Towards the Design and Development of a New Architecture for Geographic Information Systems

Niki Pissinou
Center For Advanced Computer Studies
University of Southewestern Louisiana
Lafayette, Louisiana
pissinou@cacs.usl.edu

Kia Makki
Dept. of Computer Science
University of Nevada
Las Vegas, Nevada
kia@unlv.edu

E. K. Park
Computer Science Dept.
United States Naval Academy
Annapolis, Maryland
eun@usna.navy.mil

Abstract

Existing Geographic Information Systems lack many important features such as the ability to model the real world more adequately and facilities for logical deduction and geometric computation. In this paper, we study the structure and behavior of existing Geographic Information Systems, isolate their drawbacks and explore the applicability of object oriented design, logical deduction and hypermedia to developing better and more efficient geographic information systems. In particular, we focus on the concept, design and development of an architecture for the next generation geographic information systems, which will be able to access, synthesize and reason about large volumes of geographic information more efficiently and effectively, without sacrificing functionality, extensibility and consistency. Of significance is the integration of many diverse forms of technological advancements, including object oriented design, expert systems and multi-media systems.

1 Introduction

Geographic Information Systems (GIS) [2,5,10,14,18,20,22] are on the way of becoming the focus of engineering, in particular of the entire realm of computer-intergrated design. For example, the urban development industry has recognized the central role computer aided design GIS play for the design of urban communities while geological centers have recognized the need of earth resource analysis systems for tracking changes in the environment based on human-made and natural events. In the later case, the information required to represent these changes and the impact of these changes must be represented so that the earth resource analyst can query for relevant information on a particular geographic area, feature or time-period and perform an analysis based on the resulting information.

There are numerous areas where geographic information systems are or could be employed to good benefit. Among them, energy resources management, waste management, forestry and wildlife management, geology, hydrology, archaelogy, municipal facilities management, global scale applications such as ecology, planning (e.g., environmental, military, subdivision, agriculture, land use and municipal), oceanography, cartography demographic and seismology. In a natural disaster contingency planning, for example, GIS systems can be used to model a flood plain, map earthquake fire fighting plans and tracking toxic waste gas plumes. Each of these areas rely on statistical data, historical information, aerial photographs, satellite images for analyzing and presenting empirical data, satellite images for drawing conclusions on certain phenomena and satellite images for predicting future events through sophisticated computer simulations using the information at hand. In general, these new applications are much more demanding that the standard applications and require an array of added functionalities, and advanced information and analysis features which current geographic information systems do not provide.

In this paper, we discuss some of the limitations of existing systems and examine a number of major objectives and areas of challenge which remain for researchers and implementors of NGGIS. In particular, we look at the issues of dealing with the design and development of the Next Generation of Geographic Information Systems (NGGIS.) Our main objective here is to provide the necessary background and motivation to designing and developing the architectural model for the next generation of geographic information systems, thus supporting the temporal, object oriented and deductive needs of such systems in an unified framework. Such work will present a significant step towards the synthesis of an integrated geographic information model that supports added functionalities in a unified framework.

Our approach leads to the precise characterization of the requirements of the next generation of geographic information systems without being unduly influenced by traditional systems that were not tailored to model sufficiently the real-world or meet some sophisticated functionalities. As such, we expect our work to provide new insights into the evolution of geographic information systems. Our proposed model should also have a direct impact on how various temporal properties of objects and deductive reasoning can be incorporated into existing GIS.

The remainder of this paper is organized as follows. In the next section we provide a brief overview of the current limitations of existing geographic information systems. Section 3 examines a number of major objectives and areas of challenge which remain for researchers and implementors of geographic information systems. In section 4 we describe our approach to designing and developing more efficient and effective GIS and provide the framework of our proposed system architecture and our methodology. The last section

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contains some concluding remarks.

2 Limitations of Current GIS

The explosion of interest in specialized advanced geographic application environments in the last few years has led to a proliferation of commercially available geographic information systems such as ARC/INFO and MOSS. In the 80s the evolution of the geographic information system technology was mainly characterized by database management systems that embody relational database models and on concentrating on more "sophisticated" user interfaces to cope with a diverse range of applications. Currently, database models for geographic information systems are based on the relational technology. However, because of the present nature of existing geographic information systems, such systems have several drawbacks such as:

1. There is limited support for object orientation. In consequence the real world is not adequately modeled which leads to several limitations (these are explored shortly.)

