UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

Axis Communications AB, Canon Inc., and Canon U.S.A., Inc.,

Petitioner

v.

Avigilon Fortress Corporation,

Patent Owner

Cases: IPR2019-00235 & IPR2019-00236

U.S. Patent No. 7,868,912
Issue Date: January 11, 2011

Title: Video Surveillance System Employing Video Primitives

DECLARATION OF EMILY R. FLORIO

I, Emily R. Florio, state and declare as follows:

1. I have prepared this Declaration in connection with the Petitions of Axis Communications AB, Canon Inc., and Canon U.S.A., Inc. (collectively "Petitioner") for two *inter partes* reviews of U.S. Patent No. 7,868,912 ("the '912 patent"), Case Nos. IPR2019-00235 and IPR2019-00236, which I understand will be filed concurrently with this Declaration.

2. I am currently the Director of Research & Information Services at Finnegan, Henderson, Farabow, Garrett & Dunner LLP, 901 New York Avenue NW, Washington, DC 20001-4413.

3. I am over 18 years of age and am competent to make this Declaration. I make this Declaration based on my own personal knowledge, based on my knowledge of library science practices, as well as my knowledge of the practices at the Massachusetts Institute of Technology ("MIT") Libraries.

4. I earned a Master's of Library Science ("MLS") from Simmons College in 2006, and I have worked as a librarian for over a decade. I have been employed in the Research & Information Services (formerly Library) Department of Finnegan since 2013, and from 2005-2013, I worked in the Library Department of Fish & Richardson P.C.

5. I am currently the Vice-President Elect of the American Association of Law Libraries and the President of the Law Librarians' Society of Washington, DC, and a member of the International Legal Technology Association.

Attachments

6. Attached as Exhibit A (Exhibit 1003 to the Petition in IPR2019-00235) is a true and correct copy of "Visual Memory," May 1993, pp. 1-92, by Christopher James Kellogg ("*Kellogg*"), obtained from the MIT Libraries.

7. Attached as Exhibit B is a true and correct copy of the "Standard" record from the MIT Libraries' catalog system (known as the Barton Catalog) for its copy of *Kellogg*.

8. Attached as Exhibit C is a true and correct copy of the MARC record of the MIT Libraries for its copy of *Kellogg*.

9. Attached as Exhibit D (Exhibit 1005 to the Petition in IPR2019-00235) is a true and accurate copy of B. Flinchbaugh et al., "Autonomous Video Surveillance," SPIE Proceedings, 25th AIPR Workshop: Emerging Applications of Computer Vision, Feb. 26, 1997, Vol. 2962, p. 144-151 ("*Flinchbaugh*"), obtained from the MIT Libraries.

10. Attached as Exhibit E is a true and correct copy of the MARC record of the Library of Congress for its copy of the SPIE Proceedings publication that includes *Flinchbaugh*.

11. Attached as Exhibit F is a true and correct copy of the MARC record of the MIT Libraries for its copy of the SPIE Proceedings publication that includes *Flinchbaugh*.

12. Attached as Exhibit G (Exhibit 1004 in each Petition in IPR2019-00235 and IPR2019-00236) is a true and correct copy of. Brill et al., "Event Recognition and Reliability Improvements for the Autonomous Video Surveillance System," Proceedings of the Image Understanding Workshop, Monterey, CA, Nov. 20-23, 1998, Vol. 1, pp. 267-283 ("*Brill*"), obtained from the Duderstadt Center, formerly known as the University of Michigan Media Union (UMMU).

13. Attached as Exhibit H is a true and correct copy of the MARC record of the University of Virginia Library for its copy of *Brill*.

14. Attached as Exhibit I is a true and correct copy of the MARC record of the North Carolina State University library for its copy of *Brill*.

The MARC Cataloging System

15. The MAchine-Readable Cataloging ("MARC") system is used by libraries to catalog materials. The MARC system was developed in the 1960s to standardize bibliographic records so they could be read by computers and shared among libraries. By the mid-1970's, MARC had become the international standard for bibliographic data, and it is still used today.

16. Each field in a MARC record provides information about the cataloged item. MARC uses a simple three-digit numeric code (from 001-999) to identify each field in the record.

17. For example, field 245 lists the title of the work and field 260 lists publisher information. In addition, field 008 provides the date the item was cataloged. The first six characters of the field 008 are always in the "YYMMDD" format.

18. It is standard library practice that once an item is cataloged using the MARC system, it is shelved. This process may take a relatively nominal amount of time (i.e., a few days or weeks). During the time between the cataloging and shelving of an item, the public may still find the item by searching the catalog and requesting the item from the library.

Kellogg

19. As indicated in Exhibit A (Exhibit 1003 to the Petition in IPR2019-00235), *Kellogg* has an MIT Libraries date stamp of "JUL 09 1993" on page 1, indicating that the MIT Libraries received *Kellogg* on July 9, 1993. Further, as indicated in Exhibit B, the Standard record of the Barton Catalog confirms that *Kellogg* is shelved at the MIT Libraries and was published in 1993. In view of the above and the following, *Kellogg* was published and accessible to the public in 1993, years before October 1999.

20. As indicated in Exhibit C, *Kellogg* has a cataloging date of September 28, 1993 (shown as "930928" in field 008). This confirms that *Kellogg* was entered into the OCLC database, in which MIT does its cataloging, on September 28, 1993. This is also consistent with its noted year of publication in the MARC record (shown as "1993" in field 260). The OCLC database (also referred to as "WorldCat") is the largest online public access catalog (OPAC) in the world.

21. Soon after *Kellogg* received a cataloging date, a record of its existence would have appeared in and been keyword-searchable through the Barton Catalog of the MIT Libraries. The Barton Catalog is currently available online to any user of the World Wide Web. Before it was accessible by Web (i.e., at the time the *Kellogg* thesis was received by the MIT Libraries in July 1993), it would have been accessible to anyone on the MIT campus *and* anyone who had access to the OCLC database.

22. During the time period from September 1993 through October 1999, the Barton Catalog allowed keyword searching for words in the thesis title, and *Kellogg* would have appeared in a relevant Barton Catalog search conducted on or shortly after September 28, 1993.

23. After being cataloged, a document such as *Kellogg* will undergo a process of being labeled and then shelved at the MIT Libraries. Based on my knowledge of MIT Libraries' current and prior practices, *Kellogg* would have been

shelved in a relatively nominal amount of time (i.e., a few days or weeks). Thus, *Kellogg* was cataloged and shelved at the MIT Libraries at least before the end of 1993.

24. Once shelved, *Kellogg* can be borrowed by any member of the MIT community. Furthermore, a copy of *Kellogg* can be purchased from MIT by any member of the public. Indeed, the first page of *Kellogg* confirms that there were no restrictions placed on its publication, as it states that "[t]he author hereby grants to MIT permission *to reproduce and to distribute copies of this thesis document* in whole or in part, and to grant others the right to do so."

25. Further evidence of the public availability of *Kellogg* before October 1999 is provided in Exhibit D, which is a copy of *Flinchbaugh*. In its Bibliography, *Flinchbaugh* cites to *Kellogg* (reference [4] on p. 151). As addressed below, *Flinchbaugh* was published in SPIE Volume 2962, which corresponds to the Proceedings from the 25th Annual AIPR Workshop on Emerging Applications of Computer Vision. The Workshop was held October 16-18, 1996, and the Proceedings were published by at least 1997. Thus, *Kellogg* was at least available to members of the public in 1997, as shown by its citation in *Flinchbaugh*.

26. For the avoidance of any doubt, I note that on June 23, 2001, *Kellogg* was also cataloged in the MIT Archive Noncirculating Collection 1,

Noncirculating Collection 3, and in microfiche form in the Barker Library, as indicated in the three entries for PST8 and in the second, third, and fourth instances of field 008 on page 1 of Exhibit C. However, none of this alters the fact that *Kellogg* was published and accessible to the public in 1993, as indicated above.

Flinchbaugh

27. As indicated in Exhibit D, *Flinchbaugh* (Exhibit 1005 to the Petition in IPR2019-00235) was published in the Proceedings of the 25th AIPR Workshop: Emerging Applications of Computer Vision, SPIE Vol. 2962. The Workshop was held in Washington, D.C. during October 16-18, 1996, and the Proceedings was published by SPIE (The International Society for Optical Engineering). Ex. D at 1. In view of the above and the following, *Flinchbaugh* was published and accessible to the public before October 1999.

28. Page 2 of Exhibit D shows a copyright date of 1997. The edition of the SPIE Proceedings that was published with *Flinchbaugh* is Volume 2962, and it was "Printed in the United States of America." Ex. D at 2.

29. Although the copyright date of *Flinchbaugh* is listed as 1997, it appears that *Flinchbaugh* was actually published before that, in 1996. First, as noted above, the Workshop was held in Washington, D.C. during October 16-18, 1996. Second, a copy of *Flinchbaugh* was received and cataloged by the Library of Congress in November 1996. *See* Ex. E at 1. Exhibit E is the MARC record for

the SPIE Proceedings, including *Flinchbaugh*, that was obtained from the Library of Congress. As shown in field 008 near the top of page 2 of Exhibit E, *Flinchbaugh* was cataloged by the library on November 21, 1996. Based on standard library practices, this reference would have been shelved shortly after it was cataloged (i.e., within a few days or weeks). Collectively, Exhibits D and E show that *Flinchbaugh* was published and accessible to the public years before October 1999.

30. Further evidence of the publication and public availability of *Flinchbaugh* can be found in Exhibit F, which is the MARC record for the SPIE Proceedings, including *Flinchbaugh*, that was obtained from the MIT Libraries. As shown in field 008 on page 1 of Exhibit F, *Flinchbaugh* was cataloged by the library on March 10, 1997. Based on standard library practices and my understanding of the practices of the MIT Libraries, this reference would have been shelved shortly after it was cataloged (i.e., within a few days or weeks) and accessible to the public before October 1999.

31. For the avoidance of any doubt, I note that on April 8, 2011, online access to *Flinchbaugh* was provided to certain MIT-associated individuals, as indicated by the fields 008 and 8528 and the URL entry at the top of page 2 of Exhibit F. Also, on June 23, 2001, the SPIE Proceedings, including *Flinchbaugh*, was archived at the MIT Library Storage Annex ("LSA"), as indicated by the

second 008 field and subsequent 8520 entry on page 2 of Exhibit F. However, none of this alters the fact that *Flinchbaugh* was published and accessible to the public years before October 1999, as indicated above.

Brill

32. As indicated in Exhibit G, *Brill* (Exhibit 1004 to each Petition in IPR2019-00235 and IPR2019-00236) is part of the published Proceedings of the 1998 Image Understanding Workshop. The Workshop was held in Monterey, California during November 20-23, 1998, and the Proceedings were "APPROVED FOR PUBLIC RELEASE" with "DISTRIBUTION UNLIMITED." Ex. G at 1. In view of the above and the following, the Proceedings, including *Brill, w*as published and accessible to the public before October 1999.

33. Evidence of *Brill's* publication and availability to the public includes the hand-written receipt date of "8-13-99" at the top of page 3 of Exhibit G. This indicates it was received by the UMMU (the University of Michigan Media Union, now known as the Duderstadt Center) on August 13, 1999. In my experience as a librarian and knowledge of standard library practices, the hand-written information at the top of p. 2 of Exhibit G appears to be the catalog record information for *Brill*. Based on standard library practices, this reference would have been shelved shortly after being received and cataloged by UMMU.

34. Further evidence of the publication and accessibility of *Brill* to the public can be found in Exhibit H, which is the MARC record for the Proceedings, including *Brill*, that was obtained from the University of Virginia Library. As shown in field 008 near the top of page 2 of Exhibit H, *Brill* was cataloged by the library on December 15, 1998. Based on standard library practices, this reference would have been shelved shortly after (i.e., within a few days or weeks) and been accessible to the public prior to October 1999.

35. Further evidence of the publication and public availability of *Brill* can be found in Exhibit I, which is the MARC record for the Proceedings, including *Brill*, that was obtained from North Carolina State University. As shown in field 008 on page 1 of Exhibit I, *Brill* was cataloged by the library on December 15, 1998. Based on standard library practices, this reference would have been shelved shortly after (i.e., within a few days or weeks) and been accessible to the public prior to October 1999.

I declare under penalty of perjury that the foregoing is true and correct. Executed on November 9, 2018 in Washington, D.C.

Emily R. Florio

EXHIBIT A

Visual Memory

by

Christopher James Kellogg

Submitted to the Department of Electrical Engineering and Computer Science
in partial fulfillment of the requirements for the degrees of

Bachelor of Science
and
Master of Science in Computer Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1993

Author ..... Signature redacted
Department of Electrical Engineering and Computer Science
April 21, 1993

Certified by ..... Signature redacted
Alex P. Pentland
Associate Professor of Media Arts and Sciences
Thesis Supervisor

Certified by ..... Signature redacted
Bruce E. Flinchbaugh
Manager of Image Understanding Branch at Texas Instruments
Thesis Supervisor

Accepted by ..... Signature redacted
Campbell L. Searle
Chairperson, Departmental Committee on Graduate Students

Visual Memory

by

Christopher James Kellogg

Submitted to the Department of Electrical Engineering and Computer Science
on April 21, 1993, in partial fulfillment of the
requirements for the degrees of
Bachelor of Science
and
Master of Science in Computer Science

Abstract

Visual memory supports computer vision applications by efficiently storing and retrieving spatiotemporal information. It is a unique combination of databases, spatial representation and indexing, and temporal representation and indexing. This thesis designs a visual memory architecture that meets the requirements of a number of computer vision applications. It also presents an implementation of part of this design in support of a scene monitoring prototype.

Thesis Supervisor: Alex P. Pentland
Title: Associate Professor of Media Arts and Sciences

Thesis Supervisor: Bruce E. Flinchbaugh
Title: Manager of Image Understanding Branch at Texas Instruments

Acknowledgements

My primary thanks goes to my two thesis supervisors, Bruce Flinchbaugh at Texas Instruments and Sandy Pentland at MIT. Bruce pointed me to the visual memory project that he was starting and guided my research at Texas Instruments. Sandy provided useful feedback throughout the research stage. They were both very helpful in critiquing the thesis document.

I'd also like to thank the other people at Texas Instruments who helped me with this project. Steve Ford and Tom Bannon were especially helpful in developing the visual memory design. In addition, I don't think I would have survived the bugs in PC++ without Steve's expertise. Tom Bannon and Tom O'Donnell provided a nice tracking system with which to test the visual memory prototype.

Finally, I'd like to thank my family, Fred, Jeannette, and Mark Kellogg, my fiancée Christine Bailey, and my brothers at Phi Kappa Sigma for their support throughout my MIT career.

Contents

List of Figures

Chapter 1

Introduction

Visual memory supports computer vision applications by efficiently storing and retrieving spatiotemporal information. It is a unique combination of databases, spatial representation and indexing, and temporal representation and indexing. Visual memory provides representational flexibility and high-performance information access to meet the requirements of a variety of computer vision applications.

1.1 Needs for Visual Memory

Applications use spatiotemporal data in many different ways and place many different demands on a visual memory. Studying possible uses helps to clarify the concept of a visual memory and to identify the functionality it provides.

Visual memory could serve as the repository for static information, such as object descriptions, maps, and environment models, that applications reference during execution. For example, a vehicle navigator could store maps and images to help it later recognize its location. A large amount of such information could be established prior to application execution, and the visual memory would subsequently provide an application with efficient access to desired pieces of information.

An application could store dynamic information in the visual memory. For example, a vehicle navigator's input systems could maintain in the visual memory a description of the vehicle's local environment, updating it as the vehicle moved. The

visual memory could provide the navigator's planning processes with information about the vehicle's latest state and could analyze its progress to help determine a course of action. The high performance of the visual memory allows it to handle the frequent updates and queries needed by such dynamic, real-time systems.

Visual memory could manipulate spatiotemporal information about objects and collections of objects too large to fit into volatile memory. For example, a computer-aided design and modeling system could use the visual memory in building up a large design layout and simulating its execution over time; a photo interpretation system could similarly construct in the visual memory a complex representation of a scene. The visual memory would retrieve into main memory only a manageable part of a large representation at a time.

Visual memory could act as the interface between inputs and applications in a computer vision system. For example, computer vision algorithms for a security system could analyze data provided by various cameras and store information in the visual memory. Applications could then retrieve this data to track objects, watch for suspicious events, and respond to user queries. The visual memory would coordinate the information from its inputs and eliminate the need for full connectivity between inputs and applications.

Finally, visual memory could serve as a means for data transfer. A computer vision application could store spatiotemporal information in the visual memory for other applications to retrieve at any time in the future. To run comparative studies, different algorithms could use common data stored in the visual memory.

1.2 Goals

This thesis explores visual memory design and implementation. The primary goal of the thesis is to design a visual memory architecture that meets the requirements of various computer vision applications. A secondary goal is to implement a visual memory prototype to support a real-time scene monitoring prototype.

Chapter 2

Background

Visual memory builds on research in database design, spatial representation and indexing, and temporal representation and indexing. While there has been significant research in each of these areas, no previous project has combined them in this manner. The visual memory design uses knowledge gained from research projects in all these areas. This chapter summarizes and discusses some especially relevant projects.

2.1 Database Research

Visual memory must address concerns that a great deal of database research has already investigated. It must provide everything from information storage techniques to concurrency control for multiple inputs and outputs. Visual memory should build on the results of research into these topics. Presented here are two databases that address a number of the issues important to visual memory and that could be the basis for a visual memory system.

2.1.1 DARPA Open OODB

The DARPA Open Object-Oriented Database (Open OODB) project at Texas Instruments outlines an extensible architecture that allows "...tailoring database functionality for particular applications in the framework of an incrementally improvable system ...." [25] The architecture meets functional requirements such as an object

data model and concurrent access, along with "meta requirements" including openness and reusability. The open architecture lets separate modules handle extensions to the basic storage mechanism. These extensions cover standard database issues such as transactions, versions, and queries.

The Open OODB architecture is very suitable for visual memory. The object-oriented model can flexibly and intuitively represent the information used by computer vision applications. Following the Open OODB architecture, visual memory could avoid confronting standard database issues by letting other modules support those features. Instead, visual memory would consist only of those extensions necessary to support efficient manipulation of spatiotemporal information. If new features were needed, extra modules could easily be added to the architecture.

2.1.2 POSTGRES

The POSTGRES database [23] expands the relational database model to meet the needs of complex applications. Because it builds on traditional relational databases, it provides a number of standard features, such as transactions, a query language, and recovery processing. In addition, it allows applications to specify new data types, operators, and access methods. POSTGRES supports active databases and rules, letting applications set up daemons in the database that react to changes in the data. A versioning mechanism keeps track of old data and works with the query language to let applications retrieve this information. Finally, the POSTGRES storage server can "vacuum" old data onto archival media.

POSTGRES supplies many features useful to a visual memory, such as transactions, queries, and application-defined access methods. However, the relational model might not be sufficiently expressive to meet the representational needs of complex computer vision applications. In addition, the POSTGRES design does not support application-specific extensions to the database, so it would be hard for the visual memory to expand to meet future requirements.

2.2 Spatial Research

There are many ways to describe spatial objects and to handle their storage and retrieval. Visual memory must consider how well different spatial models meet the representational needs of computer vision applications and how efficiently information in these models can be stored and retrieved.

2.2.1 CODGER

Researchers at Carnegie Mellon University developed the CODGER (COmmunications Database with GEometric Reasoning) "whiteboard" database and communication system to support the autonomous NAVLAB vehicle [20]. CODGER stores data to be communicated among the various modules that control vehicle navigation. It represents this information as tokens consisting of attributes and values.

CODGER uses a fairly simple spatial model. Token attributes represent basic spatial information such as position and object extent. The tokens support some standard geometric operations like area calculation. A query mechanism can answer some spatial queries like the proximity query "Return the tokens with location within 5 units of (45,32)." CODGER does not provide an indexing mechanism, and spatial operations and queries are performed in memory.

2.2.2 Core Knowledge System

The Core Knowledge System (CKS) [24], developed at SRI International, stores information for a robot. Like CODGER, it encodes this information as attribute-value tokens. CKS introduces special support for the uncertainty that results from inconsistent or incomplete information provided to the database. Its query mechanism includes keywords such as *apparently* and *possibly* to discern multiple opinions. Since spatial information is often imprecise, this support for uncertainty would be very useful in a visual memory context. However, CKS does not provide any special spatial operations or query constructs.

2.2.3 ISR

The ISR project at the University of Massachusetts at Amherst [3] defines a spatial representation (the Intermediate Symbolic Representation) and a management system for accessing data represented this way. The intermediate symbolic representation includes tokens for basic spatial objects such as lines, regions, and sets of parallel lines, but not for higher-level spatial objects such as people and vehicles. The data management system manipulates these tokens in an efficient manner. Applications built with ISR perform classification and in-memory spatial indexing.

2.2.4 Image Understanding Environments

The Image Understanding Environments (IUE) program [16] specifies a spatial representation to meet the needs of a wide variety of computer vision applications. An IUE spatial object is defined by a set of points; this point set can be concrete (a list of all the points) or abstract (an equation defining the points in the object). IUE spatial objects are manipulated through set operations – complex objects can be constructed through conjunction and disjunction of point sets. In addition to its point set, each spatial object also defines a bounding box, a centroid, and other attributes for different, and perhaps more efficient, methods of spatial manipulation. The IUE specification only briefly discusses data transfer and does not provide database support for storage and retrieval of spatial information.

2.2.5 PROBE

The PROBE database [15], developed at the Computer Corporation of America, extends an object-oriented database management system to meet the requirements of a variety of computer vision applications. It implements a number of spatial data types and supports operations on sets of points. It outlines a query language with some support for spatial queries. To provide more efficient spatial access, it also provides what the authors call *approximate geometry*, a limited form of spatial indexing.

2.2.6 Spatial Indices

A large number of spatial data structures can provide efficient access to spatial information. Samet [18] describes a number of these, including quadtrees, hash tables, grid files, range trees, and R trees. Each index is specialized for specific storage and retrieval characteristics; visual memory would benefit from including a number of different indices to efficiently manipulate data for different applications.

2.3 Temporal Research

Databases manipulate two different types of time: *transaction time*, specifying when updates for events are stored in the database, and *valid time*, specifying when events actually happen. *Rollback databases* implement transaction time, *historical databases* implement valid time, and *temporal databases* implement both. Sometimes historical and rollback databases are informally called temporal databases to indicate their concern with time. Since the computer vision applications discussed in the Introduction are concerned with the times at which events happen, visual memory should be a historical database.

A number of different historical and temporal databases represent and store temporal information. Each addresses a different set of concerns, and some designs suit visual memory better than others. The following research projects address many of the issues that visual memory must consider.

2.3.1 TQuel

The temporal database TQuel [21] is a temporal extension to a relational database. TQuel associates with each database record the slots *valid-from* and *valid-to*, defining an interval during which the record is valid. For example, the Employees relation might have three records for Frank, one valid from 0 to 1/1/93, another valid from 1/1/93 to 5/7/93, and a third valid from 5/7/93 to ∞. If Frank were changed on 8/7/93, then the third record's *valid-to* slot would be changed to 8/7/93, and a new

record valid from 8/7/93 to ∞ would be added.

TQuel extends the query language Quel [12] to support temporal access of records. A temporal query specifies an interval of interest; the database retrieves any record whose valid interval overlaps that interval. A query can also ask for records before, after, or as of a given moment. TQuel provides operators such as *overlaps* and *extend* to form complex query intervals.

2.3.2 Temporal Sequences

The temporal database outlined in [19] models object state changes with temporal sequences. A temporal sequence can be discrete or continuous; for example, sales per month could be modeled as a discrete temporal sequence, while the voltage in alternating current could be modeled as a continuous temporal sequence. A temporal sequence is always represented by a set of state snapshots; interpolating functions estimate continuous sequences. Characteristics such as granularity and regularity of state snapshots define each temporal sequence. Functions including selection, aggregation, and accumulation operate on sets of time sequences. The database also includes a powerful SQL-like [1] query language for retrieving temporal sequences.

2.3.3 Temporal Sets

Researchers at the University of Houston proposed some temporal additions [8] to the Extended Entity-Relationship Model. The basic temporal representation in this temporal model is a finite union of time intervals; for example, a particular state could be valid during the set of time intervals { [50,60), [90,230), [231,239) }. The database stores with each object a temporal element denoting its valid time. Basing temporal representation on sets of intervals preserves closure under set operations and provides a standard means for manipulating temporal information and querying the database.

This model was later augmented to better represent temporal uncertainty [13]. The extended model preserves the definition of a temporal element but modifies the

definition of a temporal interval. Each endpoint in an interval specifies a valid time method that returns an ordered set of time points. The endpoint belongs to this set, but in order to allow for uncertainty, it is not explicitly specified. The model also modifies the standard set operations to manipulate uncertain temporal elements.

2.3.4 Relative Time

Some applications, such as computer-aided design systems, know how events are ordered but not the actual times of the events. Chaudhuri [5] proposes a temporal model to handle these cases. This model represents time as a graph rather than as a time line. Events are ordered with binary relations like *before* and *simultaneously*. These relations must obey properties such as transitivity and antisymmetry so that the database can navigate through a graph and infer additional relationships. The model supports temporal queries about event relations; for example, a query could ask for a lower time bound on an event or for common ancestors of two events. This capability could be useful in a visual memory to support efficient handling of temporal information for some applications.

2.3.5 Temporal Indices

Much of the spatial indexing research also applies to temporal indexing. For example, interval trees can store intervals in space or in time. To handle more complex, specialized temporal representations, however, requires additional research. Some of the databases described above provide their own temporal indices; [22] references many other systems with temporal indices.

Chapter 3

Design

This chapter presents a design for a visual memory system. It examines requirements and considerations that the design must take into account. It discusses key visual memory topics such as representation and indexing of spatial, temporal and spatiotemporal information. This chapter outlines a concrete, implementable system; the next chapter presents the prototype implementation of this design.

3.1 Requirements and Considerations

The design of a visual memory must address a number of concerns. Some of these come from anticipated uses of the visual memory, while others are common themes in spatial, temporal, and database research. This section covers a number of these requirements and considerations.

3.1.1 Database Considerations

One database issue relevant to visual memory is how to represent and store information. There are several standard models, including the relational model, the entity-relationship model, and the object-oriented model. The visual memory should use an object-oriented model to meet the broad representational requirements of a variety of applications. An object-oriented approach is intuitive and highly extensible, allowing applications to define new, complex objects at any time.

Another important consideration is concurrency control. The visual memory must be able to handle multiple, dynamic inputs and outputs. For example, in a scene-monitoring system, many different cameras could update the visual memory simultaneously. The visual memory must ensure data consistency.

Much database research involves well-defined program interfaces, including explicit storage mechanisms and query algebras. Applications using the visual memory do not need to know how it achieves its results, but they should know what results to expect. For example, performance-enhancing measures such as indexing and caching do not affect the objects returned by a query and can be added without affecting the query algebra.

Recoverability is another database issue important to some visual memory applications. The visual memory must work to guarantee that, even in the case of a system crash, it does not lose stored information. In addition, it must be able to remove inconsistencies resulting from system failure during information storage.

3.1.2 Spatial and Temporal Considerations

The purpose of visual memory is to store information about the history of a visual environment. Visual memory is not just a generic database — it must have spatiotemporal concerns at the heart of its design.

A visual memory must provide representational flexibility. Rather than forcing one spatiotemporal representation on all applications, the visual memory should be tailorable to an application's needs. Applications can trade off between representational power and performance.

A visual memory must handle dynamic objects. Some computer vision applications need to update spatial information in response to changes in the environment. The visual memory must define spatiotemporal representations to effectively handle such changes. It must provide a versioning mechanism to store and retrieve different state snapshots of objects.

A visual memory must provide a flexible, expressive query mechanism with extensive spatiotemporal support. This query mechanism should support a wide variety of spatiotemporal queries. For example, a security system might ask the visual memory to retrace a person's path over the past five minutes, a vehicle navigator might ask it to watch for objects entering the field of view, and a CAD system might ask for simulation results for everything electrically connected to a specific chip. The visual memory should let applications conveniently express such queries.

3.1.3 Performance Considerations

High performance is one of the key requirements for a visual memory. Some visual memory applications, such as a vehicle navigator, need to store and retrieve information very quickly. Many spatial and temporal models in the literature are very expressive but do not provide the necessary information throughput. A visual memory must be both expressive and fast enough to meet the demands of its applications.

