Integrating GIS, GPS and GSM technologies for the effective management of ambulances

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Abstract

In this paper, we describe a system offering a solution to the problem of ambulance management and emergency incident handling in the prefecture of Attica in Greece. It is based on the integration of geographic information system (GIS), global positioning system (GPS) and global system for mobile communication (GSM) technologies. The design of the system was the result of a project funded by the Greek Secretariat of Research and Technology. A significant operation for the handling of emergency incidents is the routing of ambulances to incident sites and then to the closest appropriate hospitals. The response time of a real-time system like ours to such queries is of vital significance. By using efficient data structures for the implementation of the graph representing the road network, the time performance of the shortest-path algorithm can be enhanced. Incorporating the efficient algorithm within the GIS will increase our system’s viability. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The efficient management of ambulances in order to achieve fast transportation of patients to the appropriate hospitals is a vital aspect of the quality of health services
offered to citizens. Accomplishing an effective routing and districting of ambulances will minimize their response times and will thus improve the way emergency incidents are being handled.

In this paper, we describe a system offering a solution to the problem of ambulance management and emergency incident handling in the prefecture of Attica in Greece. It is based on the integration of geographic information system (GIS), global positioning system (GPS) (Kaplan & Elliott, 1996) and global system for mobile communication (GSM) (Mouly & Pautet, 1992; Rahnema, 1993) technologies. The design of the system was the result of a project funded by the Greek Secretariat of Research and Technology. It will operate in the National Center of Immediate Assistance (EKAB in Greek), which deals with emergency medical incidents by coordinating and routing ambulances to appropriate hospitals and health units as well as offering medical care to patients during their transport to hospitals. Our research unit was mainly responsible for designing the GIS subsystem, which constitutes the primary focus of this paper. The paper is an extended version of one presented at TeleGeo 2000 (Derekenaris, Garofalakis, Makris, Prentzas, Sioutas, & Tsakalidis, 2000).

An operation with substantial importance for the handling of emergency incidents is the routing of an ambulance to an incident site and from there to the closest appropriate hospital. The optimal routes correspond to minimum required transportation times. Finding such routes may prove to be time-consuming in the case of large cities such as Athens with very dense road networks. However, by exploiting recent advances in the field of data structures, the performance of a shortest-path algorithm in terms of the required computational time can be significantly enhanced. The incorporation of the enhanced shortest-path algorithm within the GIS will lower our system’s response time, thus increasing its inability.

This paper is organized as follows. Section 2 briefly presents primary aspects of a GIS’s facilities in modeling and analyzing spatial networks. In Section 3 the overall integrated system is described. Section 4 deals with the GIS subsystem and describes its key functions. Section 5 briefly explains how the performance of a shortest-path algorithm can be enhanced, while Section 6 demonstrates how to incorporate this enhanced algorithm within a commercial GIS such as ArcInfo. Finally, Section 7 summarizes the results of the project.

2. Modeling and analysis of spatial networks

GIS technology integrates common database operations such as query and statistical analysis with the unique visualization and geographic analysis benefits offered by maps (ESRI Web site; Franklin, 1992; Muller, 1993). Among other things, a GIS facilitates the modeling of spatial networks (e.g. road networks),

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1 Other partners in this project were the University of Piraeus, the National Technical University of Athens, the Aristotle University of Thessaloniki and the companies ITCC and Relational Technology.
offering algorithms to query and analyze them. Spatial networks are modeled with graphs. In the case of road networks, the graph’s arcs correspond to street segments whereas the nodes correspond to street segment intersections. Each arc has a weight associated with it, representing the impedance (cost) of traversing it. In most cases, an arc’s impedance is a function of the corresponding street segment’s length and traffic volume.