2. There are limited reasoning capabilities which provide the user with more powerful tools for solving and analyzing problems efficiently and effectively.

3. There is limited support for advance user interface tools which allow efficient interaction of users with the computer.

4. There is limited support for hypermedia and multimedia environments.

5. There is is limited support for integration of image processing and limited three dimensional (3D) support even though many spatial object must be considered in 3D space.

At the present time there are commercially available Geographic Information Systems (GIS) which support many applications such as earth resource analysis. However the underlying database of such systems is based on the relational model. But the record based approach to designing the underlying database models for these systems has limited their ability to adequately model the real world. As such, existing geographic information systems have several other drawbacks such as:

- Vast quantities of data, which typically require complex data structures and access paths cannot be handled easily;

- Sharability of objects, abstraction hierarchy, object identity and encapsulation is not allowed;

- Only the structural aspects of data modeling are supported. There is no support for the semantic or behavioral aspects of data;

- Complex objects, such as polygons, which comprise an arbitrarily long list of vectors (or coordinates), can not be handled as a single unit within the database;

- Complete temporal information and versioning is not handled.

There has been growing awareness among researchers of the importance of adequately modeling the real world as well as providing reasoning capabilities in an information system [6,18,34]. The spatial nature of GIS data and the operations performed on them, and the need to consider complex objects as single entities, as well as the need to maintain different versions has led us to believe that the object-oriented approach is better suited for GIS applications than existing GIS approaches. In addition, the need for deductive capabilities has led us to believe that a "deductive object-oriented" approach will greatly enhance the functionality of such systems. In fact, a preliminary analysis of the characteristics of geographic information systems suggests the need for the following functionality in any environment supporting GIS applications:

1. The ability to model the behavioral/dynamic aspects of objects as well as 3-D objects and spaces and natural phenomena.

2. The ability to support (rule based) inferencing for decision making.

3. The ability to maintain temporal information pertaining to an event or activity including tracing its progress, querying and inferencing.

4. The ability to maintain and manage a data/knowledge base shared by several activities.

5. The ability to manage large quantities of diverse data types and the dynamic evolution of types.

With these approaches, more complete information of the dynamics of a GIS's application environment is retained. The vast majority of research on geographic information systems is on relational or pseudo-relational database models, and has focused on the extension of such models in an attempt to inadequately meet some of these basic functionalities. Little attention has been given to the temporal aspects of spatial data, object-oriented features or deductive capabilities for geographic information systems. As such our work concentrates on the design of a new architecture for GIS that will support these added functionalities and will allow us to further study the structure and behavior of existing Geographic Information Systems, the applicability of object oriented design, logical deduction and hypermedia to developing better and more efficient geographic information systems. To meet this goal we developed an architecture that integrates many areas as described in the next section.

3 Design Issues and System Prespective

It is our view that the advances which culminate in the next generation of geographic information systems will not come from any single area within the field of information technology. To a certain extent geographic information systems have matured enough that while further enhancements are desirable, such as the substitution of relational databases with object databases, the most promising opportunity for technological advancement comes from the integration of several areas into a whole. Our challenge is to integrate these threads into a single system design that maintains desired features from each field. However, many issues must be understood better before hybrid geographic information systems supporting both object-oriented modeling and inferencing techniques, can be placed on a formal footing and become commercially feasible.

A state of the art Next Generation Geographic Information System (NGGIS) should be able to manage, coordinate and expand resource data and information, provide decision making and analytical support in many diverse applications such as county sponsored nuclear waste studies, viz., tracking and management of hazardous material spill and process geographical and spatial information, and in general establish a local and global repository of geographic information. Such as system should contain many features that current GIS databases lack or are not adequately modeled, such as temporal/historical data and versions (storage, control and update) while improving existing features of GIS databases. The NGGIS model will also have the ability to collect, update, manage, analyze and display the results of the analysis of data as well as providing deductive capabilities and explanations on goals and facts.

As such, we take the view system architecture for the next generation of geographic information systems must satisfy the following broad objectives:

1. Extend existing GIS database technology with an intrinsic class of operators, which is extensible and responds to the growing needs of the scientific technology;
2. Includes in GIS models, the modeling of 3-D objects and spaces and models for natural phenomena.
3. Provide an intelligent geographic system which will be able to access, synthesize and reason about large volumes of geographic information and and support spatio-temporal reasoning.
4. Incorporate a GIS model which supports the semantic and behavioral aspects of data as well as the structural ones, allow knowledge representation, inference and reasoning.
5. Support an advanced "state of the art" graphical user interface for the display and manipulation of the data, from browsing and querying the database and retrieving structural and dynamic information.
6. Provide a fully distributed and heterogeneous environment for geographic information systems.