Indexing can help a visual memory achieve high performance by quickly identifying objects satisfying given constraints. Visual memory indices should be *conservative*,

never mistakenly omitting objects that satisfy a query. In this manner, indices can improve query performance but are guaranteed to not affect the results.

A visual memory must provide a variety of indices to meet the needs of different applications. For example, a real-time scene monitoring system could set up an index to track the centroids of moving objects, while a photo interpretation system could index the areas covered by objects. A visual memory indexing mechanism should be extensible, handling additional application-defined indices.

A visual memory must let applications control which objects are indexed. For example, an application could establish one index on all objects, another index on everything in the current session, and yet another index only on certain objects of interest. This would prevent the visual memory from wasting time and space updating unimportant indexing information.

Caching and look-ahead techniques can increase the performance of a visual memory. Caching improves storage performance by not requiring the visual memory to wait for information to be written to disk. Both caching and look-ahead improve retrieval performance by reducing the number of disk accesses.

Visual memory performance can be increased by letting applications tailor the visual memory to their specific requirements. For example, some applications can afford to lose a small amount of data, so they could eliminate recoverability information. Other applications could optimize specific storage and retrieval cases; for example, a vehicle navigator could optimize its real-time performance by sacrificing some historical performance.

3.2 Design Overview

The visual memory design consists of a set of extensions to an open database architecture like DARPA Open OODB [25]. An open architecture allows the visual memory to add spatiotemporal customizations to the database. The visual memory can take full advantage of other modules implementing features such as concurrency control, caching, and versioning, without having to handle these capabilities directly.

The visual memory design follows the object-oriented model discussed in the previous section. A class hierarchy defines representations for spatiotemporal information. Abstract superclasses define the interfaces for manipulating spatiotemporal information, and their subclasses extend the definitions to represent more specific types of objects. This document denotes classes in italics; for example, *SpatialObject* is the class representing spatial objects. A concrete member of this class is referred to as "a *SpatialObject* instance" or informally just as "a spatial object."

The visual memory design specifies a number of classes for representing spatiotemporal information. These classes provide methods through which computer vision applications and the visual memory can manipulate them. For example, the spatial class *Square* could include a method to return its area, the temporal class *TemporalInterval* could have a method to determine its duration, and the spatiotemporal class *Person* could implement a method plotting its space-time trajectory. Applications can design their own classes inheriting from these classes and extending them to meet additional needs.

The visual memory design extends the database's storage mechanism. It provides a mechanism for object identity and maintains a history for each object. Each version of an object specifies when it was valid, and the visual memory can manipulate versions based on valid time. The design lets applications customize the database storage server based on characteristics of the data they typically store.

The visual memory design extends the database's query mechanism to provide spatiotemporal support. The additional spatiotemporal constructs allow computer vision applications to flexibly and expressively specify objects of interest.

To achieve suitable query performance, the visual memory provides spatiotemporal indices that can efficiently identify objects satisfying query conditions. A visual memory index is an object that maintains information about other objects, allowing it to efficiently indicate those objects that meet certain constraints. For example, a visual memory spatial index might store object centroids so that it can quickly identify all the objects within a specified area. The visual memory provides a powerful and flexible indexing mechanism.

3.3 Spatial Representations

The visual memory spatial class hierarchy provides a powerful framework that allows applications flexibility in designing spatial representations while ensuring that the visual memory can access the information it requires. The class hierarchy draws on the research outlined in the Background chapter. It provides the basic framework for any visual memory application, and it allows applications to extend it to meet additional needs.

Spatial operations are often complex and require much computation. Spatial indices, described in Section 3.8, can increase the performance of these operations by maintaining information about sets of spatial objects. This chapter presents a number of spatial operations; Section 3.8 describes related performance issues.

3.3.1 Core Spatial Classes

SpatialObject

The *SpatialObject* class is the basis for all high-level spatial representations. Possible subclasses derived from *SpatialObject* include *Cube*, *QuestionMark*, and *Person*, depicted in Figure 3-1. *SpatialObject* captures the common representational requirements of a variety of such spatial objects. It provides a standard set of slots and methods to yield a consistent spatial interface. Applications can design additional spatial representations as long as they provide the same functionality.

A spatial object is defined by a set of points and a local coordinate system. This information is sufficient to fully represent a spatial object. The point set specifies what area of space the object fills. The coordinate system relates these points to the points in other spatial objects. Additional information, such as centroid, orientation, and bounding box, is derivable from this information.

SpatialObject provides a wide variety of methods to manipulate its data. These methods can translate and rotate an object, operate on its point set, and find the object's bounding box, among other things. Most of these are actually point set and coordinate system functions and will be discussed further below. Concrete spatial

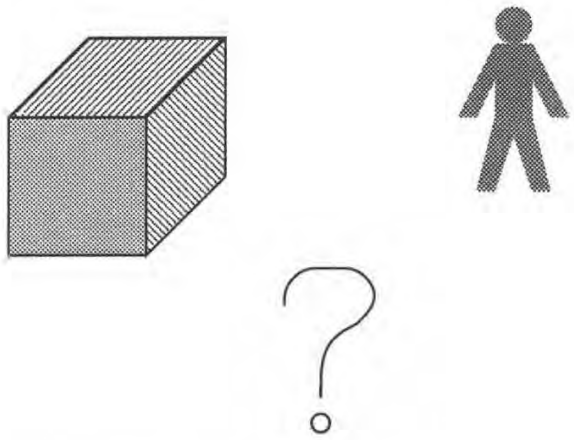


Figure 3-1: Spatial objects

objects can provide additional relevant information; for example, a cube could have functions returning the length of its side, its surface area, and its volume. Using the methods of *SpatialObject* and its subclasses, an application can manipulate spatial data in many different ways.

Several lower-level classes manipulate information for the high-level *SpatialObject* class. The following sections present these classes.

Point

The most elementary unit of spatial representation is the point. The visual memory provides the abstract class *Point* and subclasses *TwoDPoint*, *ThreeDPoint*, etc., to represent this elementary unit. *Point* is a fairly simple class, only storing and manipulating a coordinate in some space. As will be shown below, however, it is an important building block.

PointSet

Complex spatial information can be represented as a collection of points, or point set. The visual memory provides the class *PointSet*, derived from a generic *Set* class,

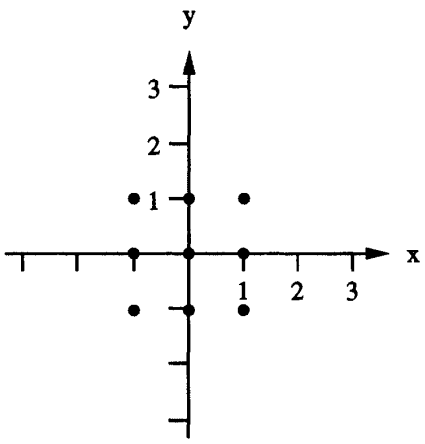


Figure 3-2: Discrete point set

to store and manipulate sets of points. Since *PointSet* is a kind of *Set*, it provides standard set operations, such as union, disjunction, member, and difference. This allows a powerful means for constructing complex objects. It also furnishes a well-defined and sound mathematical basis for spatial representation and manipulation.

The class *DiscretePointSet* represents a set of points simply as an exhaustive list of all desired points. This representation is feasible only for small point sets. For example, consider the task of representing the square area of the points plotted in Figure 3-2. A system could, by convention, represent a square area by such a discrete set of points. Standard set operations can easily manipulate this information. Unfortunately, the space required for this representation grows too quickly to be broadly applicable.

The class *AbstractPointSet* is a far more efficient means for representing large or even infinite point sets. It abandons an exhaustive list of all points in favor of a functional definition of the points in the set. An abstract point set specifies a function that returns TRUE for points in the set and FALSE for points not in the set. For example, the function for the continuous square in Figure 3-3 would check for $-1 <= x, y <= 1$. This fully represents the square area. A point set's representation function grows complex as the set is modified by operations such as conjunction and

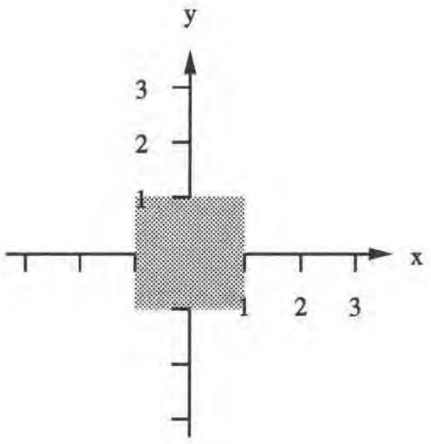


Figure 3-3: Abstract point set

disjunction, but a suitably complex function can represent any desired set of points.

Some visual memory applications start with discrete approximations to the continuous world but want to interpolate to a continuous description. For example, an application might recognize only the list of discrete points above that make up just a small part of an actual continuous square. For these applications, a subclass of *AbstractPointSet*, *InterpolatingAbstractPointSet*, can apply a specified interpolation function to that list of points to derive a continuous function. For example, an interpolation of the point set in Figure 3-2 could yield the point set in Figure 3-3.

An instance of *PointSet* is more than just a set of points; it also includes a number of methods deriving spatial information from this set. Important methods find a point set's centroid, boundary, bounding box, and surface normal, among other things. These methods extend the power of the point set and enhance the visual memory spatial support.

CoordinateSystem

A point in space is useful only in relation to other points. The *CoordinateSystem* class establishes relationships between points in the visual memory. Figure 3-4 shows a couple of possible coordinate systems. Each *CoordinateSystem* subclass must define

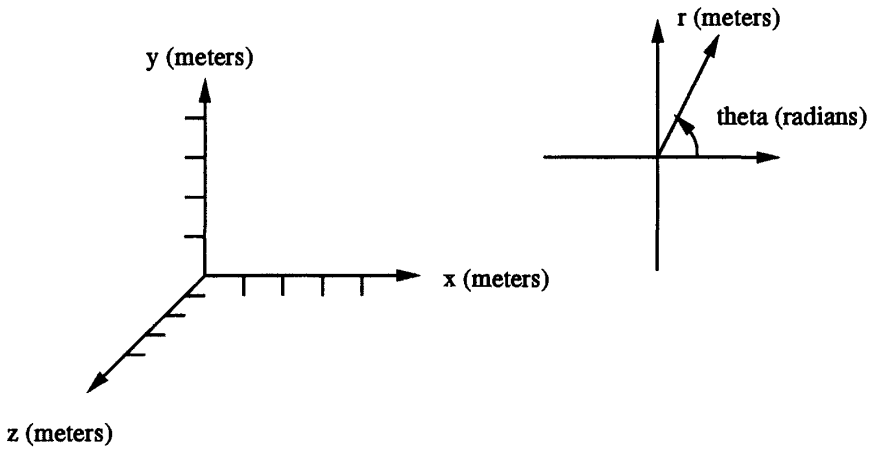


Figure 3-4: Coordinate systems

dimensions, axes, and other features of the space. These specifications give meaning to points and provide the basis for relating points. The visual memory defines a coordinate system for a set of points; the *SpatialObject* class associates a local coordinate system with each point set.

The main job of a coordinate system is to relate points. To do this, it maintains a list of coordinate transforms between it and other coordinate systems. To achieve high run-time speed efficiency, a coordinate system can maintain transforms between it and several other coordinate systems. Alternatively, it can trade off speed of operation for lower space requirements by storing only a few transforms and letting the visual memory follow a chain of transforms among related coordinate systems.

To reduce the cost of multiple transforms, an application can adopt a unified coordinate system to relate a number of nearby local coordinate systems. This unified coordinate system would maintain transforms to and from each local coordinate system. In this manner each coordinate system would not need to keep a large list of transforms, and only two transforms would be needed to relate points in one coordinate system to those in any other. A limitation of this approach is that it does not scale well for large distances, because the error induced by each transform could

compound significantly.

The *CoordinateSystem* class provides methods to transform a coordinate system's relationship with other coordinate systems. For example, one coordinate system might translate and rotate with respect to others. Transforming a coordinate system modifies its list of coordinate transforms, and all coordinate transforms between it and other systems must be updated. This is automatically provided by the visual memory as part of the transformation method.

Transforms like translation and rotation are *CoordinateSystem* methods rather than *PointSet* methods for a number of reasons. The coordinate system relates the point set to other coordinate systems, and it is probably more efficient to store a transform than a transformed point set for each other coordinate system. It is also more efficient to accumulate a set of transforms into one transform than to repeatedly apply transforms to a whole set of points. If the points are represented by a function, it could be hard to determine how the transform should modify that function. The transform could be applied only when needed; if it were used repeatedly, the results could be cached.

Coordinate system transforms permit the construction of multiple-object scenes. Each spatial object is developed in its local coordinate system, and then coordinate system transforms construct relations between local coordinate systems. The opposite effect occurs when multiple sets of points in one coordinate system are split into separate spatial objects with local coordinate systems. In this case, the transformation from each local coordinate system to the original unified coordinate system is already defined. Standard computer graphics texts, such as [11], discuss coordinate system transforms and the construction of multiple-object scenes in further detail.

3.3.2 Relative Spatial Specification

In many cases, a coordinate system has explicitly-defined relationships to other coordinate systems. For example, one coordinate system might have an origin 3 units to the east of the origin of another coordinate system. In other instances, however, this information is not so clear. For example, an application might only need to know

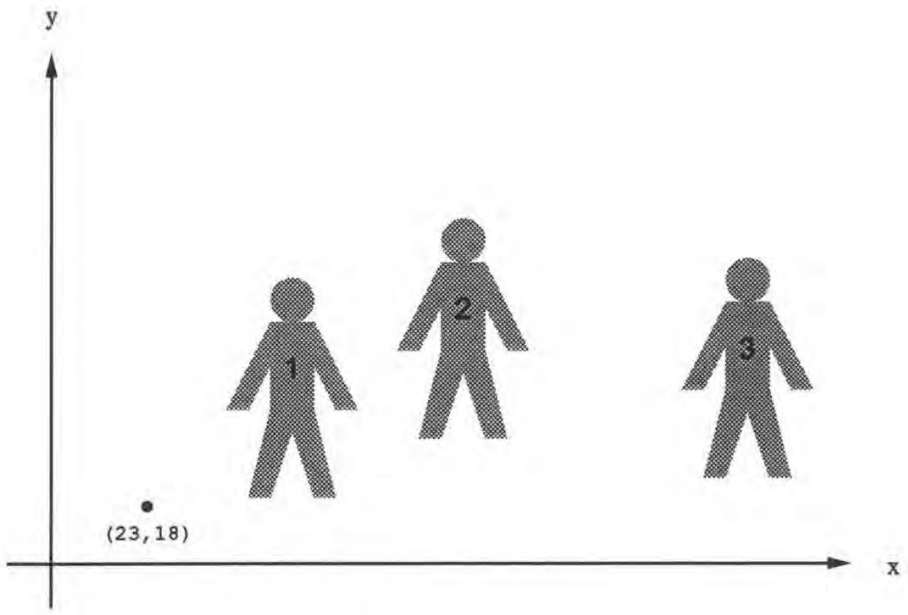


Figure 3-5: Relative spatial objects

that one block was to the east of another block, without knowing an explicit distance. In these cases a relative spatial specification is required.

There are actually two kinds of relative spatial specification: specification relative to a concrete position or object with concrete position, and specification relative to another relative spatial specification. For example, in Figure 3-5 the visual memory knows that object 1 is to the east of the point (23,18), object 2 is to the east of object 1, and object 3 is to the east of object 2. This description does not precisely specify the scene; for example, object 2 could be further to the north and east and still meet the specification.

The visual memory provides the class *RelativeSpatialObject*, a subclass of *SpatialObject*, to handle relative spatial specification. A relative spatial object simply keeps lists of objects relative to it in various ways. For example, one subclass of *RelativeSpatialObject* might provide lists for objects west, east, north, and south of it, while another subclass might provide a list for nearby objects, where "near" is defined by a method of the class. *RelativeSpatialObject* can represent both kinds of relative

spatial specification mentioned above, since an instance can be defined relative to any spatial object, including a fixed position or another relative spatial object.

An application can construct arbitrary graphs of relative spatial objects. For example, in Figure 3-5, object 1 is to the west of object 2, which is to the west of object 3, and so forth. *RelativeSpatialObject* provides methods to trace through the transitive closure of a graph operation. In the above example, since object 1 is to the west of object 2 and object 2 is to the west of object 3, it follows that object 1 is to the west of object 3. Both objects must keep track of the relationship so that the connection can go in either direction; in the above example, it also follows that object 3 is to the east of object 1. If a large number of links separate two related objects, an application might want to establish a direct connection. Alternatively, the visual memory could cache this information.

The design of *RelativeSpatialObject* must determine how to handle transformation of an object in a relative object graph. In Figure 3-5, object 2 was to the east of object 1. If object 2 moved west, it could be either to the east or to the west of object 1, as shown in Figure 3-6 and Figure 3-7 respectively. When an object is transformed, the visual memory must eliminate all of its relative dependencies. If objects maintain their relationship after transformation, that relationship must be reasserted. If objects are somehow connected so that the relationship is always maintained, they should be established as subobjects of a larger object that maintains the relationship.

3.3.3 Uncertain Spatial Specification

Some computer vision applications do not know exactly where objects are located and exactly which points are in the point sets. They deal with approximate information and conflicting evidence from multiple sources. These applications require uncertain spatial specifications.

The visual memory class *ProbabilisticPointSet*, a subclass of *PointSet*, represents uncertain spatial information. *ProbabilisticPointSet* associates with each point the probability that it belongs to the point set. Thus instead of just knowing that point (3,4,5) was in a point set, a probabilistic point set would know that point (3,4,5) was

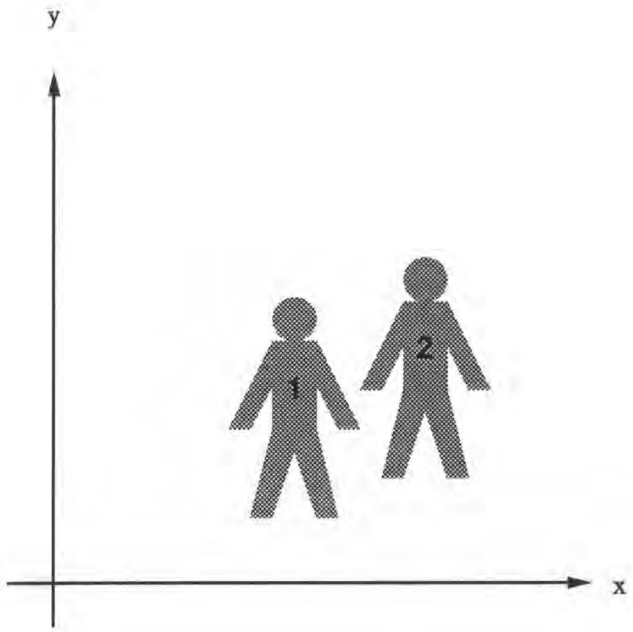


Figure 3-6: Breaking a relative spatial specification, part 1

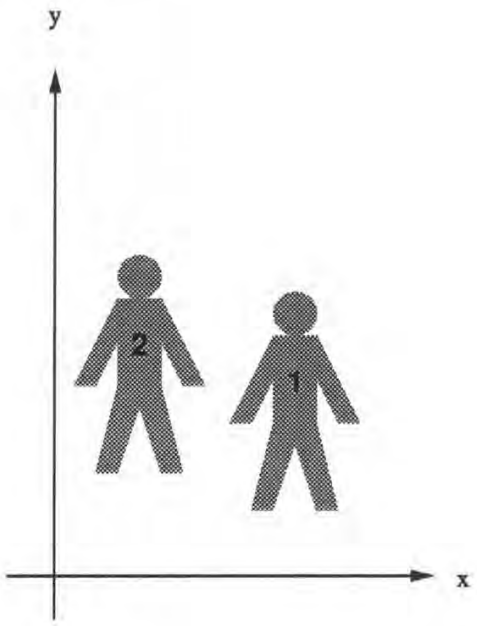


Figure 3-7: Breaking a relative spatial specification, part 2

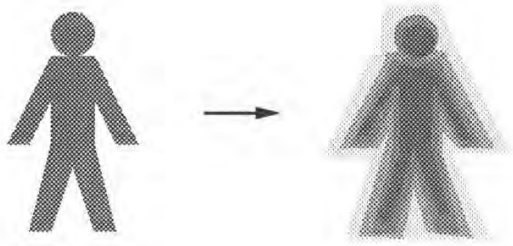


Figure 3-8: Uncertain edges

in the point set with probability 0.7. Point probabilities allow applications to specify empirical certainty factors for point sets. As will be shown below, this provides great flexibility in representing uncertain spatial information.

The standard *PointSet* methods must be modified to take point probabilities into account. The methods can reflect uncertainty in various ways. For example, there is no real boundary to a point set with point probabilities asymptotically approaching 0. However, an application can define the boundary as the set of points with probability 0.1. Subclasses of *ProbabilisticPointSet* support such variations.

Like *PointSet*, *ProbabilisticPointSet* has both discrete and abstract subclasses. The discrete subclass maintains a list of <point, probability> pairs, while the abstract subclass defines a function that returns a probability for a given point. Set operations can combine the point probabilities from different point sets by maximizing, minimizing, or averaging, among other operations.

Probabilistic point sets can handle a number of different types of uncertain spatial specification. The following sections examine a few of these.

Uncertain Edges

ProbabilisticPointSet lets applications be fuzzy about the region of space occupied by an object. For example, the probability function can decrease at the edges of an object, where a segmentation algorithm might be unsure of exactly how to separate regions. Figure 3-8 shows examples of a standard person and a person with uncertain edges, where darker regions have higher probability.

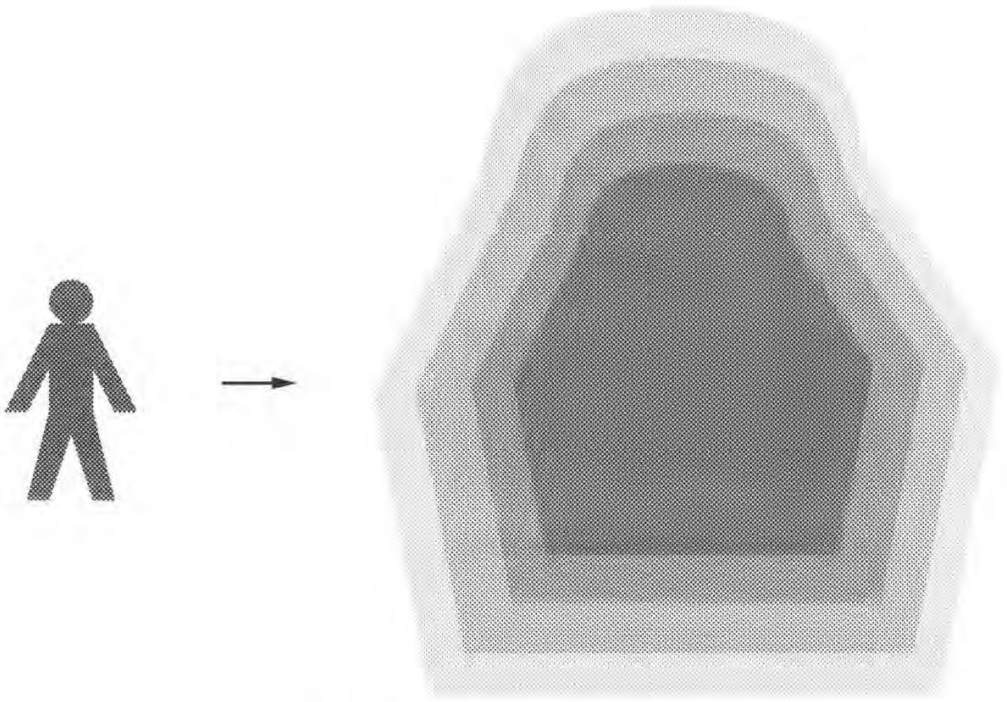


Figure 3-9: Uncertain location

Uncertain Location

An application might know the points in the point set but might not be sure of its exact location. For example, a tracking algorithm might identify a group of points as a person and decide to use the default point set to represent it. However, it might know the person's location only to within a meter. The point set for this particular person can be "spread out" to cover the range of possibilities. An application can indicate the areas most likely to contain the object by giving them the highest probability. Figure 3-9 shows a person and a "spread out" probabilistic point set, with darker regions for points with higher probability.

Conflicting Information

An application might have separate processes providing inconsistent information to the visual memory. For example, one process in a vehicle navigator might identify a

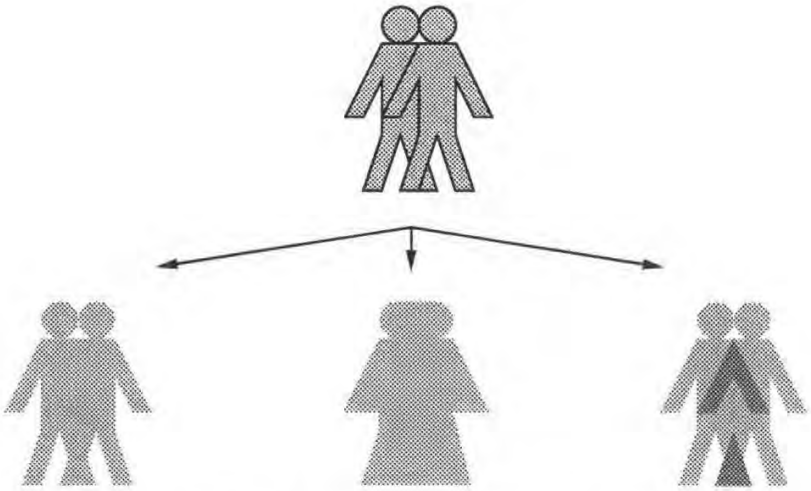


Figure 3-10: Conflicting information

car at one location, while another process might identify the same car at a slightly different location. *ProbabilisticPointSet* handles this situation similarly to uncertain location, but it must combine only a discrete set of point sets rather than spreading out one point set over a continuous area.

ProbabilisticPointSet provides several different ways to combine point sets. For example, it can combine point probabilities by maximizing, minimizing, summing, or differencing (with probabilities staying between 0 and 1), or it can interpolate between the point sets. These approaches to combining probabilities are similar to those taken by expert systems [7] and multi-valued logics [14].

Figure 3-10 shows two point sets to be combined and the results of three different types of combination. The points in the original point sets have the same probabilities. The leftmost combination is formed by maximization; since the probabilities are all the same, this is equivalent to a point set union operation. The middle combination interpolates horizontally between the two point sets. The rightmost combination adds probabilities, assigning higher probabilities to the areas where the point sets overlap.

3.4 Temporal Representations

Temporal representations fit into another branch of the visual memory class hierarchy. There are some parallels between the spatial branch and the temporal branch, but the temporal branch has many of its own requirements and features. This section presents the visual memory temporal representations. Like spatial operations, many temporal operations are complex and require the indexing mechanism of Section 3.8 to achieve high performance.

3.4.1 Core Temporal Classes

TemporalObject

The class *TemporalObject* is the basis for high-level representation of temporal information in the visual memory. Visual memory is concerned with *valid time*, the time at which events happen. *TemporalObject* provides slots and methods defining a standard interface for visual memory temporal support. Its subclasses extend the definition to handle additional temporal information. Any class that needs to keep track of its valid time should inherit from *TemporalObject*.

TemporalObject represents valid time as a set of time intervals and a local clock. It provides methods to manipulate this information, setting and retrieving the valid time, relating the clock to other clocks, and so forth. Most of these methods are furnished by the lower-level classes that make up *TemporalObject*, discussed further in the following sections.

VMTime

The most elementary temporal representation is the class *VMTime*, an abbreviation for *Visual Memory Time*. An instance of this class represents exactly one point in time. Like its spatial counterpart *Point*, *VMTime* is a fairly simple but essential building block in the visual memory class hierarchy.

TemporalInterval

Most objects are valid not for just one point in time but rather for some duration of time. The visual memory provides the class *TemporalInterval* to represent temporal extents. *TemporalInterval* is defined as an open interval $[t_1, t_2)$ to denote valid time from time t_1 to time t_2. The interval is open because applications generally recognize when an object is first valid (t_1) and when it is first invalid (t_2); its valid interval then extends from t_1 up to but not including t_2.