A GIS usually provides a number of tools for the analysis of spatial networks. It generally offers tools to find the shortest or minimum impedance route through a network and heuristic procedures to find the most efficient route to a series of locations, commonly called the traveling salesman problem. Allocation functions assign portions of the network to a resource supply location and tracing tools provide a means to determine whether one location in a network is connected to another. Distance matrix calculation can be used to calculate distances between sets of origins and destinations whereas location-allocation functions determine site locations and assign demand to sites. Moreover, street addresses can be converted to map coordinates (address geocoding). Finally, dynamic segmentation operations offer ways of modeling events (e.g. pavement quality, speed zones) along routes (ESRI Web site). These capabilities of GIS for analyzing spatial networks enable them to be used as decision support systems for the districting and routing of vehicles (Crossland, Wyne, & Perkins, 1995; Keenan, 1996, 1998).

3. The overall integrated system

Up till now, EKAB’s employees were using paper maps and their own experience in order to achieve the effective routing and districting of ambulances. However, these two functions, which constitute significant areas in the field of decision support systems (Eom, Lee, & Kim, 1993), require the integration of a computer-based system with geographic analysis and visualization tools and a telecommunication network. The operation of the integrated system will automate and enhance many of EKAB’s services.

The system’s architecture is depicted in Fig. 1. It is based on the integration of GIS, GPS and GSM technologies. The GPS and GSM technologies will be used to transmit the exact positions of ambulances to the GIS operating in EKAB’s Operations Center. The integration of these technologies enables the management of vehicles such as company trucks, patrol cars and ambulances (Hafberg, 1995). All these applications are parts of the new emerging disciplines of telegeoprocessing and telegeomonitoring (Laurini, 1999, 2000; Tanzi, 2000).

Each ambulance will be equipped with a GPS receiver to determine its exact position based on the signal transmitted by satellites. In addition, it will have a GSM modem in order to transmit its position to the base station in the Operations Center. This will be achieved through the GSM network. Furthermore, through the GSM network other useful data, as well as voice messages, can be transmitted. Each ambulance may also be equipped with a computer or a
mobile data terminal to display the route computed by the GIS operating in the Operations Center.

EKAB’s Operations Center will exchange data with the ambulances through the GSM network. It will receive the ambulance positions and will use the GIS to perform the functions described in Section 4. The optimal route calculated for a specific ambulance will be transmitted to it. In the Operations Center there will be a computer dedicated to communication with the ambulances and another one for the operation of the GIS. In addition, there will be one or more computers for the operation of the database management system (DBMS) containing data used by the GIS.

Nowadays, most GIS software packages offer a rich set of tools and extensions, enabling the incorporation of GPS data and offering real-time tracking capabilities. ESRI ArcView, for instance, offers an extension called Tracking Analyst that allows direct feed and playback of real-time data within the ArcView GIS environment (ESRI Web site).

The system’s architecture follows the centralized approach (Laurini, 2000; Tanzi, 2000) whereby a control center (in our case EKAB’s Operations Center) coordinates the fleet of mobile vehicles. Data from the vehicles and sensors are sent to this center and, after being evaluated, data and instructions are transmitted to the vehicles. A strong point of this architecture is the easiness with which it is designed.
However, the danger of a crash in the control center constitutes a major weakness (Laurini, 2000; Tanzi, 2000).

4. The GIS subsystem

The GIS will make use of various data that are either stored in spatial databases and DBMS or transmitted through the GSM network. Spatial data will cover the road network, the locations of hospitals and medical centers, the positions of ambulances, the distribution of incidents occurring in the past, the distribution of population characteristics (e.g. demographic characteristics or disease spreading), and locations of various landmarks.

Basic spatial data for the road network relate to intersections and the road segments between them. These form the framework for defining other features. Intersections are coded based on intersection type (e.g. railroad crossing, street intersection) and the type of traffic control device present (e.g. stop sign, stop light). Road segments form the framework for a number of other geographic features defined using route systems. Street names, for instance, are defined as routes. Along them speed zones and speed limit signs are recorded as linear and point events, respectively. In addition, lanes are recorded as linear events along these routes. Since the majority of streets are only two-lane residential streets, only sections with more than two lanes are recorded. Another important aspect is the recording of the locations of hospitals and gas stations. Moreover, address information related to the road network is being stored, facilitating geocoding operations.

