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MODELLING URBAN ROAD NETWORKS INTEGRATING MULTIPLE REPRESENTATIONS OF COMPLEX ROAD AND JUNCTION STRUCTURES

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Abstract

Generalization is certainly one of the most important current issues in cartography, with particular emphasis being placed on its automation. This paper considers the automation of generalization applied to road networks - primarily urban roads. The user context for this study is car navigation, which entails such activities as route planning, the recognition of locations and landmarks on a route, and the negotiation of complex junctions. As noted by Timpf et al. (1992), these activities require data at a wide range of scales and at different levels of abstraction.

Key problem areas for navigation are those parts of the network where a change in topology occurs with a change in scale. A divided highway with a two-line representation will be represented by a single line at a sufficiently small scale and, with continued scale change, may even be completely eliminated. Such changes can be expected to produce many problems to the navigating user, and hence to the cartographer. Fundamentals of multiple representational databases are developed for the urban road data, where the significant transformations in junctions and roadways are identified and tracked. Tools for formalizing and handling multi-scale representations are presented.

1. INTRODUCTION

1.1 General

Continued technological developments have affected cartography as with other disciplines. In particular, developments in computer technologies and the use of geographical information systems (GIS) have led to significant changes in map production and generalization processes. Successful automation of these processes has become a major goal of cartographers and related researchers. Fundamental contributions on these subjects have been made since the beginning of the 1960s to the present by, for example, Töpfer and Pillewizer (1966), Brassel and Weibel (1973), Shea and McMaster (1989). Most of such studies have resulted in the development of different algorithms for the automation of map production (especially generalization). In this period studies were also done on the acquisition, storage, and maintenance of spatial data. The concept of the Multiple Representation Database (MRDB) is one significant product of these attempts.

Such technological developments mentioned above have affected the automobile industry: car navigation systems have recently become an important part of the market. As a result, the use of maps by the driver has evolved from the classical roadmaps to screen maps useable while travelling.

1.2 Aim of This Work

This work is a product of an on-going study that aims to produce maps for navigation purposes, making use of MRDBs. Car navigation is considered as the basic case among different navigation concepts. Different levels of representation of highways, which will be displayed on in-vehicle devices, are examined. The problems that occur on problematic parts of the road networks while finding optimal routes are determined – at this stage only road junctions are considered. Optimal representations of junction for any scale are then proposed. This work aims to establish the fundamentals of MRDB use for the production of navigation maps.

2. GENERALIZATION

Generalization may be defined as the selection and simplified representation of detail appropriate to the scale and/or purpose of a map (ICA, 1973). Generalization is one of the most important subjects of cartography, central to the science and art of map design and production. It is remains problematic, however, for although the widespread use of GIS and spatial databases - and the subsequent need for visualisation of spatial data over a huge range of scales - has stimulated much research and development effort, success in the automation of generalization has been limited.

In map creation spatial data obtained from the real world is generalized in two steps: Model and Cartographic generalization. As stated in Kilpelainen (1997), model generalization is the simplification of the abstract digital model represented by the geographic information, and this stage contains no artistic components. It is applied in the database and can be considered as a preprocessing stage for cartographic generalization. On the other hand cartographic generalization contains both artistic and intuitive components and provides one reason why cartography is considered as an art. As a result, cartographic generalization has the leading role in the transmission of data through the use of symbols to represent geographic reality, and it is a significant stage of the map production process.

McMaster and Shea (1992; Shea & McMaster 1989) defined ten generalisation operators in detail, such as simplification, amalgamation, etc.. Other authors studying special issues may define different additional operators, as Kilpelainen (1997) did for MRDB system. It is generally agreed that scale is the most important constraint on generalization (Bildirici, 2000). Another limitation for the generalization is the aim of the map. In addition to these factors Robinson *et al.* (1978) considered that the quality and quantity of data and graphic limitations constrain the generalization process. Moreover, Kilpelainen (1997) emphasised the effects of the human factor, the cartographer, over the generalization process.

Topology is the mathematical concept of spatial structure, sometimes defined as "characteristics of geometry that do not change when the coordinate space is deformed" (Hardy *et al.*, 2003). Hardy *et al.* state that for good generalization the following properties must be made explicit:

- Shared edges between land polygons,
- Junctions between streets in the road network,
- Collinearity of administrative boundaries with roads and streams,
- Adjacency of buildings to roads,

Clearly, topology is of crucial importance for road networks. If any model is to be developed for roads, first its topological relations should be defined and then this topological structure should be formalized using an appropriate method. Such an approach is followed in this work.