TemporalInterval provides a variety of methods for manipulating temporal information. Standard methods set and retrieve the starting and ending times of the interval. Additional methods check interval overlap, combine overlapping intervals, and check the equality of intervals.

TemporalElement

While some temporal databases use the temporal interval as the main temporal representation, that is insufficient for all visual memory applications. One problem is that the difference of two temporal intervals might not be a temporal interval: if interval 1 covered [10, 30) and interval 2 covered [15, 25), the difference would be [10,15) $\cup$ [25,30). The same problem occurs with disjunction, when an object is valid for multiple distinct intervals. The visual memory follows Elmasri [10] and goes one step further than *TemporalInterval* to provide a more powerful temporal representation.

The class *TemporalElement* maintains a temporal object's valid time in the visual memory. A temporal element consists of a set of temporal intervals. Thus it is closed under set operations and can represent complex temporal specifications. Each of the less expressive temporal representations is a subcase of *TemporalElement*: *TemporalInterval* is a singleton *TemporalElement* and *VMTime* is a singleton *TemporalElement* with the same starting and ending point. Figure 3-11 depicts an example temporal element.

TemporalElement furnishes many methods for manipulating its temporal information. It is a subclass of the generic *Set* class, so it provides standard set operations such as member, conjoin, disjoin, and difference. In addition, by using *TemporalEle-*

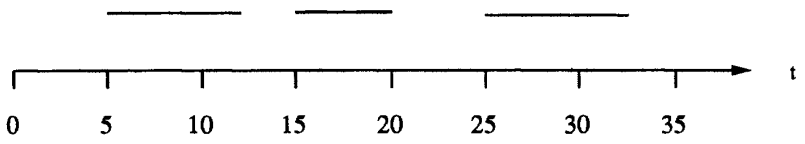


Figure 3-11: Temporal element

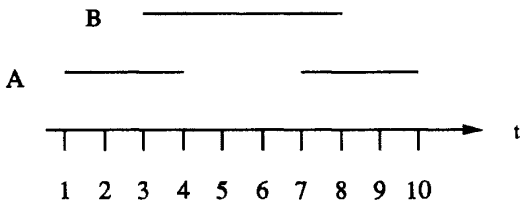


Figure 3-12: Overlapping temporal elements

ment methods, an application can set and retrieve valid times, compare valid times, combine overlapping intervals in a temporal element, and resolve two temporal elements, eliminating overlapping times from one in favor of the other.

Resolution of conflicting temporal elements is an important concept in the visual memory. An application can specify what to do in case of conflict between valid times: it can resolve in favor of the original valid time, it can resolve in favor of the new valid time, or it can leave them in an inconsistent state. Figure 3-12 shows two overlapping temporal elements, version A and version B; Figure 3-13 and Figure 3-14 show the two ways in which they can be resolved. Temporal resolution is especially useful for an application that is initially unsure of the full extent of an object's valid time. The application could assume that the object was valid from a given point until told otherwise and then later resolve that when it learned more information.

Like its spatial counterpart *PointSet*, *TemporalElement* has both discrete and abstract subclasses. The class *DiscreteTemporalElement* lists all the temporal intervals in the set, while the class *AbstractTemporalElement* uses a function to determine whether or not a given temporal interval is in the set. Since time is one-dimensional

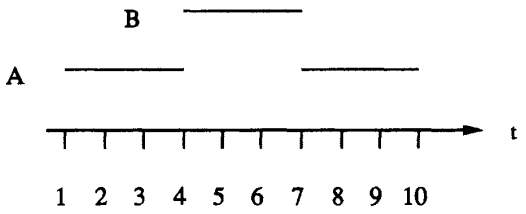


Figure 3-13: Temporal resolution in favor of version A

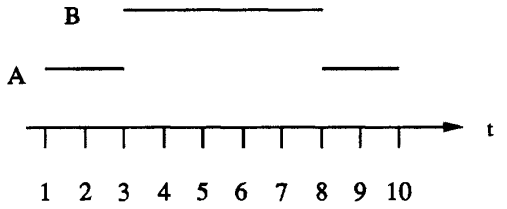


Figure 3-14: Temporal resolution in favor of version B

and most valid times are in just a few continuous blocks, the discrete class is probably more useful for most applications. The abstract class is available for applications that need to represent a large number of disjoint intervals.

Clock

A time point makes sense only with specification of the clock on which it was measured. The visual memory provides the class *Clock*, the temporal analog of the spatial class *CoordinateSystem*, to represent this information. Each clock can assign a different meaning to time points: one clock might use milliseconds since January 1, 1900, while another might use seconds since March 8, 1970. In addition, a *Clock* instance can specify the machine on which the clock is located so that applications can try to account for inaccuracies and differences between system clocks.

The *TemporalObject* class associates a clock with a temporal element. Clocks are associated at this level of granularity because *TemporalElement* is the main visual memory temporal representation. Using a finer granularity would hurt performance

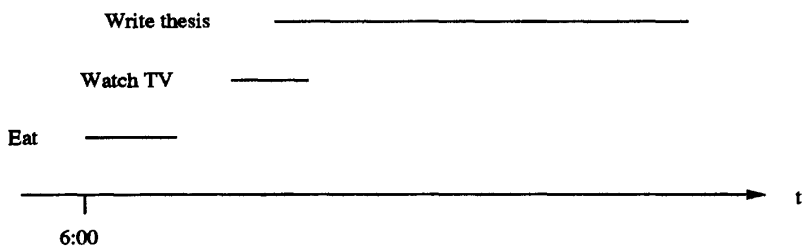


Figure 3-15: Relative temporal specification

for complex temporal specifications and would not greatly improve performance for simple temporal specifications that can be represented as trivial temporal elements.

Like each coordinate system, each clock provides a set of transforms between it and other clocks. This establishes meaning behind the time points associated with a clock and allows the visual memory to convert times among clocks. To increase performance, applications can use the same or compatible clocks.

3.4.2 Relative Temporal Specification

Some applications, such as planners and schedulers, do not know explicit temporal information but can specify some relative ordering of events. For example, a planner might know that it must move to the other side of the room, which will take 5 seconds, before it can pick up a block. To support these applications the visual memory provides classes representing relative temporal specifications.

There are two kinds of relative temporal specification: specification relative to a definite time or object with a definite time, and specification relative to another relative temporal specification. For example, Figure 3-15 illustrates that I plan to eat dinner after 6:00, watch TV after that, and start writing my thesis while I watch TV. This description does not precisely specify the times of these events; if I took a longer break between eating and watching TV the relative specification would be the same.

The visual memory class *RelativeTemporalObject*, a subclass of *TemporalObject*,

supports relative temporal specification. A relative temporal object maintains a list of other objects to which it is temporally related. For example, one subclass of *RelativeTemporalObject* might keep track of events before and after it, while another might maintain a list of events happening at approximately the same time.

RelativeTemporalObject allows applications to build arbitrary graphs of temporal relations. For example, the specification in Figure 3-15 directly relates a time and three temporal objects. *RelativeTemporalObject* also provides methods to trace through the transitive closure of a graph. In this example, it could report that I will study after 6:00. Both related objects must keep track of the relationship so that the link can be traversed in either direction. In this manner, the visual memory could also report that 6:00 is before the time when I will study.

3.4.3 Uncertain Temporal Specification

In many cases an application might be unsure about the valid time of an object's state. This could happen, for instance, if the application did not notice an abrupt change of state or could not pinpoint the time of the state change. The visual memory provides two classes, *ProbabilisticTemporalInterval* and *ProbabilisticTemporalElement*, to support uncertain temporal information. Like their spatial counterpart *ProbabilisticPointSet*, these classes follow in the tradition of multi-valued logics and expert system certainty factors.

ProbabilisticTemporalInterval

ProbabilisticTemporalInterval extends the definition of an interval to include a function that, given a time, returns the probability that the interval includes that time. Thus, as shown in Figure 3-16, a probabilistic temporal interval can specify that the valid time most likely includes [10,25), is increasingly less likely to include times on the other sides of 10 and 25, and definitely does not include times outside of [5,30). This probability drop-off could indicate where the application was trying to determine state-change boundaries. The deterministic temporal interval is merely a special case where the probability is 1 during a specific interval and 0 elsewhere.

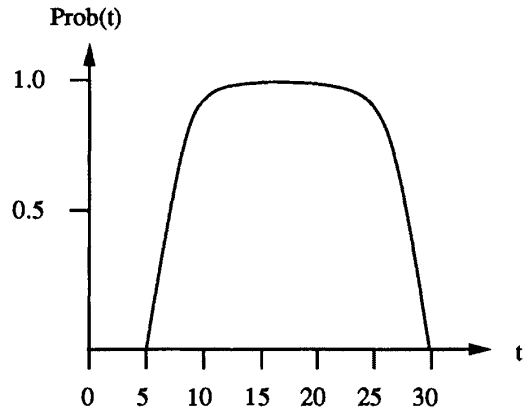


Figure 3-16: Probabilistic temporal interval

ProbabilisticTemporalInterval modifies standard *TemporalInterval* methods to use the temporal probability function. For example, a probabilistic temporal interval does not have clearly-defined endpoints; the method to find endpoints uses a threshold supplied by the application to separate points in the interval from those outside it.

ProbabilisticTemporalElement

ProbabilisticTemporalElement, a subclass of *TemporalElement*, contains a set of probabilistic temporal intervals rather than a set of temporal intervals. This allows a temporal object to represent the probability that it is valid during a time in a set of disjoint intervals.

The methods of *ProbabilisticTemporalElement* are specialized to handle temporal probability. For example, multi-valued logic systems often define probabilistic conjunction as a minimization operation and probabilistic disjunction as a maximization operation [14]. Figure 3-17 shows two overlapping temporal elements; Figure 3-18 demonstrates conjunction by minimization and Figure 3-19 shows disjunction by maximization.

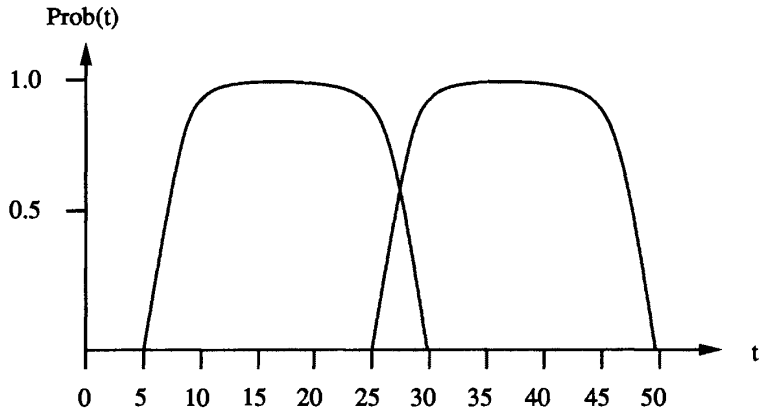


Figure 3-17: Overlapping probabilistic temporal intervals

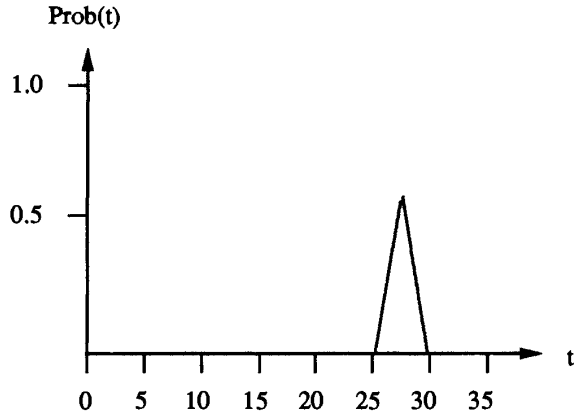


Figure 3-18: Probabilistic conjunction by minimization

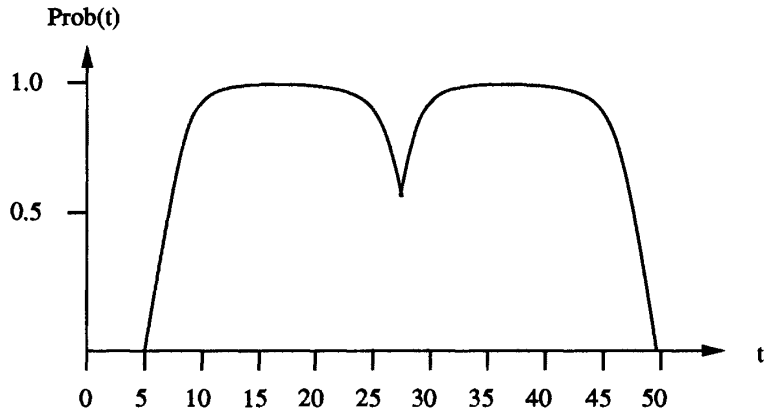


Figure 3-19: Probabilistic disjunction by maximization

3.5 Spatiotemporal Representations

Many objects stored in the visual memory have both spatial and temporal components. For example, a vehicle navigator might watch other vehicles driving nearby and a security system might track people walking in a hall. In both of these cases, objects are moving in space over an extent of time. The meshing of spatial and temporal information in these cases suggests that, in addition to spatial and temporal support, the visual memory should provide spatiotemporal support.

The class *SpatiotemporalObject*, a subclass of both *SpatialObject* and *TemporalObject*, represents spatiotemporal information in the visual memory. Because it is a subclass of both *SpatialObject* and *TemporalObject*, it contains the same information, including a point set, a coordinate system, a set of valid times, and a clock. It also supports all the *SpatialObject* and *TemporalObject* methods for manipulating this information.

The class *DiscreteSpatiotemporalObject*, a subclass of *SpatiotemporalObject*, stores state snapshots of objects. For example, a vehicle navigator could use an instance of this class to periodically store information indicating the spatial extent of the vehicle over some interval of time. In this way it could build up a whole history of the vehicle's motion.

DiscreteSpatiotemporalObject provides interpolation methods to estimate additional spatiotemporal information from existing information. For example, from the information in Figure 3-20, the visual memory could interpolate the snapshot of Figure 3-21. *DiscreteSpatiotemporalObject* subclasses implement a variety of interpolation procedures; for example, the circle in Figure 3-21 could be interpolated by radius or by area, and acceleration over several snapshots could be taken into account. Interpolation allows applications to store spatiotemporal information more sparsely and still closely approximate necessary information.

Like *SpatialObject* and *TemporalObject*, *SpatiotemporalObject* also provides an abstract subclass to represent information by means of a function. *AbstractSpatiotemporalObject* uses a trajectory method to determine which points are in its point set

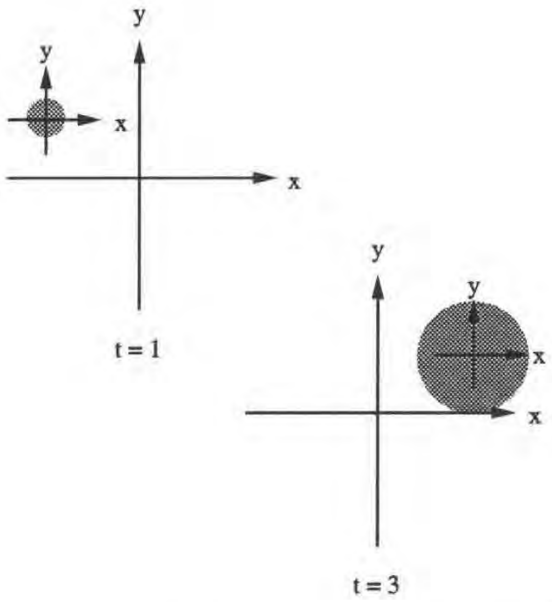


Figure 3-20: Discrete spatiotemporal information

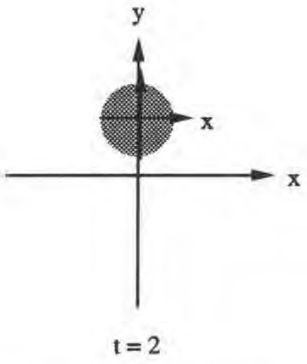


Figure 3-21: Interpolated spatiotemporal state

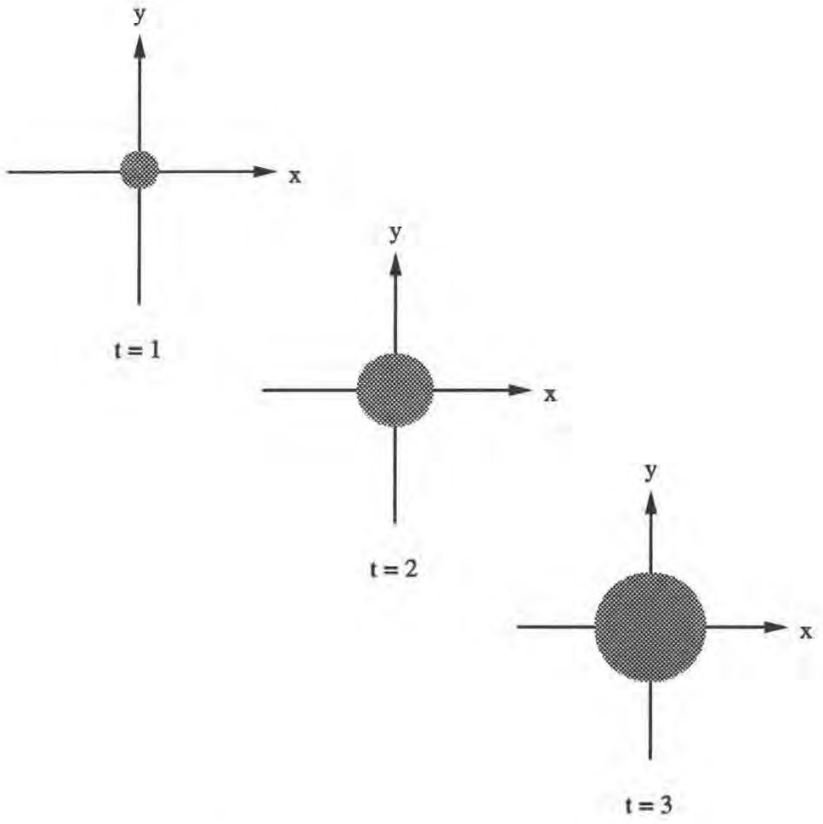


Figure 3-22: Point set trajectory

at specified times. The trajectory specifies how the object's point set and coordinate system change with time. Thus an abstract spatiotemporal object is equivalent to a set of discrete spatiotemporal state snapshots.

The spatial description of an object can change over time in two different ways: the point set itself can change, or the point set's relation with other points can change. The circle with an expanding radius shown in Figure 3-22 is an example of a changing point set, while the translating circle shown in Figure 3-23 demonstrates changing relationships. A trajectory for an abstract spatiotemporal object can handle either or both types of change.

The trajectory can modify a point set over time by supplying a time point as an additional argument to the point set function. For example, the trajectory for the

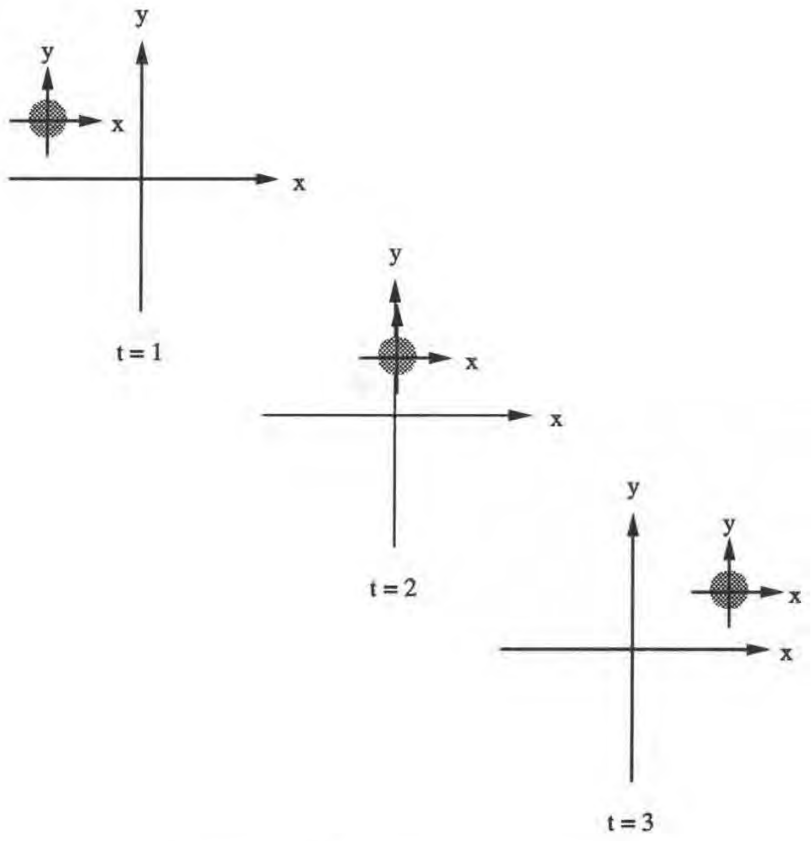


Figure 3-23: Coordinate system trajectory

circle with expanding radius in Figure 3-22 could check $x^2 + y^2 <= t$ to determine all points (x, y) in the point set at time t. If the changes in the point set follow some pattern, the spatiotemporal point set function can capture that pattern; otherwise, the discrete approach is probably more suitable.

The trajectory can change relationships between point sets over time by establishing a function to specify coordinate system transforms as a function of time. In Figure 3-23, the trajectory would translate the coordinate system one unit along the x-axis every second. This can be implemented by establishing an initial coordinate system and its relationships to other coordinate systems and then identifying differences between the coordinate system at a given time and the initial coordinate system. This way the trajectory does not have to establish all the coordinate system's relations at each time; instead, it can transform from a given coordinate system to the established coordinate system and from it to any other related coordinate system.

Visual memory provides the class *RelativeSpatiotemporalObject* to express spatiotemporal relationships. For example, an application could describe a relative spatiotemporal object as being to the right of another object sometime after 6:00. *RelativeSpatiotemporalObject* and its subclasses simply combine the relative spatial and temporal classes detailed in earlier sections.

Spatiotemporal representations can benefit from probabilistic methods. The visual memory class *ProbabilisticSpatiotemporalObject* combines the spatial and temporal probabilistic methods previously described. It allows applications to express uncertainty about both the spatial and temporal extents of spatiotemporal objects. Probabilistic functions are especially useful with spatiotemporal interpolation, allowing a measure of uncertainty to accompany an interpolated object description. Abstract spatiotemporal objects can establish probabilistic trajectories to be imprecise about the changes in an object's spatial description over time.

3.6 Object Storage

An important part of the visual memory design addresses how to store and retrieve spatiotemporal information. The object-oriented database on which the visual memory builds provides basic support for object storage and retrieval. This section discusses the concepts and issues most relevant to the visual memory design.

3.6.1 Identity

Each object in the visual memory has a unique identity. This identity does not necessarily correspond to physical identity; for example, an application might not recognize a person appearing in its view as the same person who disappeared moments ago, causing it to create a new object for the person. To preserve identity, the visual memory assigns each object an object identitifier (OID), a number that distinguishes that object from all others. The object maintains the same OID through all of its state changes.

Each object can have multiple versions. For example, a security system could track a person walking down a hall and store a new version describing that person's location every tenth of a second. The versions of an object maintain the same OID, but each has a different version number. Thus an <OID, version number> pair uniquely distinguishes a particular state snapshot of a particular object. By maintaining all of an object's versions, the visual memory can answer questions about the object's history.

Some visual memory applications might need to combine the histories of different objects to form the history of one object. This could happen, for example, if a tracking system lost sight of a person, found a new person and created a new object, and later realized that the two people were actually the same. The visual memory can consolidate object histories to create versions of one object from versions of other objects.

An application can report to the visual memory that an object has disappeared. Making an object disappear is quite different from deleting that object, which actu-

ally removes old versions of the object from the visual memory. Disappearing does not affect an object's history but instead removes it from the current state of the visual memory. Visual memory queries after an object's time of disappearance do not retrieve that object.

3.6.2 Storage Mechanism

The database underlying the visual memory decides how to store objects. To implement an appropriate storage policy, the database should consider the visual memory's storage needs and the characteristics of the objects that it stores. This section discusses how object storage should be tailored for the visual memory.

Many visual memory objects change very little from one version to the next. For example, a rigid object moving across the room changes only its coordinate system and valid time; the point set, clock, and other information remains the same. In cases like this, the database should store one base version of the object and then indicate differences for each new version.

The visual memory obeys a nondeletion policy: it creates a new version each time an object changes, and it never deletes old versions. Deleting a version would cause problems for other object versions containing references to it. The visual memory is not an append-only database since it actually modifies old versions, as discussed below in section 3.6.3. Only the visual memory can modify old versions, since uncontrolled modification could lead to inconsistencies. These considerations allow the database to implement a simpler storage policy.

Some visual memory applications store a great amount of data. Since old information might never be deleted, the available space can quickly fill. Once old information has settled down and will not be accessed or modified often, the database can move it onto long-term, high-capacity storage devices. This keeps the most useful information readily available while increasing the amount of information that can be stored.

3.6.3 Time

As a historical database, the visual memory keeps track of when events happened. It stores with each version of a temporal object information about that version's valid time. Since one version's valid time might conflict with the valid times of other versions, the visual memory attempts to ensure consistency by resolving these valid times. Section 3.4.1 discusses temporal resolution strategies.

The valid time of a new version could conflict with the valid times of many old versions. The indexing strategies discussed below in Section 3.8 allow the visual memory to quickly identify which old versions must be changed. The necessity of resolving old temporal information encourages the use of caching techniques to reduce the number of disk accesses.

Applications can improve the performance of temporal resolution by operating in "real-time mode." In real-time mode, the valid time of the latest version of an object is an infinite interval starting from the current time. Thus each new version must be resolved only with the previous version. For example, if the first version were valid $[0, \infty)$, then a second version valid $[5, \infty)$ would change the first version's valid time to $[0, 5)$, a third version valid $[10, \infty)$ would change the second version's valid time to $[5, 10)$, and so forth. Performing only one temporal resolution per object update can greatly improve storage performance.

3.7 Queries

The visual memory provides a powerful and expressive mechanism for retrieving information. This query mechanism is tailored to the spatial and temporal representations presented in earlier sections. It is also designed to meet a wide variety of retrieval needs, providing flexibility in specifying objects of interest. This section describes the query mechanism and the types of queries supported by the visual memory.

3.7.1 Query Mechanism

The visual memory query mechanism extends a standard SQL-based [1] object query language, such as OQL [2]. The queries below demonstrate the basic form and functionality of such a query language.

Find everyone with the same age as the object stored in program variable "me":

```
Select p from Person
  where p.age() == %me.age()
```

Find everyone named Larry who used to play professional basketball:

```
Select p from Person
  where p.firstname() == "Larry" and
    p.occupation().title() == "pro basketball player" and
    p.occupation().status() == "retired"
```

Find the children of the above people:

```
Select p from Person
  where p.father() in
    (Select p from Person
        where p.firstname() == "Larry" and
            p.occupation().title() == "pro basketball player" and
            p.occupation().status() == "retired")
```

The database literature contains many examples demonstrating the power of query

languages. The visual memory query language extensions allow applications to construct complex spatiotemporal queries.

A query language provides flexibility and expressiveness but can be hard to use. For applications that do not need the full power of a query language, graphical query specification might be more suitable. A graphical query could be specified by outlining regions of space and intervals of time; objects satisfying the specification could also be displayed graphically. A graphical query language could be built over the visual memory query language by transforming graphical specifications into visual memory queries. Chapter 4 discusses an implementation of such a graphical query language.

A query mechanism works on two levels, on disk and in memory. The visual memory indices, discussed further in Section 3.8, provide information to help the query mechanism eliminate objects that do not satisfy a query before bringing them into memory. The query mechanism then further filters these objects to determine which objects satisfy the specification. A number of the query constructs outlined below could easily be performed in memory but are implemented as part of the query language to allow the query language to optimize object retrieval.

Rather than adding a large number of special spatial and temporal constructs to the query language, the visual memory bases its query support on instances of the spatial and temporal classes discussed in previous sections. Each query includes spatial or temporal keywords and a spatial or temporal object; the keyword describes how instances satisfying the query must interact with the given object. The specified spatial or temporal object could be a program variable, allowing the application to form a complex specification before posing the query. Alternatively, it could be the result of another query, allowing an application to compose queries. These mechanisms provide great flexibility in spatial and temporal query specification.

