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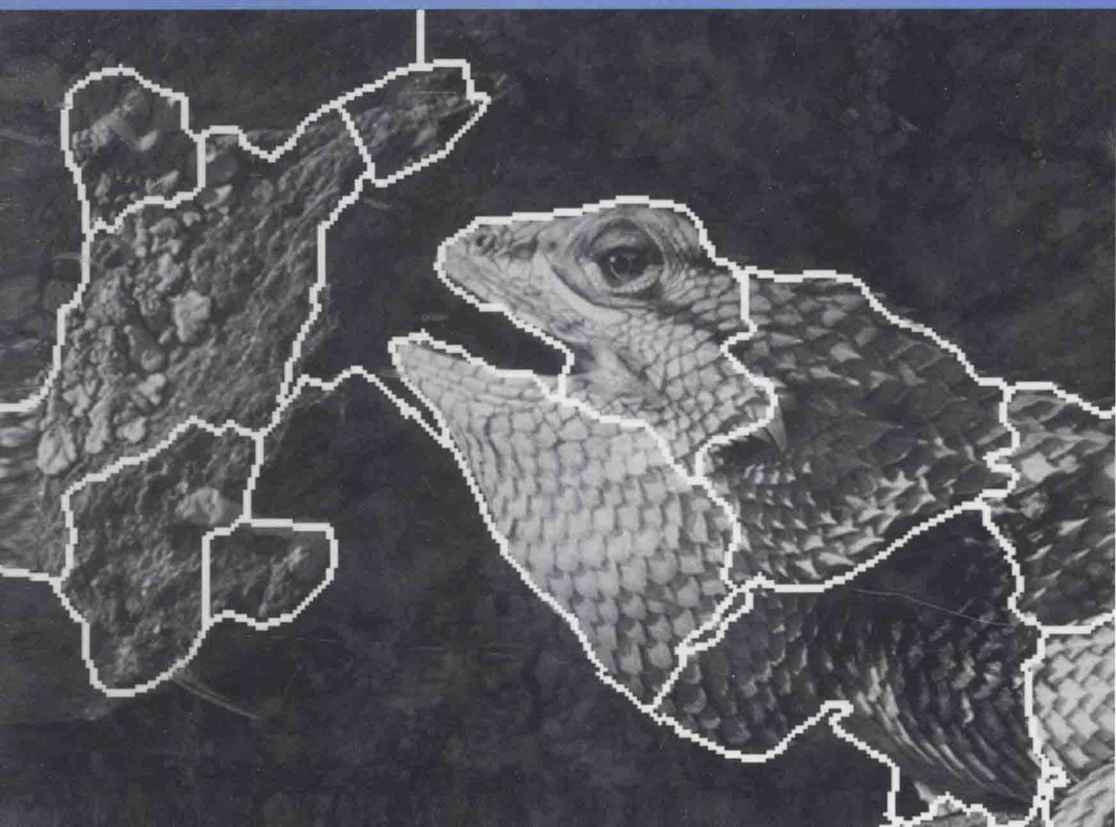
Image Databases

Search and Retrieval of Digital Imagery

Edited by
Vittorio Castelli and Lawrence D. Bergman



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PREFACE

Image databases pose new and challenging problems to the research community. Over the past 40 years, database technology has matured with the development of relational databases, object-relational databases, and object-oriented databases. Extensions to these databases have been developed to handle nontraditional data types, such as images, video, audio, and maps. The core functionalities of classical databases, however, are tailored toward simple data types and do not extend gracefully to nonstructured information.

As the amount of digital imagery grows, techniques that are specifically tailored to such data types need to be developed and more widely deployed. Over the last few years, standardization efforts have taken place in fields such as medicine, geographic information systems, and video in parallel with the development of large digital archives. Search and indexing technology has developed over the same time frame, leading to a wide variety of research prototypes and ad-hoc commercial solutions for searching imagery, video, and other multimedia types. There still is a lack, however, of large commercial systems that integrate existing techniques for storage, indexing, and retrieval of image databases.

