Digital Map Requirements of Vehicle Navigation

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ABSTRACT

We consider digital maps for electronic navigation systems, and present characteristics of the map and its presentation that are required for navigation assistance. The Etak Navigator™ and its requirements serve as examples. The most important are topological structure, positional accuracy, identifying information like names and addresses, and street classification. Topological structure is needed for retrieving data in the ever-changing neighborhood of a moving vehicle. Positional accuracy is needed in navigation systems that, like Etak's, use map-matching. Identifying information is needed both for display and destination finding. Street classification is used in several ways: to display different classes of features differently, to select data to show at various scales, and in routing. We also consider the merits of various forms of presentation and their effects on the map requirements. For example, a visual heading-up display has the merit of giving an oriented context to the local navigational information.

INTRODUCTION

Automated navigation aids impose varying requirements on the supporting digital map. With sufficient information in the database it is possible to present a new map on a screen or compose new or updated instructions at each significant change in the driver's situation. Such changes include turning onto a different road, advancing along the same road, and changing one's mind. It is also possible to abstract essential navigational data for particular situations and drop unimportant detail. These can be powerful aids to a driver.

Navigation always involves knowing your current location, finding your destination, usually with respect to a map, retrieving relevant maps or map data, and presenting the data to the driver. The Etak Navigator™ constantly tracks current location by dead reckoning augmented with map matching, i.e. matching the dead-reckoned path to possible paths on the road map (Zavoli 1986). This imposes topological and metrical requirements on the digital map content and speed requirements on retrieval.

Destination finding can impose heavy demands on the digital map. To find street addresses or intersections, for example, requires a great deal of data as well as high speed retrieval.

Map retrieval is also crucial to navigation assistance and deserves consideration apart from map content. It is a support function at the core of navigation assistance and related applications.

Presentation of the data to the driver is also always a part of navigation assistance. Presentation can be graphical with simple interaction, as in the Etak Navigator™ or at the other extreme can be driving instructions written or given by voice. There are many differences beyond human factors considerations; in particular, digital map support for graphics is more demanding in coordinate accuracy and for instructions is more demanding in traffic flow restriction data, such as one-way or turn prohibitions.

We consider below the implications of providing various kinds of navigation assistance on digital map content, retrieval and how these relate to presentation. Neukirchner and Zechnall have presented their findings on map requirements with particular emphasis on map sources and precision (Neukirchner 1986). In this paper, we emphasize categories of information required in relation to retrieval and presentation. We find:

- o topology to be fundamental to both content and retrieval;
- o metrical data (coordinates) important for map matching and display;
- o names, addresses and geographic codes required for destination finding;
- o cartographic generalization important for both display and routing; and
- o many kinds of ancillary data useful in many ways.

Fast retrieval from a huge store is needed to keep track of current location, find destinations, and find paths in the network. We also consider interactive graphic presentation and its demands on retrieval and content in contrast to giving instruction and its greater demands on completeness and content.

CONTENT

The simplest aspect of a digital map to consider is content. Format and organization are related and are sometimes called data structure. It is important to understand that the structure, if you have topology in mind, is the data, or at least part of the data content and must be captured just as street name or priority must.

<u>Topology</u>
There have been demonstrations of navigation systems that use images of maps and entirely avoid encoding topology. The Etak operates at at the opposite extreme: we use topology nearly everywhere.

Even if the only use were in destination finding (say finding intersections), while navigation, display, etc. depended not at all on topology, it would be worthwhile to store the map as a topological database. In the first place, capturing the intersections is the bulk of the topological work and in the second, topological map storage is much more efficient than image storage.

Additional reasons for using a topological database abound. Finding a path through a network is a topological calculation. Connectedness (a topological property) is useful in map matching. As a vehicle advances on the ground, so does its relevant neighborhood; retrieval of a new neighborhood related to the last is a topological operation. Annotation and ancillary data is efficiently associated with elementary topological data; this is important for both destination finding and presentation of data.

Taken together, these facts are compelling evidence that to provide navigational assistance of even modest sophistication topological data must be included and further the database must be organized topologically to permit topological operations.