3.7.2 Spatial Queries

Instances of the class *SpatialObject* form the basis for all spatial queries. A query specifies a spatial object of interest and how objects satisfying the query must interact with that spatial object. Described below are the ways that applications can use a

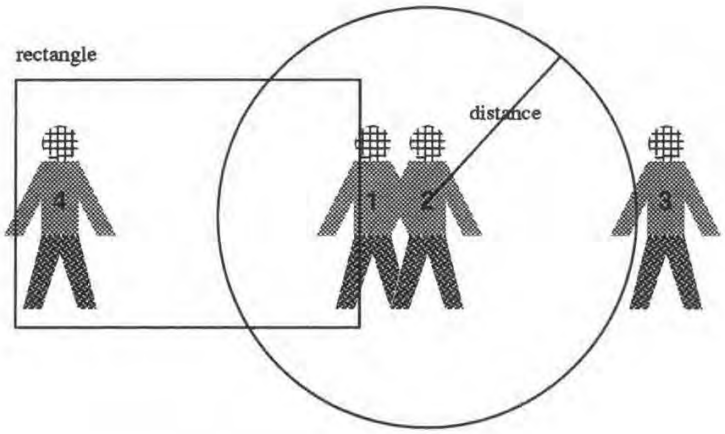


Figure 3-24: Spatial queries

specified spatial object to retrieve objects of interest. The accompanying examples demonstrate the query language syntax and reference objects of Figure 3-24.

Intersects Query

The *intersects* query looks for the intersection of spatial objects. For example, the following query returns the set { person-1, person-4 }:

```
Select p from Person
  where p intersects %rectangle
```

This is one of the most broadly useful spatial query constructs. The specified spatial object can be a point, line, pentagon, pyramid, or just about any other spatial specification imaginable. This construct is also useful when negated. For example, the set { person-2, person-3 } satisfies the following query:

```
Select p from Person
  where not p intersects %rectangle
```

A security system could use intersection to find all the objects within a room, and a vehicle navigator could use negated intersection to make sure that nothing was on

the road in front of the vehicle.

Borders Query

The *borders* query checks for bordering objects. The set { person-4.torso() } satisfies the following query:

```
Select p from Person
  where p borders %person-4.head()
```

A VLSI system could use this query construct to look for electrical contact, and a photo interpretation system could use it in constructing a high-level representation of connected regions. Applications can use probabilistic point sets to specify imprecise borders for this query.

Centroid-Within Query

The *centroid-within* query ignores the spatial extent of objects and checks distances between centroids. For example, the following query returns the set { person-1 person-2 }:

```
Select p from Person
  where p centroid within %distance of %person-2
```

This distance parameter specifies within how many units, using the specified spatial object's coordinate system, an object must be to satisfy the query. With this query, applications can quickly gather objects roughly within a given distance from a specified object. The estimation is fairly accurate if the point sets are much smaller than the distance between them.

Point Set-Within Query

To select nearby objects with greater accuracy than the *centroid-within* query provides, applications can use the *point set-within* query. The following example selects the set { person-1, person-2, person-3 }:

```
Select p from Person
  where p point set within %distance of %person-2
```

This query is similar to the *centroid-within* query, but it retrieves all objects that have at least one point within the given distance of any point of the specified spatial object. To select objects meeting some specialized definition of nearness, an application can construct any spatial object and perform an *intersects* query; this is just a specialized, optimized version of that process.

Transitive-Closure Query

The *transitive-closure* query compounds any of the above specifications, applying a query to its results until there are no new results. It returns all objects identified in the process. For example, the transitive closure of a *borders* query shown below returns the set { person-4.torso(), person-4.legs() }:

```
Select p from Person
  where p borders by transitive closure %person-4.head()
```

This query retrieves any objects bordering the given object, any object bordering those objects, and so forth. A photo interpretation system could use it to find connected regions.

3.7.3 Temporal Queries

The visual memory temporal query mechanism retrieves all the versions of objects that satisfy some set of constraints. A temporal query specifies a *TemporalObject* instance to describe the times of interest and a keyword to describe how the valid time of a satisfying version must interact with those times. Described below are the visual memory temporal query specifications. Accompanying examples demonstrate the query language syntax using versions shown in Figure 3-25.

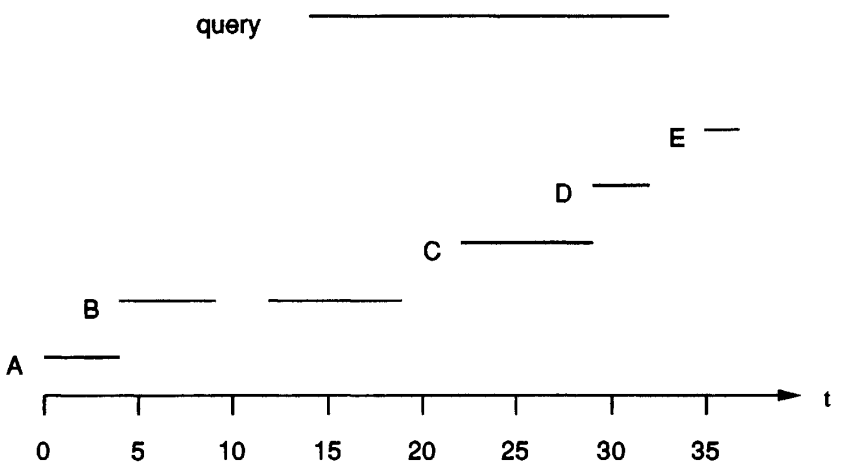


Figure 3-25: Temporal queries

During Query

The *during* query checks for versions whose valid times intersect the given valid time. For example, the following query returns the set { Version-B, Version-C, Version-D }:

```
Select p from Person during %query
```

This is a very powerful query, allowing applications to retrieve versions during any specified set of times. It is also useful in its negated form, where it returns versions whose valid times do not intersect the given valid time. The negated query below selects the set { Version-A, Version-E }:

```
Select p from Person
  not during %query
```

Latest-During Query

The *latest-during* query retrieves only the latest version of an object during some specified temporal element. For example, the set { Version-D } satisfies the following query:

```
Select p from Person
  latest during %query
```

An application could use this query to update a memory-resident model with the latest information in the visual memory. For example, a vehicle navigator could establish a model of static objects at the beginning of its execution and then use this query to update that model with the latest dynamic information stored by image processing software.

3.7.4 Spatiotemporal Queries

In addition to spatial and temporal queries, the visual memory supports spatiotemporal queries. Some of this support comes from the query language's natural ability to handle combined specifications. For example an application could pose the following query:

```
Select p from Person
  where p intersects %square
  during %times
```

This query retrieves all versions of all objects valid during the specified times and intersecting the specified square. Figure 3-26 depicts five states of a spatial object, at time $t = 1$ through $t = 5$. Figure 3-27 depicts a square valid over [1,5) and shows that the above query would return the third state of the object.

The joint spatial and temporal query checks a static spatial object over time, so it does not handle interactions between spatial and temporal information. Some applications want to track a moving object and retrieve versions near it at various times. To handle cases like this, the visual memory provides spatiotemporal queries.

A spatiotemporal query specifies a spatiotemporal object and a temporal object, and how objects must interact with these to satisfy the query. The spatiotemporal object's history describes where an object must be at given times, and the temporal object specifies a portion of the history of the spatiotemporal object. The query can use any of the spatial constructs discussed above to specify spatiotemporal interac-

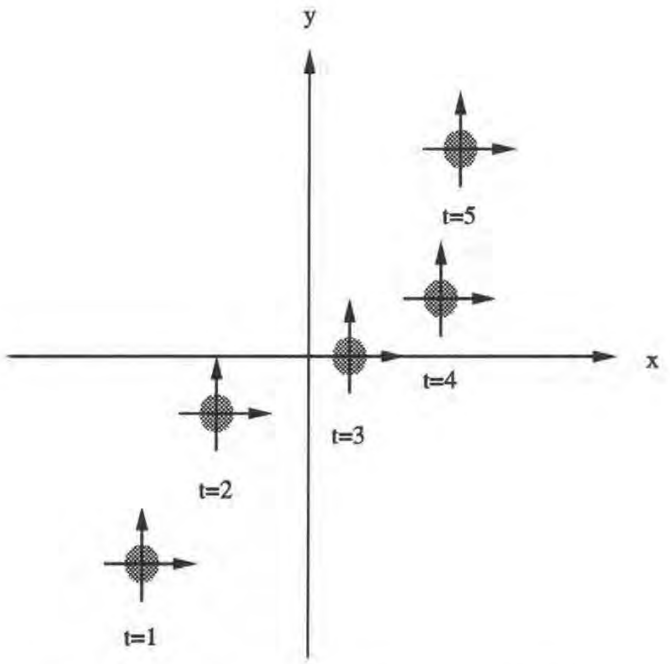


Figure 3-26: States of a spatiotemporal object

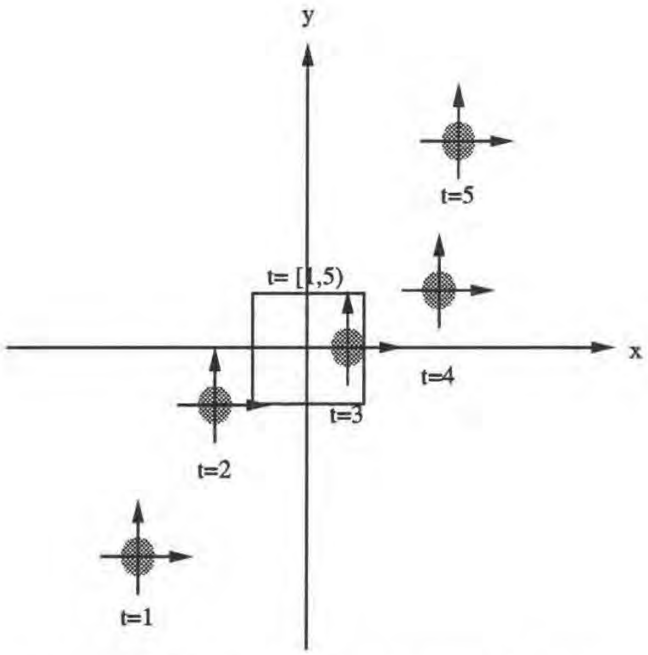


Figure 3-27: Joint spatial and temporal queries

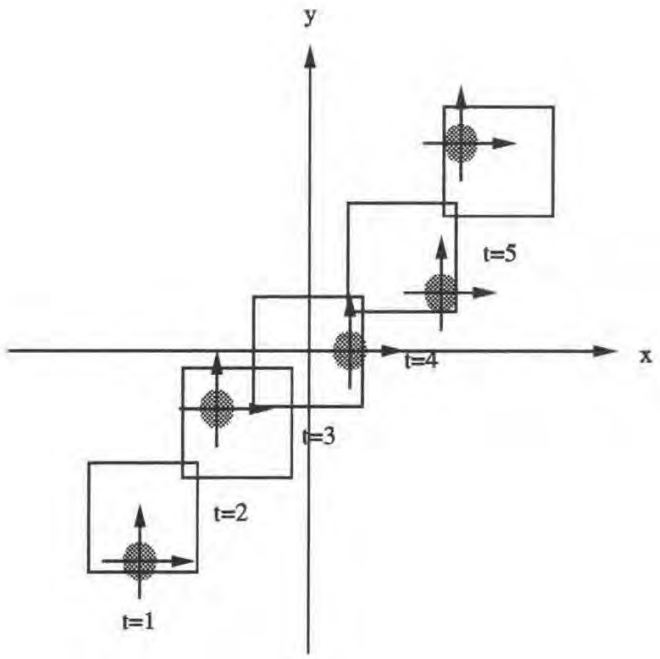


Figure 3-28: Spatiotemporal queries

tions. For example, consider the following query:

```
Select p from Person
  where p intersects %square
  during %times
```

This query construct retrieves versions of objects that intersect the square in its trajectory over a set of times. The query shown in Figure 3-28 uses as the spatiotemporal query object a square translating equally in the x and y dimensions over time. This query returns all five states of the object of Figure 3-26.

This powerful query construct can handle many complex queries, especially when combined with the join capability of the query language. For example,

```
Select p from Person
  during %times-1
  where p in
     (Select q from Person
       where q centroid within 3 of %spatiotemporal-spec
       during %times-2)
```

This query tracks all objects that came within 3 units of a given object on its trajectory during a certain set of valid times. Queries like this demonstrate the power of a query language extended with the visual memory spatiotemporal constructs.

3.8 Indices

The visual memory provides an indexing mechanism to quickly identify objects meeting sets of constraints. Indices tie in with both the query mechanism and the various spatial, temporal, and spatiotemporal operations described in preceding sections. For example, a spatial index can help identify solutions to an intersection query retrieving objects stored in the visual memory, and it can help identify intersecting memory-resident objects. The two types of indexing work similarly, so for conciseness this section primarily considers how indices can improve retrieval performance.

Indices maintain information allowing them to quickly eliminate objects that do not satisfy a query. They provide *conservative* approximate answers to queries; that is, they can mistakenly retrieve objects that do not satisfy a query, but they can never mistakenly leave out objects that do satisfy a query. The design of an index must trade off between how quickly the index can answer a query and how much overhead is necessary to maintain the indexing information. A well-designed index can greatly help query performance while adding minimal information overhead.

3.8.1 Mechanism

Visual memory indices are object-oriented: they are objects and they maintain information about objects. This yields a consistent approach to information representation. The database can store and retrieve indices just like other objects. Indices can keep track of other indices, a technique further discussed below. Finally, due to the extensible nature of the object-oriented approach, it provides flexibility in designing indices.

The purpose of an index is to maintain information to help it efficiently identify objects that might satisfy a query. In the visual memory design, this information consists of <OID, version number> records, each uniquely specifying a particular version of a particular object. An index structures these records so that it can quickly provide a set of records identifying the objects that meet specific constraints.

Indices maintain information in many different ways, such as tables, arrays, and

trees. The visual memory can handle a very large index by retrieving only a necessary, manageable part at a time. However, an index must strive to minimize the amount of retrieval required to reach an answer, so that the the cost of using the index does not outweigh the query efficiency it yields.

An application can specify which sets of objects it wants to index and how it wants to index them. It simply specifies the class of the index desired and the set of objects for which it should maintain information. For example, consider the following examples of index specification:

```
Index temporal-btree on
  (Select p from Person)

Index spatial-grid on
  %my-set

Index spatial-quadtree on
  (Select o from Object
     where o intersects %my-room)
```

The first example establishes a temporal index for all people; the second establishes a spatial index on a specific set specified by a program variable; the third indexes all the objects in a certain scene. The visual memory maintains a list of all the indices in use and knows when to update them and for which queries they are appropriate.

The following sections present issues in the design of spatial, temporal, and spatiotemporal indices. Chapter 4 discusses additional indexing issues raised by one visual memory application and describes indices designed for the application.

3.8.2 Spatial Indices

Spatial indices organize information about the objects in a scene. The literature describes many different spatial indices; see [18] for descriptions of quite a few. Different spatial indices use different parts of an object's spatial representation and thus are most appropriate for different queries. For example, a point quadtree uses an object's centroid and works best with proximity queries, while an interval tree uses spatial in-

tervals and is most suitable for intersection queries. An application must pick spatial indices applicable to its retrieval needs.

3.8.3 Temporal Indices

Temporal indices store information about object histories. The task of ordering the temporal component of an object is similar to that of ordering the spatial component, if time is viewed as just another dimension. Thus a lot of spatial indexing research applies to temporal indexing as well. For example, a spatial interval tree could store lists of versions valid during temporal intervals. However, temporal representation poses some concerns unique to temporal indexing.

Temporal indices must address the monotonicity of time. The visual memory allows applications to modify the past or predict the future, but some applications maintain an always-increasing sense of time. This could hurt the performance of some temporal indices; for example, a tree could become unbalanced. Temporal indices still need to support nonmonotonic temporal specification, but some could be optimized for the monotonic case.

Because a temporal index retains historic information, it constantly increases in size throughout its lifetime. A temporal index must not lose too much efficiency as it grows. Some temporal indices should even partition their data between short- and long-term storage, as in [9].

Temporal indices must be able to represent infinite temporal intervals. An infinite interval occurs, for example, when an application assumes that an object will be valid until otherwise notified and assigns the object a valid time extending to infinity. An infinite interval would cause problems for a temporal index representing intervals as collections of subintervals in a tree.

3.8.4 Spatiotemporal Indices

Spatiotemporal indices store spatial information about a scene as it varies in time. The interaction of space and time makes spatiotemporal indexing a complex problem.

There are two kinds of spatiotemporal indexing, corresponding to the discrete and abstract spatiotemporal classes discussed in Section 3.5.

The first type of spatiotemporal indexing stores information about versions of discrete spatiotemporal objects. The indexing is a two-step process: spatial indices maintain spatial descriptions of objects, and temporal indices maintain the temporal descriptions of the spatial indices. To perform a spatiotemporal query, the indexing mechanism finds the temporal description in the temporal indices, retrieves the corresponding versions of the spatial indices, finds the spatial description in them, and retrieves the corresponding spatiotemporal object versions.

Discrete spatiotemporal indexing must address some concerns. Spatiotemporal objects that move continuously cause constant index updates. This leads to large temporal indices, raising the issues previously discussed. The structure of a spatial index used in spatiotemporal indexing should not depend on the objects contained within it, since those objects move.

The second type of spatiotemporal indexing stores information about abstract spatiotemporal objects. An abstract spatiotemporal index could build up its own spatiotemporal function representing a set of object trajectories. Given a spatiotemporal specification, this function would return a list of those objects satisfying it. This function could grow very complex, so the index would have to devise some means of efficiently storing, retrieving, and evaluating it. In this manner an index could efficiently answer queries about abstract spatiotemporal objects.

Chapter 4

Implementation

To test the visual memory design, a subset of it was implemented in support of a real-time scene monitoring prototype. In this prototype, image processing using video cameras tracks objects and stores information about them in the visual memory. Through a graphical query interface, users can specify queries to the visual memory and view the results in various ways. Figure 4-1 shows the basic flow of information in the prototype. This chapter describes the implementation of the scene monitoring prototype and the visual memory supporting it.

Scene monitoring is a good testbed for the visual memory. Its constant updates and retrievals of information test the visual memory's performance. Multiple sensors and outputs test concurrency issues. The query interface tests the power of the query language by specifying a variety of queries, including spatial ("Watch for anything that comes within 3 feet of that button."), temporal ("Play back the last 10 seconds."), and spatiotemporal ("Did anybody come into the room between 12:00 and 1:00?"). Finally, the construction of such a prototype tests the usefulness of the visual memory spatiotemporal representations.

4.1 Database

An object-oriented database called Persistent C++, or PC++ for short [17], is the basis for the visual memory prototype. This database is a prototype for the DARPA

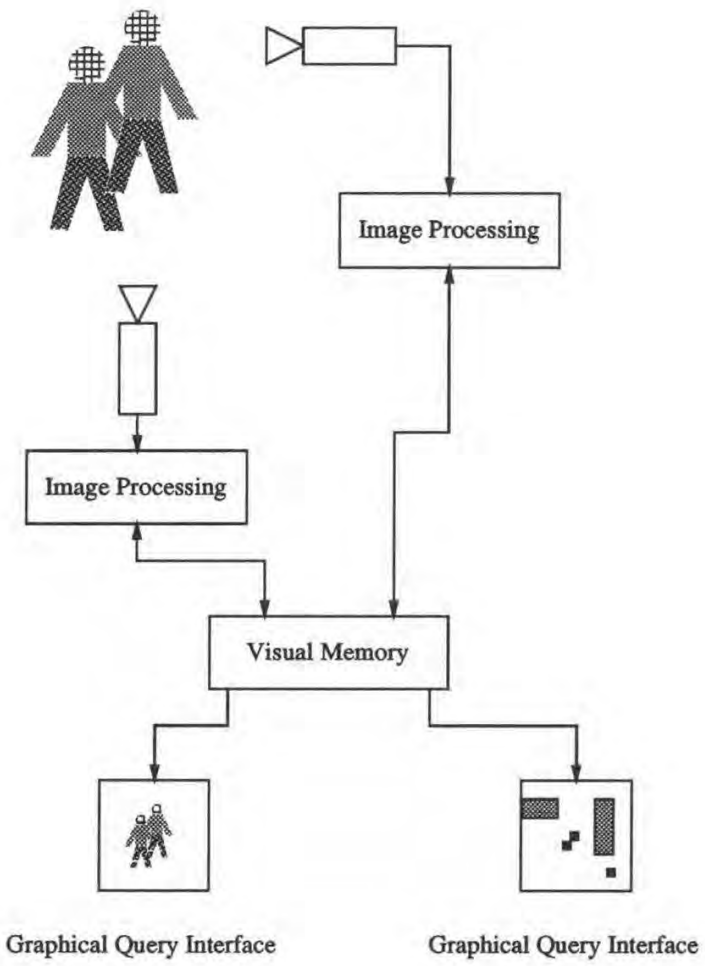


Figure 4-1: Scene monitoring prototype

Open Object-Oriented Database project at Texas Instruments [25]. PC++ has an open architecture, allowing the visual memory to add spatiotemporal extensions and take advantage of the features provided by other modules.

Some of the features provided by Persistent C++ are particularly useful to the visual memory. A versioning mechanism allows access to any previous state of any object. Transactions ensure atomicity, consistency, isolation, and durability. The object storage mechanism caches recently accessed information to increase performance.

A Persistent C++ preprocessor gathers information about the classes of objects to be stored in the database. This particular prototype preprocessor is somewhat limited, not allowing multiple inheritance or function pointers; these constraints limit the prototype in some situations. The preprocessor adds extra information to the class descriptions and forms actual C++ classes for an application to use. It adds function hooks into these classes so that the application can establish daemons to be executed when objects are stored or retrieved. Finally, when one object contains a pointer to another object, its class specification indicates either that the referenced object should be automatically retrieved with the referring object or that it should be retrieved only on demand.

Persistent C++ stores objects with the Exodus storage manager [4]. It stores a whole Exodus object for each version of a PC++ object, rather than storing differences between versions. This could hurt performance for objects that change very little from one version to the next. PC++ maintains a B-tree structure to map its OIDs to Exodus OIDs; this hurts performance as the number of OIDs grows large.

Persistent C++ can retrieve an object specified by OID and version or by a character string previously assigned to that object. It provides an object query language extension, OQL [2], but this query language does not interface well with the visual memory indexing mechanism. Thus the visual memory prototype has its own spatiotemporal query mechanism.

4.2 Spatiotemporal Representations

The prototype visual memory implements as Persistent C++ classes a number of the spatial, temporal, and spatiotemporal representations discussed in Chapter 3. These representations conform to the design except for some differences due to limitations in Persistent C++ and some optimizations and simplifications tailored to the scene monitoring application.

The prototype implements only the basic discrete classes. Since Persistent C++ cannot store functions, an instance cannot construct an arbitrary abstract function for its point set, temporal element, or trajectory function. In addition, the scene monitoring prototype does not need relative or probabilistic specifications.

To increase performance, the prototype uses a global coordinate system and a global clock. This eliminates the need for spatial transforms between coordinate systems and temporal transforms between clocks. Translation and rotation methods act on objects themselves rather than on their coordinate systems.

The prototype implements specific subclasses of the class *SpatiotemporalObject* to represent the objects tracked by the scene monitoring system. For example, the *Person* class adds a slot for estimations of the person's height; it could also store the person's name and other such information if it were connected to face recognition software.

4.3 Indices

4.3.1 Mechanism

Index updates occur in the visual memory prototype at transaction commit time, through Persistent C++ commit daemons. When the database stores an object, it automatically calls the object's commit daemons. The visual memory establishes commit daemons for all objects to update index information.

The visual memory prototype implements the discrete spatiotemporal indexing described in Section 3.8.4. Spatial indices store information about object locations,

and temporal indices store information about the valid times of these spatial indices.

The visual memory prototype handles multiple indices. An application can create sets of indices and specify the types of information they should store and the types of queries they should answer. However, the prototype only implements start and stop control over indices; that is, an application can tell an index to start recording information about all objects committed, or to stop recording such information. This is a simpler approach than the specification of arbitrary index sets discussed in the design, but it is adequate for the prototype application.

4.3.2 Spatial Indices

The prototype spatial indices store information about the centroids of objects stored in the visual memory. This information allows them to efficiently answer locational and proximity queries, such as "Find everything in this square" and "Find everything within 5 units of this coordinate." Two such indices were implemented; this section describes the two-dimensional version of each.

The first spatial index is a simple fixed grid [18], dividing space into a number of cells. Each cell stores a list indicating those objects with centroids in the cell. The index can determine the correct cell for an object by rounding down the coordinates of the object's centroid, modulo the cell size. Figure 4-2 shows a fixed grid with a cell size of 5. Using the scheme described above, object G at spatial coordinate (14,18) belongs to cell (2,3).

To answer a spatial query, the grid determines relevant cells in the manner described above and retrieves the objects they list. A query for objects within the shaded rectangle in Figure 4-2 searches cells (2,3), (2,4), (3,3), (3,4), (4,3), and (4,4), and returns objects C, F, and G. The fixed grid index is most suitable for visual memory applications with unknown distributions of object positions and frequent needs for efficient updates.

The second spatial index implemented in the prototype is a bucket PR quadtree [18]. Each node in the tree keeps a bucket of object records for some region. The index initially consists of one node covering the entire indexed region and containing

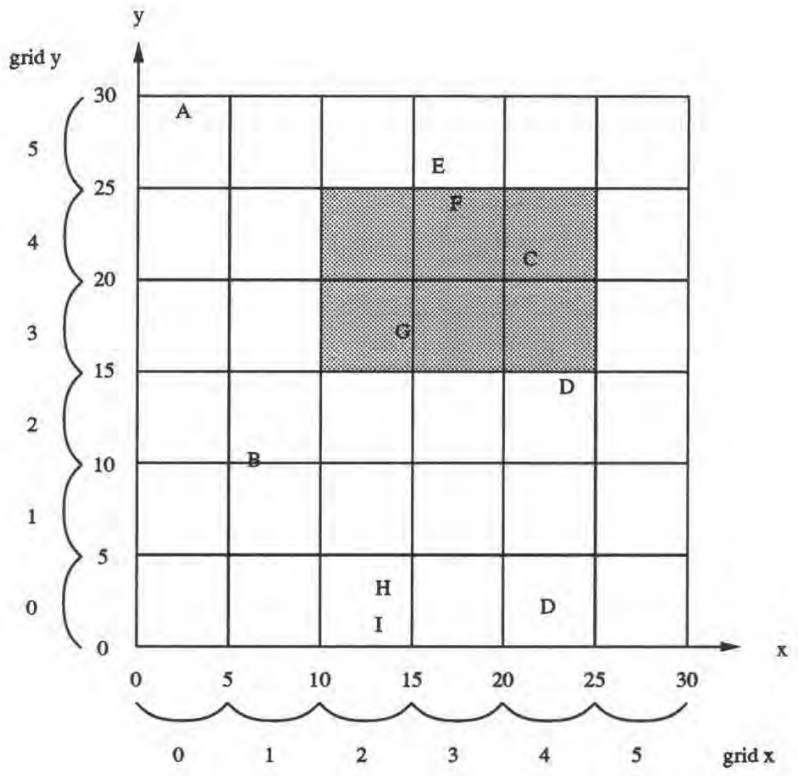


Figure 4-2: Fixed grid spatial index

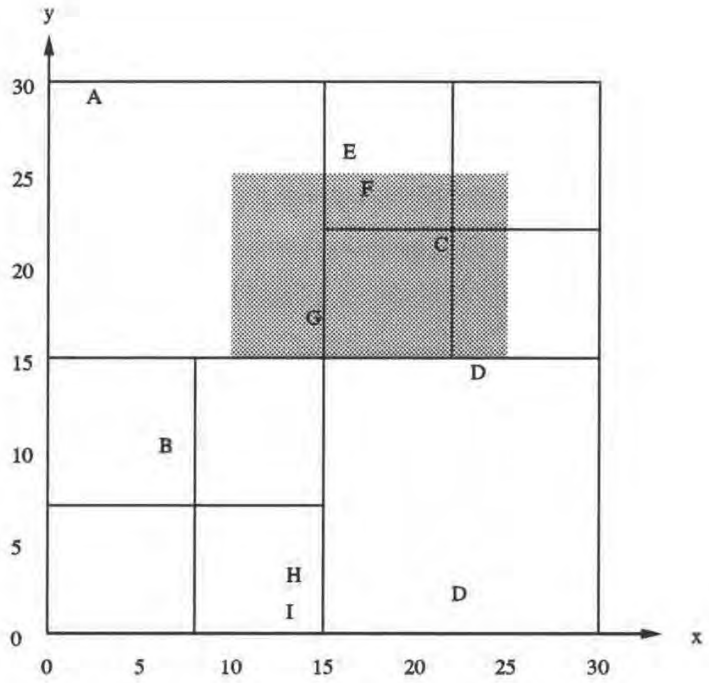


Figure 4-3: Segmented space for bucket PR quadtree

no records. As objects are added to a node's bucket, it eventually becomes full and the node must be split. A node is split into four children, one for each quadrant, and the node's bucket is appropriately divided among the children; full children are recursively split. Figure 4-3 shows how space would be segmented for a quadtree with bucket size of 2 and the given objects. Figure 4-4 shows the corresponding index structure.