In this volume, we present the state of the art of a number of disciplines that converge in image database technology. We motivate the volume by presenting selected applications, including photographic, remotely sensed, petroleum, and medical imagery.

The technology section is divided into two main areas: a portion on storage and one on retrieval. We start with a chapter on system architecture, detailing hierarchical storage management schemes, the role of caching, storage layout issues, and architectural trade-offs. This is followed by a chapter on applications of traditional databases to indexing image repositories, with emphasis on data modeling and organization. Image compression is an integral part of image storage management, and we devote a chapter to the topic, describing the fundamental concepts, reviewing and comparing the main existing standards, outlining nonstandard compression techniques, and discussing evaluation and trade-offs in selecting appropriate methods. Since delivery of imagery over limited bandwidth channels is a universal problem, we include a chapter describing the transmission of imagery in digital format, including techniques such as progressive transmission.

The second half of the technology section describes search and retrieval techniques. We begin with an overview of the area. Low-level image features, such as color, texture, and shape, are typically used to index image archives, and we devote a chapter to each of these. This is followed by a chapter on indexing techniques for spatial queries, range queries, similarity, and nearest-neighbor queries. The next chapter discusses the use of multiple abstraction levels and compressed or transformed images for improving search efficiency. The last chapter addresses the automatic extraction of semantic information from imagery.

This book is intended for several audiences. It can be used as a textbook for a graduate-level course on image databases, as it provides a wide range of introductory material and extensive bibliographies that are appropriate for directing further reading. It is also a valuable reference for developers and researchers in the field, as well as an introduction for IT professionals who need to further their understanding of the discipline.

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1.1 DIGITAL IMAGERY

Digital images have a predominant position among multimedia data types. Unlike video and audio, which are mostly used by the entertainment and news industry, images are central to a wide variety of fields ranging from art history to medicine, including astronomy, oil exploration, and weather forecasting. Digital imagery plays a valuable role in numerous human activities, such as law enforcement, agriculture and forestry management, earth science, urban planning, as well as sports, newscasting, and entertainment.

This chapter provides an overview of the topics covered in this book. We first describe several applications of digital imagery, some of which are covered in Chapters 2 to 5. The main technological factors that support the management and exchange of digital imagery, namely, acquisition, storage (Chapter 6), database management (Chapter 7), compression (Chapter 8), and transmission (Chapter 9) are then discussed.

Finally, a section has been devoted to content-based retrieval, a large class of techniques specifically designed for retrieving images and video. Chapters 10 to 17 cover these topics in detail.

1.2 APPLICATIONS OF DIGITAL IMAGES

Applications of digital imagery are continually developing. In this section, some of the major ones have been reviewed and the enabling economical and technological factors have been discussed briefly.

1.2.1 Visible Imagery

Photographic images are increasingly being acquired, stored, and transmitted in digital format. Their applications range from personal use to media and advertising, education, art, and even research in the humanities.

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In the consumer market, digital cameras are slowly replacing traditional film-based cameras. The characteristics of devices for acquiring, displaying, and printing digital images are improving while their prices are decreasing. The resolution and color fidelity of digital cameras and desktop scanners are improving. Advancements in storage technology make it possible to store large number of pictures in digital cameras before uploading them to a personal computer. Inexpensive color printers can produce good quality reproductions of digital photographs. Digital images are also easy to share and disseminate: they can be posted on personal web sites or sent via e-mail to distant friends and relatives at no cost.

The advertisement and the media industries maintain large collection of images and need systems to store, archive, browse, and search them by content.

Museums and art galleries are increasingly relying on digital libraries to organize and promote their collections [1], and advertise special exhibits. These digital libraries, accessible via the Internet, provide an excellent source of material for the education sector and, in particular, for K-12.

