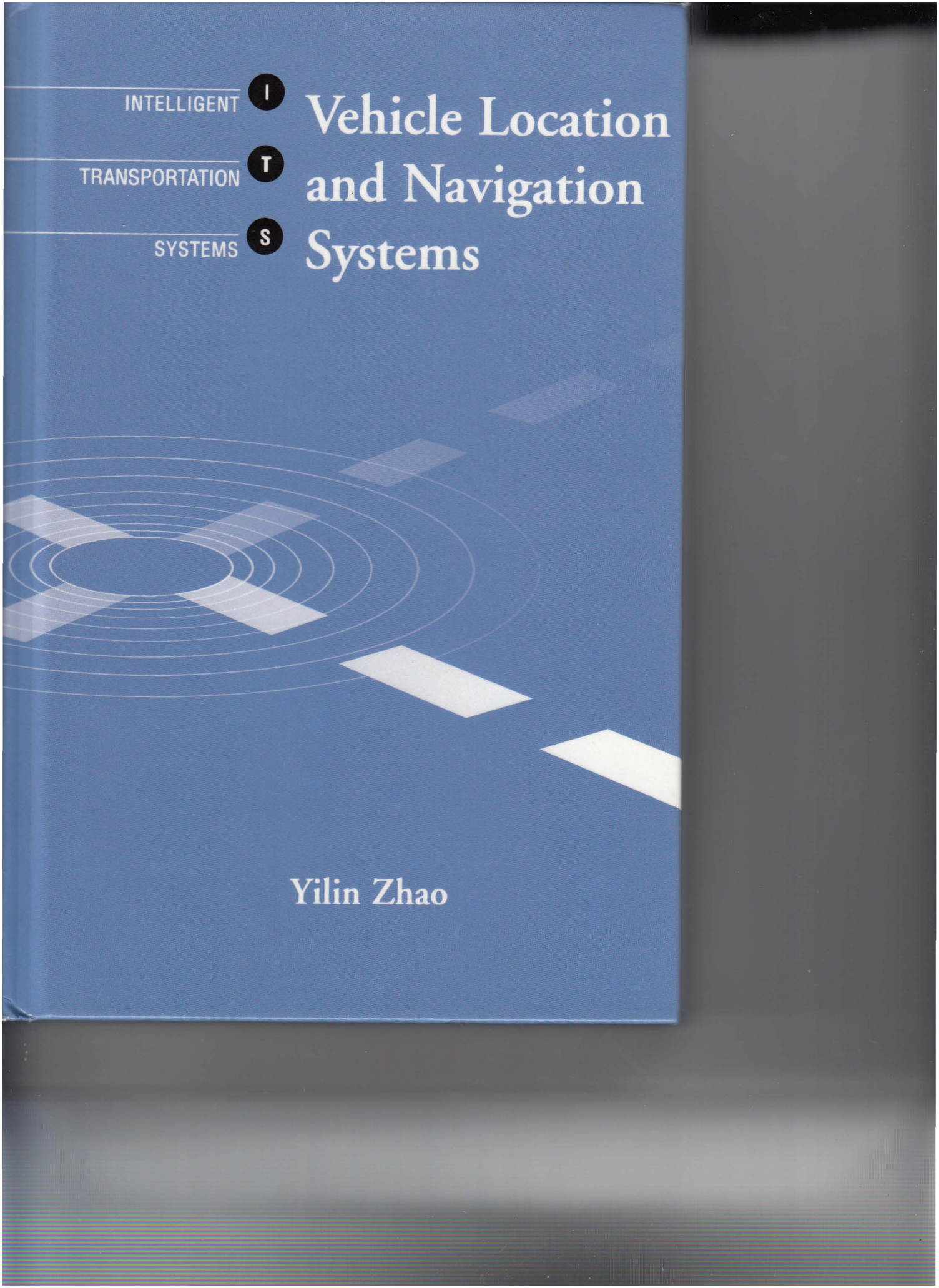


Petitioner Honda Ex-1038, 0001

VEHICLE LOCATION AND NAVIGATION SYSTEMS

Yilin Zhao

Artech House, Inc.
Boston • London

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To everyone w

Petitioner Honda Ex-1038, 0003

for local surveying and other mapping operations are also based on transverse Mercator projections. For projection methods used by individual states in the United States, the reader may refer to [4].

There are no widely accepted standards available for digital maps. It is very common for a map database vendor and its customers to agree on a software interface standard. In this way, the interface provides flexibility in the storage and retrieval of data. In the following sections, some of the emerging map database standards are discussed. Two proprietary digital maps are presented as examples of how software interface approaches are used. An introduction to the map compilation process is presented in the last section.

2.4 STANDARDS

Recently, the International Organization for Standardization (ISO)/TC 204 has approved a new task on an application program interface (API) for digital map databases, in addition to the existing task to create a map database physical storage format (PSF). Some believe that this will lead to an open global standard in digital map databases. One difficult work lying ahead is to make sure that the industry will actually use these standards once they are developed. The API task group held its first meeting in December 1996. It plans to create a standard method for navigation software to link with different data formats used by different digital map database vendors. The PSF task group aims to standardize the location of data on the storage medium so the system knows where to look for it. In short, the purpose of these activities is to provide a standard mechanism for navigation software to interact with map databases stored on different media as mentioned in Section 2.6.1. These standardization activities will certainly boost the market for vehicle location and navigation systems.