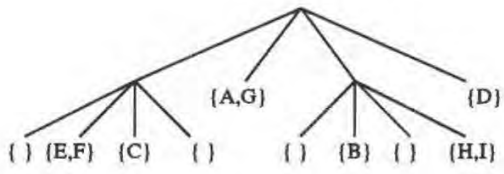


Figure 4-4: Data structure for bucket PR quadtree

A bucket PR quadtree answers a spatial query with a recursive search through all nodes intersecting the region of interest. A query for objects in the shaded rectangle in Figure 4-3 searches the left half of the tree in Figure 4-4, and it returns objects C, F, and G.

The bucket PR quadtree index is best suited for visual memory applications where objects are spread out and do not move often. In these cases, it has much less overhead than the fixed grid. Thus an application might use a quadtree to store static background information and a grid to store dynamic information.

4.3.3 Temporal Indices

The prototype temporal indices keep track of the valid times of object versions. They can efficiently answer temporal intersection queries, such as "Find all events that happened after work last Tuesday and Wednesday." The prototype implements two different temporal indices.

The first temporal index is a segment tree [18]. Each node in the tree represents a temporal interval and contains a list of all versions valid throughout the entire interval. The children of a node represent subintervals of their parent's interval, so that a version that is not valid throughout a node's interval can be stored in one of its descendants. For example, if version A were valid from time 35 to time 140, it would appear at the indicated nodes in Figure 4-5.

To answer a temporal intersection query, the temporal segment tree retrieves the versions referenced by all nodes with intervals intersecting the specified temporal element. To find all versions valid during [105, 118) in Figure 4-5, the index searches the darkened branches and returns versions A and E.

The second temporal index is a B+ tree [6] with times as its keys. Each leaf node maintains a start-list containing versions that become valid at the node's key time and a stop-list containing versions that stop being valid at that time. The keys in an internal node separate its children. Leaves are connected in a linked list, and the start-list for the first leaf of an internal node also indicates "carry-over" versions still valid after the last key in the previous node. In Figure 4-6, version A, valid from

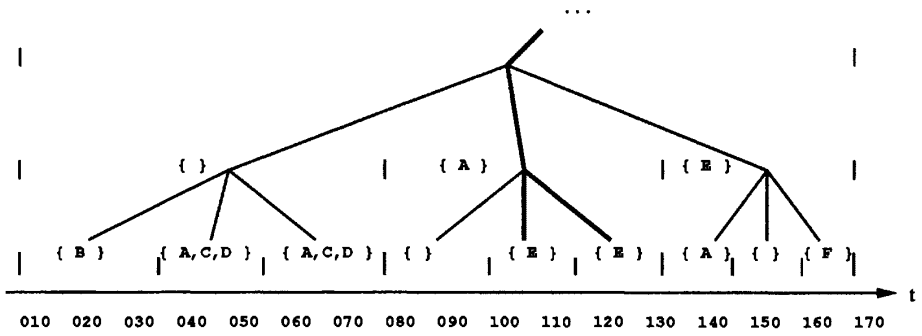


Figure 4-5: Temporal segment tree

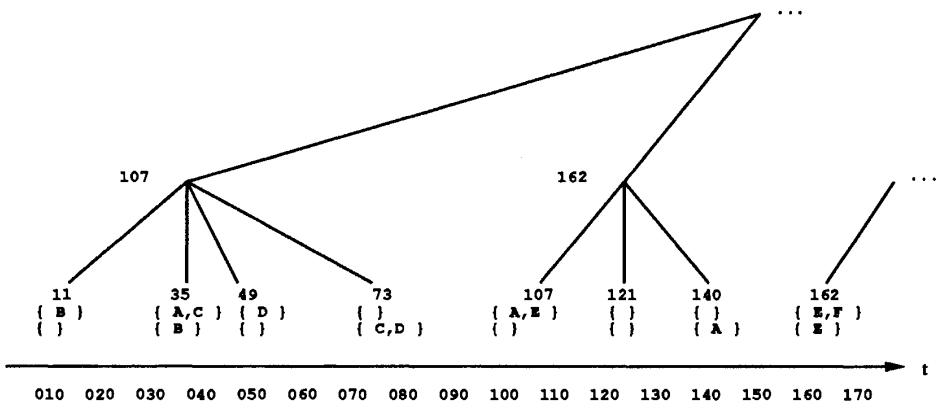


Figure 4-6: Temporal B+ tree

time 35 to time 140, has a start record at node 35, a stop record at node 140, and a carry-over record at node 107.

A temporal intersection query proceeds down the tree to the first leaf of an internal node with a time less than the earliest specified time. There it gathers the carry-over records and traverses the linked list to the earliest specified time to determine which carry-over versions are still valid then. Next it continues through the list to the latest specified time, noting which versions become valid during the temporal element. In Figure 4-6, a query for the interval [105,118) would go down to leaf node 11 and traverse the linked list to leaf node 107, noting that only version A was still valid at

time 105. It would then proceed to leaf node 121 to find the remaining valid versions, finally returning versions A and E.

4.4 Queries

The prototype visual memory implements a functional query interface rather than a full query language. To pose a query, an application calls a visual memory function, passing it parameters specifying the query. For example, a spatial proximity query's parameters are a point and a radius, while a temporal intersection query takes a temporal element. The visual memory returns a set of <OID, version number> index records indicating objects that might satisfy the query. This set can be combined with other such sets to construct complex queries. Once a query has been fully specified, the query mechanism can retrieve the indicated objects. The indices provide only approximate answers, so the query mechanism filters the retrieved objects to return only those objects satisfying the specification. This query mechanism allows applications to pose fairly complex queries.

4.5 Input

The input for the scene monitoring prototype comes from real-time processing of CCD camera images. This software, which tracks people walking in its field of view, was implemented by Tom Bannon and Tom O'Donnell in the Image Understanding Branch at the Texas Instruments Computer Science Laboratory. Using a calibrated internal model of its field of view, the software estimates the positions and heights of people and updates the visual memory a few times per second. This yields enough information to test the visual memory's performance and to provide interesting data for queries to retrieve.

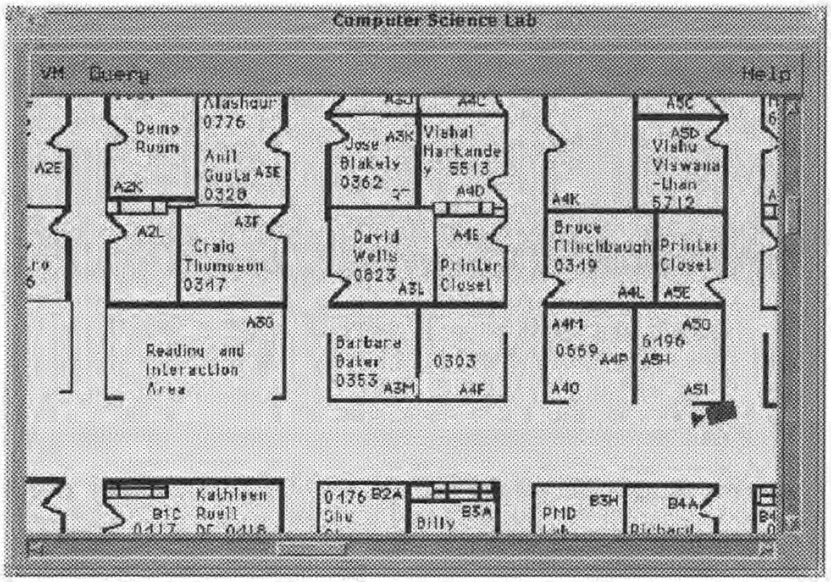


Figure 4-7: Graphical query interface viewing region

4.6 Graphical Query Interface

The scene monitoring prototype includes a graphical interface through which users can query the visual memory to retrieve information stored by the tracking software. A user establishes regions, times, and object types of interest, and the visual memory retrieves the corresponding objects. The query interface can display the results by dynamically stepping through the state changes of the objects, by displaying all the changes at once, or by displaying textual information about the objects.

The first step in posing a query is to select the query region. The query interface allows a user to step through a map hierarchy to select the map for the region of interest. The user can resize and scroll the query interface window to select an exact query region. This region specifies the spatial area for which objects should be retrieved. Figure 4-7 demonstrates a typical viewing region.

The next step is to establish alarm regions by shading rectangles on the map. In addition to displaying objects in the query region, the scene monitoring system alerts

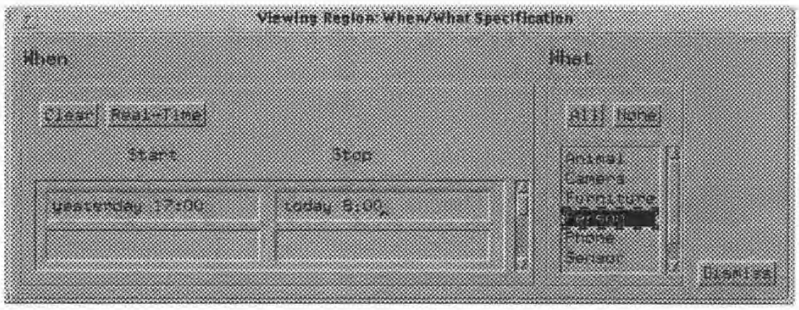


Figure 4-8: Specification of query times and classes

the user to events in alarm regions. Alarm regions can be established all over the map, allowing the user to monitor a number of disjoint regions without having to watch them all.

Another step in query specification is to indicate a set of time intervals for each region, as shown in the left half of Figure 4-8. The system can parse times such as "3/8/93 8:00" and "today 13:00." It includes a special construct "..." to represent infinite queries retrieving all information after a given point. In addition, it provides the keyword "now" to signify a real-time query, one that constantly polls the database for new information.

An alarm region's temporal specification defaults to that of the query region. If an alarm region has an explicit temporal specification, that specification is conjoined with the query region's specification. This allows a user to specify, for example, that an alarm region should be active only during certain hours. The temporal specification for the query region identifies times of interest, and the temporal specification for an alarm region further restricts that specification to indicate exactly when the alarm should be active.

The user can specify for each region what types of objects are important, as shown in the right half of Figure 4-8. For example, the query region might return all objects, an indoor alarm region only people, and an outdoor alarm region both people and vehicles. Alarm regions default to the same type specification as the query region.

Associated with each alarm region is a delay specification that indicates how long

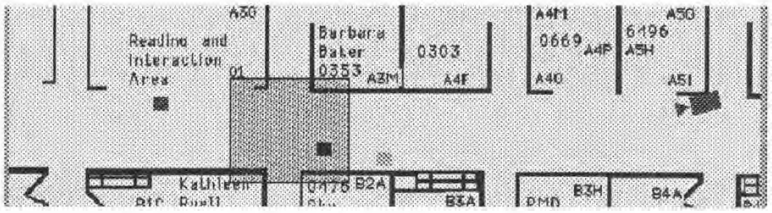


Figure 4-9: Graphical query results

an object must remain in that region before the system triggers an alarm. This lets the user specify that an alarm should fire only if an object remains in a region for a suspicious amount of time. The default value is 0 seconds, causing an alarm to be sounded as soon as an object enters the alarm region.

Once a query is fully specified, the results can be displayed in one of three ways: playback, event report, and trail trace. A playback steps through the retrieved information in temporal order, displaying moving blocks for moving objects and printing alarm information in another window. An event report textually describes alarms that were triggered. A trail trace displays blocks for all the retrieved information simultaneously and provides information about a certain object in response to a button press over its picture. Figure 4-9 shows part of a playback window, with one object inside an alarm region and two other objects also being monitored.

Chapter 5

Performance

One of the key requirements for the visual memory is to provide high-performance storage and retrieval of spatiotemporal information. The scene monitoring prototype described in Chapter 4 not only demonstrates the representational power of the visual memory design, it also provides a means for examining the performance of the prototype visual memory. This chapter studies some tests conducted to analyze the prototype's performance.

Visual memory performance can be measured in two main ways: by the number of objects stored and retrieved, and by the amount of time taken to store and retrieve those objects. The scene monitoring prototype is most concerned with how fast it can manipulate information, suggesting the use of temporal performance measurement. However, measuring the number of objects stored and retrieved can give an idea of the bottom-line visual memory performance and can help predict how changes in the storage and retrieval mechanism could affect the temporal performance. This chapter only discusses temporal performance, since both measurements follow approximately the same pattern and since timing measurements provide an intuitive benchmark.

The results of timing tests vary from machine to machine and from one execution to the next depending on system load, so they are most useful in providing comparative information. To reduce inaccuracy, times discussed here are the averages of three test executions. To provide more valid comparisons, the tests were run during the same time frame on a single machine with approximately the same system load.

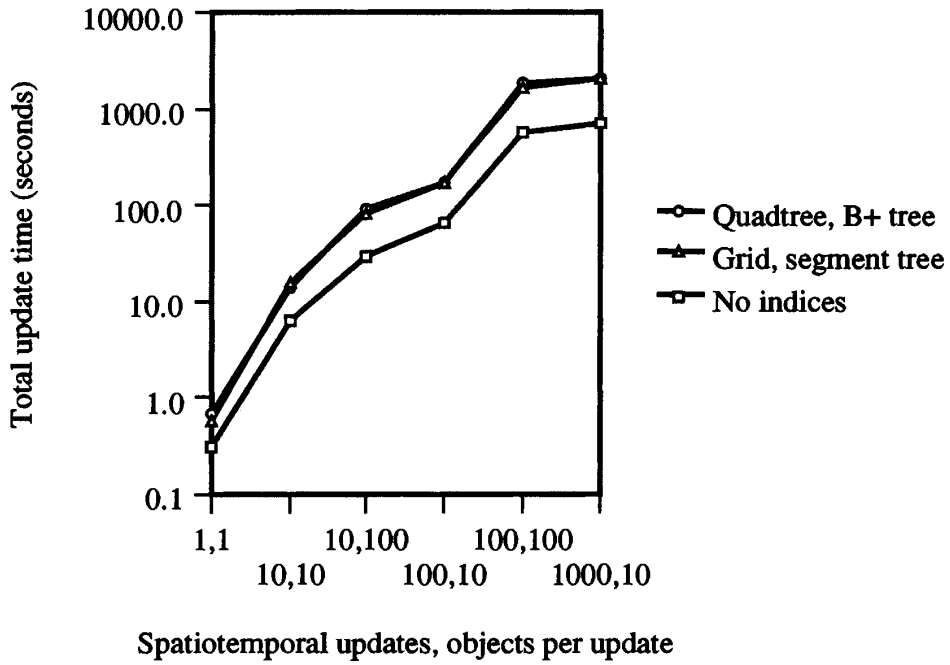


Figure 5-1: Spatiotemporal update performance

5.1 Spatiotemporal Object Storage and Retrieval

The prototype visual memory achieves reasonable spatiotemporal object storage performance. The underlying database limits the attainable performance, since it is responsible for actual object storage. With every spatiotemporal object update, the visual memory stores additional indexing information. A useful test of storage performance compares the time to store raw spatiotemporal objects with that to store both spatiotemporal objects and associated index information. The graph in Figure 5-1 shows storage times for spatiotemporal objects and different sets of indices as a function of the number of objects per update and the number of updates.

This graph shows that both raw storage time and indexed storage time steadily increase with the number of updates and the number of objects per update. Indexed storage costs a nearly constant factor of 2 to 3 times the raw update time. This overhead factor follows from the spatiotemporal indexing strategy discussed in Sec-

tion 3.8.4, since for each update the visual memory stores spatiotemporal objects in a spatial index and the spatial index in a temporal index. While this seems to be a high price, it is necessary so that the visual memory can provide efficient spatiotemporal access to the stored information.

As a result of storing spatiotemporal index information, the visual memory can quickly answer spatiotemporal queries. Depending on indices, query complexity, and number of satisfying objects, the visual memory answered test spatiotemporal queries in 0.1 to 2.1 seconds. Clearly, retrieval performance is much better than storage performance.

5.2 Index Comparison

Chapter 4 describes two spatial and two temporal indices implemented in the visual memory prototype. The spatial indices can answer the same queries, but they differ in structure: the grid has a static structure built prior to execution, while the quadtree has a dynamic structure defined by the objects stored in it. Similarly, the temporal indices provide the same functionality, but the segment tree has a static structure and the B+ tree has a dynamic structure. The visual memory prototype provides a basis for comparing the performance of these indices.

Parameters such as branching factor and cell size affect index structure, so the tests must use comparable parameters. The spatial tests cover a 100-unit by 100-unit square. The quadtree has a bucket size of 10 objects and the fixed grid has a cell size of 10 units; this implies that the grid has 100 nodes and the quadtree has from 1 to a few hundred nodes. The temporal tests cover a time interval of up to 1000 seconds, and both temporal indices have a branching factor of 64.

In addition to the indices described above, each test also includes a "bucket" index. A bucket index simply maintains a list of all the objects stored in the visual memory. Since there is no overhead for the storage of complex index structure, a bucket index can achieve the highest update performance. A bucket index answers a query by retrieving all the objects in its list and checking them against the query specification.

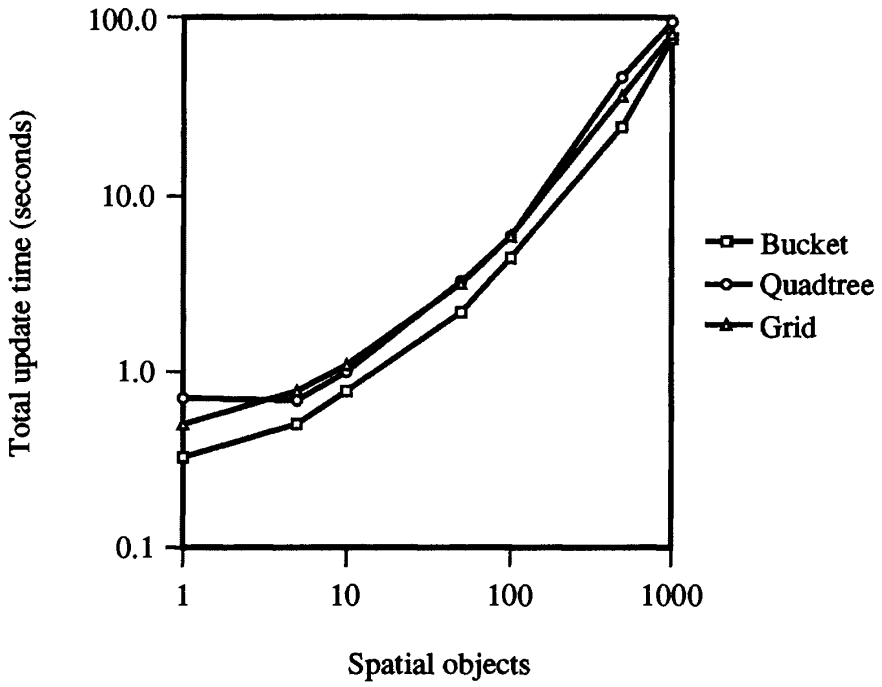


Figure 5-2: Spatial update performance

This is not an efficient query mechanism for large queries, but it provides a useful basis for comparing the performance of other indices.

One important performance measure compares how quickly indices can update information about objects. Figure 5-2 shows the update performance of spatial indices, and Figure 5-3 shows the update performance of temporal indices.

As expected, the bucket indices achieve the highest performance for small numbers of objects. However, the temporal bucket cannot store much more than 100 updates, since it saves an entire list with each update and quickly fills the database. Dynamic structures tend to perform slightly better than static structures for small numbers of objects, while static structures are better for large numbers of objects. This follows from the relative sizes of the structures; dynamic indices are initially small but grow as they store information about additional objects, while static indices maintain the same structure no matter how much information is stored.

Another important measure for index comparison is query performance. Timing

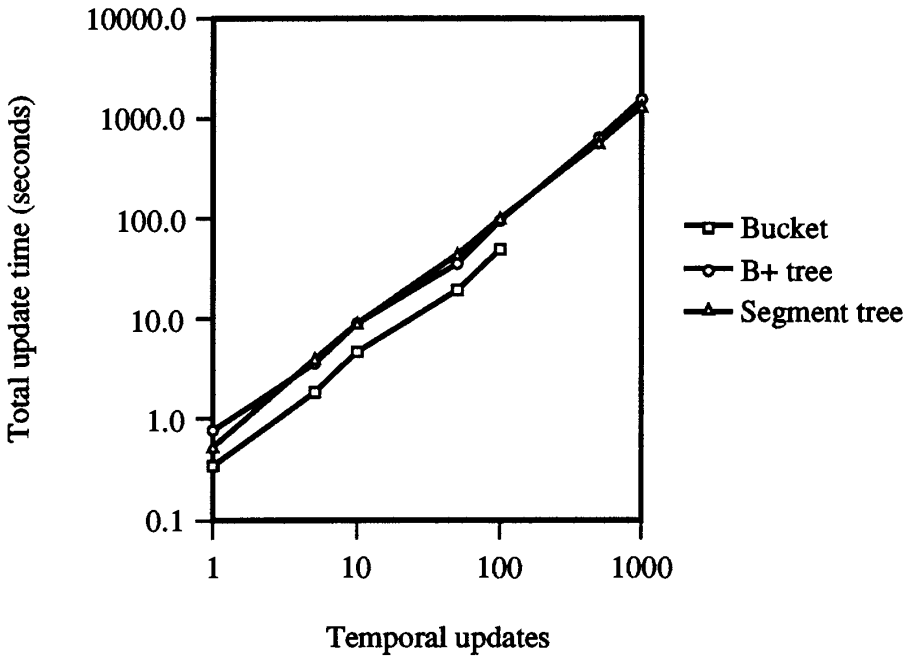


Figure 5-3: Temporal update performance

tests show that query performance follows a pattern similar to that of update performance: bucket indices achieve the best performance with small numbers of objects, dynamic structures work better than static structures with small numbers of objects, and static structures work better than dynamic structures with large number of objects. Figure 5-4 shows the performance for spatial indices with a 10-unit by 10-unit query square. Figure 5-5 shows the performance for temporal indices with a query interval of 10 seconds.

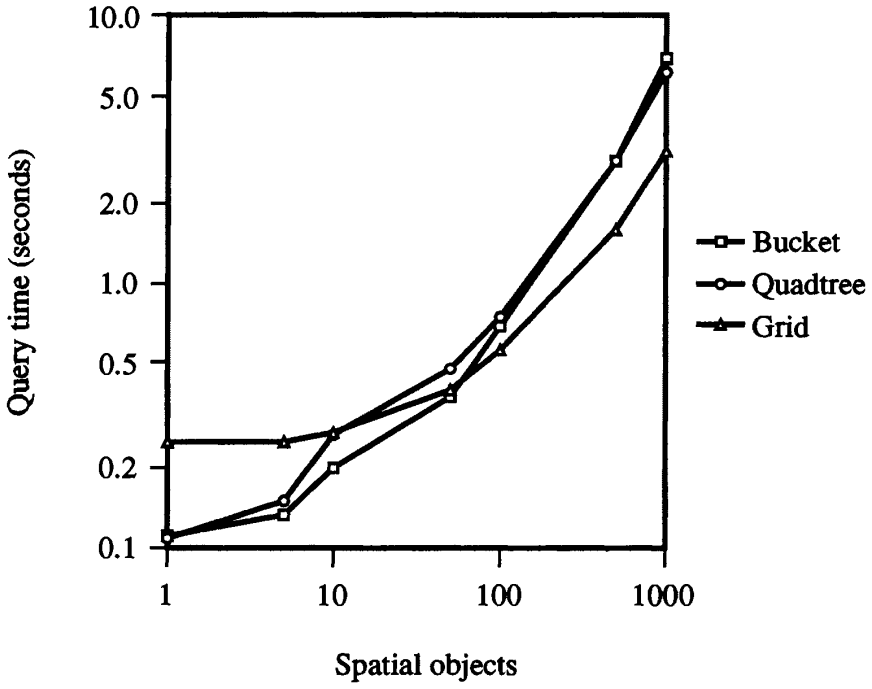


Figure 5-4: Spatial query performance

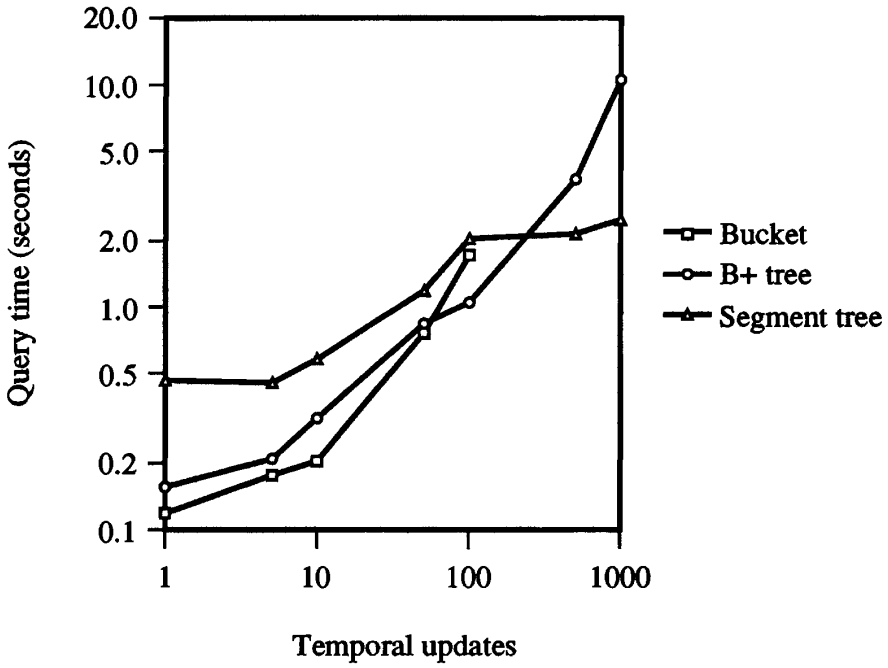


Figure 5-5: Temporal query performance

Chapter 6

Conclusion

The visual memory design presented in this thesis combines and extends spatial, temporal, and database research to meet the needs of a number of computer vision applications. It provides powerful and expressive spatiotemporal representations that it can efficiently manipulate, store, and retrieve. A prototype visual memory implemented in support of a scene monitoring prototype demonstrates the potential of this design. This prototype achieves useful storage and query performance and provides a basis for comparison of different indices.

Visual memory research could continue in many different directions. One step is to more fully implement the design. Some of the unimplemented spatiotemporal representations, such as probabilistic, relative, and abstract objects, could be beneficial to the scene monitoring prototype. The prototype visual memory could be connected to a number of different computer vision applications. Further implementation and testing would provide more feedback on the design and help identify areas for additional research.

The visual memory could furnish additional functionality if it used a different database. For example, if the database provided active rules, a security system could establish visual memory daemons to automatically check for alarms and to resolve old data. If the database provided real-time guarantees, a vehicle navigator could be sure that it would not crash because of visual memory performance. Finally, if the database provided data partitioning capabilities, applications that store large

amounts of spatiotemporal data could make use of separate storage devices.

A number of extensions could improve the performance of the visual memory. Visual memory customization of caching and look-ahead could improve both storage and retrieval performance. Lightweight transactions could reduce overhead and increase storage performance for applications that continuously update the visual memory. Query optimization could increase retrieval performance by ordering parts of a query to reduce the number of retrievals. These extensions could help the visual memory reach its potential as high-performance system for manipulating spatiotemporal information.

