based and area correlation stereo methods provide complementary disparity information to a stereo reconstruction system [2]. Further, investigation of the use of coarse terrain models to constrain high resolution stereo matching shows promise.

5.4. Spatial Databases

As traditional geographic information systems are augmented with knowledge-based image interpretation modules, we will begin to close the loop between map feature extraction and its representation for a variety of production tasks. Such systems require the capability to represent detailed knowledge of foliage and vegetation, surface material and composition, and hydrology and drainage as well as man-made structures. There are subtle, and important differences between this type of spatial knowledge representation and those found in current remote sensing systems. Remote sensing uses known or modeled spectral properties of various terrain classes to perform statistical classification. Spectral information captures only one component of knowledge about the terrain and there are a variety of errors introduced by sensors, such as atmospherics, and temporal changes that are difficult to model. The construction of spatial databases containing knowledge from a variety of sources can be achieved as a result of cooperation and joint projects between the mapping and image understanding communities. To effectively capture general rules used by photo analysts requires interaction between domain experts and computer scientists focusing on small, well defined problems with careful analysis of the strengths and limitations of the approach.

5.5. Workstation Environments

The development of workstation environments for feature extraction will greatly aid the application of image understanding to digital mapping problems. In order to achieve increased performance, accuracy, and productivity, we must find ways to combine many of the steps of traditional feature extraction into a workstation environment. Within this environment it should be transparent to the user whether the various subtasks are being performed locally at his workstation or are performed remotely at specialized processing sites. This allows for modular development and integration of new capabilities without adverse impact to the user. The user need not be an expert at each stage of the feature extraction process, but can be assured that the portions not locally done are being reliably performed. In order to achieve a level of performance suitable for production requirements, automated feature extraction programs must have access to a wide variety of information. It is clear that image intensity alone is not sufficient to perform complex analysis. Other components of the information model are *a priori* map knowledge, knowledge of terrain, hydrography, etc. The workstation should provide the focus for this knowledge; it must be carefully organized so that information is relevant and specific to the analysis task at hand.

6. Prospects For The Future

It is interesting to speculate about ways in which image understanding will contribute to automated mapping. First, the contribution will be evolutionary rather than revolutionary. Some tasks are inherently harder than others. Further, there is a major difference between capabilities needed to perform interactive or guided scene analysis, and a truly automated system. The required level of detail of the analysis also affects the time frame for success. In the near term, interactive tools are most likely, with various degrees of automation. As these techniques mature, automated systems will evolve.

Experience with operational "expert" systems in other domains gives insight into scaling systems for greater performance. Simply speaking, achieving higher performance is non-linear. If one can capture 80% of the situations for a small, well-defined task with 500 rules, 90% performance may require 1000 rules, and 95% performance 2000 rules. In an application area such as digital mapping, any small task, such as reliable extraction of road networks, may exhibit such behavior. Therefore, it is best not to set requirements such as 90% performance without understanding the complexity of the technology for achieving simpler goals.

Secondly, techniques related to image understanding may improve productivity in unexpected ways. For example, the introduction of powerful image analysis workstations communicating via local area networks, the use of integrated image databases, and the ability to reference and display known geographic information while compiling new data will create digital mapping environments where feature extraction and map compilation can be aided without major breakthroughs in artificial intelligence and image understanding. As the cost of embedding more powerful processors in local workstations decreases, work that was partitioned due to organizational artifacts will become more integrated.

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