Data concerning road traffic will be very useful for the routing of ambulances. These data will be updated by processing traffic statistics and simultaneously taking into consideration online data deriving from traffic sensors installed on the road network. The National Technical University of Athens has installed loop sensors on the road network of Athens, providing essential information on traffic conditions. Traffic data will be stored in a DBMS. Data pertaining to events such as road works or demonstrations that also affect road traffic will be made available from the municipality or the police.

Data concerning hospitals, ambulances, and their personnel will also be stored in the DBMS and used by the GIS whenever it is necessary. Information linking conventional telephone numbers with addresses is also stored in a DBMS. Its importance will become evident in the next section.

Some of the primary functions performed by the GIS operating in EKAB will be the following:

1. Depiction on a map of ambulance positions and hospital locations. Useful queries that will be performed include the display of information about an ambulance or a hospital chosen from the map, locating all ambulances positioned within a block, all ambulances that are closer to a hospital or some other spot, etc. Different symbols will be used for displaying an ambulance,
depending on its status: an ambulance may be standing by, handling an incident, or returning to its base after fulfilling its mission.

2. **Ambulance districting.** The analysis tools of the GIS will take into consideration the data concerning the road network, past incident distribution, population distribution, hospital locations, locations of gas stations and traffic conditions and will propose efficient distributions of ambulances. A variety of criteria should be considered in order to perform this operation. For example, areas where many incidents take place should be allocated more ambulances. A densely populated area entails a higher probability of an incident occurring. Additionally, an area’s urban planning affects the way incidents are handled. Areas close to major streets facilitate ambulance access to whereas areas with narrow streets inhibit it. If the administrator of the GIS chooses to distribute ambulances according to his/her own criteria, the depiction on the map of all the available information and the interaction with the GIS will be of significant assistance.

3. **Finding the site of the incident.** Based on the address given by the person calling EKAB’s Operations Center for help, the GIS can use address geocoding functions to find the incident’s coordinates on the map. However, in many cases the person calling for help may be at a loss for words and thus unable to give precise information about the site of the incident. Therefore, the system should include a mechanism for matching a call to an address. The DBMS linking conventional telephone numbers with addresses will facilitate this matching. Things are more complicated if the call is made from a cellular phone, however. In this case, the assistance of the cellular phone providers will be required in order to match a caller’s location to the closest address or landmark.

4. **Choosing the appropriate ambulance to handle an emergency incident.** According to ambulance positions, the type and location of the incident and traffic conditions, the GIS finds the ambulance requiring the least time to reach the site of the incident. The choice of ambulance depends on the type of incident because some ambulances are equipped to handle special emergency cases.

5. **Routing an ambulance to the incident site and from there to the closest appropriate hospital.** The GIS will be used to find the optimal routes corresponding to minimum required transportation time. The distance as well as traffic data will be taken into account. The appropriate hospital will furthermore depend on the type of incident. Such information will be derived from communication through the GSM network between the ambulance personnel and the personnel in the Operations Center. The GIS can also present the driver with directions corresponding to the routes generated (e.g. go straight ahead, turn right to Ermou Street, etc.). These directions will be transmitted to the ambulance. In a real-time system like ours, the time performance of the routing function is of vital significance.

6. **Generation of statistics regarding incidents.** The GIS, in cooperation with the DBMS containing incident records, can significantly assist in the statistical analysis of incidents. Consequently, important conclusions supporting the ambulance districting can be obtained.
5. The most efficient implementation of Dijkstra’s algorithm

An operation with substantial importance for the handling of emergency incidents is the routing of an ambulance to an incident site and from there to the closest appropriate hospital. The optimal routes correspond to minimum required transportation times. Finding such routes may prove to be time-consuming in the case of large cities such as Athens with very dense road networks. A real-time system however, must be able to give a prompt reply to such queries.

