Geographic Information Systems: A Survey Add Authors Name, Address And Contact

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Abstract

At its core GIS, or Geographical Information System, is a mapping tool that allows various types of information to be linked to geolocation. With advances in Big Data technologies, the availability of a large and ever increasing streams of geolocated data, the new services based on geolocation that are used by massive numbers of people especially on mobile devices, GIS systems are becoming fundamental and increasingly important to large numbers of individuals as well as businesses and industry. The purpose of this paper is to review the current state of the art of GIS technology and provide a summary view of its functionality and the major issues around its use. It is aimed to be readable by a wide readership familiar with computing technologies but not necessarily versed in GIS.

Keywords: Geographic Information Systems, GIS, Spatial Databases, Data Visualization, Layered Data

Introduction

GIS systems are becoming increasingly important for many services, businesses, and individuals in today's mobile world. The use of an ever increasing number of connected mobile devices equipped with GPS aparatus makes it possible to collect vast amounts of geolocated data ranging from simple position, to motion speed, and various readings ranging from scalar values to large image files. At the same time there is a need for geolocated services for large numbers of people who via their mobile devices have access to information and computing and who need services within their (varying) proximity. That alone has pushed the need as well as the boundaries of GIS, and yet there are so many other challenges for which GIS systems are supremely fit, like disaster response, emergency management, etc.

Geographical information system, or GIS, is a powerful and broad tool to help scientists create maps and analyze data. It is widely used across many disciplines including health care, criminology, demographics, environmental sciences, and more. The purpose of this article is to give the reader a foundation of the different types of GIS software, how it works, and research applications. The field is ever changing, with new software constantly being developed and new applications and uses being discovered. Using maps and data to understand spatial relationships and patterns has been done for a long time. However now researchers can input this information into GIS software which has the ability to analyze the data in more powerful ways. GIS allows a user to start with a base map as large or small as needed and add a multitude of data layers. These layers could include a vast array of different data sets from topographic information to crime rates. The user then has the artistic freedom to customize the aesthetics of the information to create a visually appealing and useful map. The map can be a simple 2D image or it can be interactive using pop ups and real time data. The usefulness of the GIS systems lays in their flexibility. More broadly, GIS is a specialized set of computer databases along with the program designed to collect, store, manipulate, retrieve, and analyze the spatial data. There are a multitude of different applications to build maps and many data sets open for public use. Maps can also be created online using programs like ArcGIS Online. The maps can be used by businesses or educational institutes for many applications. This versatility makes it much more than simply a mapping tool. The most important aspect of GIS is its ability to draw parallels and see connections between sets of data [1].

This paper is intended to serve as a primer to the state of the art of GIS as of 2019. It is organized as follows. A brief history of GIS is followed by a simplified explanation of how GIS systems work. Data modelling and representation for GIS is also discussed. Further, challenges, research, and application posibilities are discussed.

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History

Roger Tomlinson is widely known as the father of GIS. In 1968 he developed a system titled "A Geographic Information System for Regional Planning" [2]. However, his initial product was a far cry from the GIS systems popular today. In 1960 Tomlinson worked for the Canadian government on an outreach project to increase industry in Kenya. Canada had long been a part of the papermaking industry and thought their aid would be most useful if they tried to set this industry up in Kenya as well. However, the trees native to Kenya were not well suited for paper making. Tomlinson was then tasked with determining what land areas would be most suited to a tree plantation. This task involved the use of maps as well as a large amount of data including topographic information, soil type, atmospheric conditions, demographic information and more. Tomlinson found that it was too difficult to clearly compare all these data sets on different maps to determine the best area. At the time this issue arose for Tomlinson, computer technology was making great strides. He considered the idea of using this new technology to make the data sets more useful. The goal was to use the map areas of interest, called polygons, and overlay them with the data sets. Before this could be done the data would have to be converted to data points which would be geographically connected to a location on the map. In this way multiple data sets could be used to compare large amounts of data. For his first attempt, he made physical maps. To solve his tree plantation problem Tomlinson created five separate maps on clear surface, each with its own relevant set of information such as rainfall patterns. He then overlaid them onto the base map, and he was able to pinpoint the best locales based on the comparison of many data sets. This is inherently how current GIS systems work, however instead of doing them by hand they can now be created online or through GIS programs [2]. Tomlinson was not the first to overlay maps, but he was one of the first to connect this idea to draw from the data processing power of the computers that were being developed at the time. Although the project was eventually abandoned, he gained success by using the same ideas to create data sets for the land use of Canada. The Canada Land Inventory wanted to identify the land resources currently available and future producibility. The northern parts of Canada had always been difficult to accurately map and collect data from so Tomlinson's work was vital. He created the Canada Geographic Information System (CGIS) as a measuring tool to compile vast amount of tabular information instead of simply a mapping tool [4].