With these objectives in mind and to motivate our discussion, we raise some intriguing questions that must be solved and important research contributions that are required in order to make next generation geographic information systems viable. In general, the integration of object-oriented, multi-media and inferencing techniques into a geographic information system raises several fundamental and intriguing open questions [1] such as:

- How do we manage large quantities of diverse data types and the dynamic evolution of types?
- How do we achieve a seamless integration of sophisticated computer graphic images with complex structured attribute data?
- What approaches can be employed to manage different views of data?
- How do we manage both transient and persistent data?
- What are the temporal and spatial aspects of objects and what properties of an object are essential in a geographic domain?
- What approaches can be employed to identify generic intelligent queries and what query processing techniques are appropriate?
- How do we easily and directly integrate multi-media data with spatial and temporal data?
- Is a three dimensional graphical interface a necessity for GIS applications?
- How do we handle large volumes of data and what methods should we use for performing extensive numerical tabulations on data?
- What algorithms, data structures and access methods are best suited for implementing the model? In particular, how we prevent the exponential explosion of storage space required?

To provide a specific context of our proposed approach to the questions we have just raised we concentrate on developing a rich, extensible GIS model. We will use our model as a basis for exploring our ideas, by implementing the model and examining the advantages and drawbacks of several alternatives.

Object-oriented notions present an opportunity to provide more concurrency than more traditional approaches allow, as well as modeling of the semantic and behavior aspects of objects. In the object-oriented approach, the database system knows more about the operations that are being performed. They are not simply reads or writes, but rather have more semantics. The organizational and economic motivations are probably the most important reasons for developing such an environment.

4 System Architecture

Given the proceeding overview of the issues pertaining to the next generation of GIS, it is now possible to briefly illustrate our approach to the problem. We are proposing a system that incorporates features from the database technology as well as the expert and multi-media systems technology as shown in figure 1.

In view of this, the focus of our work concentrates on the long-term objectives of developing generic geographic information systems to support the next generation of GIS which will be able to access, synthesize and reason about large volumes of geographic information. We call our proposed system *"Next Generation Geographic Information System"* (NGGIS) [2]. The central premise of our system is neatly summed up in figure 2. As shown in figure 2, the system consists of the following four basic components.

1. High Level GIS Tools.
2. Multiagent User Interface.
3. OODTGIS Model[3].

[1] The questions raised here are not exhaustive but provide an insight into the complexity and significance of the problem.

[2] For our purposes, a geographic information system will be distinguished from a database management system by having a different set of design priorities and by integrating the tools and the database into a single unit. We also distinguish an information system from a database system

[3] OODTGIS stands for Object Oriented, Deductive, Temporal GIS.