Dijkstra’s algorithm is a simple and consequently easily implemented algorithm for finding shortest routes and is the most widely used in GIS software packages. Its performance depends on the data structures (e.g. heaps or priority queues) used to implement the graph representing the spatial network. By exploiting recent advances in the field of data structures the performance of a shortest-path algorithm in terms of the required computational time can be significantly enhanced.

We assume that we are given a graph with $n$ nodes, $m$ arcs, and integral arc lengths in the range $[0,...,C]$, where $C$ is the largest arc length. This graph represents the road network. Boris V. Cherkassky, Andrew V. Goldberg and Craig Silverstein developed the hot queue data structure (Cherkassky, Goldberg, & Silverstein, 1996, 1999) that combines the best features of heaps and multi-level buckets (Denardo & Fox, 1979) in a natural way. They proved in theory that if $C$ is very small compared to $n$, the data structure performs as a multi-level bucket structure. If $C$ is very large, the data structure performs as the heap used in it. For intermediate values of $C$, the data structure performs better than either the heap or the multi-level bucket structure. They proved this in practice by giving experimental results for the shortest-path problem.

Using hot queues, the shortest-path problem can be solved in $O(m+n(logC)^{1/3})$ deterministic or $O(m+n(logC)^{1/4}+e)$ expected time, where $e$ is any positive constant. This improves the deterministic bound of $O(m+nlog^{1/2}C)$ achieved by using radix heaps (Ahuja, Mehlhorn, Orlin, & Tarjan, 1990). Therefore, the application of hot queues currently gives the most efficient shortest-path algorithm, both in theory and practice. The great advantage of this structure is that it can be easily implemented. This contributes to the ease with which the enhanced shortest-path algorithm can be incorporated within a GIS.

6. Incorporating the efficient shortest-path algorithm within a GIS

Incorporating the efficient shortest-path algorithm within the GIS will lower our system’s response time, thus increasing its viability. The algorithm was implemented in C and incorporated within an Arc/Info environment. Hence, the mapping visualization capabilities as well as the user-friendly interface of a commercial GIS such as Arc/Info are combined with an efficient algorithm. The version of Arc/Info used is 7.0.4 and runs on a Sun Sparc Station with a Solaris Operating System.

Communication between Arc/Info and the C code is achieved by means of the Inter-Application Communication which makes it possible for an Arc/Info
application to exploit the capabilities of other applications by acting as a client of those applications. This communication takes place when a routing operation or an update of an arc’s weight is performed. Whenever a routing operation is performed, the appropriate parameters are passed to the C code implementing the shortest-path algorithm and the calculated optimal route is returned to Arc/Info and displayed on the road map. When an arc’s weight is updated, the appropriate C function performing this update is used.

This incorporation is in the form of a prototype. The road map used represents the road network of the city of Patras, the third largest city in Greece and a busy port, since it is the main gateway of Greece to the West. It is estimated that the Port of Patras deals with about half of all foreign passengers travelling to and from Greece by sea. Most of the ensuing traffic moves through the city. The remaining part of this section describes the incorporation process.

First of all, a map representing the Patras road network was embedded into Arc/Info. From this process two of the files created were the arc attribute table and the node attribute table containing data pertaining to the network’s segments and nodes, respectively. In Fig. 2 the attribute types of these two tables are shown. Using this data, the corresponding graph based on the efficient data structures is constructed.

The notion of road traffic is incorporated in terms of traffic occupancy. In many real-time applications, traffic volume is measured in vehicles/h with the help of sensors. Occupancy is the percentage of time that the sensors detect vehicles and defines the level of traffic congestion. Table 1 defines the various types of traffic according to traffic volume and occupancy.