Metrical data

Coordinates are often regarded as the quintessential map data and a great deal of attention is given to coordinate reference systems with passionate pleas for particular ones, such as UTM. This is a mistake. Topology is more important for the reasons mentioned above as well as deeper mathematical and philosophical reasons (Corbett 1979). It is possible to give effective instructions for driving from one point to another using no metrical data and one can even imagine diagrammatic graphic presentations using no metrical data. So coordinates are unnecessary for some very useful navigation aids.

Nevertheless, distances and headings are helpful in driving instructions. Coordinates are very useful in graphic presentations and required for map matching or interpreting radio navigation data. So coordinates are important in navigational assistance.

Coordinate accuracy requirements vary with the application. Etak's map matching algorithms, for example, impose accuracy requirements on the coordinate data equal to the requirements for USGS 1:24000 quads. these requirements are local; relative accuracy is critical global accuracy hardly matters. One reference ellipsoid is as good as another and, as is the case with most extant maps, different ellipsoids for different continents work well. Because of their applications to geodesy, coordinate systems used in topographic map series are usually geodetic using a reference ellipsoid whose axis does not coincide with the Earth's but is parallel.

Etak's Navigator also dynamically recalibrates the sensors by gleaning information from the map matching. This means that position errors in the digital map not only cause failure to match and incorrect matches, but also degrade calibration, making navigation performance worse. So relative coordinate accuracy is very important for Etak's navigation both in map matching and in maintaining navigation performance in the dynamic environment of a car.

Radio navigation requires coordinates matched to the particular system, be it LORAN, Geostar or GPS. Relative accuracy is less important here; indeed local distortions matching characteristics of the particular system may be helpful. Satellite systems, being global in nature, use a single geocentric reference ellipsoid rather than the set of ellipsoids used for map series in different continents.

The high precision promised by GPS implies that GPS coordinates will meet the relative accuracy requirements of the Etak Navigator™. A GPS receiver could be connected to a Navigator as an additional sensor that works especially well in open terrain. This would be adding an absolute navigation device to a dead-reckoning device, which is by its nature relative.

Using GPS or other absolute navigation devices puts additional requirements on the map. The coordinates output by the GPS receiver must be transformed to those of the map to be displayed (or visa versa) so that position relative to objects on the ground is known, which is essential for navigation. In fact, it is far more important to know your position relative to nearby objects than to a set of satellites. The ability to accept data gathered using different techniques and interpreted using different coordinate systems is and will remain important. It won't suffice to declare GPS coordinates a world standard.

Still another consideration for using an absolute device like GPS is that map matching may be needed to smooth the motion of the display. The noise in the coordinates from the GPS receiver, if used directly, would cause the vehicle position to bounce with respect to the map. Map matching would remedy the problem.

By using more accurate coordinates one can plot more pleasing map displays, but pleasing map displays do not in themselves require accuracy. Most paper road maps pay no heed to accuracy and even purposely distort position to enhance legibility. The requirement to plot good looking maps taken with accuracy requirements for map matching implies rather high accuracy for Etak's applications.

We have discussed the need for relative accuracy in some cases, global accuracy in others, the use of different coordinate systems, geodetic, geocentric, as well as using different reference ellipsoids, and there are still other considerations that can be important such as projections. So coordinate accuracy is a complicated matter and its interpretation depends on the context. It is possible, perhaps common, to determine one's position very precisely and be completely lost, by misunderstanding coordinate systems (Ashkenazi 1986).

Generalization and Abstraction

To provide a regional context and help a driver navigate to distant destinations, a navigation system should provide various scale displays showing more or less detail for larger or smaller scales respectively. So a driver can zoom out to a small scale map and see the major limited access highways in an entire region and zoom in to a large scale to see all the streets in the immediate vicinity of the vehicle. Intermediate scale displays drop streets of lesser priority as the scale gets smaller: first local streets and trails vanish, then collectors, then arterials, and finally lesser highways. The presentation is also generalized in that curving roads are straightened at smaller scales.

This same prioritization scheme is useful in path finding. One prefers major highways to cross a region, for example. The classification of roads for use by computers is, at least in Etak's case, richer than that found on commercial street maps. This is because the use is different. One usually takes some time to read a paper map and the cartographer can depend on the reader to use remarkably good gestalt interpretation to find, say, a reasonable path out of a labarinthine neighborhood. The Navigator must present a map that the driver assimilates in a glance. The roads at various priorities must typically form a network to be helpful in finding routes to a destination, but for paper maps the need is much diminished.