2.4.1 Geographic Data Files

The first version of the draft Geographic Data Files (GDF), which is a product of the EUREKA project DEMETER undertaken by Philips and Bosch in Europe, was released in October 1988. This standard was designed to specify the data content, the means by which data representation and structure of data supplied for vehicle navigation systems. The second version of the GDF (GDF 2.0) was developed under work package 3532 of the European Digital Road Map (EDRM) Task Force. The GDF 2.0 Working Group consisted of representatives of EDRM Task Force partners Daimler Benz (prime contractor), Bosch, Philips, Renault, Tele Atlas and Intergraph, and MVA Systematica, a participant in the PANDORA project. The partners in the PANDORA project are Philips, Bosch, the Ordnance Survey, and the Automobile Association. GDF 2.0 differs from GDF 1.0 both in its treatment of the architecture of certain data structures and in its use of specification. It defines standards for des of the road environment, which will sup

GDF 2.0 includes the following c clear definition of "real-world objects" su and settlements that are the concern of environment. The Attribute Catalogue Dedicated attributes of particular featur Catalogue describes relations between fe tion in a realistic manner. The Feature world objects should be represented in Content Specification makes clear which The Global Data Catalogue classifies geo related to the geometric and geographi information needed to supply GDF 2.0 d the Media Record Specification.

GDF 2.0 has three major parts: Firs part lists the information required for na of data acquisition (SDA) part describes a for representation of the nonspatial asp format (EF) part defines the records and

One important aspect of this stand attributes, and relationships are formally Layers are groupings of features that are administrative areas, settlements, buildi waterways. For example, roads consist o tions, and the road itself. In turn, each fea element has attributes of traffic direction, etc. Relationships represent driving-relate features such as posted sign information topology of the road network and related of geodetic coordinates, relative location appropriate.

After the release of GDF 2.0, GDF 2.2 was released in November 1994, GD de Normalisation (CEN) or the Europea for official approval as ENV in October these new versions involve introduction o the concept of time domain, of new info review comments. The revisions and refine requirements. There are also several natio moving toward compatibility with the inte

Petitioner Honda Ex-1038, 0004

of certain data structures and in its use of terminology. It is also a far more extensive specification. It defines standards for describing, classifying, and encoding features of the road environment, which will support a broad family of application areas.

GDF 2.0 includes the following content: The Feature Catalogue provides a clear definition of "real-world objects" such as roads, buildings, administrative areas, and settlements that are the concern of the broad area of application for the road environment. The Attribute Catalogue defines the characteristics of each feature. Dedicated attributes of particular features are cross referenced. The Relationship Catalogue describes relations between features that can be used to convey information in a realistic manner. The Feature Representation Scheme specifies how real-world objects should be represented in terms of GDF logical structures. The Data Content Specification makes clear which data are required for different applications. The Global Data Catalogue classifies geodetic requirements and other information related to the geometric and geographic characteristics of the data. Finally, the information needed to supply GDF 2.0 data as physical data records is provided in the Media Record Specification.

GDF 2.0 has three major parts: First, the specification of data content (SDC) part lists the information required for navigation systems. Second, the specification of data acquisition (SDA) part describes a set of features, attributes, and relationships for representation of the nonspatial aspects of information. Third, the exchange format (EF) part defines the records and fields.

One important aspect of this standard is the data model in which features, attributes, and relationships are formally defined, along with the concept of a *layer*. Layers are groupings of features that are strongly related such as roads and ferries, administrative areas, settlements, buildings, bridges and tunnels, railroads, and waterways. For example, roads consist of features such as road elements, intersections, and the road itself. In turn, each feature has attributes. For instance, the road element has attributes of traffic direction, name, class, speed limit, impedance value, etc. Relationships represent driving-related information and are a function of several features such as posted sign information and prohibited turns. The geometry and topology of the road network and related geographic features are described in terms of geodetic coordinates, relative location to neighboring features, and shape where appropriate.

After the release of GDF 2.0, GDF 2.1 was released in October 1992, GDF 2.2 was released in November 1994, GDF 3.0 was submitted to Comité Européen de Normalisation (CEN) or the European Committee for Standardization TC 278 for official approval as ENV in October 1995 [5]. The main changes contained in these new versions involve introduction of the concept of a segmented attribute and the concept of time domain, of new information items, and the incorporation of review comments. The revisions and refinements will continue to meet international requirements. There are also several national standards for map transfer, which are moving toward compatibility with the international version of GDF. Some anticipate

Petitioner Honda Ex-1038, 0005

that the ISO version of GDF will form the foundation for a single international family of transfer standards for ITS map data [6].

GDF is an interchange database standard. Users must develop their own compilers to translate it into *navigable* databases. A navigable database is a database that provides information which can be used to navigate a vehicle through a road network. For instance, in order to provide turn-by-turn route guidance, the database must contain some important attributes such as one-way streets and turn restrictions. Most digital map database suppliers can provide GDF maps for their European customers. Major companies currently involved in the production of map databases are Etak, Inc., Intergraph Corporation, Navigation Technologies Corporation, Tele Atlas International BV, etc.