3. MULTIPLE REPRESENTATION DATABASES (MRDB)

Although there is just one world reality, its representation in a database will vary with different aims, contents or display scale. Thus different levels of representation of (aspects of) the real world are required. This requirement is increased by the development of GIS applications: different applications want different representations. The search for a solution to these kinds of needs resulted in the MRDB. The National Center for Geographic Information and Analysis began discussion of the objectives and process of developing a research agenda in MRDB in the late 1980s (Buttenfield & Delotto 1989).

Multiple representations provide different representations of the same spatial data. These representations can differ in scale, aim and resolution. An MRDB is a spatial database, which can be used to store the same real world phenomena at different levels of precision, accuracy and resolution (Kilpelainen, 1997). Kilpelainen (1997) presents a comprehensive description of the MRDB and develops an MRDB model for generalization of geo-databases for topographic maps. According to the Kilpelainen model, an MRDB consists of three main components: representation levels, connectivities and reasoning process. Representation levels cover the base level, which has the most detailed representation of the objects, and higher levels, in which object representations vary with the scale, aim or resolution. The number of the higher levels is application dependent. The MRDB aims for the automatic propagation of updates made on the base level to the other representational levels. Accordingly, connectivities should be described and formalized between objects in the same or different levels. Kilpelainen (1995) separates the relations between different objects at one level – termed relationships – from the relations between the different representations of the same object at different levels – connectivities. Finally, the reasoning processes are needed to provide full functionality in the MRDB. This means that the updates can be propagated from lower level representations by using the model generalization operators applied automatically in the modules to be generalized (Kilpelainen, 1997).

4. CASE STUDY

4.1 General

As Timpf *et al*. (1992) stated, navigation is a fundamental human activity and an integral part of everyday life. Wayfinding is one of the most important parts of this activity. People have navigated themselves with no maps; technological developments facilitated navigation by providing paper maps. Nowadays, advanced navigation systems have been developed, integrating positioning and communication techniques, digital mapping, computer and handheld device technologies. Today, these systems are used in different applications, so navigation is specified according to its application area – such as aircraft, marine, nautical, personal, and car navigation etc. Although these navigation types have significant differences because of their application dependent constraints and aims, the demand for wayfinding lies at the core of them all. Timpf *et al*. (1992) examined car navigation at the planning, instructional and driver level. This study tries to propose an approach for the production of navigation maps in terms of MRDB, with car navigation being considered as the basic activity.

4.2 Requirements of the Process

Maps are designed for users: as stated in the GiMoDig project (2003), the purpose of a map is always transmission of information (Nissen *et al.,* 2003). Map design for navigation purposes is not scanning or digitising existing paper maps. In designing such maps the usage conditions (psychological factors, external impacts, road conditions, etc.) should be considered in addition to normal design criteria. Moreover, design details should be evaluated with cartographers. Since the targeted presentation medium for the navigation data is an in-vehicle computer or pocket PC, small display cartography takes a very important place in map design for navigation purposes. Although the dimensions of devices used in car navigation are mostly outside the small display limits accepted in GiMoDig, results of that research are very important and adoptable for car navigation.

The updating of maps is another requirement of a car navigation system. Changes in navigation conditions should be updated regularly and, if possible, in real time. Especially important is that changes in the geometric structure of road networks should be automatically updated in the system, so the database for the system should be available for update propagation. Further, this database structure should be based on MRDB.

Finally, the desired cartography for map production has to support the map purpose, satisfy the aims and user requirements (GiMoDig, 2003). For example, a driver using a navigation system in a foreign city or country wants the system to navigate him as well as possible so the system maps should display world reality in correct scale and resolution. In the specific case of road networks complex junction types should be visualized in detail. Since junctions are the most critical parts of the road networks for drivers more care should be taken while modelling and displaying them. In most of the current systems, roads are generalized to single lines and the junctions considered as points of intersection of two roads. But these network structures should be represented in greater detail. Timpf *et al*. (1992), state that the existence of multiple lanes is assumed but it is not needed for locating correct exits and entrances on a road network. That assumption will be tested in this work: different representational levels should be examined, as with difficulties in formalization, exchangeability among software, usage and design costs.

4.3 Study Area and Work Steps

The city of Istanbul is taken as the study area: Europe's largest city provides a challenging range of road features for consideration, in challenging quantities.