Another important historical use of GIS can be found through the US Bureau of the Census in the 1960s. They created a program called DIME, Dual Independent Map Encoding, in order to create digital records of all US streets in order to create more accurate census records. There were many similarities between this program and the CGIS system which led to the understanding of the great need for research in this field. That demand led to the creation of a major at Harvard University's Laboratory for Computer Graphics and spatial analysis. Their goal was to create a single GIS system that could be used across the board. This led to the ODYSSEY GIS system which became prominent in the 1970s [4].

Simultaneously mapmakers were investigating the use of computers to edit maps. Up until this point maps were still being made and edited by hand. Mapmakers realized that they could greatly cut costs and time by digitizing their maps. This process however took some time and it was not until the 1980s that most maps were digitized. This, as well as the decreased cost of computing hardware, allowed GIS to be much more feasible and it's uses really took off as well [5].

How it Works

A geographic information system (GIS) is a computer system that allows the management and use of large geolocation-linked data sets and makes them not only intuitively accessible and useful but also user friendly and aesthetically pleasing. The system can build and process a virtually unlimited number of layers of spatially tagged information. Spatial information is simply information that is linked to a specific location. Then tabular data, such as demographics or topography, would be related to this spatial location. Different types or classes of data viewed as different layers are stored in the system which must ensure that sata from all sources are spatially aligned [6]. Subsequently these layers of data can be accessed simultaneously, they can be combined, and they can be used to answer questions based on combined considerations of the various types of data in the various data layers. For example, one layer of data could be the population density related to geographic longitude and latitude. Another layer can be data about various services or businesses related to similar geographic longitude and latitude. Combining this information one can make better decisions about new services that would likely do well in a particular area. Or, combining a layer of data about precipitation with a layer of data about heat over a recent period of time one can make better predictions about crops. Or, combining a layer of data about population density, with one that indicates roads and road capacities, one can better device an evacuation plan from a given hurricane projected path.

There is no one definition or program that encompasses all of GIS, it is a very general term. However, the current and most widely used definition followed some basic guidelines. All modern GIS systems operate with a combination of computer hardware and software tools, they all require data input, and human input is necessary to streamline and perfect the data processing [7].

GIS platforms typically have the same basic architecture made up of a data source to store information, a way to share data with other systems, access to the internet to view and search for other data, and a GIS software to view, process and display the data [7].

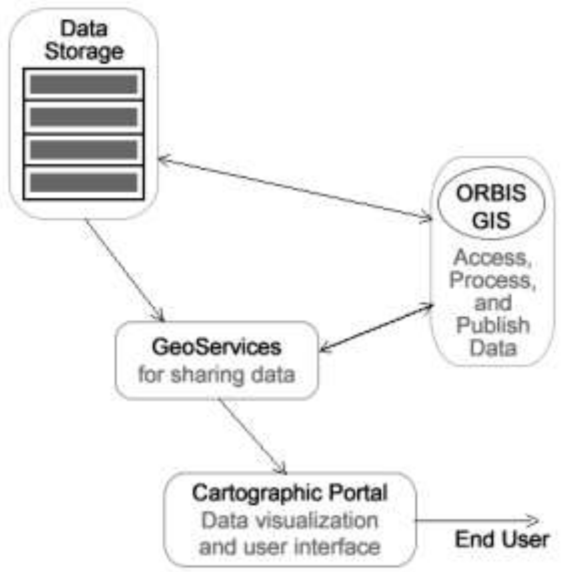

Figure 1 Basic architecture of GIS platforms (Bucher, 2012)

