Integrating Multiple Data Representations For Spatial Databases

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Abstract

An intelligent spatial database must be able to organize and store information from diverse sources. Aerial imagery, map, and terrain data must be merged with textual and collateral information. Future systems will integrate the results of automated analysis of remotely sensed imagery within the context of the spatial database. No single internal representation can efficiently provide for the variety of the needs and problems for these types of spatial databases. For example, in order to efficiently search large databases it is critical to be able to partition the search based on spatial decompositions, whether hierarchical, regular, or mixed. In this paper we discuss some recent work on integrating multiple spatial and factual data representations so as to capitalize on their inherent advantages for search, geometric computation, and maintenence of topological consistency.

1. Introduction

An intelligent spatial database must be able to organize and store information from diverse sources. Aerial imagery, map, and terrain data must be merged with textual and collateral information. Future systems will integrate the results of automated analysis of remotely sensed imagery within the context of the spatial database. No single internal representation can efficiently provide for the variety of the needs and problems for these types of spatial databases. For example, in order to efficiently search large databases it is critical to be able to partition the search based on spatial decompositions, whether hierarchical, regular, or mixed. However, the data structures used for such a decomposition, hierarchy trees, quadtrees, and k-d trees, are not particularly well suited to (for example) the maintenance of topological consistency. Arc-node, or segment-node representations have been developed for this purpose, but they introduce problems for spatial decomposition algorithms. Finally, neither addresses the problem of feature attribution, coupling semantic descriptions of the feature with its spatial component. Semantic networks or frame-based systems can be expected to compete with relational models in this area.

Thus, there are several dimensions along which one can choose appropriate data structures and representations. In this paper we describe some research results in integrating multiple data representations within the context of an experimental spatial database system, MAPS. developed at Carnegie Mellon University. The areas covered are:

- The use of a schema-based description that allows queries based on user-defined attributes as well as shape, size, and spatial relationships computed and maintained by the system.
- The maintenance of an arc-node feature representation for feature editing and display while maintaining a parallel entity-based spatial database in a hierarchical containment tree.
- Some comparisons of the relative properties and merits of various component databases for storage and retrieval of data in different representations.

2. An Overview of MAPS

The MAPS spatial database[1,2,3,4] was developed between 1980-1984 supported by the DARPA Image Understanding Program as research into large-scale spatial databases and spatial knowledge representation. It is interesting that this system has expanded from its original research goal of developing an interactive database for answering spatial queries into a component of several knowledge-based image understanding systems under development at Carnegie Mellon University. MAPS is a large-scale image/map database system for the Washington D.C. area that contains approximately 200 high resolution aerial images, a digital terrain database, and a variety of map databases from the Defense Mapping Agency (DMA). MAPS has been used as a component for an automated road finder/follower, a stereo verification module, and a knowledge-based system for interpreting airport scenes in aerial imager. In addition, MAPS has an interactive user query component that allows users to perform spatial queries using high resolution display of aerial imagery as an method for indexing into the spatial database. This capability to relate, over time, imagery at a variety of spatial resolutions to a spatial database forms a basis for a large variety of interpretation and analysis tasks such as change detection, model-based interpretation, and report generation.