Due to the fact that only a few roads in Patras have traffic sensors, we updated the occupancy information by using statistical data concerning road traffic. The weight

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Fig. 2. The attribute types for the arc attribute table and the node attribute table.
of each road segment is calculated as a function of the segment’s occupancy, length and vehicle speed limit.

The prototype user interface consists mainly of form menus implemented in AML (Arc Macro Language). Fig. 3 shows the main form menu. With the option “Road Network”, the C code is called upon to construct the graph representing the road network with the efficient data structure as described in the previous section. In addition, the map of the road network is displayed. With the option “Road Network characteristics”, a number of form menus can be opened enabling the viewing of data involving the road network characteristics (segments, nodes). For instance, Fig. 4 displays the attribute values of a road segment. With the option “Traffic”, the traffic occupancy of all road segments is updated. Their weights are updated by using the appropriate C function. With the option “Routing”, the routing operation is performed. The user can set the start and end points of the shortest path either by clicking with the mouse on the appropriate map points or by giving their addresses. Their coordinates are passed as parameters to the C code. The C function implementing the shortest-path algorithm writes the resulting optimal route connecting

Table 1
Traffic types according to traffic volume and occupancy

<table>
<thead>
<tr>
<th>Traffic type</th>
<th>Traffic volume ( V ) (vehicles/h)</th>
<th>Occupancy ( O ) (%)</th>
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<tbody>
<tr>
<td>Minimum</td>
<td>( V &lt; 500 )</td>
<td>( O &lt; 25 )</td>
</tr>
<tr>
<td>Small</td>
<td>( 500 &lt; V &lt; 1000 )</td>
<td>( 25 &lt; O &lt; 45 )</td>
</tr>
<tr>
<td>Medium</td>
<td>( 1000 &lt; V &lt; 1500 )</td>
<td>( 45 &lt; O &lt; 70 )</td>
</tr>
<tr>
<td>Heavy</td>
<td>( 1500 &lt; V &lt; 2000 )</td>
<td>( 70 &lt; O &lt; 90 )</td>
</tr>
<tr>
<td>Very heavy</td>
<td>( V &gt; 2000 )</td>
<td>( O &gt; 90 )</td>
</tr>
</tbody>
</table>

Fig. 3. Main form menu for the prototype application.

Fig. 4. A form displaying a segment’s attributes.
the given points into a particular Arc/Info route file, which is then read by Arc/Info in order to color the route on the map. Fig. 5 depicts a route on a partial map of the Patras road network.

7. Conclusion

In this paper, we have described a system offering a solution to the problem of ambulance management and emergency incident handling in the prefecture of Attica in Greece. It is based on the integration of GIS, GPS and GSM technologies. The design of the system was the result of a project funded by the Greek Secretariat of Research and Technology.

An operation of great significance for the handling of emergency incidents is the routing of ambulances to incident sites and from these to the closest appropriate hospitals. A real-time system like ours must be able to give prompt replies to such queries since in emergency incidents the response time is of vital significance. By using efficient data structures for the implementation of the graph representing the road network, the time performance of the shortest-path algorithm can be enhanced. We have given a brief presentation of the data structure used by the most efficient (up till now) shortest-path algorithm and described a prototype application demonstrating how it can be incorporated within a GIS. The incorporation of the efficient algorithm within the GIS will lower our system’s response time, thus increasing its viability.

Fig. 5. A route on a partial map of the road network.
The prototype application has been tested mainly against statistical traffic data. Our intention in the future is to extensively test it against real-time data deriving from traffic sensors. These tests will guarantee the full efficiency of the system.

Due to the possible long distances, an ambulance may require considerable time to reach the site of the incident and from there the appropriate hospital. During this period, traffic conditions may have changed and the data according to which the optimal route was calculated may have become obsolete. Therefore, one point that needs to be addressed in real-time situations is the ability to predict traffic conditions and adapt the routing scheme accordingly.

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