Data Models Within GIS

GIS uses computer software to present spatial information in the form of datasets to the user. The product of a GIS data set has become commonly referred to as a digital map, however this is a misnomer. In reality, a digital map would not have similarities to a map made by a cartographer because it would be made up of only numbers, or digits. The goal of a GIS system is to create an analog map from digital map data. This information used to create these maps is broken into two types: vector data and grid data. Vector data is represented as a polygon whereas grid data breaks the area down into small grid lines populated with dots to represent geographical information [5].

Vector Data Model

With respect to GIS, vector data usually refers to the use of vector graphics (comprised of vertices and paths). Data within GIS at it's most basic uses a grid or coordinate system to determine a set of cartesian coordinates. This requires a location to use as a reference point. For example, the beginning of a road. The first location would be identified as a single point on the road, but this single point would not accurately represent the road on a map. Assuming the road follows a straight line North for .25 miles, another point would be identified .25 miles North from the original location. Essentially a vector has now been created to show the location of the road on a map. However, most roads do not follow a straight line, so the user would create multiple points along the road to show the path of the road. This method would suffice if all the data consisted of straight lines, but this is not usually the case. If you wanted to identify an area on the map that is forested, you would start by identifying one location on the boundary of the forest. You would then start as before by connecting straight vectors of various lengths around the boundary of the forest. Eventually the points would match back up creating a polygon. The system would then know that the area bound by the polygon represents a forested area [5]. These lines or areas become discrete units which carry information, i.e. inside the polygon means forested area and outside means non-forested area. This also indicates a primary use of vector data modelling; it is mostly used to specify regions in which a parameter of interest is constant. For example a map showing countries and borders is essentially 2D geometric shapes whose boundaries are approximated by straight line segments (of varying lengths) and these baoundaries designate the territory of each country by specifying what locations are inside a particular country and what are outside. More information can be attached to these polygons, such as economic parameter values, tax rates, area codes, etc. and an informative composite map becomes the output. This data is then coded by assigning a unique numerical code to identify objects on the map. Typically, this is done using thematic coding. This process is comparable to the layering of clear maps historically done by hand. In this process data is divided into topics with only one type in each group. For example, highways may be layered separately from interstates. The user could then choose to show both on the final map product or not so long as the data all uses the same coordinate system [3].

Vector location data is rather straightforward and is typically presented in a simple XY coordinate system. However, the main application of GIS is to attach more data than simple spatial data based on a location. The amount of data processed by a system can get large very quickly. To work around this, most GIS systems store their location data using specific software which is written to handle the large amount of data. The attribute data is then stored in a standard database package. In order to properly use this information, the system must be able to quickly relate the data from two different locales. To ensure that this happens smoothly each feature must have a unique identifier that is tied to both the location data and the attribute data. In this system, both sets of data will have the same unique identifier in their separate storage locations. The identifier is typically numerical, but it may have a combination of letters and numbers [5]. This system is important because the data is related to a spot on the three-dimensional Earth which is being transferred to a two-dimensional map. If the map data is focused on only a small area the curvature of the Earth may be negligible, but when comparing larger areas, it is crucial to use the correct coordinate system. There have been many efforts to project the globe onto a 2D image with different strengths and drawbacks. Most GIS allow you to select a coordinate system upon importing data to ensure that the attribute and location data match up correctly [3].