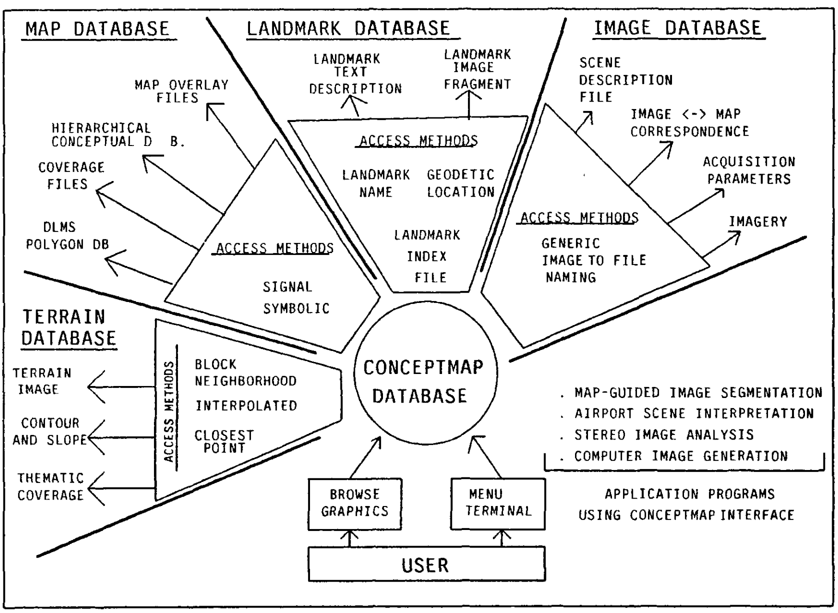

Figure 2-1: MAPS: System Overview

Figure 2-1 shows the system organization of MAPS. Four databases are maintained within MAPS: a digital terrain database, a map database, a landmark database, and an image database. A fifth database, CONCEPTMAP, consists of a schema-based representation for spatial entities and a set of procedural methods that provide a uniform interface to each of the four component databases for interactive users or application programs. It is this interface that allows us to represent and access image, map, terrain, and collateral data in a manner that best suits the intrinsic structure of the data. At the same time the CONCEPTMAP database provides uniform access to a variety of spatial data independent of the particular internal structure. This is in sharp contrast to methods proposed for uniform representation of image and cultural data such as raster data sets and regular decompositions such as quadtrees or k-d trees. In the following sections we touch on some interesting aspects of the CONCEPTMAP database. Figure 2-2 gives another view of the structure of spatial data within the MAPS system, that of the physical representation of data as stored in the component databases. There are currently four data representation types: semantic knowledge, geometrical and topological descriptions of spatial data, raster representation, and spatial hierarchies.

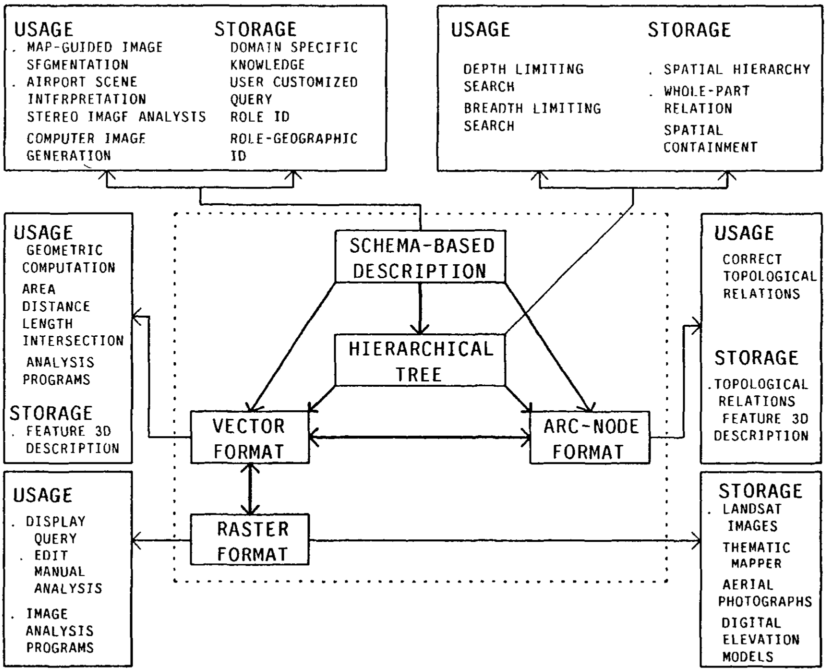

Figure 2-2: Data Representations In MAPS

A key point is that there is not a one-to-one mapping between the source or type of data and its representation methods within the MAPS system. For example, raster formats are used to store both digital image data as well as digital elevation models since this is the natural representation even though the access semantics for a two-dimensional image are different than for a three-dimensional DEM. The access functions associated with each datatype implicitely make use of information concerning properties of the raster such as sensor and camera models for image access and elevation cell size and ground coordinate when accessing elevation data. In the case of map features their coordinates can be stored as in either vector or arc-node formats, and relationships between features can be conputed in either representation. This flexability allows MAPS to provide flexible access to spatial entities using several independent methods. Thus, the location of a spatial entity can be retrieved via its intrinsic properties, as stored in the schema-based description, its relationships with other entities via a hierarchical containment tree, or via topological relations maintained within an arc-node representation.