Bibliography

[1] American National Standard for Information Systems. Database language SQL. Technical Report ANSI-X3.138-1986, American National Standards Institute, October 1986.

[2] José A. Blakeley. ZQL[C++]: Extending a persistent C++ language with a query capability. Technical Report 91-06-01, Texas Instruments Information Technologies Laboratory, 1991.

[3] John Brolio et al. ISR: A database for symbolic processing in computer vision. *IEEE Computer*, December 1989.

[4] M. Carey, D. DeWitt, and E. Shekita. Storage management for objects in EXODUS. In W. Kim and F. Lochovsky, editors, *Object-Oriented Concepts, Databases, and Applications*. Addison-Wesley Publishing Company, 1989.

[5] Surajit Chaudhuri. Temporal relationships in databases. In *Proceedings of the Conference on Very Large Databases*, 1988.

[6] Douglas Comer. The ubiquitous B-tree. *ACM Computing Surveys*, June 1979.

[7] Randall Davis, Bruce Buchanan, and Edward Shortliffe. Production rules as a representation for a knowledge-based consultation program. *Artificial Intelligence*, February 1977.

[8] Ramez Elmasri, Ihab El-Assal, and Vram Kouramajian. Semantics of temporal data in an extended ER model. In *Proceedings of the Entity-Relationship Conference*, October 1990.

[9] Ramez Elmasri, Muhammad Jaseemuddin, and Vram Kouramajian. Partitioning of time index for optical disks. In *IEEE Data Engineering Conference*, February 1992.

[10] Ramez Elmasri and G. Wiederhold. GORDAS: A formal high-level query language for the ER model. In *Proceedings of the Entity-Relationship Conference*, October 1981.

[11] James D. Foley and Andries Van Dam. *Fundamentals of Interactive Computer Graphics.* Addison-Wesley Publishing Company, 1984.

[12] G. D. Held, M. R. Stonebraker, and E. Wong. INGRES: A relational data base system. In *Proceedings of the National Computer Conference*, May 1975.

[13] Vram Kouramajian and Ramez Elmasri. Support for uncertainty in a generalized temporal model. Available from the authors at {kouramaj,elmasri}@cse.uta.edu.

[14] Jon Lukasiewicz. Numerical interpretation of the theory of propositions. In Borkowski, editor, *Jon Lukasiewicz: Selected Works.* North-Holland Publishing Company, 1970.

[15] Frank Manola and Jack A. Orenstein. Toward a general spatial data model for an object-oriented DBMS. In *Proceedings of the Conference on Very Large Databases*, August 1986.

[16] J. Mundy et al. *The Image Understanding Environments Program*, June 1992.

[17] Edward Perez and Robert W. Peterson. Zeitgeist Persistent C++ user manual. Technical Report 90-07-02, Texas Instruments Information Technologies Laboratory, February 1992.

[18] Hanan Samet. *The Design and Analysis of Spatial Data Structures.* Addison-Wesley Publishing Company, 1989.

[19] Arie Segev and Arie Shoshani. Logical modeling of temporal data. In *Proceedings of the ACM SIGMOD Conference*, June 1987.

[20] Steven A. Shafer, Anthony Stentz, and Charles E. Thorpe. An architecture for sensor fusion in a mobile robot. In *Proceedings of the IEEE International Conference on Robotics and Automation*, 1986.

[21] Richard Snodgrass. The temporal query language TQuel. *ACM Transactions on Database Systems*, June 1989.

[22] Michael D. Soo. Bibliography on temporal databases. *ACM SIGMOD Record*, March 1991.

[23] Michael Stonebraker and Lawrence A. Rowe. The design of POSTGRES. In *Proceedings of the ACM-SIGMOD Conference on the Management of Data*, 1986.

[24] Thomas M. Strat and Grahame B. Smith. Core Knowledge System: Storage and retrieval of inconsistent information. In *Proceedings of the DARPA Image Understanding Workshop*, April 1988.

[25] David L. Wells, José A. Blakely, and Craig W. Thompson. Architecture of an open object-oriented database management system. *IEEE Computer*, October 1992.

EXHIBIT B

Full Record

Permalink for this record: http://library.mit.edu/item/000656176

Results List | **Add to Bookshelf** | **Save/Email**

Choose format: **Standard** | **Citation** | **MARC tags**

Record 1 out of 1

Author	Kollogg, Christopher James.
Title	Visual memory / by Christopher James Kellogg.
Shelf Access	Find it in the library/Request item
Shelf Location	Institute Archives - Noncirculating Collection 1 | Thesis E.E. 1993 M.S.
Shelf Location	Institute Archives - Noncirculating Collection 3 | Thesis E.E. 1993 M.S.
Shelf Location	Barker Library - Microforms | Thesis E.E. 1993 M.S.
Published	c1993.
Description	92 leaves : ill. ; 29 cm.
Format	Book
Thesis Note	Thesis (M.S.)--Massachusetts Institute of Technology, Dept. of Electrical Engineering and Computer Science, 1993.
Thesis Supervisor	Supervised by Alex P. Pentland.
Bibliography	Includes bibliographical references (leaves 90-92).
Local System Number	**000656176**

EXHIBIT C

Full Record

Permalink for this record: http://library.mit.edu/item/000656176

Results List | **Add to Bookshelf** | **Save/Email**

Choose format: **Standard** | **Citation** | **MARC tags**

Record 1 out of 1

FMT	BK
LDR	00968nam 2200265K 45q0
003	MCM
005	20010608211241.0
008	930928s1993 xx a b 000 0 eng d
035	|a MITb10656176
035	|a (OCoLC)28904769
035	|a GLIS00656176
040	|a MYG |c MYG
099	|a Thesis E.E. 1993 M.S. |a Thesis E.E. 1993 M.S. Mfch
099	|a Thesis |a E.E. |a 1993 |a M.S.
1001	|a Kollogg, Christopher James.
24510	|a Visual memory / |c by Christopher James Kellogg.
260	|c c1993.
300	|a 92 leaves : |b ill. ; |c 29 cm.
502	|a Thesis (M.S.)--Massachusetts Institute of Technology, Dept. of Electrical Engineering and Computer Science, 1993.
504	|a Includes bibliographical references (leaves 90-92).
59900	|a Supervised by Alex P. Pentland.
599	|a GRSN 656176
CAT	|a CONV |b 00 |c 20010620 |l MIT01 |h 1525
CAT	|a lti0904 |b 00 |c 20090523 |l MIT01 |h 2117
049	|a MYGG
910	|a jlh
949	|a MYTT |b 39080008599745 |a [Micro-] [fiche] MYTT |b 39080008664614 |a MYTE |b 39080008666296 |a [Micro-] [fiche] MYTE |b 39080008664663
PST8	|0 Z30 |1 000656176000020 |b ARC |c NOLN1 |o BOOK |d 02 |y 00000 |f N |r MIT60-000584976 |n 8 |h Thesis E.E. 1993 M.S. |k THESIS |a MCM |3 Book |4 Institute Archives |5 Noncirculating Collection 1 |6 Room Use Only |p Avail
PST8	|0 Z30 |1 000656176000010 |b ARC |c NOLN3 |o BOOK |d 02 |y 00000 |f N |r MIT60-000579310 |n 8 |h Thesis E.E. 1993 M.S. |k THESIS |a MCM |3 Book |4 Institute Archives |5 Noncirculating Collection 3 |6 Room Use Only
PST8	|0 Z30 |1 000656176000030 |b ENG |c MFORM |o BOOK |d 12 |y 00000 |f N |r MIT60-000584981 |n 8 |h Thesis E.E. 1993 M.S. |k THESIS |a MCM |3 Book |4 Barker Library |5 Microforms |6 Thesis Loan
LDR	nx 22 zn 4500
008	0106230u 0 4 uu 1
004	000656176
8528	|a MCM |b ARC |c NOLN3 |h Thesis E.E. 1993 M.S. |k THESIS |z
LDR	nx 22 zn 4500
008	0106230u 0 4 uu 1
004	000656176
8528	|a MCM |b ARC |c NOLN1 |h Thesis E.E. 1993 M.S. |k THESIS |z
LDR	nx 22 zn 4500
008	0106230u 0 4 uu 1
004	000656176
8528	|a MCM |b ENG |c MFORM |h Thesis E.E. 1993 M.S. |k THESIS |z

001 000656176
SFX01 |s 0-0-0-6-5-6-1-7-6 |l MIT01 |9 000 |z ~~~~~~~~~~ |p Avail |f 000
LU564 BK
SYS 000656176

Basic Search of Full Catalog

Search type:

Keyword
Title begins with...
Title Keyword
Author (last name first)
Author Keyword
Call Number begins with...
----- Scroll down for more choices -----

Search for:

Search

Barton Questions: Ask Us! | Contact Us
Massachusetts Institute of Technology
77 Massachusetts Avenue, Cambridge, MA 02139-4307 USA

-- Quick Links --

EXHIBIT D

American Defense
Preparedness Association's
Security Technology Division

10th Joint Annual Government-Industry Security Technology Symposium & Exhibition

"Reducing Security Vulnerabilities Through Innovation and Technology— The Risk Management Challenge"

PROCEEDINGS

Williamsburg, Virginia
June 20-23, 1994

TABLE OF CONTENTS

TABLE OF CONTENTS (Continuation)

TABLE OF CONTENTS (Continuation)

TABLE OF CONTENTS (Continuation)

TABLE OF CONTENTS (Continuation)

ALTERNATE PAPERS

SESSION VI

Department of Justice

Speakers will focus on the new technologies & policies developing in light of the modern challenges and risks in law enforcement and security policy

Session Chairperson:

James Mahan, Session Chairperson
Federal Bureau of Prisons - Washington, DC

Autonomous Scene Monitoring System

Bruce Flinchbaugh & Tom Bannon

Texas Instruments
Systems & Information Science Laboratory
P.O. Box 655474, MS 238
Dallas, TX 75265
Phone: 214-995-0349

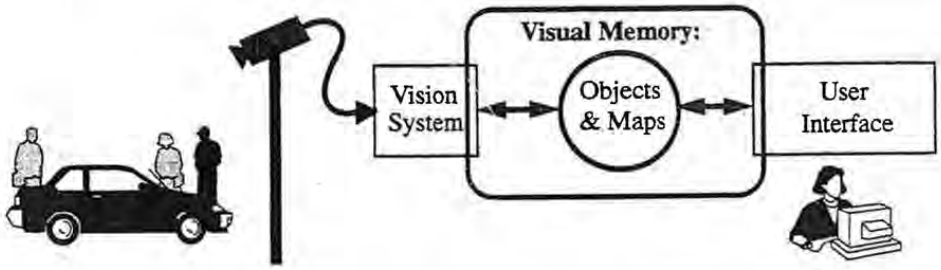
Abstract

Autonomous scene monitoring poses substantial requirements for extracting, storing, and displaying information about three-dimensional (3-D) scenes. We have developed and demonstrated a data base system called visual memory that interfaces automated video camera monitoring systems with end-user applications requiring real-time and historical information about observed objects. This paper describes our visual memory and real-time camera monitoring capabilities. The visual memory prototype uses state-of-the-art object-oriented data base technology with spatio-temporal indexing extensions. The video monitoring system reports 3-D positions of people in the field of view of a CCD camera to visual memory, which dynamically maintains the information with respect to a map, and a user interface provides interactive access to the data via historical and real-time queries.

1 Motivation

CCTV surveillance cameras provide valuable data in many security monitoring situations. For example, in some cases CCTV images are recorded using time lapse video recorders. Security system operators use CCTV monitors for remote situation assessment when an alarm detector signals a potential problem. And in some systems video motion detectors are used to automatically signal alarms when changes are detected in the CCTV data.

Interestingly, practically all of the information available from CCTV cameras is essentially ignored. In many time-lapse video surveillance situations, the images recorded on tape are never viewed or used in any way unless a specific event occurs, such as an accident or a theft, and even then only a small portion of the data may be viewed. Although people are generally good at assessing situations using CCTV data, it is well known that operator performance deteriorates significantly with fatigue. And video motion detectors



Vision System:

People Detection

3-D Localization & Tracking

Visual Memory:

Spatio-Temporal Indexes, Queries, & Object Classes

User Interface:

Real-Time Displays

Historical Queries

Figure 1: Autonomous Scene Monitoring System.

simply detect changes in the incoming light, relying on operators to visually assess the situation.

In principle, situation assessment can be performed automatically by computers, to continuously exploit available CCTV surveillance data all of the time. Computer vision systems can be used to extract information about the scene, such as how many people are in the field of view, and whether a particular kind of vehicle has entered the scene. In some cases this descriptive information may be all that is needed to facilitate efficient security monitoring and concise record keeping.

2 Autonomous Scene Monitoring Architecture

At Texas Instruments we have developed a prototype scene monitoring system that automatically extracts complex information about scenes from CCTV camera images and provides operators with convenient access to the information.

The overall scene monitoring system is illustrated in Figure 1. The *Vision System* detects people walking in the CCTV camera field of view and continuously reports their 3-D positions as they move. The *Visual Memory* at the center of the scene monitoring system is an object-oriented data base that stores the information reported by the vision system. As people walk, their current 3-D positions are updated in visual memory, and a history of their movement is maintained for future reference. The *User Interface* provides interactive graphical access to real-time and historical events stored in visual memory.

The Vision System, Visual Memory, and User Interface software are implemented on two computers. The Vision System uses a Datacube MaxVideo 20 real-time image processor and a Sun SPARCstation 10, while the Visual Memory and User Interface run

on the Sun workstation. Users may also access Visual Memory over a network using an X Window System server or another workstation. The camera is a Texas Instruments monochrome MC-780PH CCD camera with a resolution of 755x484 8-bit pixels, of which 492x460 pixels are used by the Vision System. The camera is mounted in a pan/tilt/zoom unit about 8 feet high on a hallway ceiling in our laboratories. From this vantage point the camera can observe several hallways, including a section approximately 9 feet wide, 117 feet long, and 12 feet high. The hallway is illuminated by overhead and wall-mounted fluorescent lighting, with significant variations caused by natural light from large windows at one end of the hall.

3 Real-Time Scene Monitoring

Algorithms of the Vision System report where people are walking in the field of view. The algorithms use basic image processing techniques to continuously detect scene motion. Regions of motion are analyzed for consistent interpretations as people standing or walking. By using knowledge of the scene geometry, the algorithms estimate positions and heights of people in the scene. The system detects and updates the positions of people at a rate of ten frames per second.

4 Visual Memory

Our visual memory prototype project developed an architecture [1] to interface vision systems with applications requiring access to information about 3-D objects, events and their environment. Visual Memory requirements include:

- Storage of objects at high frame rates
- Retrieval from multi-gigabyte data volumes
- Support for diverse data structures

We selected an object-oriented data base (OODB) [2, 3] to use as the basis for the visual memory prototype. Relational data base technology is poorly suited for Visual Memory because it does not adequately support diverse data structures. The OODB is illustrated in Figure 2. For Visual Memory, the Indexing and Address Space modules of the OODB were extended to speed object storage and retrieval. In particular, several spatio-temporal indexing mechanisms were introduced as described below.

4.1 Spatial Indexing

Spatial indexing provides fast, efficient answers to questions such as, "Is anyone in area X?" Spatial indices typically provide conservative approximate answers, allowing false positives but not false negatives, and rely on further filtering for exact results.

Several different spatial indices are available, catering to different types of questions. For example, grids and point quadtrees are good for determining objects near a given

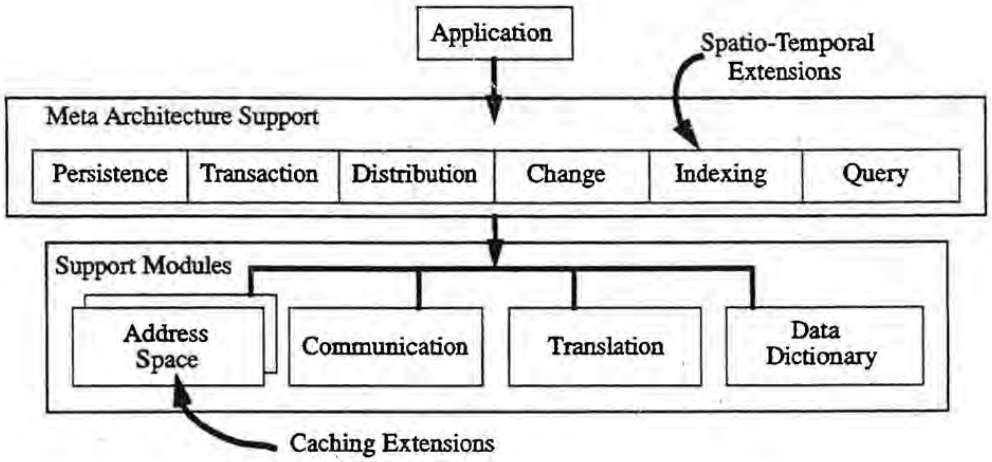


Figure 2: Object-Oriented Data Base.

point, while interval trees are better for finding object intersections [4]. The visual memory architecture supports multiple indices, and its query mechanism determines the appropriate index for a given question.

4.2 Temporal Indexing

Temporal indices provide means for accessing object histories by efficiently determining an object's state at a given time and how objects changed over a given interval of time. They help answer questions such as, "Was anyone in hall X during the night?" and "Where was object Y at 10:00am?"

Mathematically, temporal indexing mechanisms may be regarded as special cases of spatial indices for one dimension (time). Thus selection of a particular temporal index depends on the intended use. For example, image processing inputs to visual memory use only increasing time. Also, old information becomes increasingly unimportant and can be archived [5] for infrequent access. Tree indices support these requirements.

5 User Interface

The user interface provides interactive access to visual memory data via historical and real-time queries. To make historical queries, the user specifies periods of time, regions of space, and object types. Then the system retrieves the corresponding objects. To display real-time information, locations of people are indicated on a floor plan display and changed dynamically as the visual memory is updated.

Users may specify alarm regions on the map so that when someone enters that area an alarm is signaled. Digital snapshots of the scene may be kept and saved for future reference. Other user interface features provide interactive control of the camera pan, tilt, zoom, focus, and gain settings.

6 Concluding Remarks

The autonomous scene monitoring system currently operates in our laboratories with two remotely controlled pan/tilt/zoom cameras. We have also demonstrated operation of the system outdoors, using an infrared camera to map the position of a person walking along a sidewalk and across a street. The object-oriented data base architecture [3] underlying the Visual Memory facilitates expansion of the prototype scene monitoring system to handle hundreds of cameras, vision systems, and many users. As vision systems and visual memory evolve, increasingly sophisticated surveillance tasks will be automated to enhance security systems.

Acknowledgments

We thank Chris Kellogg, Steve Ford and Tom O'Donnell for their contributions in the conception, design, and development of the autonomous scene monitoring system.

References

[1] Kellogg, C., "Visual Memory", MIT Thesis, May 1993. *Also available as:* Technical Report CSL-93-05-20, Texas Instruments, Systems & Information Science Laboratory.

[2] S. Ford, et al, "ZEITGEIST: Database Support for Object-Oriented Programming," Advances in Object-Oriented Database Systems, 2nd International Workshop on Object-Oriented Database Systems, Springer-Verlag, Sep. 1988.

[3] Wells, D.L., J.A. Blakeley, & C.W. Thompson, "Architecture of the Open Object-Oriented Database Management System," *IEEE Computer*, Vol. 25, No. 10, Oct. 1992.

[4] Samet, H., The Design and Analysis of Spatial Data Structures. Addison-Wesley Publishing Company, Inc., 1989.

[5] Elmasri, R., M. Jaseemuddin, & V. Kouramajian, "Partioning of Time Index for Optical Disks," *IEEE Data Engineering Conference*, Feb. 1992.

EXHIBIT E

LIBRARY OF CONGRESS ONLINE CATALOG

Search Navigation ▾ < 9 of 11 >

BOOK

Emerging applications of computer vision : 25th AIPR Workshop, 16-18 ...

Full Record | MARC Tags

000		01814cam a2200409 a 4500
001		1638062
005		20160811120013.0
008		961121s1997 waua b 101 0 eng d
906	__	|a 7 |b cbc |c copycat |d 2 |e opcn |f 19 |g y-gencatlg
925	0_	|a acquire |b 1 shelf copy |x policy default
955	__	|a pb20 10-21-97 to cat.; jf00 10-23-97; jf09 to sub 10-23-97; jf08 10-24-97 to SL; je25 11-12-97 to ddc;aa05 11-14-97
010	__	|a 96071104
020	__	|a 0819423661
035	__	|9 (DLC) 96071104
035	__	|a (OCoLC)36514905
040	__	|a MoKL |c MoKL |d DLC
042	__	|a lccopycat
050	04	|a TA1634 |b .A37 1996a
082	00	|a 006.3 |2 21
111	2_	|a AIPR Workshop |n (25th : |d 1996 : |c Washington, D.C.)
245	10	|a Emerging applications of computer vision : |b 25th AIPR Workshop, 16-18 October 1996, Washington, D.C. / |c David Schaefer, Elmer F. Williams, chairs/editors ; sponsored by SPIE--the International Society for Optical Engineering, AIPR Executive Committee.
260	__	|a Bellingham, Wash. : |b SPIE, |c c1997.
300	__	|a x, 302 p. : |b ill. ; |c 28 cm.
490	1_	|a Proceedings / SPIE--the International Society for Optical Engineering ; |v v. 2962
504	__	|a Includes bibliographical references and index.
650	_0	|a Computer vision |x Congresses.
650	_0	|a Image processing |x Databases |x Congresses.
650	_0	|a Database management |x Congresses.
650	_0	|a Optical storage devices |x Congresses.
700	1_	|a Schaefer, David.
700	1_	|a Williams, Elmer F.
710	2_	|a Society of Photo-optical Instrumentation Engineers.
710	2_	|a AIPR Executive Committee.
830	_0	|a Proceedings of SPIE--the International Society for Optical Engineering ; |v v. 2962.
920	__	|a ** LC HAS REQ'D # OF SHELF COPIES **
922	__	|a co
991	__	|b c-GenColl |h TA1634 |i .A37 1996a |t Copy 1 |w BOOKS

Request this Item | LC Find It

Where to Request

CALL NUMBER: TA1634 .A37 1996a FT MEADE
Copy 2

EXHIBIT F

Full Record

Permalink for this record: http://library.mit.edu/item/000819773

Results List | Add to Bookshelf | Save/Email

Choose format: Standard | Citation | MARC tags

Record 1 out of 1

FMT	BK
LDR	01492nam 2200325Ia 45r0
003	MCM
005	20010609092045.0
006	m d
007	cr un-
008	970310s1997 waua b 101 0 eng d
020	|a 0819423661
035	|a MITb10819773
035	|a (OCoLC)36514905
040	|a LHL |c LHL |d MYG
090	|a TA1634 |b .A37 1996
1112	|a AIPR Workshop |n (25th : |d 1996 : |c Washington, D.C.)
24510	|a Emerging applications of computer vision : |b 25th AIPR Workshop, 16-18 October 1996, Washington, D.C. / |c David Schaefer, Elmer F. Williams, chairs/editors ; sponsored by SPIE--the International Society for Optical Engineering, AIPR Executive Committee ; published by SPIE--the International Society for Optical Engineering.
260	|a Bellingham, Washington : |b SPIE, |c c1997.
300	|a x, 302 p. : |b ill. ; |c 28 cm.
4901	|a Proceedings / SPIE--the International Society for Optical Engineering ; |v v. 2962
530	|a Also available online via the World Wide Web; access restricted to licensed sites/users.
504	|a Includes bibliographical references and author index.
650 0	|a Image processing |x Databases |v Congresses.
650 0	|a Image processing |x Digital techniques |v Congresses.
650 0	|a Database management |v Congresses.
650 0	|a Optical storage devices |v Congresses.
7001	|a Schaefer, David.
7001	|a Williams, Elmer F.
7102	|a Society of Photo-optical Instrumentation Engineers.
7102	|a AIPR Executive Committee.
85641	|u http://spiedigitallibrary.org/proceedings/resource/2/psisdg/2962/1
830 0	|a Proceedings of SPIE--the International Society for Optical Engineering ; |v v. 2962.
CAT	|a CONV |b 00 |c 20010620 |l MIT01 |h 1548
CAT	|a spieurl |b 00 |c 20060331 |l MIT01 |h 1607
CAT	|a lti0904 |b 00 |c 20090523 |l MIT01 |h 2259
CAT	|a EDWARDSJ |b 00 |c 20110408 |l MIT01 |h 1056
95641	|u http://libraries.mit.edu/get/spie
049	|a MYGG
910	|a tn970627
PST0	|0 Z30 |1 000819773000010 |b LSA |c OCC |o BOOK |d 15 |y 00000 |f N |r MIT60-000781407 |n 0 |h TA1634.A37 1996 |a MCM |3 Book |4 Library Storage Annex |5 Off Campus Collection |6 OCC 60 |p Avail

```
LDR      nx  a22    1i 4500
008   1104082u   8  4001uueng0000000
8528  |b NET |z MIT Access Only |h **See URL(s)
004   000819773
LDR      nx  22    zn 4500
008   0106230u   0  4  uueng1
004   000819773
8520  |a MCM |b LSA |c OCC |h TA1634.A37 1996
001   000819773
SFX41 |s 0-0-0-8-1-9-7-7-3 |l MIT01 |9 001 |z button~~~ |p Avail |f 001 |a Click button for available online volumes
URL   |u http://spiedigitallibrary.org/proceedings/resource/2/psisdg/2962/1 |9 001
U564  |u http://spiedigitallibrary.org/proceedings/resource/2/psisdg/2962/1 |9 001
LU564 |u http://spiedigitallibrary.org/proceedings/resource/2/psisdg/2962/1 |f 001
SYS   000819773
```

Basic Search of Full Catalog

Search type: Keyword / Title begins with... / Title Keyword / Author (last name first) / Author Keyword / Call Number begins with... / ----- Scroll down for more choices -----

Search for: Search

Barton Questions: Ask Us! | Contact Us
Massachusetts Institute of Technology
77 Massachusetts Avenue, Cambridge, MA 02139-4307 USA

-- Quick Links --

EXHIBIT G

Image Understanding Workshop

Proceedings of a Workshop held in Monterey, California

November 20–23, 1998

Volume I

Sponsored by:
Defense Advanced Research Projects Agency
Information Systems Office

This document contains copies of reports prepared for the DARPA Image Understanding Workshop. Included are Principal Investigator reports and technical results from the basic and strategic computing programs within DARPA/ISO-sponsored projects and certain technical reports from selected scientists from other organizations.

Distributed by:
Morgan Kaufmann Publishers Inc.
340 Pine Street, 6th Floor
San Francisco, Calif. 94104-3205
ISBN: 1–55860–583–5
Printed in the United States of America

Table of Contents

Volume I

Event Recognition and Reliability Improvements for the Autonomous Video Surveillance System

Frank Z. Brill, Thomas J. Olson, and Christopher Tserng
Texas Instruments
P.O. Box 655303, MS 8374, Dallas, TX 75265
brill@csc.ti.com, olson@csc.ti.com, tserng@csc.ti.com

Abstract

This report describes recent progress in the development of the Autonomous Video Surveillance (AVS) system, a general-purpose system for moving object detection and event recognition. AVS analyses live video of a scene and builds a description of the activity in that scene. The recent enhancements to AVS described in this report are: (1) use of collateral information sources, (2) camera hand-off, (3) vehicle event recognition, and (4) complex-event recognition. Also described is a new segmentation and tracking technique and an evaluation of AVS performing the best-view selection task.

1. Introduction

The Autonomous Video Surveillance (AVS) system processes live video streams from surveillance cameras to automatically produce a real-time map-based display of the locations of people, objects and events in a monitored region. The system allows a user to specify alarm conditions interactively, based on the locations of people and objects in the scene, the types of objects in the scene, the events in which the people and objects are involved, and the times at which the events occur. Furthermore, the user can specify the action to take when an alarm is triggered, e.g., to generate an audio alarm or write a log file. For example, the user can specify that an audio alarm should be triggered if a person deposits a briefcase on a given table between 5:00pm and 7:00am on a weeknight. Section 2 below describes recent enhancements to the AVS system. Section 3 describes progress in improving the reliability of segmentation and tracking. Section 4 describes an experiment that quantifies the performance of the AVS "best view selection" capability.