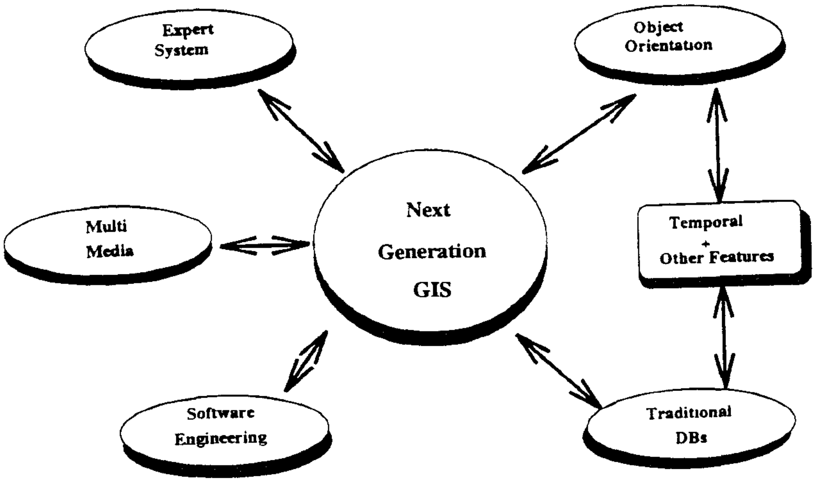

Figure 1: Next Generation GIS Technology

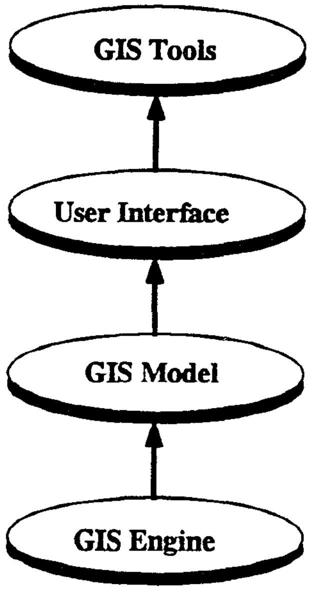

Figure 2: Conceptual View of the Architecture Levels of NGGIS

4. GIS Engine.

The breakdown of the system into four different layers follows the "separation principle" of software engineering. For example, with this separation the DBMS developer who implements the generic database service does not have to have any knowledge of GIS. Our conceptual system design configuration represents a very abstract view of our system. For example, it does not provide insight information in how the four levels are connected; instead it provides a framework of the design. Figure 6. gives an elaborate representation of the NGGIS architecture. In next sections we briefly describe each of these components and their respective functions.

4.1 High Level GIS Tools

The first component of our system, the *High Level GIS Tools* consists of an external library of powerful tools provided to users. These tools would be used for knowledge discovery (such as machine learning and statistical analysis,) data integrity and control (for reducing the number of errors,) hypermedia management (for linking images and sounds,) decision support tools and intelligent system design tools.

4.2 Multiagent User Interface

The second component of our system, the *User Interface*, consists of several modules which provide generic services at the user level, which are subsequently translated into different sets of specific procedures for different entities with a minimal knowledge requirement from the user. The user interface also supports distributed displays to create multiple views of the same collection of objects. Our user interface model is "multiagent." This means that the interactive system is structured into a collection of specialized agents that produce and react to events. Thus each agent is an information entity, viz. a complete information processing system. As such, it includes event receivers and tramsmitters, a memory to maintain a state, and a processor that cyclically processes input events, updates its own states and produces events etc. Since agents share common properties they can be grouped into classes which define the common protocol which can be understood by an agent's children. The user interface consists of a Monitor, ShowCase, Workshop and an interaction expert as shown in figure 3.

The *Monitor* is one of the intelligent agents of the system and has two important functions. First it controls the overall consistency of the system, and thus can detect any operation of any agent in the system which has a side effect and send an update message to other agents informing them of the side effect (it is the receiver's responsibility to interpret this message.) For example, if both an architect and a civil engineer work on the same project, once the architect changes the location of a building, the civil engineer's view should be informed immediately. Because each system may have several users and each user may have several active agents which themselves may have several instances, maintaining the overall system consistency is not simple. As such, the monitor maitains a "semantics view" dictionary dynamically. In addition the monitor acts as an advisor.

The *ShowCase*'s main functionality is to cooperate the work of its cooperative agents while the functionality of the *Workhop* is to provide a complete user interface to maniputate the GIS domain specific databases. The user interface also consists of "view managers" which in corporation with the multiagents generate instances of views as well as manage different user views. We define a view to be a representation of a collection of objects. Based on this definition, a view could be a histogram, a graph, an event or simultaneous perspective views for one or more users. For example, a civil engineer and an architect will be able to co-operate together using a single terminal where both the architect's view of a project (such as park locations) as well as the civil enginer's view (such as city pipes and telephone lines) will be represented and an integrated view can be derived.

4.3 OODTGIS Model

A major component of this system is the *OODTGIS model*[4]. In general, data models are central to Geographic information systems because they not only provide the conceptual basis for thinking about GIS applications but also provide a formal basis for tools and techniques used in developing geographic information systems. Our proposed model represents both spatial and temporal knowledge about natural and human-made entities on the earth's surface, following the object oriented paradigm. The model will aplly procedures to perform operations on the data, including comparison, derivation, prediction, validation, and visualization. It is an effort to extend the database technology with an intrinsic class of operators, which is extensible and responds to the growing needs of scientific research and integrate a diverse spectrum of data into the database, including geographic, hydrography, images, urban planning and temporal data.

One important consideration in designing an object oriented model must be the specialization of sub-types from their parent types. The abstract types can be used as intermediate types which will never be instantiated as objects, but exist as semantic placeholders to group common properties and operations of children types. Abstract types have no additional cost to the system and they add much to constructing a rich representation within the database. When sibling object types share common properties, the properties are grouped in a parent type. As such, the design description will be partitioned into six general areas. These are: Version Objects, Graphic Objects, Geographic Objects, Data Objects, Temporal Objects, and Multimedia Objects.