As shown in Figure 2-2 there are many relationships between data that are explicitely stored within each representation. For example, the hierarchical containment tree is generated using the CONCEPTMAP schemata and their associated spatial data as stored in vector format. Once generated, the containment tree can be used to efficiently search our arc-node representation for features within an arbitrary area of interest using spatial decomposition based on the underlying structure of the area. It is the role of the CONCEPTMAP interface to support conversions between different representations and spatial data retrieval in a manner that hides the actual physical representation(s) of the underlying data. Given this organization application programs can be written which capitalize on the most efficient data access methods, and can use these representations as primitives to construct customized access and query mechanisms to support specific tasks. In the following Section we discuss the organization of the CONCEPTMAP schema-based represention. This representation stores the semantics of each spatial entity as well as symbolic methods for access of the associated spatial data. In Section 4 we briefly discuss some experiments in representation of spatial data using vector and arc-node representations.

3. A Schema-Based Representation For Spatial Entities

The CONCEPTMAP database uses a *schema-based* representation for spatial entities. Using schemas (or frames) is a well understood AI methodology for representing knowledge. Such a representation can be combined within several problem-solving methods such as semantic networks, scripts or production systems to construct a problem-solving system[5]. Each entity in the CONCEPTMAP database is represented by one *concept* schema and at least one *role* schema. A *concept* can represent any spatial object and associates a name with a set of attributes stored in the *concept* and *role* schemata. Figure 3-1 gives definitions of the slot names for *concept* and *role* schemata. Figure 3-2 gives an partial list of the concepts in the MAPS WASHDC database.

GENERAL SCHEMA DEFINITION
SLOT VALUE
LIST OF SLOT VALUES
SYSTEM GENERATED IDENTIFIER

CONCEPT SCHEMA DEFINITION
CONCEPT-NAME
CONCEPT-ID
PRINCIPAL ROLE
LIST OF ROLE-IDS
LIST OF ROLE-PRINTNAMES

ROLE SCHEMA DEFINITION
ROLE-ID
ROLE-NAME
ROLE-SUBNAME
ROLE-CLASS
ROLE-TYPE
ROLE-DERIVATION
ROLE-MARK
LIST OF USER-DEFINED-SLOTS
LIST OF VALUES FOR USER-DEFINED-SLOTS
ROLE-GEOGRAPHICS-ID

SYSTEM GENERATED IDENTIFIERS	INDEX INTO SPECIALIZED DATABASES
CONCEPT-ID	ROLE PRINT-NAMES LANDMARK
ROLE-ID	PROPERTY LIST GEOMETRIC QUERY LIST TEXT HISTORY HIERARCHICAL DECOMPOSITION
ROLE-GEOGRAPHICS-ID	SPATIAL RELATIONSHIPS (MEMO FILES) 2D SHAPE DESCRIPTION 3D DESCRIPTION CONVEX HULL IMAGE SEGMENTATION IMAGE COVERAGE

Figure 3-1: MAPS: Concept and Role Schemata Definitions

CONCEPT1	tidal basin	CONCEPT195	l enfant plaza
CONCEPT2	district of columbia	CONCEPT196	forrestal building
CONCEPT3	northwest washington	CONCEPT197	east potomac park
CONCEPT4	mcmillan reservoir	CONCEPT198	folger library
CONCEPT5	southwest washington	CONCEPT199	senate office building
CONCEPT6	northeast washington	CONCEPT200	visitors center
CONCEPT7	virginia	CONCEPT201	capital hill park
CONCEPT8	maryland	CONCEPT202	capitol plaza park
CONCEPT9	kennedy center	CONCEPT203	mall ice rink
CONCEPT10	ellipse	CONCEPT204	federal office building 6
CONCEPT11	washington circle	CONCEPT205	natural history museum
CONCEPT12	state department	CONCEPT206	federal aviation administration
CONCEPT13	executive office building	CONCEPT207	freer gallery
CONCEPT14	white house	CONCEPT208	smithsonian institution
CONCEPT15	treasury building	CONCEPT209	george mason memorial bridge
CONCEPT16	department of commerce	CONCEPT210	group hospital building
CONCEPT17	arlington memorial bridge	CONCEPT211	lisner auditorium
CONCEPT18	rfk stadium	CONCEPT212	doctors hospital
CONCEPT19	museum of history and technology	CONCEPT213	route 1
CONCEPT20	key bridge	CONCEPT214	dulles airport
CONCEPT21	kutz bridge	CONCEPT215	rock creek park
CONCEPT22	george mason bridge	CONCEPT216	constitution pond
CONCEPT23	fort stanton reservoir	CONCEPT217	georgetown reservoir

Figure 3-2: Concepts from 'washdc' CONCEPTMAP Database [partial list]

There are three unique identifiers generated by the CONCEPTMAP system which allow for indirect access to additional factual properties of concept or role schemata.