This research was sponsored in part by the DARPA Image Understanding Program.

2. New AVS functionality

The structure and function of the AVS system is described in detail in a previous IUW paper [Olson and Brill, 1997]. The primary purpose of the current paper is to describe recent enhancements to the AVS system. These enhancements are described in four sections below: (1) collateral information sources, (2) camera hand-off, (3) vehicle event recognition, and (4) complex-event recognition.

2.1. Collateral information sources

Figure 1 shows a diagram of the AVS system. One or more "smart" cameras process the video stream to recognize events. The resulting event streams are sent to a Video Surveillance Shell (VSS), which integrates the information and displays it on a map. The VSS can also generate alarms based on the information in the event streams. In recent work, the VSS was enhanced to accept information from other sources, or "recognition devices" which can identify the objects being reported on by the cameras. For example, a camera may report that there is a person near a door. A recognition device may report that the person near the door is Joe Smith. The recognition device may be a badge reader, a keypad in which a person types their PIN, a face recognition system, or other recognition system.

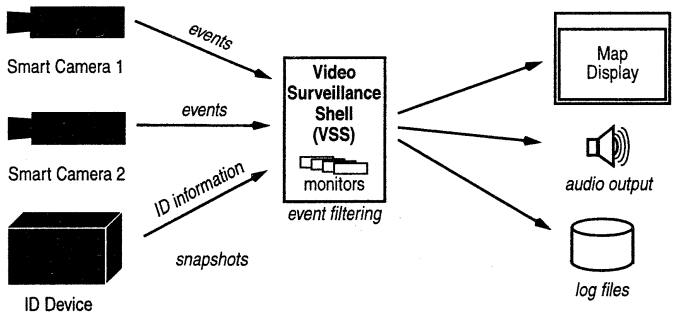


Figure 1: AVS system diagram

The recognition device we have incorporated is a voice verification system. The user stands in a predefined location in the room, and speaks his or her name. The system matches the utterance to previously captured examples of the person speaking their name, and reports to the VSS if there is a match. The VSS now knows the identity of the person being observed, and can customize alarms based on the person's identity.

A recognition device could identify things other than people, and could classify actions instead of objects. For example, the MIT Action Recognition System (MARS) recognizes actions of people in the scene, such as raising their arms or bending over. MARS is trained by observing examples of the action to be recognized and forming "temporal templates" that briefly describe the action [Davis and Bobick, 1997]. At run time, MARS observes the motion in the scene and determines when the motion matches one of the stored temporal templates. TI has obtained an evaluation copy of the MARS software and used it as an recognition device which identifies actions, and sends the result to the AVS VSS. We successfully trained MARS to recognize the actions of opening a door, and opening the drawer of a file cabinet. When MARS recognizes these actions, it sends a message to the AVS VSS, which can generate an appropriate alarm.

2.2. Camera hand-off

As depicted in Figure 1, the AVS system incorporates multiple cameras to enable surveillance of a wider area than can be monitored via a single camera. If the fields of view of these cameras are adjacent, a person can be tracked from one monitored area to another. When the person leaves the field of view of one camera and enters another, the process of maintaining the track from one camera view to another is termed *camera hand-off*. Figure 2 shows an area monitored by two cameras. Cam-

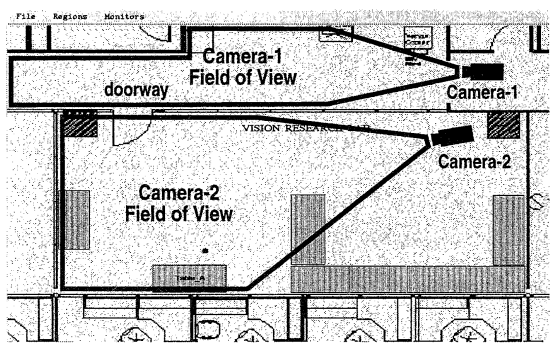


Figure 2: Multiple cameras with adjacent fields of view

era-1 monitors the hallway, and Camera-2 monitors the interior of the room. When a person moves through the doorway to enter the room from the hall or vice-versa, camera hand-off is necessary to enable the system to know that the person that was being monitored in the hall via Camera-1 is the *same* as the person being monitored in the room via Camera-2.

The AVS system accomplishes camera hand-off by integrating the information from the two cameras in the map coordinate system. The AVS "smart" cameras report the locations of the monitored objects and people in map coordinates, so that when the VSS receives reports about a person from two separate cameras, and both cameras are reporting the person's coordinates at about the same map location, the VSS can deduce that the two separate reports refer to the same person. In the example depicted in Figure 2, when a person is standing in the doorway, both cameras can see the person and report his or her location at nearly the same place. The VSS reports this as one person, using a minimum distance to allow for errors in location. When Camera-2 first sees a person at a location near the doorway and reports this to the VSS, the VSS checks to see if Camera-1 recently reported a person near the door. If so, the VSS reports the person in the room as the same one that Camera-1 had been tracking in the hall.

2.3. Vehicle event recognition

This section describes extensions to the existing AVS system that enable the recognition of events involving interactions of people with cars. These new capabilities enable smart security cameras to monitor streets, parking lots and driveways and report when suspicious events occur. For example, a smart camera signals an alarm when a person exits a car, deposits an object near a building, reenters the car, and drives away.

2.3.1. Scope and assumptions

Extending the AVS system to handle human-vehicle interactions reliably involved two separable subproblems. First, the system's vocabulary for events and objects must be extended to handle a new class of object (vehicle) and new event types. Second, the AVS moving object detection and tracking software must be modified to handle the outdoor environment, which features variable lighting, strong shadows, atmospheric disturbances, and dynamic backgrounds. The work described here in section 2.3 addresses the first problem, to extend the system for vehicle events in conditions of uniform overcast with little wind. Our approach to handling general outdoor lighting conditions is discussed in section 4.

The method is further specialized for imaging conditions in which:

1. The camera views cars laterally.
2. Cars are unoccluded by other cars.
3. When cars and people overlap, only one of the overlapping objects is moving
4. The events of interest are people getting into and out of cars.

2.3.2. Car detection

The first thing that was done to expand the event recognizing capability of the current system was to give the system the ability to distinguish between people and cars. The system classifies objects as cars by using their sizes and aspect ratios. The size of an object in feet is obtained using the AVS system's image coordinate to world coordinate mapping. Once the system has detected a car, it analyzes the motion graph to recognize new events.

2.3.3. Car event recognition

In principle, car exit and car entry events could be recognized by detecting characteristic interactions of blobs in difference images, in a manner similar to the way AVS recognizes DEPOSIT and REMOVE events. In early experiments, however, this method turned out to be unsatisfactory because the underlying motion segmentation method did not segment cars from people. Whenever the people pass near the car they appear to merge with it, and track is lost until they walk away from it.

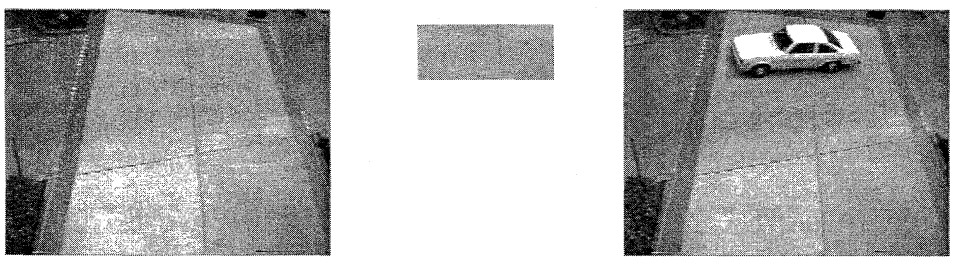
To solve this problem, a new approach involving additional image differencing was developed. The technique allows objects to be detected and tracked even when their images overlap the image of the car. This method requires two reference images: one consists of the original background scene (background image), and the other is identical to the first except it includes the car. The system takes differences between the current video image and the original reference image as usual. However, it also differences the current video image with the reference image containing the car. This allows the

system to detect objects which may be overlapping the car. Using this technique, it is easy to detect when people enter and exit a car. If an object disappears while overlapping with a car, it probably entered the car. Similarly, if an object appears overlapping a car, it probably exited the car.

2.3.4. Basic method

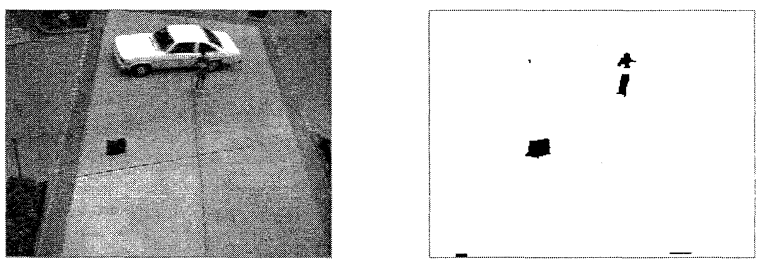
When a car comes to rest, the following steps are taken. First, the image of the car object is removed from its frame and stored. Then, the car image is merged with the background image, creating an updated reference image containing the car. (Terminology: a *reference car image* is the subregion of the updated reference image that contains the car.) Then, the *car background image*, the region of the original background image that is replaced by the car image, is stored.

For each successive frame, two difference images are generated. One difference image, the *foreground difference image*, is calculated by differencing the current video image with the updated reference image. The foreground difference image will contain all the blobs that represent objects other than the car, including ones that overlap the car. The second difference image, the *car difference image*, is calculated using the car background image. The car difference image is formed from the difference between the current frame and the car background image, and contains the large blob for the car itself. Figures 3 and 4 show the construction and use of these images.



(a) (b) (c)

Figure 3: (a) Background image. (b) Car background image. (c) Updated reference image



(a) (b)

Figure 4: (a) Current video image. (b) Foreground difference image

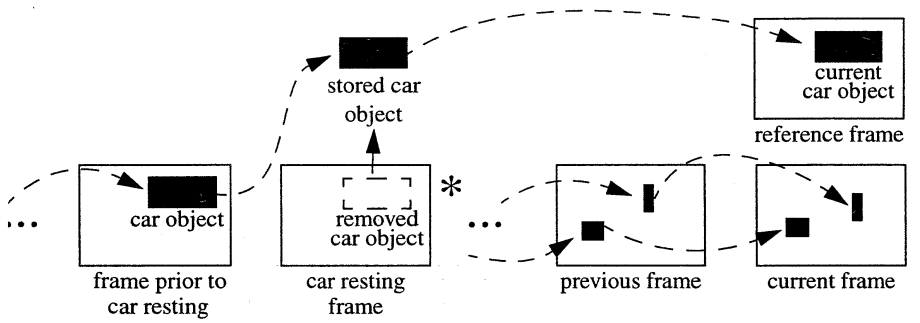


Figure 5: Creation of the motion graph.
The starred frame represents the frame prior to the background image being updated.

The blobs in the foreground difference image are grouped into objects using the normal grouping heuristics and placed in the current frame. The blobs in the car difference image necessarily represent the car, so they are all grouped into one current car object and placed in a special *reference frame*. Normal links occur between objects in the previous frame and objects in the current frame. Additionally, the stored car object, which was removed from its frame, (from Step 1) is linked to the current car object which is in the reference frame. In any given sequence, there is only one reference frame.

Figure 5 demonstrates the creation of this new motion graph. As indicated by the dotted lines, all objects maintain their tracks using this method. Notice that even though the car object disappears from future frames (due to the updated reference image), it is not detected to have exited because its track is maintained throughout every frame. Using this method, the system is able to keep track of the car object as well as any objects overlapping the car. If an object appears intersecting a car object, an INCAR event is reported. If an object disappears while intersecting a car object, an OUTCAR event is reported. Figure 6 shows the output of the system. The system will continue to operate in this manner until the car in the reference frame begins to move again.

When the car moves again, the system reverts to its normal single-reference-image state. The system detects the car's motion based on the movement of its centroid. It compares the position of the centroid of the stored car object with the centroid of the current car object. Figure 7 shows the slight movement of the car.

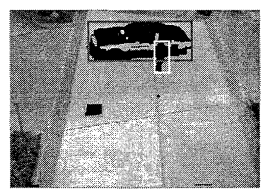


Figure 6: Final output of system

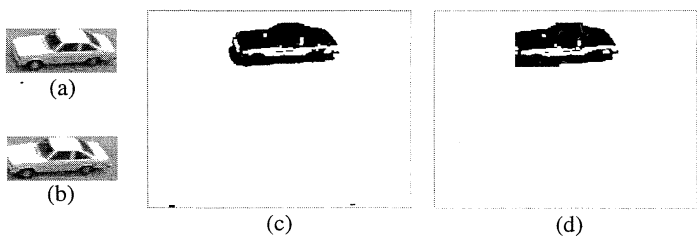


Figure 7: (a) Reference car image. (b) Moving car image.
(c) Reference car difference image. (d) Moving car difference image

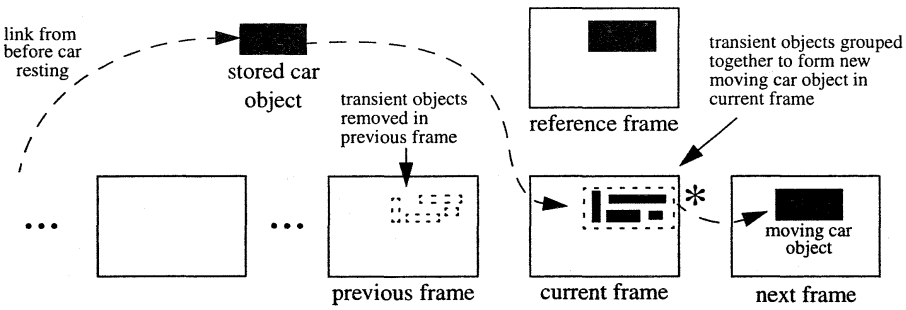


Figure 8: Restoration of normal differencing. The starred frame represents the last frame prior to the original reference image being restored.

If the centroid locations differ by more than a threshold, the following sequence of events occur to restore the system to its original state:

1. An object representing the moving car is created in the current frame.
2. The stored car object is linked to this new moving car object in the current frame.
3. Objects in the previous frame that intersect the moving car are removed from that frame.
4. The car background image is merged with the updated reference image to restore the original reference image.
5. Normal differencing continues.

Figure 8 demonstrates how the system is restored to its original state. Note that there is one continuous track that represents the path of the car throughout.

When the car begins to move again, transient blobs appear in the foreground difference image due to the fact that the car is in the updated reference image as seen in Figure 9. Therefore, to create a new moving car object in the current frame, these transient objects, which are identified by their intersection with the location of the resting car, are grouped together as one car object. If there are no transient objects, a copy of the stored car object is inserted into the current frame. This way, there is definitely a car object in the current frame to link with the stored car object. Transient objects might also appear in the previous frame when a car is moving. Therefore, these transient objects must be removed from their frame in order to prevent them from being linked to the new moving car object that was just created in the current frame. After the steps described above occur, the system continues as usual until another car comes to rest.

2.3.5. Experiments: disk-based sequences

To test the principles behind the modified AVS system, three sequences of video that represented interesting events were captured to disk. These sequences represented events which the modified system should be able to recognize. Capturing the sequences to disk reduces noise and ensures that the system processes the same frames on every run, making the results deterministic. In addition to these sequences, longer sequences were recorded and run directly from videotape to test how the system would work under less ideal conditions.

(a) (b) (c)

Figure 9: (a) Updated reference image. (b) Current video image. (c) Foreground difference image

2.3.5.1. Simple sequence. The first sequence was filmed from the 3rd story of an office building overlooking the driveway in front of the building. A car drives up and a person exits the car, walks away, deposits a briefcase, and finally reenters the car. Then, the car drives away. In this segment, the system successfully detects the person exiting the car. However, the person entering the car is missed because the person gets grouped with a second person walking near the car.

Further on in the sequence, the car drives up again and a person exits the car, walks away, removes the briefcase, and finally reenters the car. Again, the car drives away. In this segment, both the person entering and exiting the car are recognized. In both these sequences, there was only the one false negative mentioned earlier and no false positives.

2.3.5.2. Pickup sequence. This sequence was filmed in front of a house looking at the street in front of the house. In the sequence, a person walks into the scene and waits at the curb. A car drives up, picks up the person, and drives away. The system correctly detects the person entering the car. There are no false positives or negatives.

2.3.5.3. Drop off sequence. This sequence was filmed in the same location as the previous one. In this sequence, a car drives up and a person is dropped off. The car drives away with the person still standing in the same location. Then, the person walks off. The system correctly detects the person exiting the car and does not report a false enter event when the car moves away.

2.3.6. Experiments: videotaped sequences

These sequences were run on the system straight from videotape. These were all run at a higher threshold to accommodate noise on the videotape. However, this tended to decrease the performance of the system.

2.3.6.1. Dark day. This is a 15 minute sequence that was recorded from the 3rd floor of a building on a fairly dark day. In that time span, 8 cars passed through the camera's field of view. The system detected 6 cars correctly and one false car (due to people grouped together). One car that was not detected was due to its small size. The other car was undetected because the system slowed down (due to multiple events occurring) and missed the images with the car in them. In this sequence, two people entered a car. However, both events were missed because the car was not recognized as resting due to the dark lighting conditions on this rainy day.

2.3.6.2. Cloudy day. This is a 13 minute sequence in the same location as the previous sequence except it is a cloudy day. In this time span, 9 cars passed through the camera's field of view and all of them were detected by the system. There were a total of 2 people entering a car and 2 people exiting a car. The system successfully detected them all. Additionally, it incorrectly reported one person walking near a car as an instance of a person exiting a car.

2.3.6.3. Cloudy day—extended time. This is a 30 minute sequence in the same location as the previous two. In this time span, 28 cars pass through and all of them were detected. The system successfully detected one person exiting a car but missed two others. The two people were missed because the car was on the edge of the camera's field of view and so it was not recognized immediately as a car.

2.3.7. Evaluation of car-event recognition

The modified AVS system performs reasonably well on the test data. However, it has only been tested on a small number of videotaped sequences, in which much of the action was staged. Further experiments and further work with live, uncontrolled data will be required to make the system handle outdoor vehicle events as well as it handles indoor events. The technique of using multiple reference images is interesting and can be applied to other problems, e.g. handling repositioned furniture in indoor environments. For more detail on this method, see [Tserng, 1998].

2.4. Complex events

The AVS video monitoring technology enables the recognition of specific events such as when a person enters a room, deposits or picks up an object, or loiters for a while in a given area. Although these events are more sophisticated than those detected via simple motion detection, they are still unstructured events that are detected regardless of the context in which they occur. This can result in alarms being generated on events that are not of interest.

For example, if the system is monitoring a room or store with the intention of detecting theft, the system could be set up to generate an alarm whenever an object is picked up (i.e., whenever a REMOVE event occurs). However, no theft has occurred unless the person leaves the area with the object. A simple, unstructured event recognition system would generate an alarm every time someone picked up an object, resulting in many false alarms; whereas a system that can recognize complex events could be programmed to only generate an alarm when the REMOVE event is followed by an EXIT event. The EXIT event provides context for the REMOVE event that enables the system to filter out uninteresting cases in which the person does not leave the area with the object they picked up. This section describes the design and implementation of such a complex-event recognition system.

We use the term *simple event* to mean an unstructured atomic event. A *complex event* is structured, in that it is made up of one or more *sub-events*. The sub-events of a complex event may be simple events, or they may be complex, enabling the definition of event hierarchies. We will simply say *event* to refer to an event that may be either simple or complex. In our theft example above, REMOVE and EXIT are simple events, and THEFT is a complex event. A user may also define a further event, e.g., CRIME-SPREE, which may have one or more complex THEFT events as sub-events.

We created a user interface that enables definition of a complex event by constructing a list of sub-events. After one or more complex events have been defined, the sub-events of subsequently defined complex events can be complex events themselves.

2.4.1. Complex-event recognition

Once the user has defined the complex events and the actions to take when they occur, the event recognition system recognizes these events as they occur in the monitored area. For the purposes of this section, we assume *a priori* that the simple events can be recognized, and that the object involved in them can be tracked. In the implementation we will use the methods discussed in [Courtney, 1997, Olson and Brill, 1997] to track objects and recognize the simple events. In order to recognize a complex event, the system must keep a record of the sub-events that have occurred thus far, and the objects involved in them. Whenever the first sub-event in a complex event's sequence is recognized, an *activation* for that complex event is created. The activation contains the *ID* of the object involved in the event, and an *index*, which is the number of sub-events in the sequence that have been recognized thus far. The index is initialized to 1 when the activation is created, since the activation is only created when the first sub-event matches. The system maintains a list of current activations for each defined complex-event type. Whenever any new event is recognized, the list of current activations is consulted to see if the newly recognized (or *incoming*) event matches the next sub-event in the complex event. If so, the index is incremented. If the index reaches the total number of sub-events in the sequence, the complete complex event has been recognized, and any desired alarm can be generated. Also, since the complex event that was just recognized may also be a sub-event of another complex event, the activation lists are consulted again (recursively) to see if the indices of any other complex event activations can be advanced.

To return to our THEFT example, the complex THEFT event has two sub-events, REMOVE and EXIT. When a REMOVE event occurs, an activation for the THEFT event is created, containing the ID of the person involved in the REMOVE event, and an index set to 1. Later, when another event is recognized by the system, the activation is consulted to see if the event type of this new, incoming event matches the next sub-event in the sequence (in this case, EXIT). If the event type matches, the object ID is also checked, in this case to see if the person EXITing is the same as that of the person who REMOVEd the object earlier. This is to ensure that we do not signal a THEFT event when one person picks up an object and a different person exits the area. In a closed environment, the IDs used may merely be track-IDs, in which each object that enters the monitored area is assigned a unique track-ID, and the track-ID is discarded when the object is no longer being tracked. If both the event type and the object ID match, the activation's index is incremented to 2. Since there are only 2 sub-events in the complex event in this example, the entire complex-event has been recognized, and an alarm is generated if desired. Also, since the THEFT event has been recognized, this newly recognized THEFT event may be a sub-event of

another complex event. When the complex THEFT event is recognized, the current activations are recursively checked to see if the theft is a part of another higher-level event, such as a CRIME-SPREE.

2.4.2. Variations and enhancements

We have described the basic mechanism of defining and recognizing complex events. There are several variations on this basic mechanism. One is to allow unordered events, i.e., complex events which are simply the conjunction or disjunction of their sub-events. Another is to allow negated sub-events, which can be used to cancel an activation when the negated sub-event occurs. For example, considering the definition for THEFT again, if the person pays for the item, it is not a theft. Also, if the person puts the item back down before leaving, no theft has occurred. A more complete definition of theft is one in which "a person picks up an item and then leaves without putting it back or paying." Assuming we can recognize the simple events REMOVE, DEPOSIT, PAY, and EXIT, the complex THEFT event can now be expressed as the ordered list (REMOVE, ~DEPOSIT, ~PAY, EXIT), where "~" indicates negation. Another application of the complex event with negated sub-events is to detect suspicious behavior in front of a building. The normal behavior may be for a person to park the car, get out of it, and then come up into the building. If the person parks the vehicle and leaves the area without coming up into the building, this may be a car bombing scenario. If we can detect the sub-events for PARK, OUTCAR, ENTER-BUILDING, and EXIT, we can define the car-bombing scenario as (PARK, OUTCAR, ~ENTER-BUILDING, EXIT).

Another variation is to allow the user to label the objects involved in the events, which facilitates the ability to specify that two object be different. Consider a different car bombing scenario in which two cars pull up in front of the building, and a person gets out of one car and into the other, which drives away. The event definition must specify that there are two *different* cars involved: the car-bomb and the getaway-car. This can be accomplished by labelling the object involved when defining the event, and giving different labels to objects which must be different.

Finally, one could allow multiple activations for the same event. For example, the desired behavior may be that a separate THEFT event should be signalled for each item stolen by a given person, e.g., if a person goes into a store and steals three things, three THEFT events are recognized. The basic mechanism described above signals a single THEFT event no matter how many objects are stolen. We can achieve the alternate behavior by creating multiple activations for a given event type, differing only in the ID's of the objects involved.

2.4.3. Implementation in AVS

We have described a method for defining and recognizing complex events. Most of this has been implemented and incorporated into the AVS system. This subsection describes the current implementation.

AVS analyzes the incoming video stream to detect and recognize events such as ENTER, EXIT, DEPOSIT, and REMOVE. The primary technique used by AVS for event recognition is motion graph matching as described in [Courtney, 1997]. The AVS system recognizes and reports these events in real time as illustrated in Figure 10. When the person enters the monitored area, an ENTER event is recognized as shown in the image on the left. When the person picks up an object, a REMOVE event is recognized, as depicted in the center image below. When the person exits the area, the EXIT

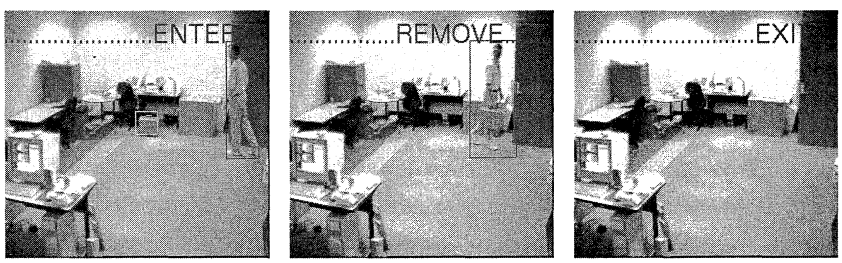


Figure 10: A series of simple events

event is signalled as shown in the image on the right

While the AVS system recognizes numerous events as shown above, the user can select which events are of interest by providing the dialog box interface illustrated in Figure 11. The user selects the event type, object type, time, location, and duration of the event of interest using a mouse. The user can also select an action for the AVS system to take when the event is recognized. This dialog box defines one type of simple event; an arbitrary number of different simple event types can be defined via multiple uses of the dialog box. The illustration in Figure 11 shows a dialog box defining an event called "Loiter by the door" which is triggered when a person loiters in the area near the door for more than 5 seconds.

AVS will generate a voice alarm and write a log entry when the specified event occurs. If the event is only being defined in order to be used as a sub-event in a complex event, the user might not check any action box, and no action will be taken when the event is recognized except to see if it matches the next sub-event in a complex-event activation, or generate a new activation if it matches the first sub-event in a complex event.

After one or more simple events have been defined, the user can define a complex event via the dialog box shown in Figure 12. This dialog box presents two lists: on the left is a scrolling list of all the event types that have been defined thus far, and on the right is a list of the sub-events of the complex event being defined. The sub-event list is initially blank when defining a new complex event. When the user double-clicks with the left mouse button on an item in the event list on the left, it is added as the next item in the sub-event list on the right. When the user double-clicks with the right mouse button on an item in the event list on the left, that item is also added to the sub-event list on the right, but as a negated sub-event. The event name is prefixed with a tilde (~) to indicate that the event is negated.

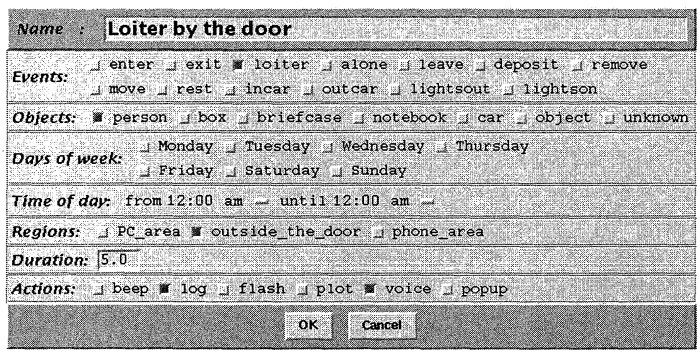


Figure 11: Selecting a type of simple event

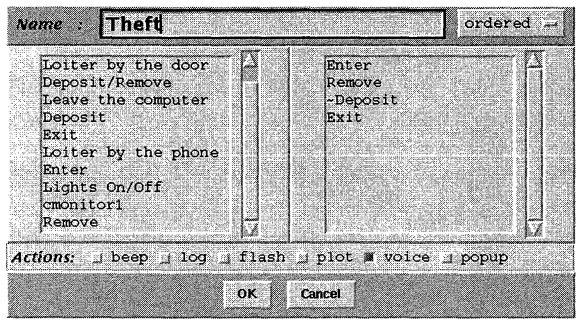


Figure 12: Defining a complex event

In the upper right corner of the complex-event definition dialog box is an option menu via which the user indicates how the sub-events are to be combined. The default selection is "ordered" to indicate sequential processing of the sub-events. The other options are "all" and "any." If "all" is selected, the complex event will be signalled if all of the sub-events are matched, regardless of order, i.e., the complex event is simply the conjunction of the sub-events. If "any" is selected, the complex event occurs if any of the sub-events occurs, i.e., the complex event is the disjunction of the sub-events. At the bottom of the dialog box, the user can select the action to take when the complex event is recognized. The user can save the entire set of event definitions to a file so that they may be read back in at a later time.