Version objects are those entities that represent a set of historical rollback information on a particular object. For example, the transfer of nuclear waste from one site to another over a period of time would be represented by a version objects. Version objects would also represent such entities as the lifespan of nuclear waste. *Graphic objects* are those entities that represent things displayed on the workstation display. It is used for objects that will be displayed on the workstation such as images, maps, icons and cursors. *Geographic Objects* represent a geographic description of objects i.e., they describe a geographic entity. The most important children of this type of object are concepts of point, line and area. The last type of objects is called *Data Objects.* This type of objects contain the conceptual information embedded in the database. Examples of data objects are readouts, observations within the imagery and the conceptual description of geographic and graphic entities.

[4] The design of this model is a major challenge and an on going effort. However for experimental purposes we have been using other Object Oriented Deductive Models such as CORAL

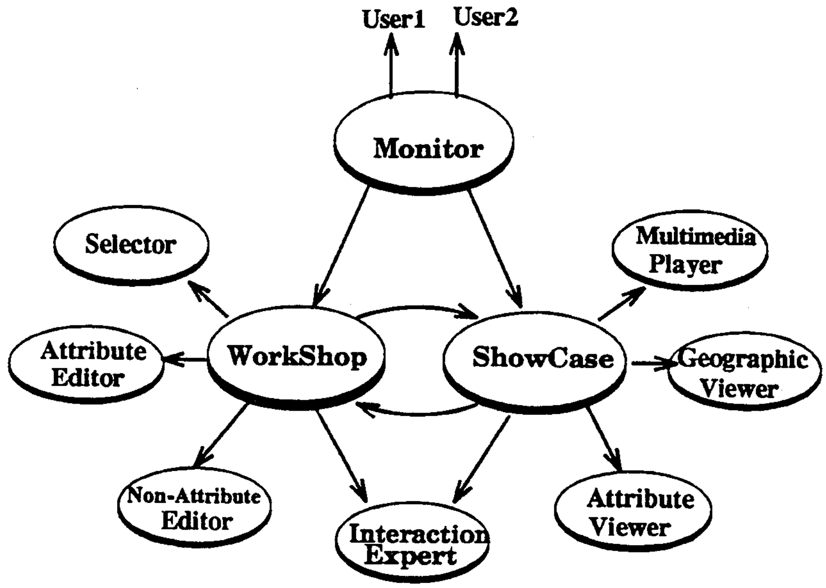

Figure 3: Multigent User Interface Architecture

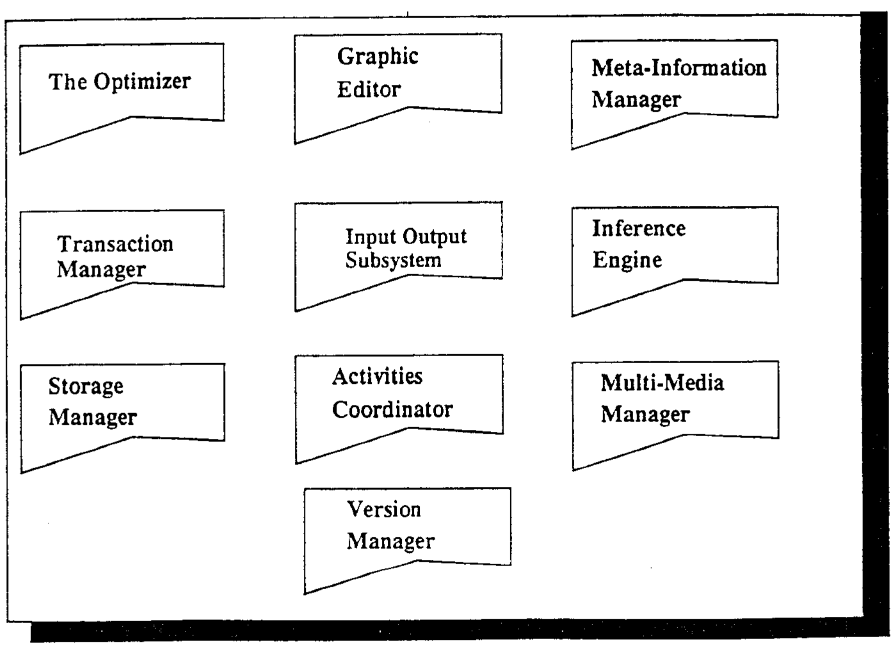

Figure 4: Major Engine Modules

4.4 GIS Engine

The key features of the architecture of the GIS engine include a close integration of data access and the inference engine and efficient support of multimedia storage and display that is built into the engine. Some of the main components of the GIS engine include the *rule manager*, the *explanation manager*, the *access module*, the *meta-data manager*, and the *multi-media manager*. The rule manager encapsulates all the algorithms that are used to perform forward and backward chaining on rules and invokes the access module. The access module performs searches and matches on the persistent object space; it contains all the access methods for performing efficient storage searches on image data, spatial data, temporal data and complex objects. The explanation manager obtains information from the rule manager regarding the searches and passes it to the user who can then request explanations on goals and facts. The meta-data manager contains all the meta-data information associated with the persistent database including inheritance hierarchies and object migration. The multi-media manager incorporates routines to handle peripherals such as scanners. Figure 5 shows some of the modules of the GIS engine, while our current conceptual design of the inference engine is shown in figure 6.

4.5 Implementation

We are currently working on a prototype for our system, as proof of the concepts and to provide a platform for further experimentation. Since this is a large, full scale system, our implementation strategy is based on working on each layer separately while using existing technology for the remaining layers with the long term objective of combining all the layers. Obviously, at this stage the focus of our prototype is on functionality rather than efficiency, so portions of the code are suboptimal and several modules are "naively" designed. Our prototype is being implemented using current object-oriented programming technology, C++, X windows, and InterViews as the user interface toolkit. It is running on Sun 4 workstations.

5 Concluding Remarks

In this paper, we examined the limitations of existing geographic information systems, analyzed the requirements of the next generations geographic information systems and mapped them to the functional as well as architectural extensions of conventional geographic information systems.