- The *concept-id* is unique across all concepts in all CONCEPTMAP databases. That is, given a concept-id one can uniquely determine the name of the spatial entity.
- The *role-id* uniquely determines a role schema across all CONCEPTMAP databases.
- The *role-geographics-id* uniquely determines a collection of points, lines or polygons in vector notation. Each point is represented as <latitude,longitude,elevation>.

ROLES:
UNKNOWN
BUILDING
BRIDGE
ROAD
RESERVOIR
AIRPORT
RESIDENTIAL AREA
INDUSTRIAL AREA
UNIVERSITY
PARKS
SPORTS COMPLEX

ROLE-TYPES:
UNKNOWN
PHYSICAL
CONCEPTUAL
AGGREGATE-PHYSICAL
AGGREGATE-CONCEPTUAL

ROLE-CLASS:	
UNKNOWN	GOVERNMENT
INDUSTRIAL	CULTURAL FEATURE
RESIDENTIAL	COMMERCIAL
TRANSPORTATION	RECREATIONAL
NATURAL FEATURE	EDUCATIONAL

ROLE-MARK:	
UNKNOWN	MODIFY-ROLE
NONE	NEW-3D
GEO-QUERY	MODIFY-3D
TEMPLATE-QUERY	MODIFY-NAMF-ROLE
NEW-CONCEPT	EXTRACT-FROM-DATABASE
NEWROLE	
MODIFY-CONCEPT	

ROLE-DERIVATION:
UNKNOWN
HAND-SEGMENTATION
MACHINE-SEGMENTATION
TERMINAL-INTERACTION
LANDMARK-DESCRIPTION
DLMS-EXTERNAL
UNKN-EXTERNAL

USER DEFINED SLOTS:	
USER-DEFINED	'COMPOSITION'
UNKNOWN	STONE/BRICK
SOIL	COMPOSITION
ASPHALT	EARTHEN WORKS
CONCRETE	ROCK
METAL	

Figure 3-3: Conceptmap Database Dictionary:
System and User Defined Attributes

As shown is Figure 3-1 these identifiers are also used to index into other components of the MAPS database. For example, the *concept-id* is used to search for landmark descriptions of measured ground control points used during the calculation of transform functions for image-to-map and map-to-image

ROLE: BUILDING	
UNKNOWN	MEDICAL CENTER
OFFICE BUILDING	BOATHOUSE
GOVERNMENT BUILDING	APARTMENTS
DORMITORY	HOTEL/MOTEL
CONCERT HALL	LIGHT MANUFACTURING
MUSEUM	GYMNASIUM
PERFORMING ARTS COMPLEX	HOSPITAL
RAILROAD STATION	LIBRARY
ADMINISTRATION	CLASSROOMS
MEMORIAL	STUDENT UNION

ROLE: AIRPORT
UNKNOWN
COMMERCIAL
MILITARY

ROLE: RESERVOIR
UNKNOWN
DRINKING WATER

ROLE: UNIVERSITY
UNKNOWN
DORMITORIES
ATHLETIC FACILITIES
UNIVERSITY CAMPUS
RESEARCH FACILITY
ADMINISTRATION
STUDENT CENTER
CAFETERIA
ADMISSION

ROLE: ROAD	
UNKNOWN	TRAFFIC CIRCLE
INTERSTATE HIGHWAY	INTERSECTION
STREET	INTRACITY HIGHWAY
AVENUE	ACCESS ROAD
RURAL ROAD	