2.4.2 Digital Road Map Association

The Japan Digital Road Map Association (DRM or JDRMA) was established by the Public Works Research Institute of the Japanese Ministry of Construction in 1988 [7,8]. Their product is both a digital map standard and a map database. The association supplies digital road map databases to member companies on magnetic tapes. DRM started digital map database production using 1/50,000 scale topographical maps and is now in the process of refining the database using 1/25,000 scale topographical maps, which offer more detailed and precise features. The topographical maps are issued by the Geological Research Institute and the Ministry of Construction. In addition, they have also used other urban planning maps and information provided by road administrators. They use custom sources, but project all the data onto a reference ellipsoid based on the Tokyo datum. This datum is defined by the location and azimuth on the 1841 Bessel spheroid, with the origin of the datum at the center of the transit circle of the old Tokyo Observatory (Table 2.1).

Three design principles are used by DRM. First, the location and configuration of features on the map are measured on two topographic maps (1:25,000 and 1:50,000) and filed according to a standard regional grid and mesh code system. Second, separate links are established for the road network indicating road configuration, interchanges, and ramps and lanes, with route searching and map matching being integral parts of the system. Third, the digital map consists of two layers of road networks, with the basic road network (main roads) used for the best route computations and the full road network for detailed operations such as map matching and zoom-in graphic displays.

The two layers of the road network are defined as follows. The basic road network consists of the national highways, prefectual highways, and roads 5.5m or wider (two lanes or more). The full road network consists of all roads covered by the basic road network plus all roads 3m or wider (one lane and more). Location is expressed using a mesh code number (with each mesh covering an area of approximately 10 × 10 km) and normaliz
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2.4.3 Spatial Data Transfer Standard

The Spatial Data Transfer Standard (SDT
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SDTS is an open and general stand
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SDTS intends to provide a solution
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Petitioner Honda Ex-1038, 0006

that the ISO version of GDF will form the foundation for a single international family of transfer standards for ITS map data [6].

GDF is an interchange database standard. Users must develop their own compilers to translate it into *navigable* databases. A navigable database is a database that provides information which can be used to navigate a vehicle through a road network. For instance, in order to provide turn-by-turn route guidance, the database must contain some important attributes such as one-way streets and turn restrictions. Most digital map database suppliers can provide GDF maps for their European customers. Major companies currently involved in the production of map databases are Etak, Inc., Intergraph Corporation, Navigation Technologies Corporation, Tele Atlas International BV, etc.

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The two layers of the road network are defined as follows. The basic road network consists of the national highways, prefectual highways, and roads 5.5m or wider (two lanes or more). The full road network consists of all roads covered by the basic road network plus all roads 3m or wider (one lane and more). Location is expressed using a mesh code number (with each mesh covering an area of approximately 10 × 10 km) and normalize within each mesh. The road network is de and links (similar to the segments defined e digit node numbers, while the full road ne link number is a combination of the numb all roads can be identified by mesh and l each link is expressed by a series of coord The database is organized as a series of fi

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2.4.3 Spatial Data Transfer Standard

The Spatial Data Transfer Standard (SDTS tee for Digital Cartographic Data Standa a wide variety of data structures that are u include cartography, geography, geology, g many other related sciences. In 1985, the Interagency Coordinating Committee on spatial data exchange standards. During were merged by the Digital Cartographic posed Digital Cartographic Data Standard

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- The first part is the SDTS logical sup tion and structure of the SDTS trans
- The second part prescribes definitio
- The third part describes the implem standard (i.e., encoding method).

SDTS intends to provide a solution t geographic and cartographic) data from th

Petitioner Honda Ex-1038, 0007

approximately 10 × 10 km) and normalized coordinates (*X*: 0-10,000, *Y*: 0-10,000) within each mesh. The road network is defined in terms of a combination of nodes and links (similar to the segments defined earlier). The basic road network uses four-digit node numbers, while the full road network uses five-digit node numbers. Each link number is a combination of the numbers for the nodes at each end. In this way, all roads can be identified by mesh and link numbers. The location and shape of each link is expressed by a series of coordinate values for the interpolating points. The database is organized as a series of files.

DRM has already covered all of Japan and version 3.0 of the map has recently been released. DRM provides the map to their users on magnetic tapes and its data structure is open to public. However, the file format, which is the key to reading the magnetic tapes properly, is only open to DRM users. The DRM does not provide any database interface to users who need to design and implement their own interface to access the map database. Furthermore, DRM does not contain information such as turn restrictions or one-way streets for route planning and guidance. Users need to further expand the database or include smaller scale information (1:10,000) for vehicle navigation.