Names, Addresses, Traffic Restrictions, etc.

Annotation on paper maps is usually called attribute data in digital maps. By either name the data is useful both for identifying map elements or instructions and for indexing maps and localities. The considerations here for navigation assistance are which classes of data to capture, degree of completeness, recency and accuracy. An important consideration is of course cost of data capture. In that regard field work is far more expensive than capturing data from available map sources. Reversing the viewpoint, the types of navigation assistance possible vary with whether or not field data capture is undertaken.

The classes of data we now capture at Etak are limited to those that do <u>not</u> require field work. Street names, addresses, relative importance of roads, major landmarks, and geographic area codes (city, ZIP, etc.) are usually available from public map sources and do not require field work. Turn restrictions and one-way flow restrictions are much less reliably available without field work and actual traffic sign content nearly always requires field work.

Giving reliable instructions often depends on having field collected data such as turn restrictions and this imposes a significant cost on the digital mapping effort. For our initial products we have avoided field work and made design decisions that take this restriction into account. Presenting the driver with a graphic display that gives enough information to safely and efficiently achieve a destination does not require knowing turn restrictions or one-ways much less sign content.

RETRIEVAL

Speed of retrieval, capacity of storage, and how to provide access to map data for application developers who may not wish to also provide navigation software or wish to provide alternative navigation software are the topics of this section. We have found this last subject to be very important, at least for Etak. We have licensed Etak navigation technology in the U.S., Europe, and Japan, and we must provide access to the map data so that different and independent developments can proceed. The requirement is the same even for Etak's own development of Navigators, Automatic Vehicle Location (AVL) systems, and map production facilities. The Map Engine, which is a software shell surrounding the data, is Etak's approach to providing access to the data.

Speed

Just keeping up with a vehicle's progress across the Earth is a non-trivial task for map retrieval software. Within the constraints of cassette tape, an 8088 CPU busily doing navigation and display calculations, and 256K bytes of RAM, the task is quite difficult. Some of the solution in the Navigator is in hardware: the tape has a capacity of 3.5 M bytes and operates at 80 inches per second. Some is in software and here topology is again important. Knowing what is neighboring the currently retrieved map elements is crucial to organizing the anticipatory sequence of reads from the tape.

The same software solutions will work well in CD/ROM storage. The capacity of CD/ROM is enormous by comparison: 500 M bytes per disk over 100 times greater than Etak's cassette tape. The speed is not so spectacularly better: average access time of 1 second, five to ten times faster than the cassette. So software that retrieves data from CD/ROM for onboard navigation may not need to be quite so clever but must still be faster than commercially available software in Geographic Information Systems (GIS).

Of course the same software works even better in the hard disk environment with 30ms average access times. In fact we have used the same software at Etak for our Automatic Vehicle Location (AVL) base stations, which are IBM/AT or similar computers with a graphics screen and mouse. So the dispatcher has the same functional capabilities as the driver but with much faster hardware. The base station has benefited greatly from the solution to fast map retrieval forced by the much more constrained vehicle environment.

Capacity

Digital maps require a great deal of memory. One EtakMap™, the cassettes containing a digital map and navigation software for the Navigator, covers the area of about two typical large scale paper road maps. Six cassettes cover, in an overlapping fashion the San Francisco Bay area. It takes ten in the Los Angeles/San Diego metro areas, three in Detroit, and five in New York, to give a few examples. EtakMaps contain both the map data for navigation and display and indexes for destination finding.

It appears to be possible to fit the entire US onto a single CD/ROM at the level of detail required for the Etak Navigator. It wouldn't make much sense to do so; the space would be better utilized for, say, Yellow Pages listing in categories like accommodations, restaurants, and services. However, it does indicate that when CD/ROM becomes available in a form that can survive in the harsh environment of a vehicle and at a price that is low enough, capacity won't be a serious constraint.