Specifically, we concentrated on some crucial issues of integrating the object-oriented paradigm and inferencing techniques to existing geographic information systems. We have identified relevant technology areas and have substantiated the need for combining techniques from seemingly diverse areas. We have also examined a number of major objectives and areas of challenge which remain for researchers and implementors of the next generation of geographic information systems.

In consequence, we proposed the architecture of an intelligent geographic information system. Our approach is based on the object oriented paradigm as an underlying mechanism for modeling and inferencing for decision making. Some specific measures of the effectiveness of such an approach will include more timely access to widely dispersed information, improved quality of reports, database updates, and analysis, maintenance and access of historical information, necessary minimum training level of the analysts, a more intuitive interface with the information in the database, improved quality of reports, database updates, and analysis, reduced costs for maintenance and update of the overall system, and the ability for knowledge representation, inference and reasoning.

The aim of this paper, was to bring a new perspective on research directions for the next generation of geographic information systems and in consequence propose a new architectural model for such systems. We anticipate that research on the next generation of geographic information systems will have significant impact on several areas. First, this work will be a significant first step towards the synthesis of an integrated GIS model that integrates many diverse forms of technological advancements, including object oriented design, expert systems and multi-media capabilities. As such, we expect that many techniques developed in the interim, would be applicable to these areas and would have a direct impact in future designs of such systems. Second, our model is one of the first models that supports the semantic and dynamic aspects of geographic data in addition to the structural ones. As such, we expect our work to provide mechanisms to modeling these aspects of objects in other environments. One result of this should be insight into dealing more effectively with the integration of version GIS and intelligent GIS. In consequence, our work should result in evolution principles and techniques useful in "temporal deductive object oriented" geographic information systems, which are of increasing significance and practicality. For example, we anticipate results in dealing effectively with schema evolution, inference mechanisms and multi-user collaboration.

The discussions in this paper seem to lead to a simple conclusion: at least one of the more promising directions in designing, developing and building the next generation of geographic information systems is in the integration of concepts and techniques from several diverse areas such as object orientated, deductive and temporal databases, software engineering and artificial intelligence. In particular, when describing NGGIS, it appears that looking beyond the techniques used in relational databases will be the most fruitful and progressive step. Work in this area will provide an integrated geographic information management testbed for scientific research, and a testbed for the development of analysis tools to understand and predict geographic information.