2.4.3 Spatial Data Transfer Standard

The Spatial Data Transfer Standard (SDTS) was begun by the U.S. National Committee for Digital Cartographic Data Standards in 1982. It is designed for transfer of a wide variety of data structures that are used in the spatial sciences. These sciences include cartography, geography, geology, geographic information systems (GIS), and many other related sciences. In 1985, the Standards Working Group of the Federal Interagency Coordinating Committee on Digital Cartography also began work on spatial data exchange standards. During 1987, the results of these parallel efforts were merged by the Digital Cartographic Data Standards Task Force into the proposed Digital Cartographic Data Standards, published as a special issue in 1988 [9].

SDTS is an open and general standard for the exchange of spatial data [10]. It is also a Federal Information Processing Standard (FIPS). Effective February 1994, U.S. federal agencies are required to provide data to other federal agencies and the general public in SDTS format. SDTS consists of three primary parts:

- The first part is the SDTS logical superstructure, which describes the organization and structure of the SDTS transfer mechanism.
- The second part prescribes definitions for spatial features and attributes.
- The third part describes the implementation of the ISO 9211 data transfer standard (i.e., encoding method).

SDTS intends to provide a solution to the problem of transferring spatial (i.e., geographic and cartographic) data from the conceptual level to the details of physical

Petitioner Honda Ex-1038, 0008

file encoding. Transfer of spatial data involves modeling spatial data concepts, data structures, and the logical and physical structure of the files. To be useful, the data to be transferred must also be meaningful in terms of data content and data quality. SDTS addresses all of these aspects for both vector and raster data structures.

The ITS America (Intelligent Transportation Society of America) Map Database and Information Systems Subcommittee is working on a vector profile for SDTS, which would be a standard for the North American highway database. This project is being worked on in conjunction with the Federal Highway Administration (FHWA).

2.4.4 Truth-in-Labeling Standard

A labeling standard, the Truth-in-Labeling Standard, has been completed after several years of work by the Map Database Standards Committee of the Society of Automotive Engineers (SAE) [11]. The purpose of this standard is to define consistent terminology, metrics, and tests for describing and comparing the content and quality of navigable map databases for vehicle location and navigation. The standard will allow users to determine whether a given map database meets the needs of an application. However, it does not specify minimum performance standards or physical database format as the other standards do.

The truth-in-labeling standard contains definitions and detailed descriptions of map database attributes, as well as metrics and tests for each map database object (i.e., physical representation of a concept such as "node" or "segment" in a digital map database) defined. Note that this standard uses "link" in place of "segment." The objects defined include the following:

- Nodes and junctions;
- Location and existence of attached links;
- Road names;
- Address ranges;
- Road classifications;
- Restricted maneuvers.

The present focus of this standard is on in-vehicle navigation applications such as address location, route determination, route guidance, vehicle positioning, and display. Later versions of the standards during the next 3 to 5 years will also be applicable to other ITS map-related applications. In addition, SAE plans to establish a testing institute to test database labels using this standard. Database vendors will specify the content, currency, accuracy, coverage, etc., of their databases in the format specified by the standard. The institute will verify their claims. Based on the verification results, users will be able to quickly and accurately select the database best suited for their applications. As a result, users can determine the usability of a particular database for their applications after the shipment of the database produc different needs to select the most appropr

Despite these standards activities, m automobiles in the United States are ba provided by private companies. The next

2.5 PROPRIETARY DIGITAL MAP DA

2.5.1 Etak

The EtakMap databases developed by E everything onto a two-dimensional r ellipsoid [12]. The sources used include aer (USGS) maps, local government maps, the cadastral maps, tax assessor information field data capture information, customer

- The USGS produces Quad Sheets, w maps of the United States. Many th highway information.
- TIGER is a standard for vector-enco using Cartesian geometry. Features tives such as points, lines, and are Census Bureau for taking Census d maps but they lack accuracy, geome
- Cadastral maps are maps showing usually with bearings and lengths, an of describing and recording owners

In North America, the reference e Datum of 1927 (NAD 27) defined by spheroid of 1866, with origin at Meade geodetic coordinate system. NAD 27 is coordinate system in which coordinates using a set of constants.

As mentioned before, Etak provides map databases. The MapBase format is a GIS formats. The MapAccess format is ba that relies heavily on the topology of the the map, rather than geometric coordinat

Petitioner Honda Ex-1038, 0009

particular database for their applications in advance, rather than finding out later, after the shipment of the database product. In short, the standard allows users with different needs to select the most appropriate database for their applications.

Despite these standards activities, most location and navigation products for automobiles in the United States are based on proprietary digital map databases provided by private companies. The next section covers this topic in detail.

2.5 PROPRIETARY DIGITAL MAP DATABASES

2.5.1 Etak

The EtakMap databases developed by Etak, Inc., use many sources, and project everything onto a two-dimensional representation of the Earth's reference ellipsoid [12]. The sources used include aerial photography, U.S. Geographical Survey (USGS) maps, local government maps, the U.S. census bureau's TIGER'92 database, cadastral maps, tax assessor information, cross reference directories, ZIP+4 files, field data capture information, customer files, and map reports.

- The USGS produces Quad Sheets, which are accurate 7.5- by 7.5-min contour maps of the United States. Many these maps are 20 to 30 years old and lack highway information.
- TIGER is a standard for vector-encoded data in which features are represented using Cartesian geometry. Features are modeled using combinations of primitives such as points, lines, and areas. TIGER maps were developed by the Census Bureau for taking Census data. They are more complete than USGS maps but they lack accuracy, geometry, and highway data.
- Cadastral maps are maps showing the boundaries of subdivisions of land, usually with bearings and lengths, and the areas of individual tracts, for purposes of describing and recording ownership.