ROLE: BRIDGE
UNKNOWN
RAILROAD
PEDESTRIAN
AUTOMOBILE

ROLE: SPORTS COMPLEX	
UNKNOWN	OPEN AREA
STADIUM	GOLF COURSE
BOAT MARINA	
ICE SKATING RINK	

ROLE: PARKS	
UNKNOWN	ZOO
PLAYING FIELD	FORMAL GARDEN
OPEN AREA	BLEACHERS
POND	SCULPTURE GARDEN
FORESTED AREA	

ROLE: POLITICAL
UNKNOWN
STATE
COUNTY
CITY
DISTRICT

ROLE: RESIDENTIAL AREA
UNKNOWN
SINGLE FAMILY HOUSING
APARTMENT COMPLEX
MIXED HOUSING

Figure 3-4: Conceptmap Database Dictionary: Subrole Attributes

correspondence. The *role-id* is used as the basic entity when building a hierarchy tree decomposition. The *role-geographics-id* is used to acquire the unique geographic position for a *role schema* as well as for linkage into the MAPS image database and segmentation files generated by human interaction or machine segmentation. There are three reasons for this approach. First, it allows CONCEPTMAP to handle very large databases with a minimal amount of information resident in the application process. The identifiers provide a level of indirection to the actual data, which is stored in a variety of formats and may or may not be present for a large subset of the database. Second, we can achieve a great deal of flexibility and modularity in processes which communicate about spatial entities. Given the name of a CONCEPTMAP database, a *concept-id* or *role-id* uniquely determines the entity in question. This facilitates the construction of application programs with simple query structures, requiring a minimum of communication overhead. Finally, given this decoupling from the CONCEPTMAP database, each of the MAPS component databases, image database, terrain database, landmark database, and map database may be physically resident on a different workstation or mainframe.

There are three levels of attribution available to users within CONCEPTMAP:

- *system-wide* attributes: stored in role schema.
- *user-defined* attributes: stored in role schema.
- *property-list* attributes: stored in property list database.

CONCEPTMAP allows users to define additional attributes, called *user-defined*, similar in function to the *role-name* and *role-subname* slots described above. Finally, *property-list* attributes can also be defined by the user and are capable of representing a variety of datatypes including 'strings', 'integers', 'double',and 'list' using a simple data structure based on lists of the following:

```
<'attribute-name' , 'attribute-value'>
```

Attributes of all three classes are interpreted by CONCEPTMAP using a database dictionary defined for each class type. CONCEPTMAP can be easily configured for a particular application such as geology or forestry simply by developing an appropriate database dictionary. *User-defined* and *property-list* attributes can be defined dynamically by a user at an interactive session. Figure 3-3 gives a partial dictionary of the *system-wide* slots and representative values for a CONCEPTMAP database. Figure 3-4 is a partial dictionary of *role-subname* values associated with *role-name* values in Figure 3-3. A more complete description of the schema structure for the CONCEPTMAP database, and the generation of hierarchical containment trees and their use in spatial search can be found in[4].

4. Mixed Representationsfor Spatial Features

In this section we expand upon our description of Figure 2-2. We discuss the use of vector formats to represent individual spatial entities within the MAPS system, the use of arc-node structures to maintain topological consistency among collections of entities organized as a CONCEPTMAP database, and the organization of spatial entities into a hierarchical containment tree for efficient spatial search. Finally we discuss some performance and sizing results in the context of two CONCEPTMAP databases.

4.1. Entity Based Vector Format

As described in Section 3 each entity in a CONCEPTMAP database is represented by one *concept* schema, and at least one *role* schema. Each *role* schema can define a point, line, or polygon represented by collections of *<latitude,longitude,elevation>* triples and given a system-wide unique identifier, *role-geographic-id*. The use of vector format on a per entity basis allows for simple per feature geometric tests and the incremental (independent) accumulation of spatial entities from a variety of sources. For example it is relatively easy to automatically convert external external databases to vector format or to allow for human delineation using graphics overlay and recovery of geographic position via image-to-map correspondence. Other issues such as the desire to partition large databases over multiple workstations raises the possibility of spatial entities being represented in several databases simultaneously. Further, hierarchical descriptions are created within the context of a particular database on a per entity basis. Thus, a representation for spatial data which treats each entity with maximal independence satisfies many of these requirements. However, it should be obvious that this independence assumption raises issues in the maintenence of topological consistency especially for entities with shared boundaries, inconsistencies that arise from errors in image-to-map correspondence and scale and accuracy mismatches. In the following section we briefly describe our attempts to reconsile these issues.