Map Engine

Not only is the data itself important but so is providing it to the various applications in an efficient and consistent manor. The applications include navigation, display, destination finding, and user specific applications. The database supporting high speed topological access to maps at various levels of abstraction using coordinates and annotation as the key for searching is, not surprisingly, complicated. To provide access to the data for other applications, other users, as well as to navigation and AVL, we have developed the Map Engine. It is a map-specific database management package accessed by subroutine calls. Examples, including some under development, of its capabilities are:

- Retrieve all map elements in a N-S E-W window
- Retrieve an open neighborhood around the current sub-map
- Retrieve a closed neighborhood ...
- Retrieve by feature name
- Set level of abstraction (generalization) for retrievals
- Retrieve a small subset of the map suitable for finding an optimal route to visit several destinations (which might return mixed levels of abstraction for distant points)
- Add, delete or change map elements
- Find a street address
- Find a intersection
- Find the nearest point on a street

By providing a software shell surrounding the data for a developer of applications has the same advantages that database systems provide. Certain parts of the job are done and debugged and proprietary advances are available prior to a patent issuing, which can be years sooner.

PRESENTATION

The extremes of styles of presentation are interactive graphic and driving instructions, written or voice. Intermediate stages are easy to imagine.

Graphics

A picture is worth a thousand words, but only if as much thought and skill went into creating the picture as the words. We endeavor to always present an uncluttered display with just a few labels, so that it is readable at a glance, but we choose what to label, the angle of the labels, the orientation of the map and the few other pieces of information to be as helpful as possible to the navigating driver.

In labelling streets we favor upcoming cross streets, higher priority streets and the streets at the destination. The map is oriented heading up so that what is ahead out the windshield is above on the screen. An arrow pointing to the destination with distance to go and a north arrow are the only other pieces of information on the screen.

The scale of the map determines the level of generalization. To always present maps of similar complexity at the various levels of generalization involves a significant effort in digital map production. In effect, digital cartographers are making driving choices for the driver in advance of actual driving; this is another place where we introduce a great deal of thought to make the picture worth the thousand words.

Not only is the resulting picture better than words, it is better than a printed map, by far. A new map is composed every few seconds designed precisely for the driver's current situation and displayed on the screen. It is a simple image, conveniently oriented (just how convenient is impossible to explain -- one has to use a Navigator to appreciate), with vast amounts of irrelevant data omitted. The information includes a star marking the destination (like the star of Bethlehem) which gets nearer to the car symbol as the vehicle approaches the destination; this provides a very warm feeling that you are making progress. Also included are nearby streets, which can give one the courage to exit a backed-up freeway and travel along surface streets. These are ways that digital maps are far superior to printed maps even for non-analytical uses.

Driving Instructions

Not everyone likes maps. There are even people who are intimidated by them. We have not seen this hostility transferred to the Navigator and this may be because the Navigator display does not suffer the intimidating clutter of many printed maps nor demand the geometrical intuition to reorient the map in your mind nor the difficulty of finding your place on the map.

Whatever the case, an alternative to a graphic display is a list of driving instructions. These can be given by voice, written on paper, or written on a screen as they are appropriate.

To generate reliable instructions, the digital map must contain turn restrictions to avoid impossible-to-follow directions but need not have a high level of coordinate accuracy, as mentioned above. To generate or modify the instructions on the fly both high speed retrieval and current location are needed. Missing a turn and encountering barricades or traffic jams are cases where modified instructions would be needed.

Both

There are many possibilities between the extremes and their demands on the digital map varies with the mix. One can present a graphic display with a preferred route highlighted. If a barricade prevents access to part of the route, the display has enough information for recovery. Audible tones or voice instructions as waypoints approach could be added to a display. The map display could be schematized even to the point of just indicating the direction of an upcoming turn with a diagram of the intersection, which would be especially useful in a many-street intersection. Such a simple display would be less demanding of coordinate accuracy (although if current location is maintained using map matching accurate coordinates would still be needed).

SUMMARY

Digital maps for navigation assistance must be topological for any significant level of sophistication. Navigation using map matching or displaying current position requires relatively accurate coordinates and satellite-based systems need globally accurate coordinates. Annotation helps to identify surroundings and to locate destinations. Fast retrieval of map data from copious storage is a requirement of tracking current location and generating dynamic driving instructions. Digital maps offer wonderful advances over printed maps for presentation of navigation data. First, far more useful and assimilable displays can be generated and second, instructions can be generated and presented graphically, in written form, or by voice.

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