In North America, the reference ellipsoid is based on the North American Datum of 1927 (NAD 27) defined by the location and azimuth on the Clarke spheroid of 1866, with origin at Meades Ranch, Kansas. Clearly, NAD 27 is a geodetic coordinate system. NAD 27 is a horizontal control datum specifying the coordinate system in which coordinates of points on the Earth can be calculated using a set of constants.

As mentioned before, Etak provides interface formats for users to access their map databases. The MapBase format is an ASCII format compatible with the major GIS formats. The MapAccess format is based on Etak 0-track, a proprietary method that relies heavily on the topology of the map, in particular, the carrier topology of the map, rather than geometric coordinates (see Table 2.2). It is said that faster map

Petitioner Honda Ex-1038, 0010

Table 2.2
Sample Data Structures for Digital Map Databases

Data Structure	*Principle*	*Usage*	*Comment*
B-trees	Partition data into a hierarchical index tree in which each node occupies a block of memory.	Text indexing	Conventional indexing
Carrier-block-trees	Partition data into carrier blocks, each one is the smallest topological closed set.	Spatial indexing	Used by Etak
k-d-trees	Partition data recursively into a binary search tree where odd and even levels have different keys to determine branching directions.	Spatial indexing	Popular in GIS but difficult to update compared with quad-trees
Oc-trees	Partition data recursively into octants, with possible duplications for features crossing octant boundaries.	Spatial indexing	For 3D data
Quad-trees	Partition data recursively into quadrants, with possible duplications for features crossing quad boundaries.	Spatial indexing	Very popular in GIS for 2D data
R-trees	Partition data recursively into nested rectangular areas, which may overlap.	Spatial indexing	More flexible than quad-trees or k-d-trees

data retrieval can be achieved using this method [12]. It is available only by using MapAccess development tools (C language libraries) to retrieve and display maps and geocode addresses. *Geocoding* is the method of applying a latitude and longitude coordinate to an address. Other formats are also available for users with different applications and interface requirements.

EtakMap premium maps are offered in standard and enhanced versions. The enhanced maps will eventually cover 80% of the U.S. population. These maps include address, zip code, road classification, graphic features, political and statistical geography, major landmarks, one-way street encoding for selected urban areas, data overlay attributes, and compliance with National Map Accuracy Standards. In other words, these enhanced maps are navigable. They provide road networks covering more than 43 million metropolitan people. By 1998, Etak plans to have a map database covering major metropolitan areas with a total population of 130 million people. In addition, its standard maps will fill the rural gaps to provide 100% national coverage. These maps include only address and zip code information and are therefore not navigable.

Etak overseas coverage includes Japan, Hong Kong, and Europe, some with complete coverage and some without. Etak has entered into a data-sharing agreement

with Tele Atlas BV, a new joint venture
Atlas International BV. Etak is focusing
the United States, and Tele Atlas BV
including Switzerland and Austria.

2.5.2 Navigation Technologies

The databases developed by Navigationa
use many sources, and project everythin
the Earth's reference ellipsoid. The basi
in NavTech's early interface standards i
data relationships, and data access met
graphical base maps, aerial photograph
well as information from a variety of
continuously updated and supported b
support organization. Information in the
roadway classification, roadway charact
of-day restrictions, cartographic and geo
landmarks, and services. NavTech data
least 97% accuracy and completeness
precisions are within 15m of ground tru
covered by intertown maps.

In North America, the reference
North American Datum of 1983 (NAD
System 1980, with its origin at the cent
that NAD 83 is a geodetic coordinate syst

The NavTech databases contain inf
ment including roads, intersections, and
organized so that certain information ca
cally organized in such a way as to prov
ships include a variety of relationships
zone, which means that road names ca
segment. The data access methodology
resides between the application and the
make high-level logical requests without

The early NavTech proprietary m
Standard Interchange File (SIF), consis
record type contains a portion of the data
Depending on the custom request, eith
record types can be created. Record types
file (data description directory) reco

Petitioner Honda Ex-1038, 0011

with Tele Atlas BV, a new joint venture formed by Robert Bosch GmbH and Tele Atlas International BV. Etak is focusing its efforts on mapping Great Britain and the United States, and Tele Atlas BV is continuing to map continental Europe, including Switzerland and Austria.

2.5.2 Navigation Technologies

The databases developed by Navigational Technologies Corporation (NavTech) also use many sources, and project everything onto a two-dimensional representation of the Earth's reference ellipsoid. The basic database concepts by NavTech contained in NavTech's early interface standards include database content, data organization, data relationships, and data access methodology [13]. Their sources include topographical base maps, aerial photography, and local ground research (field data), as well as information from a variety of additional sources. Each database area is continuously updated and supported by a local field staff and a global customer support organization. Information in the database includes road network geometry, roadway classification, roadway characteristics such as directionality, turn and time-of-day restrictions, cartographic and geopolitical boundaries, and points of interest, landmarks, and services. NavTech databases come with a written warranty of at least 97% accuracy and completeness based on "ground truth." Its guaranteed precisions are within 15m of ground truth in detailed city areas and 100m in areas covered by intertown maps.