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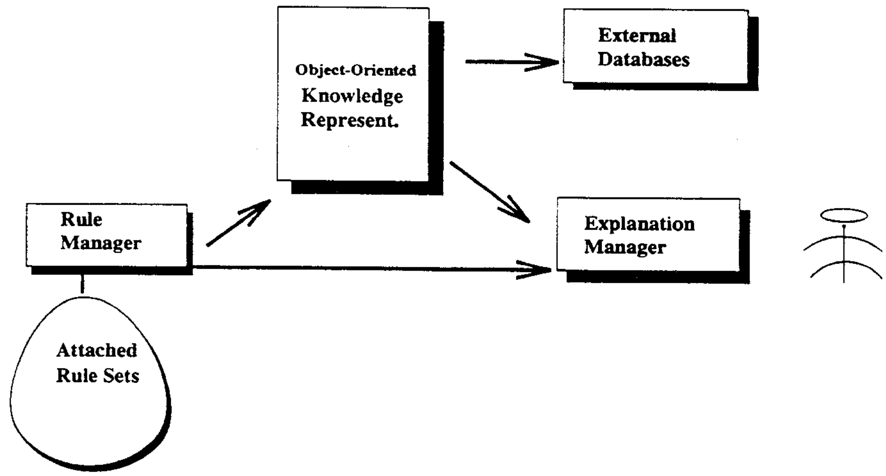

Figure 5: Inference Engine Architecture

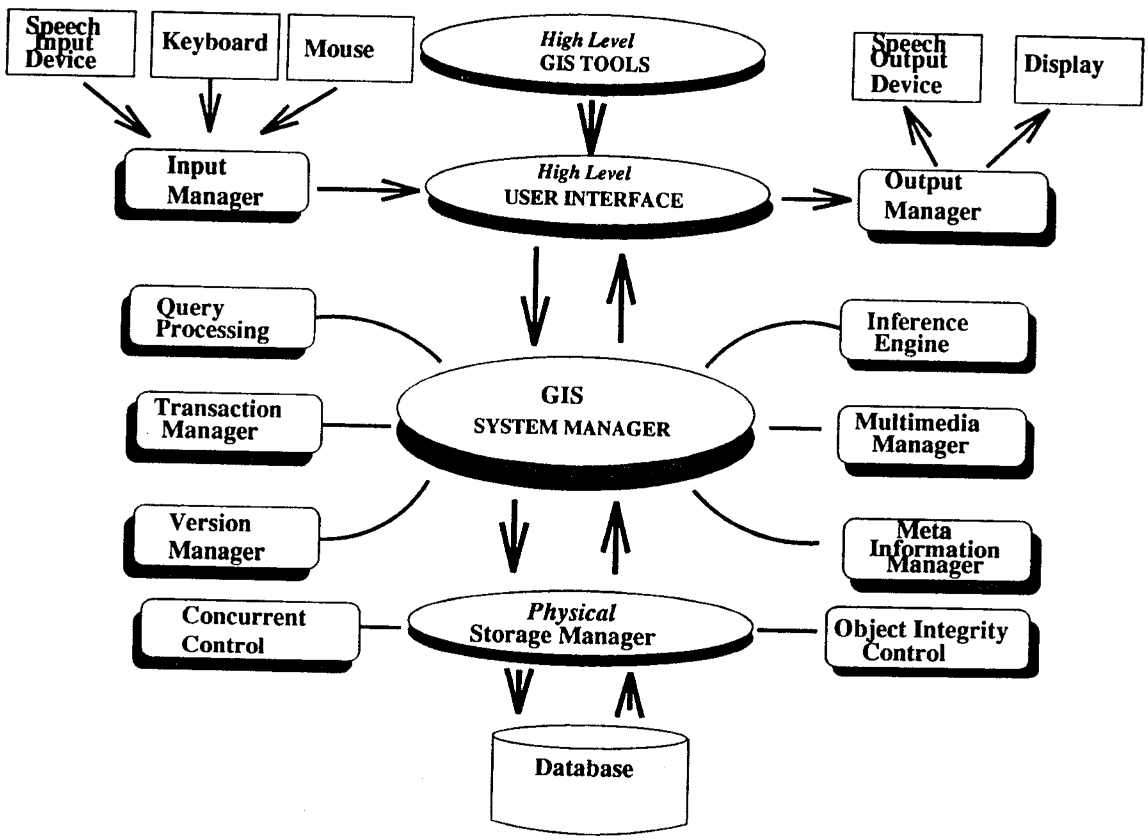

Figure 6: NGIS System Architecture

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