A novel and extremely important application of digital libraries is to organize collections of rare and fragile documents. These documents are usually kept in highly controlled environments, characterized by low light and precise temperature and humidity levels. Only scholars can gain access to such documents, usually for a very limited time to minimize the risk of damage. Technology is changing this scenario: complex professional scanners have been developed that have very good color fidelity and depth (42-bit color or more) as well as high resolution. These scanners can capture the finest details, even those invisible without the aid of a magnifying lens, without risk to the original documents. The resulting digital images can be safely distributed to a wide audience across the Internet, allowing scholars to study otherwise inaccessible documents.

1.2.2 Remotely Sensed Images

One of the earliest application areas of digital imagery was remote sensing. Numerous satellites continuously monitor the surface of the earth. The majority of them measure the reflectance of the surface of the earth or atmospheric layers. Others measure thermal emission in the far-infrared and near-microwave portion of the spectrum, while yet others use synthetic-aperture radars and measure both reflectance and travel time (hence elevation). Some instruments acquire measurements in a single portion of the spectrum; others simultaneously acquire images in several spectral bands; finally, some radiometers acquire measurements in tens or hundreds of narrow spectral bands. Geostationary satellites on a high equatorial orbit are well suited to acquire low-resolution images of large portions of the earth's surface (where each pixel corresponds to tens of square miles), and are typically used for weather prediction. Nongeostationary satellites are usually on a polar orbit — their position relative to the ground depends both on their orbital motion and on the rotation of the earth. Lower-orbiting satellites typically acquire higher-resolution images but require more revolutions to cover the entire surface of the earth. Satellites used for environmental monitoring usually produce low-resolution images, where each pixel corresponds to surface areas on the order of square kilometers. Other commercial satellites have higher resolution. The Landsat TM instrument has a resolution of about 30 m on the ground, and the latest generation of commercial instruments have resolutions of 1 to 3 m. Satellites for military applications have even higher resolution.

The sheer volume of satellite-produced imagery, on the order of hundreds of gigabytes a day, makes acquisition, preparation, storage, indexing, retrieval, and distribution of the data very difficult.

The diverse community of users often combine remotely sensed images with different types of data, including geographic or demographic information, ground-station observations, and photographs taken from planes. The resulting need for data fusion and interoperability poses further challenges to database and application developers.

1.2.3 Medical Images

Images are used in medicine for both diagnostic and educational purposes. Radiology departments produce the vast majority of medical images, while anatomic photographs and histological microphotographs account for a small fraction of the overall data volume.

Radiological images capture physical properties of the body, such as opacity to X rays (radiographies and CT scans), reflectance to ultrasounds, concentration of water or other chemicals (MRI), and distribution of elements within organs (PET). Medical images can be used to investigate anatomic features (e.g., broken bones or tumors) and physiological functions (e.g., imbalances in the activity of specific organs).

The availability of high-quality, high-resolution displays of sensors with better characteristics (sensitivity, quantum efficiency, etc.) than photographic film, of fast interconnection networks, and of inexpensive secondary and tertiary storage are driving radiology departments toward entirely digital, filmless environments, wherein image databases play a central role.

The main challenges faced by medical image databases are integration with the hospital work flow and interoperability.

1.2.4 Geologic Images

Oil companies are among the main producers and consumers of digital imagery. Oil exploration often starts with seismic surveys, in which large geologic formations are imaged by generating sound waves and measuring how they are reflected at the interface between different strata. Seismic surveys produce data that is processed into two- or three-dimensional imagery.

Data are also routinely acquired during drilling operation. Measurements of physical properties of the rock surrounding the well bore are measured with special-purpose imaging tools, either during drilling or afterwards. Some instruments measure aggregate properties of the surrounding rock and produce a single measurement every sampling interval; others have arrays of sensors that take localized measurements along the circumference of the well bore. The former measures are usually displayed as one-dimensional signals and the latter measures are displayed as (long and thin) images.

Sections of rock (core) are also selectively removed from the bottom of the well, prepared, and photographed for further analysis. Visible-light or infrared-light microphotographs of core sections are often used to assess structural properties of the rock, and a scanning electron microscope is occasionally used to produce images at even higher magnification.

Image databases designed for the oil industry face the challenges of large data volumes, a wide diversity of data formats, and the need to combine data from multiple sources (data fusion) for the purpose of analysis.