4.3.1 Junction Choice

In determining the junctions that will be used in application, it is understood that several junction types can exist in the real world. Because our study area of Istanbul is a large metropolis it was more difficult to select the junctions, and it was decided to constrain our choices. The following criteria were used:

- All chosen junctions should be complex and potentially difficult to understand for a foreign driver.
- The junction types should be common in the real world.
- These junctions should represent examples of different types.

As a result, four different commonly used junctions on TEM (Transit European Motorway) were selected for examination as test data.

4.3.2 Work Steps

After deciding which junctions will be used in the study, their topological relations are formalized for different representation levels using predicate calculus. These are then all tested in different GIS and mapping software in terms of their consistency for the basic queries used in the navigation process, such as finding shortest paths or optimal routes. The results of these tests then permit the selection of the most appropriate representation level on which the standard algorithms can be used without any additional capabilities.

4.3.3 Representation Levels

Four representation levels are considered in this study. The first of them is the base level with a scale of 1:5000. This level provides maximum detail for the junctions. Representations of the junctions become simpler from the base level to the higher levels. As is illustrated in Figure 1, it is clear that the base level can not be used as a data base for any application. The second level is a two-lane representation of the junction and road. This represents the real world with a level of generalization sufficient to allow it to serve as a database for an application. The third representation level contains less detail while the fourth level represents the junction as a node. Although most of the systems use the fourth level, which has the minimum cost for navigation, in this study it is proposed that third and second representation levels should be used in a navigation system to represent the real world as well as possible. In this context, these representation levels are compared and the better one is chosen in the following parts of the study.

4.3.4 Data Formalization

Data formalization is a very important stage for an MRDB system, because it is in this process that objects are defined and their relations are described. In other words, mathematical definitions of the spatial objects and their relations are established using a consistent formalization language. In this study predicate calculus is used for formalization, following the example of Kilpelainen (1997). Predicate calculus is a formal language based on true/false statements. It uses variables and functions of variables in a symbolic logic statement and supports reasoning (Rosen, 2003).

In this context all geometrical elements of a road network are defined (in a form that can be used for all networks) and sample junctions are examined using these definitions. For example, two base elements of a network, namely node and segment, are defined as follows:

$\forall n\ (Node(n) \rightarrow (On(n,x)\ \Lambda\ On(n,y))\ \Lambda\ (x \neq y)\ \Lambda\ n \in N)$

$\forall x\ (Road(x) \rightarrow StartPoint(x)\ \Lambda\ EndPoint(x)\ \Lambda\ \forall EndPoint, StartPoint \in D)$

The first definition states that if there is a point, n, on both x and y roads where x is not equal to y then this point is node. According to the second statement a road is an object with a start and end point that are members of the point space, D.

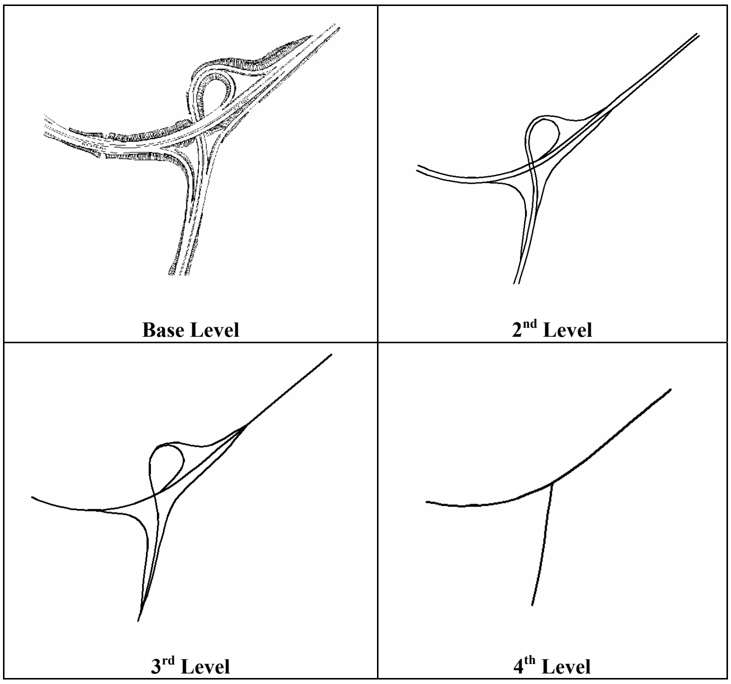

Figure 1: Representation Levels

Existent relations are categorized as connect and intersect. In this study, Kilpelainen's connection definition is used directly but extra statements are added for the definition of the intersection. The following definitions are obtained:

$\forall x,y\ (Connect(x,y) \text{ -> } On((StartPoint(x) \vee EndPoint\ (x)),y) \wedge (x \neq y))$

$\forall x,y\ (Intersect(x,y) \text{ -> } (\exists n(On(n,x) \wedge On(n,y)) \wedge n \neq (StartPoint(x) \vee EndPoint(y)))$

The first of these statements means that if a road x is connected to road y, the end or start point of the road x is on the road y. The second means that if a road x intersects road y then there is at least one point, that is a node, on both of the roads but this point can not be a start or end point.