In North America, the reference ellipsoid mentioned earlier is based on the North American Datum of 1983 (NAD 83) as defined in the Geodetic Reference System 1980, with its origin at the center of the Earth. From Section 2.3, we know that NAD 83 is a geodetic coordinate system based on a geocentric reference ellipsoid.

The NavTech databases contain information on the road network and environment including roads, intersections, and points of interest [13]. The data are logically organized so that certain information can be accessed and manipulated, and physically organized in such a way as to provide maximum flexibility. The data relationships include a variety of relationships between data entries in the same layer and zone, which means that road names can be superimposed on the correct roadway segment. The data access methodology involves a transparent user interface, which resides between the application and the database itself, thereby allowing users to make high-level logical requests without having to know the structure of the database.

The early NavTech proprietary map-data interchange interface standard, the Standard Interchange File (SIF), consists of a set of record types, in which each record type contains a portion of the database for navigation and digital cartography. Depending on the custom request, either all record types or only a subset of the record types can be created. Record types can be divided into two groups: interchange file (data description directory) records and link records (link information).

Petitioner Honda Ex-1038, 0012

Interchange file records contain information about the data format and meaning of each field. Link records contain detailed information about each link. A NavTech link is a specific segment or subsegment in the road network or an area/polygon that is a physical feature or administrative boundary. The interchange file is primarily link oriented and all information about each link is grouped. NavTech requires user applications to connect the endpoints of intersecting links.

In the United States, NavTech has navigable digital databases available for numerous major metropolitan areas. NavTech has completed detailed city coverage for a total area containing more than 100 million people and intertown map databases for less populated areas. These intertown map databases include all roads that are contained on American Automobile Association (AAA) state maps. By the year 2000, NavTech plans to have a map database covering an area with a total population of more than 210 million people.

In Europe, NavTech Europe (formerly European Geographic Technologies (EGT)) has completed a database for more than 80 cities in Germany, the greater Paris area, Lyon, and Marseille in France, Torino and Milano in Italy, and Coventry in the United Kingdom. Additional cities throughout France, Italy, the United Kingdom, and Germany have also been completed. In addition, intertown map databases now include all roads connecting municipalities and settlements larger than 250 km^2.

2.6 DIGITAL MAP COMPILATION

As mentioned, a digital map database can be encoded from existing nondigital maps or aerial photographs. The coordinates of nodes are usually encoded using special computers that can record the coordinates of any given point. The conversion or digitizing is done for a point by placing the crosshair of an instrument over the point and pressing a button. In some cases, paper maps are scanned and then converted to vector form by software. Once the basic road geometry has been encoded and the road topology has been checked, the database is further expanded by entering attributes such as road types, road names, speed limits, lengths, turn restrictions, and other details as discussed earlier. Gradually, all these data form an intricate data mesh, a virtual reality of the road network. Although the whole process has been automated to varying degrees, it still requires tedious human involvement and intervention. For instance, one quad sheet for San Antonio, California, took a week to input into a vendor's database. Although a section of the database can be as accurate as the sources, field engineers may still need to actually drive vehicles on the road to verify and update the map for final completion. The final product typically takes the form of raw cartographic data files. The accuracy of these data files is very important to systems replying on map-related functions. Significant errors (greater than 15m in city areas) may lead to poor overall system performance.

Besides providing raw cartographic data files in one of the interchange formats, all the map database vendors also compile their databases in some internal format. Users can use their map retrieval and draw
At this writing, none of the database vend
formats for customers. Most location an
their own navigable databases (files) ba
database files provided by vendors as s
database files, additional files collected fr
for the map compiler. One example is di

2.6.1 Data Structures

Many different data structures and implem
map database [14–16]. Table 2.2 lists seve
were summarized in [12]. It is not uncom
combination of these and other data stru
in the main memory of the location and
storage area such as a hard disk, a CD-R
card). Typically, around 10 to 100 MB
metropolitan area map; the size of the
selected, the complexity of the attribute
topology, and other factors. Compression
of the map, with the side effect that decom
to access the map database; this often req
the development of proper mechanisms
Depending on the system implementation
that will provide services to a set of appli

The data structures shown in Table
records and segment records. As an exampl
records and their attributes:

- *Node (point) record:* node ID, latitu
- *Segment (line) record:* segment ID,
  directionality, address range, road na
  points, road type (classification), dri
- *Area (polygon) record:* area ID, area
  zip code, etc.

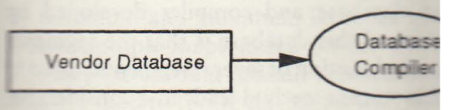


Figure 2.8 Database compilation.

Petitioner Honda Ex-1038, 0013

CHAPTER 4

MAP-MATCHING MODULE

4.1 INTRODUCTION

The map-matching module plays an important role in vehicle location and navigation systems. It employs a digital map to make the positioning system more reliable and accurate.