1.2.5 Biometric Identification

Images are widely used for personal-identification purposes. In particular, fingerprints have long been used in law enforcement and are becoming increasingly popular for access control to secure information and identity. checks during firearm sales. Some technologies, such as face recognition, are still in the research domain, while others, such as retinal scan matching, have very specialized applications and are not widespread.

Fingerprinting has traditionally been a labor-intensive manual task performed by highly skilled workers. However, the same technological factors that have enabled the development of digital libraries, and the availability of inkless fingerprint scanners, have made it possible to create digital fingerprint archives[2,3].

Fingerprint verification (to determine if two fingerprints are from the same finger), identification (retrieving archived fingerprints that match the one given), and classification (assigning a fingerprint to a predefined class) all rely on the positions of distinctive characteristics of the fingerprint called *minutiae*. Typical minutiae are the points where a ridge bifurcates or where a ridge terminates. Fingerprint collections are searched by matching the presence and relative positions of minutiae. Facial matching procedures operate similarly — extracting essential features and then matching them against pre-extracted features from images in the database.

The main challenges in constructing biometric databases are the reliable extraction of minutiae and the matching strategy. Matching, in particular, is difficult: it must rely on rotation- and translation-invariant algorithms, it must be robust to missing and spurious data (the extraction algorithm might fail to identify relevant features or might extract nonexistent features, especially if the image quality is poor), and it must account for distortions due to lighting and positioning. The development of efficient indexing methods that satisfy these requirements is still an open research problem.

1.2.6 Astronomical Imagery

Astronomers acquire data in all regions of the electromagnetic spectrum. Although the atmosphere blocks most high-energy waves (UV, X- rays and γ-

rays), as well as large portions of the infrared and lower-frequency waves, it has large transparency windows that allowed the development of visible-light and radio wave astronomy. High-energy astronomy is possible using instruments mounted on high-altitude planes or orbiting satellites. Radio telescopes acquire signals in the long-wave, short-wave and microwave ranges, and are used to produce two-dimensional maps, often displayed as images.

Traditionally, astronomy has heavily relied on plate-based photography for infrared, visual, and ultraviolet studies (in astronomy, glass plates are used instead of photographic film). Long exposures (of up to tens of hours) make it possible to capture objects that are one to two orders of magnitude too dim to be detected by the human eye through the same instrument.

Photographic plates are not the ideal detectors — they are expensive and fragile, often have small defects that can hide important information, are not very sensitive to light, lose sensitivity during exposure, and their reproduction for distribution is labor-intensive. Their main benefits are large size and high resolution.

Starting from the mid-1980s, sensors that acquire images in digital format have become more and more widely used. In particular, charge-coupled devices (CCD) have found widespread application in astronomy. High-resolution sensor arrays, with responses that go beyond the visible spectrum are now commonly available. These instruments are extremely sensitive — when coupled with photomultipliers, they can almost detect the arrival of individual photons. Images that used to require hours of exposure can now be produced in minutes or less. Additionally, techniques exist to digitally reduce the inherent electrical noise of the sensor, further enhancing the quality of the image. Since the images are produced directly in digital format, a photograph is often acquired by collecting a sequence of short-exposure snapshots and combining them digitally. Image-processing techniques exist to compensate for atmospheric turbulence and for inaccuracies in telescope movement. Solid-state devices are also the detectors of choice for orbiting telescopes.

Digital libraries that organize the wealth of astronomical information are growing continuously and are increasingly providing support for communities beyond professional astronomers and astrophysicists, including school systems and amateur astronomers.

1.2.7 Document Management

Digital imagery plays an increasingly important role in traditional office management. Although we are far from the "paperless office" that many have envisioned, more and more information is being stored digitally, much of it in the form of imagery.

Perhaps the best case in point is archiving of cancelled checks. This information in the past was stored on microfilm — a medium that was difficult to manage. Moving this information to digital storage has resulted in enhanced ease of access and reduced storage volume. The savings are even more dramatic when digital imagery is used to replace paper records.