Not all data within GIS relies on a single point, like a building, or on a line between multiple points, like a road. It is common to connect a string of data points with the same beginning and end, creating a polygon. This would be used to create boundaries, like a forest. However, it can be more difficult to relate attribute data, like a forested area, to a polygon data set. In order to accomplish this, the system will store the attribute data to a central point within the polygon which is called a centroid. The amount of data that goes into a map created through GIS can be astronomical and has spurred a new branch of mathematics called topology. Topology is the study of relationships like whether objects, such as multiple polygonal shapes on a map, are neighbors or not. This is a growing field in order to make GIS more user friendly and reliable. It is imperative that the data imported to create the map overlays remain intact even when used across different coordinate systems. The topology model makes connections between relationships or different areas and ensures that they remain fixed even if the geometry is changed [5]. This would occur if attribute data is casted to different global models. For instance, when converting from 3D to 2D there are many different coordinate systems such as the Lambert Conformal Conic, the Winkel Tripel, the Azimuthal Equidistant, the Orthographic [3]. Location data within the Lambert Conformal Conic system may be very accurate for locations within the United States but becomes skewed if using location data from Greenland due to the projection type [3]. For this reason, data imported in GIS must specify the coordinate system to reduce errors.

Raster Data Model

Another major data model is the raster model. This model relies on a grid setup of uniform cells. The cells can vary in shape from triangles to rectangles (usually are rectangles), but they are considered to be uniform. To explain how rasters are used in modelling, consider a map of geolocated temperature. This is a continous distribution in that the value of the temparature varies continuously with respect to geographic location. Now imagine that a large geographic area, with this continuous variation of the temperature, is split into a grid of rectangular cells. If this grid is made fine enough so that its cells are small enough, then the temperature within each cell would be -or it can be for practical purposes- constant. Then a single value for the temperature can be stored for each cell. The underlying assumption is that the parameter of interest (e.g. temperature) can be considered to be constant over every cell. Obviously there is a variable error in such a representation and it depends on the rate of variation of the parameter but it primarily depends on the raster (grid) size and the smaller the size the smaller the error, however, the number of cells increase as they get smaller and so does the required computer memory or storage space, and so does the amount of processing required for managing and manipulating the cells information. Vector representations represent parameters in similar ways where the raster cell is replaced by a polygon or collections of polygons within which a parameter of interest can be considered constant. This is why the vector model is prefered for mapping discrete valued parameters whereas the raster model is prefered for mapping continuous valued parameters.

The raster model varies from the vector model in two main ways. Since the map is sectioned off into uniform cells the smooth lines input from vector data become jagged. The amount of jaggedness depends on the size of the cell. Another major drawback is the degree of detail within the cells is uniform. All cells will be in the same resolution, no matter how varied the cell is. The cells are then numbered like a matrix usually starting in the upper left corner. The cell, called a pixel, would then be assigned a number value relating to a certain interest, like land use. If the user wanted to create multiple attributes for a single map area, they would make multiple raster layers with each layer relating to one attribute [5].

This data can be stored in different ways. The data can be stored in binary indicating the presence or absence of that particular attribute. Alternatively, the data can be stored using enumeration wherein a value is assigned to match a certain classification. For example, if labeling land use, 1 could represent farm land, 2 forest, etc. When using this coding system, a key would have to be made in order to connect the arbitrary number to the feature. Finally, data can be stored numerically. This would be useful when the attribute is numerical, like soil temperature. Each pixel within the grid would be assigned the value of that locations soil temperature. This type of data storage is relatively simple but depending on the degree of detail the files can become very large. Most raster layers are stored using arrays [3].

The basemap is the starting point for all GIS products. It provides a reference point and context for your product. However, there are many different types of basemaps available for use with GIS. A multiscale map is useful for covering a large area because as you zoom in to the map it becomes more detailed. A continuous map doesn't have predefined boundaries because it loops around the surface of the planet. Finally, a global coverage map, as the name implies, covers the entire globe. Basemaps can also vary in appearance depending on the application, such as satellite imagery, street maps, topographic maps, oceans, terrain, etc. Much of the data currently utilized in GIS is open source data meaning it is open to the public. Many organizations use and create open source data which can be uploaded through a GIS processor, like ArcGIS. Operational layers are then added pertaining to the subject of that map. A layer can come from any dataset, like location of oil and gas wells or live traffic conditions. Multiple operational layers can be added depending on the goal of the map. Pop-ups can also be added to give more information on a specific locale. Examples of popups include charts, images, and analytics [8].