4.2. Topological Consistency Among Spatial Entities

While the *role-geographic-id* is used within a CONCEPTPMAP database to uniqely define a spatial entity, we have extended its use as a method to represent all features within a particular CONCEPTMAP database in arc-node format. The arc-node format used in MAPS is the Standard Linear Format, SLF, which has been defined and studied by Defense Map Agency (DMA) for possible use as an internal digital data exchange format. The version of SLF that is currently implemented within MAPS uses the DMA Feature File, DMAFF, to represent limited feature semantics on a per feature basis. One can view DMAFF as a dictionary of legal cartographic features and a set of attributes used to describe properties of those features. As is well known, arc-node and other related formats explicitely represent the topological characteristics of collections of features in terms of shared boundaries, points of intersection, and some limited ability to represent containment and holes. These topological relationships can be retrieved without further computation, but for complex databases may require tradeoffs between large internal working sets and linear search.

In order to use arc-node format to maintain topological consistency we must be able to convert collections of vector format CONCEPTMAP entities into an arc-node representation. We make use of geometric information already stored in the CONCEPTMAP database such as points of intersection and common coordinate points to create *segments* and *nodes*. *Features* are defined in terms of *segments* and the segment direction within each feature and are maintained consistent with their CONCEPTMAP database counterparts by use of the *concept-id*, *role-id*, and *role-geographics-id*. Since many of the necessary spatial relationships are already computed in vector format and are stored in memo files in CONCEPTMAP the process is primarily one of generating of new nodes and segments based upon points of intersection between features. Thus, each *role-geographic-id* will generate one feature in arc-node format. In the case of partial overlap or ambiguous mismatches an arc-node editor is manually used to correct the topological relationships among the features. This interaction may cause the actual feature coodinates to be updated as in adjustment for slivers and gaps between adjacent features sharing a common boundary. Once the spatial data is converted and inconsistencies are removed we can regenerate the *role-geographic-id* database by traversing and enumerating the arc-node database on a per feature basis. Thus arc-node format is used to maintain topologically consistent collections of features that are stored and manipulated outside of the arc-node representation as independent entities.

An interesting extension to the use of arc-node format to maintain topologically consistent collections of features is in the assimilation of external databases stored in SLF format into the CONCEPTMAP database representation. Figure 4-1 shows the process by which the DMAFF attribute data is used to generate slot values for CONCEPTMAP role schema, while the topological data is used to generate the corresponding spatial entities. The DMAFF attribute sets associated with each feature are automatically translated into *concept* and *role* schemata or property lists in CONCEPTMAP. As before coordinate conversion from arc-node to vector format is accomplished by expansion of the *feature-segment-node* representaion to the vector point list.

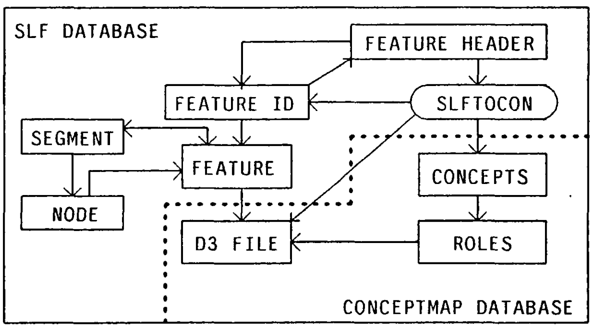

Figure 4-1: Converting SLF To CONCEPTMAP Database

4.3. Measuring Database Complexity For Vector and Arc-Node Data

In this section we briefly describe an experiment to gather empirical data on storage requirements and representation complexity for spatial data stored as vectors on a per feature basis and as topologically consistent arc-node collections. We took two CONCEPTMAP databases, WASHDC and USA, having very different properties and investigated their representation in vector and arc-node formats. The WASHDC database was composed of over 300 spatial entities in the Washington D.C. area. It consists of features such as buildings, roads, bridges, neighborhoods, and political boundaries. The USA database consists of the boundaries of the 50 states in the U.S.. In some sense these databases are at extremes in terms of their topological and geometic properties. The WASHDC database contains large numbers of isolated features such as buildings and neighborhoods, large numbers of features with sparse intersections such as roads, and relatively small numbers of features with shared boundaries, primarily political and large natural features such as rivers. Most of the features were either lines or polygons with small number of vector points. The USA database consisted of polygons with large numbers of vectors points and many shared boundaries. Figure 4-2 shows some statistics for both databases in terms of number of segments, nodes, and points per feature.