Once a simple or complex event has been defined, the AVS system immediately begins recognition of the new events in real time, and taking the actions specified by the user. The AVS system, augmented as described, provides a functioning realization of the complex-event recognition method.

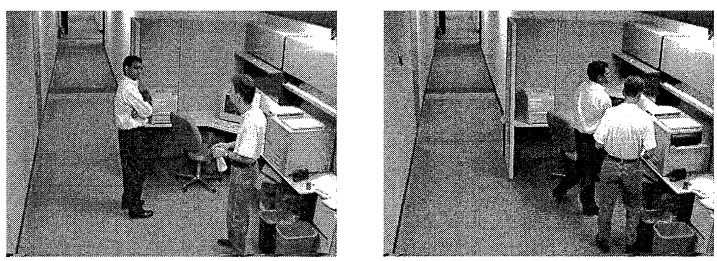
3. Advanced segmentation and tracking

In security applications, it is often necessary to track the movements of one or more people and objects in a scene monitored by a video camera. In real scenes, the objects move in unpredictable ways, may move close to one another, and may occlude each other. When a person moves, the shape of his or her image changes. These factors make it difficult to track the locations of individual objects throughout a scene containing multiple objects. The tracking capabilities of the original AVS system fail when there is mutual occlusion between the tracked objects. This section describes a new tracking method which overcomes this limitations of the previous tracking method, and maintains the integrity of the tracks of people even when they partially occlude one another.

The segmentation algorithm described here is related to tracking systems such as [Wren et al., 1997, Grimson et al., 1998, Cai et al., 1995] in that it extends the reference image to include a statistical model of the background. Our method further extends the tracking algorithm to reason explicitly about occlusion and maintain object tracks during mutual occlusion events. Unlike the capabilities described in previous sections, the new tracking method does not run in real time, and has not yet been integrated into the AVS system. Optimizations of the new method are expected to enable it to achieve real time operation in the future.

Figure 13 depicts an example scene containing two people. In (a), the two people are standing apart from each other, with Person-1 on the left, and Person-2 on the right. In (b), Person-1 moves to the right so that he is partially occluded by Person-2. Using a conventional technique such as background subtraction, it is difficult to maintain the separate tracks of the two people in the scene, since the images of the two people merge into a single large region.

Figure 14 shows a sequence of frames (in normal English reading order) in which it is particularly difficult to properly maintain the tracks of the two people in the scene. In this sequence, Person-2 moves from right to left and back again, crossing in front of Person-1. There are significant occlusions (e.g., in the third frame shown), and the orientations of both people with respect to the camera change significantly throughout the sequence,



(a) (b)

Figure 13: An example scene containing two people with occlusion

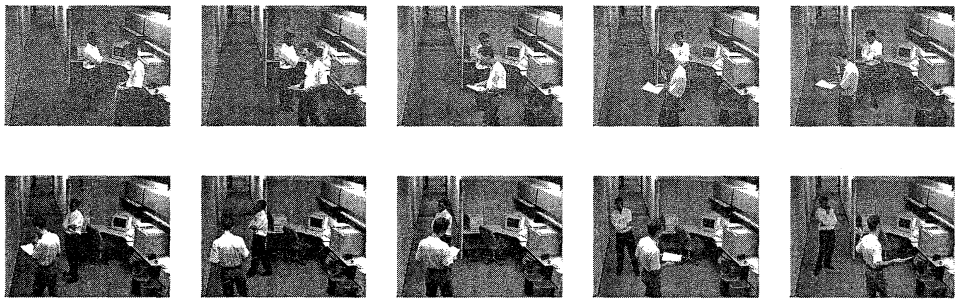


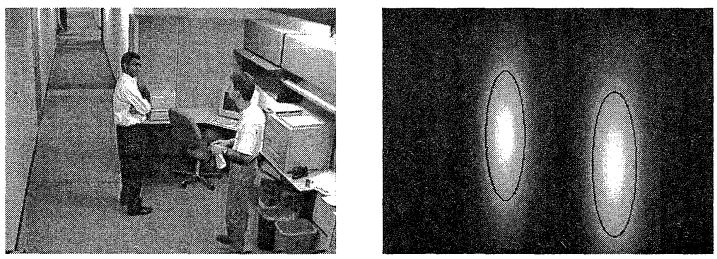
Figure 14: A difficult tracking sequence

making conventional template matching fail on this sequence.

A new tracking method is used to maintain tracks in sequences such as those depicted in Figures 13 and 14. The method maintains an estimate of the size and location of the objects being tracked, and creates an image which approximates the probability that the object intersects that pixel location. Figure 15b shows the probability images for the two person scene of Figure 13a, which is repeated here as 15a. The ellipse on the left indicates the estimated location of Person-1, and the ellipse on the right indicates the estimated location of Person-2. The brightness indicates the probability that the person's image intersects the given pixel, which is highest in the middle of the region, and falls off towards the edge. The black outlines represent the 50% probability contours. The size and shape of the regions are roughly the size and shape of a person standing at that location in the image.

We refer to the "person shaped" probability regions as *probabilistic templates* or simply *p-templates*. The path of the p-template through the scene represents the "track" of a given person which is maintained by the tracking system. P-templates can be used to reason about occlusion in a video sequence. While we only address the issue of p-templates for tracking people that are walking upright, the concept is applicable to tracking any object, e.g., vehicles and crawling people; although the shape of the p-template would need to be adapted to the type of object being tracked.

When the people in the scene overlap, the separate locations of the people can be maintained using the p-templates, and the region of partial occlusion can be detected. Figure 16 shows examples of such a situation. The two ellipses are maintained, even though the people are overlapping. The tracks of the people can be maintained through occlusions by tracking primarily on the basis of non-overlapping areas. This works for both the slight occlusion in Figures 16 (a) and (b), and often even for the very strong occlusions such as in Figures 16 (c) and (d). During the occlusions shown in Figure 14 and again in Figure 16 (c) and (d), the head of Person-1 is tracked, and the lower-body of Person-2 is tracked.



(a) (b)

Figure 15: Probability image for the locations of the people in the scene

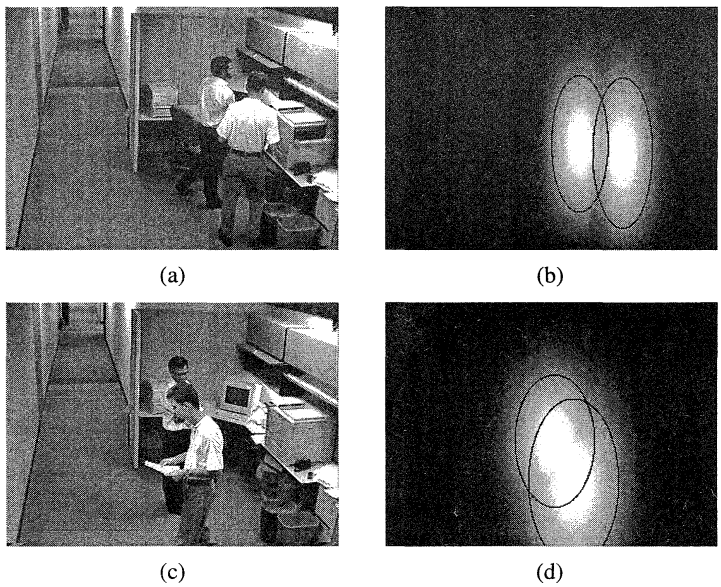


Figure 16: P-template images for partially occluding people

The new method requires a means of instantiating a new p-template when a person enters the scene, and updating the location of the region as the person moves through the scene. First we will describe the update mechanism, assuming that the p-templates have already been instantiated. The instantiation mechanism is described later.

The p-templates described above and depicted in Figures 15 and 16 represent the *prior* probabilities of the person locations, based on looking at the *previous* frame. These priors are then used to compute an estimate of the *posterior* probabilities of the person locations by looking at the new or *current* frame. The computation of the posterior probabilities takes into account both the prior probabilities and the information in the new frame. The posterior probabilities are used to update the locations of the people, and the new locations of the people are then used to compute the priors for the *next* frame.

Our current implementation computes the posteriors using a form of background differencing. Figure 17 shows the posteriors for the p-templates shown in Figure 16. Note that although there is significant overlap in the posterior estimates, especially in Figures 17 (e) and (f), there are significant differences in the brightnesses of the non-occluding areas. In Figure 17 (e), which represents the posteriors for Person-1, the head area of Person-1 is significantly brighter than in Figure 17 (f). Similarly, Figure 17 (f), which represents the posteriors for Person-2, is significantly brighter in the unoccluding area of Person-2's lower body.

Once the posteriors are computed, they are used to estimate the location of the tracked objects. In our implementation of a person tracker, we specifically need to estimate the location of the person's feet in the image, and their height in the image in pixels. Once the location and height are estimated, we can use the image-to-world coordinate transformation technique used in the original AVS system and described in [Olson and Brill, 1997]. That technique, called *quad-mapping*, computes the map locations of objects given the image locations of the bottom of the objects, e.g., in the case of a person, the location of the feet. Furthermore, if the scale of the map is known, the quad-mapping technique will estimate the size of the object, i.e., the height of a person being tracked.

If the lower portion of the p-template is unoccluded, foot locations are estimated directly from the image by looking at the bottom portion of the brightened region. If the upper portion is also unoccluded, the height can similarly obtained directly

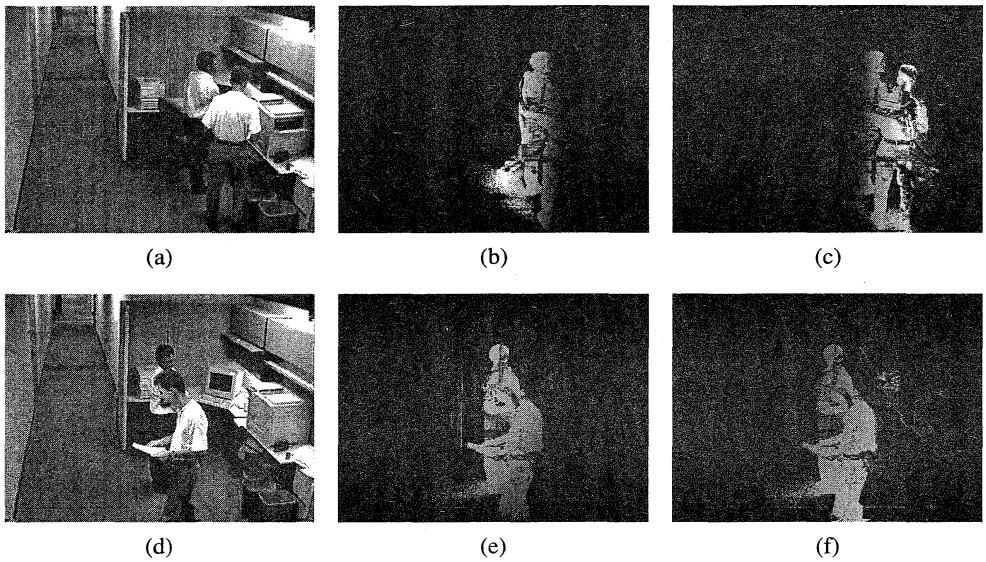


Figure 17: Posterior probability images for partially occluding people

from the image. If the upper part is occluded, but the lower part is not, the foot location is still determined directly from the image, but height is estimated using an estimate of the three-dimensional height of the person. The image height is then obtained by projecting the 3D height back into the image using the quad-mapping technique. If the lower portion is occluded, but the upper part is not, then the upper location is determined directly from the image, and then the 3D height is back-projected into the image to determine the foot location. If both the top and bottom are occluded, the location and height estimates are left unchanged from the previous frame.

Once the foot location and height of the person are computed, it is straightforward to compute the new location of the p-template, which is the Gaussian oval whose location and dimensions are determined by the foot location and image height computed above. The new p-template is then used to find the location of the person in the next frame, and the process repeats while the person remains in the scene.

A new p-template is instantiated whenever a new person enters the scene. Instantiation is best described in a Bayesian probabilistic framework. The p-templates constitute models of the objects in the environment. All of the pixels in the image are the result of a projection of some object in the environment—either from the background, or one of the people in the scene, or something else. The sum of the probabilities that the pixel is either from the background, from a person, or from "something else" must be 1.0. We maintain an "unknown" model to account for the probability that pixels may arise as a result of "something else." We compute the probability that each of the models caused the observed pixel value (where the unknown model is equally likely to produce any pixel value), and then use Bayes' formula to compute the inverse, i.e., the probability that the observed pixel value came from each of the models. When this computation is performed, for some of the pixels, the probability that the pixel came from the unknown model is the highest of all of the model probabilities. This results in a probability image for the unknown model, which represents pixels which probably came from something other than the objects the system knows about. At each frame, the probability image for the unknown model is computed, and this image is examined to see if adding a new person model would account for these unknown pixels. If so, a new person p-template is instantiated at the appropriate location, and the posteriors are recomputed.

Use of the procedure described above to track multiple people maintains tracks through occlusions where our previous technique could not. The robustness to occlusion of the new method enables video monitoring applications to improve tracking reliability in natural environments.

4. Best-view selection performance

Olson and Brill [1997] previously described the "best view selection" application of AVS technology. In this application, the system monitors and records the movements of humans in its field of view. For every person that it sees, it creates a log file that summarizes important information about the person, including a snapshot taken when the person was close to the camera and (if possible) facing it.

As the person is tracked through the scene, the tracker examines each image it captures of that person. If the new image is a better view of the person than the previously saved snapshot, the snapshot is replaced with the new view. In this manner, the system always contains the "best" view seen of the person thus far. When the person leaves the scene, the log entry is saved to a file. Each log entry records the time when the person entered the scene and a list of coordinate pairs showing their position in each video frame. The log entry also contains the "best" snapshot of the person while they were in the scene. Finally, the log entry file contains a pointer to the reference image that was in effect when the snapshot was taken. This information forms an extremely concise description of the person's movements and appearance while they were in the scene. An example of such a record in shown in Figure 18.

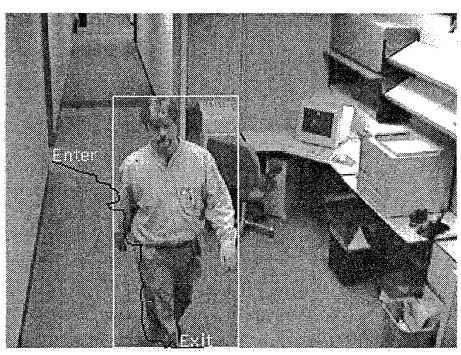


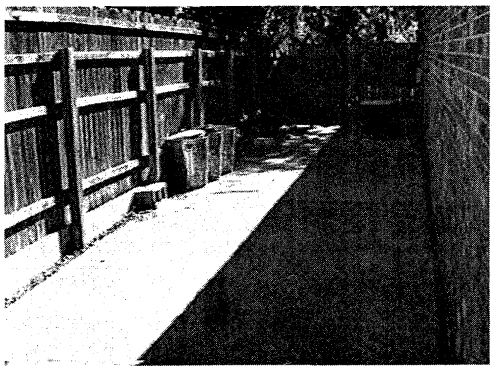
Figure 18: Example best view selection record

In an initial evaluation of this system, the system was installed in an uncontrolled office hallway and run for 118 hours. In this time, the system recorded 965 log entries in 35MB (uncompressed). The resulting records were examined to estimate the system performance, and we estimated 96% detection rate at 6% false alarm rate, with most errors due to segmentation and correspondence failure. However, for this initial experiment, there was no ground truth against which the performance could be measured.

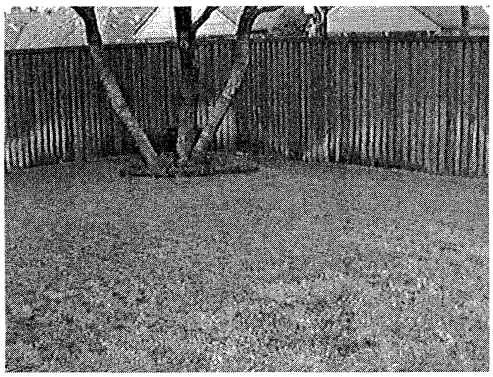
Recently, we have evaluated the system against ground truth observations. The performance of the system was initially evaluated on four hours of indoor video data. The video was manually annotated to obtain ground truth, and the surveillance system was evaluated against this ground truth. For situations in which only one person was in the scene, the system recorded exactly one record for each person, i.e., no person passed undetected though the field of view, and there is exactly one record for each such person. In the indoor condition, we observed a 100% detection rate.

For situations involving more than one person, the system occasionally failed to maintain track through partial occlusions. The result of this is that the system took extra pictures of these people when their track was re-acquired after the occlusion. On other occasions, the system failed to recognize that a motion region contained two people, and so it only took one picture that contained both people. We expect to reduce these errors via the use of the new tracking algorithms described above, once these algorithms are running in real time and are incorporated into the AVS system.

In order to evaluate and improve the system performance in outdoor monitoring environments, we have adopted an iterative research methodology in which we record representative videotape (2-3 hours), ground truth it with respect to the 'person events' that occur in the scene. One 'person event' is defined to be a video sequence in which one person enters monitored area completely, walking upright, and then exits field of view completely. We then run AVS system on the videotape and measure the false positives and negatives on person events. We then improve system as necessary to eliminate errors on video sequence and repeat the process.



(a)



(b)

Figure 19: Outdoor environments

Outdoor environments can be particularly difficult for video monitoring systems that operate based on change detection, due to the outdoor lighting variation. Figure 19 depicts two outdoor environments used to evaluate AVS best-view-selection performance. In Figure 19 (a), there is a strong shadow line running down the center of the field of view, which moves as the sun angle changes. The shadow motion here is sufficient to cause problems for a fixed background subtraction system within 5 minutes. There are also a number of trees in the background which move when the wind blows. Moreover, the shadows of these trees fall directly into the rear of the monitored area, and these shadows move with the wind as well. The shadow of the tree in Figure 19 (b) has a similar behavior. Cloud movement also causes large changes in brightness throughout the images.

Our initial outdoor evaluation was conducted in the environment depicted in Figure 19 (a). We captured two hours of outdoor video with extremely difficult imaging conditions caused by wind blown vegetation and strong shadows, which produced a large amount of "noise" motion. Additionally, the gate at the rear of the scene often blew open and closed. We manually ground-truthed the video to determine that a person entered the scene 20 times during the two hour sequence. The system recorded 16 of these events, for a detection rate of 75%. The undetected people were "lost in the noise." The system also produced 16 false detections in the two hour period, caused by noise from the moving shadows.

We were able to improve on this performance using our iterative research methodology to achieve a 100% detection rate for the 20 events in this two hour sequence. The system still recorded 8 false positives on this sequence. Four of these were caused by the gate blowing open and closed. The other four were cases in which the system lost track of the person in the field of view, and therefore took two pictures of the person, one before losing track, and another after picking up the track again. These cases are therefore more properly referred to as "extra pictures" rather than false positives.

Having achieved improved performance in the environment depicted in Figure 19 (a), we proceeded to test the system in the environment of Figure 19 (b). One three separate days we captured 1-2 hours of video, for a total of 4 hours of test video data in the environment of Figure 19 (b). We ground-truthed this video to determine that it contained 115 person events. The AVS system processed this video using the best-view-selection algorithm, and the results were compared to ground truth. We observed a 100% detection rate and a 2.6% false positive rate as a result of three false positives, all of which were "extra pictures."

In general, system performance was excellent in the indoor condition, with the exception of scenes containing multiple people, which produced extra records. We expect to address the multi-person problem using the p-template technique described in section 3. No person entered the scene without being recorded, even when there were multiple people. The system performance degrades in diffi-

cult outdoor lighting conditions, but it has improved significantly in recent work.

5. Conclusion

We have described several improvements in the video monitoring capabilities of the AVS system. Some improvements, such as vehicle event recognition, increase the functionality of the system to enable it to recognize new classes of events. Other improvements, such as the advanced segmentation and tracking, increase the robustness of the system's ability to recognize events in the presence of complications such as occlusion. We will continue to make improvements in the two categories of increased functionality and increased robustness. For the functionality improvements, we expect to recognize new classes of events, especially events regarding vehicles. For the robustness improvements, we are pursuing techniques that enable the system to be robust to lighting variation. As the techniques become more complex, additional effort will be needed to optimize the algorithms for real time operation. Our advanced segmentation and tracking will be the subject of optimization efforts in the near future.

References

[Cai, et al., 1995] Q. Cai, A. Mitiche, and J. K. Aggarwal. Tracking human motion in an indoor environment. In *Proc. of International Conference on Image Processing* (ICIP-95), 1995.

[Davis and Bobick, 1997] J. Davis and A. Bobick. Representation and recognition of human movement using temporal templates. In *Proc. IEEE Conf. on Computer Vision and Pattern Recognition (CVPR-97)*, pp. 928-934, 1997.

[Courtney, 1997] J. D. Courtney. Automatic video indexing via object motion analysis. *Pattern Recognition*, **30**(4), April 1997

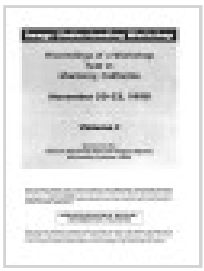
[Grimson et al., 1998] W. E. L. Grimson, C. Stauffer, R. Romano, and L. Lee. Using adaptive tracking to classify and monitor activities in a site. In *Proc. IEEE Conf. on Computer Vision and Pattern Recognition (CVPR-98)*, 1998.

[Olson and Brill, 1997] T. J. Olson, and F. Z. Brill. Moving object detection and event recognition algorithms for smart cameras. *Proceedings of the 1997 Image Understanding Workshop*, New Orleans, LA, May 11-14, 1997, p. 159-175.

[Tserng, 1998] C. H. Tserng. Event recognition in scenes involving people and cars. Master's Thesis, MIT, May 1998.

[Wren et al., 1997] A. Azarbayejani, T. Darrell, and A. Pentland. Pfinder: real-time tracking of the human body. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, July 1997, **19**(7), pp. 780-785.

EXHIBIT H



Related Names

DARPA Image Understanding Workshop (26th : 1998 : Monterey, CA)

Lukes, George E

United States Defense Advanced Research Projects Agency Information Systems Office

Related Subjects

Image Processing — Congresses

Optical Pattern Recognition — Congresses

Remote Sensing — Congresses

Computer Vision — Congresses

Item Details (Item 1 of 1)

← Return to search results | Start over Add Star **Item Actions**

Image Understanding Workshop: Proceedings of a Workshop Held in Monterey, California, November 20-23, 1998

sponsored by Defense Advanced Research Projects Agency, Information Systems Office ; [edited by George E. Lukes]

Format	Book
Published	San Francisco, Calif. : Distributed by Morgan Kaufmann Publishers, [1998]
Language	English
Variant Title	Proceedings, 1998 Image Understanding Workshop, 20-23 November, Hyatt Regency, Monterey, CA

ISBN	1558605835
Description	2 v. : ill. ; 28 cm.
Notes	Includes bibliographical references and index.
Technical Details	Access in Virgo Classic Staff View

LEADER			01549nam a2200361Ia 4500
001			u2928081
003			SIRSI
005			19990805102441.0
008			981215s1998 cau 100 0 eng d
020			a| 1558605835
035			a| (Sirsi) i1558605835
035			a| (OCoLC)40497803
040			a| XRL c| XRL d| OCL
090			a| TA1632 b| .I57 1998
111	2		a| DARPA Image Understanding Workshop n| (26th : d| 1998 : c| Monterey, CA)
245	1	0	a| Image Understanding Workshop : b| proceedings of a workshop held in Monterey, California, November 20-23, 1998 / c| sponsored by Defense Advanced Research Projects Agency, Information Systems Office ; [edited by George E. Lukes].
246	1	4	a| Proceedings, 1998 Image Understanding Workshop, 20-23 November, Hyatt Regency, Monterey, CA
260			a| San Francisco, Calif. : b| Distributed by Morgan Kaufmann Publishers, c| [1998]
300			a| 2 v. : b| ill. ; c| 28 cm.
504			a| Includes bibliographical references and index.
596			a| 5
650		0	a| Image processing v| Congresses.
650		0	a| Optical pattern recognition v| Congresses.
650		0	a| Remote sensing v| Congresses.
650		0	a| Computer vision v| Congresses.
700	1		a| Lukes, George E.
994			a| Z0 b| VA@
710	1		a| United States. b| Defense Advanced Research Projects Agency. b| Information Systems Office.
852			b| SCI-ENG c| STACKS
866		0	8| 1 a| v.1-2
999			a| TA1632 .I57 1998 v.1 w| MONO-SER i| X004283491 l| STACKS m| SCI-ENG t|BOOK
999			a| TA1632 .I57 1998 v.2 w| MONO-SER i| X004283490 l| STACKS m| SCI-ENG t|BOOK

See fewer details

Availability

Request LEO delivery

Brown SEL

STACKS

v.1-2

Library	Location	Map	Availability	Call Number
Brown Science and Engineering	Stacks	N/A	AVAILABLE	TA1632 .I57 1998 v.1

Library	Location	Map	Availability	Call Number	
Brown Science and Engineering	Stacks	N/A	AVAILABLE	TA1632 .I57 1998 v.2	

EXHIBIT I

NCSU LIBRARIES

Library Catalog

Search for words: Search

Search within results Start Over[1]

Image Understanding Workshop : proceedings of a workshop held in Monterey, California, November 20-23, 1998
sponsored by Defense Advanced Research Projects Agency, Information Systems Office ; [edited by George E. Lukes].

Author:	DARPA Image Understanding Workshop (26th : 1998 : Monterey, CA)[11]
Published:	San Francisco, Calif. : Distributed by Morgan Kaufmann Publishers, [1998]
Description:	2 v. : ill. ; 28 cm.
Format:	Book
Summary	Reports and technical results presented at the biennial workshops of the DARPA Image Understanding research program. Content provided by Syndetic Solutions, Inc. Terms of Use (more)[5]

Browse Shelf[12]

Browse Related Subjects

- Image processing[13] -- Congresses[14]
- Optical pattern recognition[15] -- Congresses[16]
- Remote sensing[17] -- Congresses[18]
- Computer vision[19] -- Congresses[20]

MARC

000			01338cam a2200313Ia 4500
003			OCoLC
005			19990810132534.0
008			981215s1998 caua b 100 0 eng d
020			|a1558605835
035			|a(OCoLC)40497803
040			|aXRL |cXRL |dOCL
049			|aNRCC |xERJ
090			|aTA1632 |b.D35 1998
111	2		|aDARPA Image Understanding Workshop |n(26th : |d1998 : |cMonterey, CA)
245	1	0	|aImage Understanding Workshop : |bproceedings of a workshop held in Monterey, California, November 20-23, 1998 / |csponsored by Defense Advanced Research Projects Agency, Information Systems Office ; [edited by George E. Lukes].
246	1	4	|aProceedings, 1998 Image Understanding Workshop, 20-23 November, Hyatt Regency, Monterey, CA
260			|aSan Francisco, Calif. : |bDistributed by Morgan Kaufmann Publishers, |c[1998]
300			|a2 v. : |bill. ; |c28 cm.
504			|aIncludes bibliographical references and index.
596			|a14
650		0	|aImage processing |vCongresses.
650		0	|aOptical pattern recognition |vCongresses.
650		0	|aRemote sensing |vCongresses.
650		0	|aComputer vision |vCongresses.
700	1		|aLukes, George E.
710	1		|aUnited States. |bDefense Advanced Research Projects Agency. |bInformation Systems Office.
948			|a08/09/1999 |b10/06/1999
919			|aAKD-4329
918			|a1089089