At the end of the formalization process it is apparent that there is a significant distinction between formalization of two lane and single lane representations. The formalization of the two lane representation is easier than the single lane case because of the difficulties that occur while formalizing the distinction between two way and one way roads in the single lane representation. This result can be considered as one of the criteria for determining which presentation will be used for navigation systems.

4.3.5 Tests for the Representations

Single and two-lane representations of the junctions are tested using three different GIS programs. In this context the network topology is created in the programs then the same queries are repeated for different representations of the junctions as in the task of finding shortest paths. As is seen in Figure 2, in which a sample result is given, while queries on two-lane representation give correct results by using standard topology, the single lane representation needs additional programs to manage it. In Figure 2 (single lane representation), arrows on the roads show the road directions. The query result for this representation shows the wrong directionality on the path found.

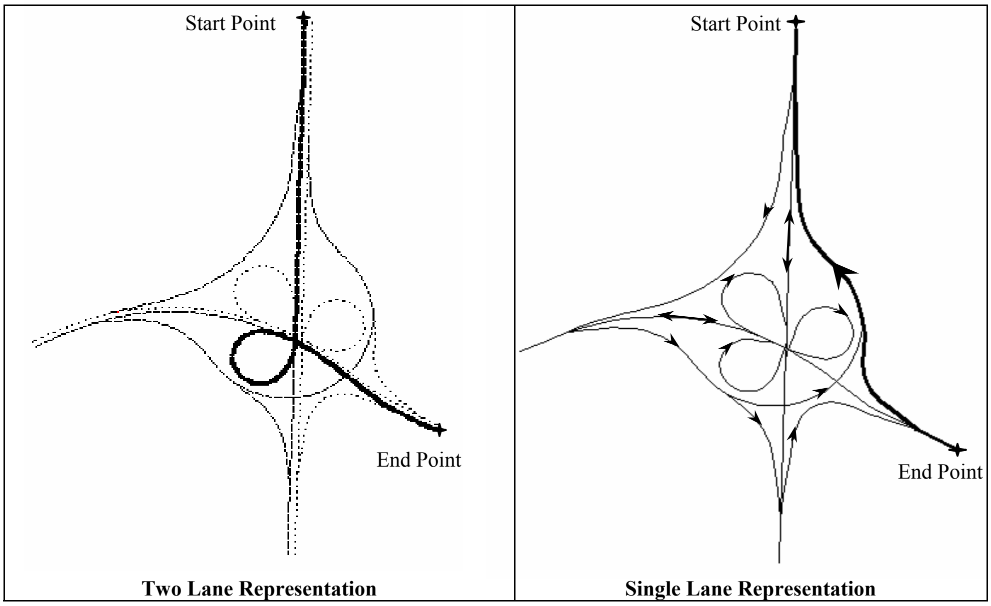

Figure 2: Shortest path query results in two and single lane representations

5. CONCLUSION AND FUTURE WORK

This paper presents initial results from an on-going study that aims to produce maps (displays) for navigation purposes, making use of MRDBs. It is clear that a user (driver) wants the navigation system to represent world reality with as much relevant detail as possible, entailing intelligent generalization. Since the ultimate goal is intelligent transportation systems, managing navigation automatically, future systems may be expected to make increasing use of artificial intelligence. Limits on the details presented to the user should be determined by considering the constraints of small display cartography, but it should not be forgotten that lack of detail can make a map unreadable.

In this study it is proposed that using two-lane representation of roads in navigation maps would be more convenient for several reasons. First of all it represents the world reality, especially junctions, better than a single-lane representation. Although processing time of the single lane representation for navigational analysis is less than for the two lane representation, the formalization of the latter is easier. Finally, while standard topological algorithms can run on two-lane representations additional programs are needed for single representations. This means that on balance the two-lane representation is better than the single one.

The whole road network must be formalized and then its relations with surrounding objects should be examined as a future work. Moreover this system should be applied on the whole road network of Istanbul. Derivation of these road maps automatically is another task that will be addressed in the next steps of this work.

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