To provide drivers with proper maneuvering instructions or to correctly display the vehicle on a map in an error-free fashion, the vehicle location must be precisely known. Therefore, an accurate vehicle location is considered a prerequisite for good system performance. In Chapter 3, we discussed how a vehicle location and navigation system can rely on sensors to determine its position. One such technique is called dead reckoning. Dead reckoning can track the position of a vehicle relative to another position, such as an origin. Typically, vehicle heading and distance traversed are used to determine incremental changes (Section 3.2) in the position of the vehicle relative to the origin. As discussed in Sections 3.2, 3.3, and 3.4, these sensory systems have errors associated with their operation. These errors (especially cumulative errors) detract from the accuracy of the dead-reckoning process. Even with very good sensor calibration and sensor fusion technologies, inaccuracies are often inevitable. As a result of these inaccuracies, the actual vehicle position will not agree with the dead-reckoned vehicle position. These inaccuracies are likely to increase or continue to accumulate with additional distance traversed, thereby

Petitioner Honda Ex-1038, 0014

increasing the dead-reckoning error. The result is more uncertainty in the true position of the vehicle.

To deal with this uncertainty, map-matching systems have been developed to match the dead-reckoned position (or trajectory) with a position associated with a location (or route) on a map. When the dead-reckoning behavior indicates that vehicle is in a certain position on the map (e.g., on a particular road segment), the vehicle position may be adjusted to some absolute position on the map. This will probably eliminate the cumulative error until the next map-matching step. By doing this process in each successive cycle of the system, a more accurate position can be determined for the system. Figure 4.1 shows a comparison for two consecutive system cycles. To convey the idea, we make the accumulated dead-reckoning errors more visible. In practice, the errors should be smaller for a well-calibrated dead-reckoning system. Although dead reckoning is often used in this chapter for the convenience of the discussion to describe the position sensing and map-matching processes, we should keep in mind that other positioning techniques, such as satellite-based positioning and terrestrial-radio-based positioning, can also be used in place of dead reckoning. Because a map and a matching process are involved, these algorithms are called *map-matching algorithms*.

A good map-matching algorithm can significantly enhance the accuracy of location on a road network. The reason is straightforward. Unlike navigation in air and sea transportation, road transportation vehicles are essentially constrained to a finite network of roads, with only temporary excursions into parking lots, driveways, or other off-road conditions. This makes it possible to use computer algorithms to correlate the trajectory of the vehicle with the digital road information discussed in Chapter 2.

A map-matching algorithm can correlate the vehicle position based on various sensors to the road network by comparing the vehicle trajectory with the routes

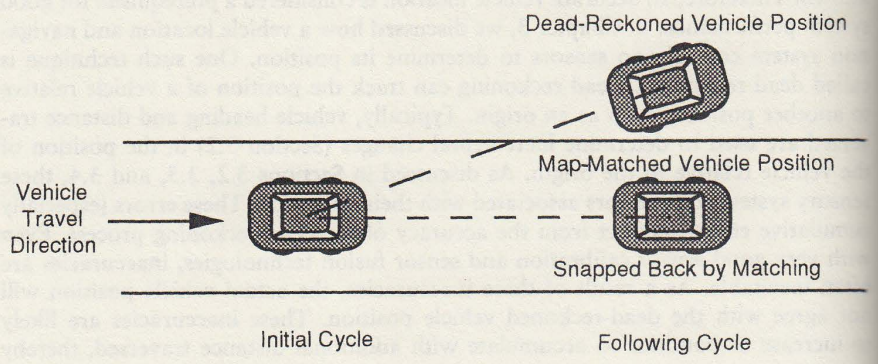


Figure 4.1 Comparison of the map-matching and dead-reckoning techniques.

present in the digital map database mod
assumes the vehicle to be on a road. In
is constantly compared with the availabl
nected roads in the road network. Thr
process, the most likely location of the ve
Because the digital map database contai
matched positions can be used to reset
magnitude of the position errors.

As mentioned, map matching is th
(path) is correlated with a digital road m
this map. This is a software-based techno
map stored in the system. Clearly, the
relatively accurate; otherwise, the system
which in turn will severely degrade syste
m be acceptable if the digital map is acc

4.2 CONVENTIONAL MAP MATCHI

The basic idea of conventional map matc
against known roads close to the previou
most closely resembles the current trajecto
as the one on which the vehicle is appare

The early conventional map-match
independently by two U.S. groups and on
deterministic method has evolved into a

4.2.1 Semi-Deterministic Algorithms

The semi-deterministic method requires th
nates) and a direction of travel be prov
applied to determine whether the vehicle
by comparing the dead-reckoned turns t
vectors computed from the map coordina
due to errors in dead-reckoning sensors
must have a threshold to help limit potenti
to locate any matching road segment. F
generally assumed to be on a road. The
distance sensors are corrected whenever
of the vehicle drifts from the road betw
heading is also corrected. This method is
is following a predetermined road. There i

Petitioner Honda Ex-1038, 0015

present in the digital map database module. Of course, this implies that the system assumes the vehicle to be on a road. In this module, the travel path of the vehicle is constantly compared with the available routes, which consist of a series of connected roads in the road network. Through a pattern recognition and matching process, the most likely location of the vehicle with respect to the map is determined. Because the digital map database contains the coordinates of the roads, the map-matched positions can be used to reset the raw vehicle positions and limit the magnitude of the position errors.