One aspect that the digitization of maps has greatly changed is the ability to map in the third, or vertical, and fourth, temporal, dimensions. This has been a useful in mapping terrain such as mountain regions in order to plan climbing routes or real time traffic maps updated with current conditions [8].

There is now a new raster format, the Multi-Resolution Raster (MRR) [9][10], which promises to unify the storage of all kinds of raster data: imagery, spectral imagery, continuous gridded data and thematic data. This model uses a data structure that stores data distributions (such as image color intensity for example) at various resolutions and without regard to what type the values are. The different resolutions can be used to quickly render an output at varying resolutions or even combined resolutions. For example it would be possible to render a map image of a fairly large region where some area of interest is at very high resolution and the rest in a lower resolution. It is also possible to store sparse data by storing only for areas of interest excluding the rest, for example, mapping the depth of a river would generally be based on sparse samples which would span a considerable length of the river but with no data outside the bounds of the river banks, in which case the use of a square rectangular overall grid would contain large areas with no data.

Challenges Within GIS

A major hurdle within the many different GIS platforms is the different types of data available to users. The geographical data comes in many forms and it is difficult to convert it all to one language to be used by the various platforms. When research first began using geospatial data it was rather basic and could be covered using simple modeling elements like points, lines, and polygons. However, as the software and resulting images have become more complex the structures used to create these images have also become more complex [7].

Another major obstacle is the varied levels of expertise among those creating new GIS resources. GIS itself is a scientific field which encompasses many other fields. Those conducting research or creating new software may be cartographers, mathematicians, geographers, etc. As a result, the vocabularies of the researchers vary widely and a common language has not been created amongst the GIS community. Due to the wide use of GIS and the applications, many efforts of pooling resources have been done [7].

Vast amounts of data is usually required and its collection as well as its storage and manipulation is not always easy or cheap. Complex overlay operations are usually required which require substantial processing power and trained personnel. Depending on how data is stored there may be increased risk in case of internal fault, and generalization may lead to loss of important information [11].

Research with GIS

There are a multitude of research opportunities using GIS. The most obvious type is descriptive research which shows data in its current state with a goal to catalog and observe that data in order to learn more about something. This type of data is important in order to determine a baseline in order to stablish an initial understanding [1]. An example would be to determine the water flow within a region using watershed data before a construction project. This data could then be analyzed to determine how the construction would affect the water flow and therefore downstream pollution [1].

Another research application of GIS is in exploration. This is necessary when the researcher is trying to answer a question or determine something for the first time. An example of this would be if you live in an area with numerous traffic accidents. Rumor has it that the accidents are caused by the students at the local university. As a researcher conducting exploratory research, you could create a GIS map which shows the location of the accidents occurring in town overlaid with the age data of the at fault driver. This research would be the starting point for a larger research project. It is a good place to start and build a larger overall project. The following is a flow chart showing the steps to follow when doing exploratory research in GIS [1].

1. Local Issue Perceived
2. Find Appropriate Existing Data
3. Visualize the Data
4. Ground Truth the Data

Figure 3. Steps for Exploratory Research in GIS [1].

The final major type of GIS research is explanation. In this type of research your goal is to examine relationships between variable. Typically, the researcher hops to make connections between data sets or explain why things happen only in certain areas. This research may begin similarly to descriptive research but would go much more in depth [1]. A researcher may want to study how an area will vote in an upcoming election. The researcher could begin with past polling and census data but would need to take additional steps to ensure accurate results for an upcoming election. The researcher might include analysis from door to door surveys, socioeconomic status, voter turnout, and distance to polling locations [1].