	number of features	number of segments	number of nodes	number of points	points /feature	points /node	points /seg	nodes /seg	nodes /fea	seg /fea
SOUTH WEST										
vector	4			2775	893.75					
converted	4	69	59	2767	891.75	46 89	40 10	0 85	14 75	17 25
corrected	4	55	50	1832	458 00	36 63	33 30	0 90	12 50	13.75
MIDDLE ATLANTIC										
vector	8			5019	827 37					
converted	8	135	109	5001	825 12	45 88	37 04	0.80	13.62	16.87
corrected	8	122	105	4063	507.87	38 69	33 30	0 86	13 12	15.25
NORTH WEST										
vector	3			2368	789 33					
converted	3	120	115	2381	787.00	20 53	19 67	0 95	38 33	40 00
corrected	3	119	114	1917	639 00	16 81	16 24	0 96	38 00	39 33
SOUTH										
vector	8			6390	798.75					
converted	8	161	140	8388	795.75	45 47	39 54	0 86	17 50	21 12
corrected	8	154	140	4955	619 37	35 39	32 17	0 90	17.50	19.25
MID WEST										
vector	15			12228	764.25					
converted	16	425	312	12189	761.81	39.06	28 68	0 73	19.50	26.56
corrected	16	326	312	7551	471 93	24 20	23 16	0 95	19 50	20 37
NEWENGLAND										
vector	6			1830	305 00					
converted	6	52	42	1816	302 66	43.23	34 92	0.80	7.00	8.66
corrected	6	49	40	1486	247 66	37.15	30 32	0 81	6 66	8.16
WASHDC										
vector	337			8825	24.49					
converted	337	2127	1295	7486	22 21	5 78	3 51	0.60	3 84	6.31
corrected	337	1533	1037	7247	21.50	6 98	4.72	0.67	3 07	4.54

Figure 4-2: Database Complexity For WASHDC And USA Databases

We divided the USA database into six zones and compiled each into a separate arc-node representation. This was primarily to look for variations within the database. As a group there was rather good consistency when compared to the statistics for the WASHDC database. For each area in Figure 4-2, the USA zones and WASHDC, statistics were computered at three points. The first point shown in the row labeled *vector* was complexity of the original vector data. The second (*converted*) was computed after the conversion to arc-node format, and the third (*corrected*) was after automatic detection and interactive correction of topological problems such as slivers, gaps, or closure problems. For the USA database one can observe that the number of points, nodes, number of segments, number of points per segment, and number of points per node decreased in each of the six zones. In addition, the percentage of points decreased more than the percentage of segments, and the percentage decrease in the number of segments was larger than decrease in the number of nodes. Figure 4-3 shows the number of points decreased more in the six regional zone data than in Washington D.C data. This is due to the large number of shared edges in the USA database. The number of segments and nodes decreased more in the Washington D.C. data set than in the regional data set since there were more occurances of slivers and gaps along shared boundaries which caused a large number of segments to be collapsed into a single segment.

	seg :	nodes:	points:
south west:	20.28	15.25	33.98
middle atlantic:	9.62	3.66	19.04
north west:	1.66	0.86	19.04
south:	4.34	0.00	22.45
mid west:	23.29	0.00	38.24
newengland:	5.76	4.76	18.79
usa:	10.83	4.09	25.26
washdc:	27.92	19.92	12.21

Figure 4-3: Percentage Reduction From Vector To Arc-Node Format

5. Conclusions

We have presented a brief description of the integration of multiple data representations within the MAPS system developed at Carnegie Mellon University. MAPS integrates schema-based representations of spatial knowledge, and multiple representations of spatial location using vector, arc-node, and hierarchical containment descriptions. We believe that the use of heterogenous representations tailored to particular data requirements or that capitalize on search or query efficiencies will be necessary if we are to reach our goal of intelligent spatial databases. Certainly this work is in sharp contrast with more homogeneous approaches such as regular decomposition (quadtree) and relational databases. There needs to be more testing and evaluation of prototype representation systems on realistic test databases as we attempt to design future spatial database systems.

6. References

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