GIS Applications

With the prominence of the internet, smart phones, and cloud computing GIS has become an essential part of our daily lives. It is now easier than ever to determine the location of local businesses or gather real time traffic data with the swipe of a finger. This field is changing daily and the possible applications of spatial data are limitless. An emerging field of interest lies within the public openly sharing their personal spatial data over smart phones. Many users choose to "check-in" at restaurants or events across many social media platforms. Many companies are using this data to help target advertising. Spatial data is also immersing itself into our home lives. Many security systems connect to multiple devise within the home such as doorbells, locks, thermostats and more. These then link to our phones to be turned on or off as needed. However an emerging field using GIS is called geofencing which defines boundaries and then acts differently depending on your location around that boundary [1]. For example your security system could reference your smart home to change its settings based on your location. Once the phone leaves the preset boundary the doors could automatically lock and arm the home. The research applicability for GIS faces few boundaries. Provided that the variables include a geographic location then a GIS-based study is applicable.

The domains of applicability are also very broad. Already as discussed in [12], electoral services, planning for government services, urban and regional planning, public health, emergency management etc, are mentioned as some of many domains where GIS are needed.

GIS Software

The leading name in GIS software is undeniably a company called Ersi founded by Jack Dangermond. It is currently one of the largest privately-owned technology companies. Esri's GIS software was originally released as ARC/INFO in 1982 as a part of the Odyssey software project completed in the Harvard Graphics Lab [13]. This product evolved into Esri's current leading product ArcGIS. This is a software program available for purchase commercially which allows for the creation of GIS maps. There are many basemaps available for free within the program which have been created by Esri. Once created within ArcGIS these maps can be embedded into a website or application as needed by the user. Esri also offers an online version of their software called ArcGIS Online. This is a browser-based application that gives the user the ability to create maps using pre-made basemaps and data or user created data. A benefit of the online version is that the maps can be shared with other users and worked on collaboratively online [14].

Another major player in GIS software is Earth Resource Data Analysis System, ERDAS [13]. ERDAS offers three tiers of their products with a range of capabilities and price points. ERDAS Imagine Essentials is the base product, recommended for novice users at a lower cost. It is a mapping and visualization tool which allows for the creation of maps and addition of data sets. Imagine Advantage and professional are the next tier products available which add more precise mapping and cloud editing [15]. Google has also become a key player since they acquired Keyhole in 2004. Keyhole is a digital mapping company and this appropriation became the groundwork for Google Earth. While Google Earth can not be used to create maps like other GIS programs, it has been crucial to making GIS relevant to the public [13].

One of the main hurdles a typical user has when trying to use GIS software is the price. To combat this several free and open source products have been created. One of the most popular is QGIS. It is licensed under GNU General Public License and has been created by the open Source Geospatial Foundation OSGeo. This program can handle both vector and raster data sets. It allows for the creation and editing of data in different formats and has the capabilities to perform spatial data analysis on spatial databases. Maps can be published on the internet or used with a plugin. The project is done completely by volunteers who have written the code and are continuously editing and working on the program [16]. OrbisGIS is another popular open source GIS software package intended for use in research. It was created by CNRS within the French Lab-STICC laboratory. It is programmed in Java and is a standalone program, making it easy to use and manipulate [17].

Conclusions

The above discussion aimed to review the state of the art of GIS systems and provide a quick primer for those who are not necessarily versed in GIS systems. The fundamental structure and data representation methods, as well as the challenges, research, and uses of GIS reviewed here, should appropriately serve this purpose. Evidently, the need for GIS will increase, and so will the need for more storage capacity that is efficiently managed and accessed, as well as the need for faster and more efficient processing, manipulation, and correlation. But the GIS technology is already fundamental as well as mature enough for many applications and so it is expected that its understanding will be useful for those technologists involved with the development or operation of such applications.

Conflicts of Interest

The authors declare that no conflict of interests exists in what regards this work.

Funding Statement

This work was supported by Southeastern Louisiana University, Hammond, LA.

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