As mentioned, map matching is the process by which the vehicle trajectory (path) is correlated with a digital road map, thereby locating the vehicle relative to this map. This is a software-based technology and makes extensive use of the digital map stored in the system. Clearly, the digital map used for this module must be relatively accurate; otherwise, the system will generate an incorrect position output, which in turn will severely degrade system performance. It is generally considered to be acceptable if the digital map is accurate to within 15m of "ground truth."

4.2 CONVENTIONAL MAP MATCHING

The basic idea of conventional map matching is to compare the vehicle's trajectory against known roads close to the previous matched position. The road whose shape most closely resembles the current trajectory and previously matched road is selected as the one on which the vehicle is apparently traveling.

The early conventional map-matching algorithm was invented in the 1970s independently by two U.S. groups and one U.K. group [1]. As time passed, this semi-deterministic method has evolved into a probabilistic method.

4.2.1 Semi-Deterministic Algorithms

The semi-deterministic method requires that an initial vehicle location (initial coordinates) and a direction of travel be provided. Conditional tests are intermittently applied to determine whether the vehicle is traveling on the known road network by comparing the dead-reckoned turns to the turns implied by the road segment vectors computed from the map coordinates. Exact correspondence is not possible due to errors in dead-reckoning sensors and in the map coordinates. The module must have a threshold to help limit potential matches. Otherwise, it would be difficult to locate any matching road segment. For this technique to work, the vehicle is generally assumed to be on a road. The accumulated errors in the dead-reckoning distance sensors are corrected whenever the system detects a turn. If the trajectory of the vehicle drifts from the road between turns, the accumulated error of the heading is also corrected. This method is based on the presumption that the vehicle is following a predetermined road. There is considerable uncertainty when the vehicle

Petitioner Honda Ex-1038, 0016

travels off-road because there is no longer any way for the sensor errors to be corrected. For this reason, contemporary map-matching-based positioning systems tend not to use this method.

4.2.2 Probabilistic Algorithms

The probabilistic method requires that the dead-reckoning sensor errors be statistically propagated into the position determination. Elliptical or rectangular confidence regions defined based on these errors and error models are used to outline the boundary within which the true vehicle position may lie. This confidence region is superimposed on the road network. If the region contains only one intersection or road, a match is made and the coordinates are sent to be integrated or further processed as a vehicle position. If more than one intersection or road is in the region, connectivity checks are made to determine the most probable location of the vehicle. The main enhancement of this method over the semi-deterministic method is that it does not require the assumption that the vehicle is always on a road. If the vehicle appears to be off the known road network, this method repeatedly compares the sensor-detected coordinates with those road segments surrounding the off-road area and tries to identify the road segment to which the vehicle appears to have returned. Figure 4.2 contains a flowchart for a typical conventional map-matching algorithm.

Even though the flowchart for this diagram looks simple, many approaches may be used for the actual computation. Within each step, different algorithms can be used. As discussed in Section 3.5, different sensor fusion methods can be used for the first step (or logic box) in Figure 4.2.

As for the second step, many methods are available for calculating the error region associated with a particular positioning system. One way is to derive an error ellipse. From estimation theory, we know that many input and output signals can be modeled as stochastic processes. Variables associated with the true and measured values can be modeled as random variables. Variance-covariance information is propagated through appropriate algorithms to derive the variances and covariances as functions of the original random variables or as functions of parameters estimated from the original observations. These variances and covariances are often used to define error ellipses. To learn more about stochastic processes and estimation theory, readers are encouraged to consult [2–4]. The following simplified discussion should give you a basic idea of how this statistical theory is used in practice.

Suppose that the variance-covariance matrix of the system being modeled is

$$P = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{yx} & \sigma_y^2 \end{bmatrix}$$

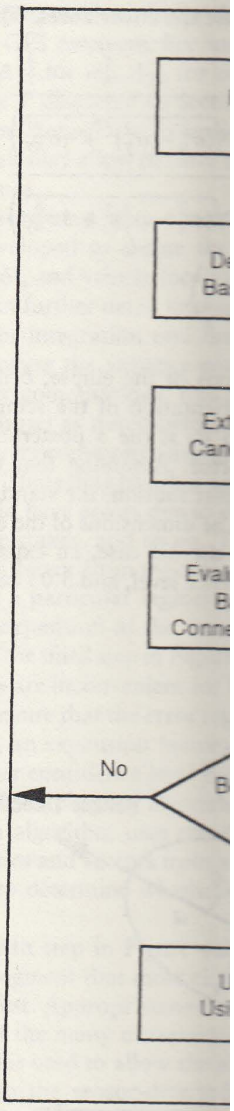


Figure 4.2 A simplified conventional map-matching

Petitioner Honda Ex-1038, 0017

where σ_x and σ_y are the standard deviations of the sensor measurement errors, σ_x^2 and σ_y^2 are the variances, and σ_{xy} and σ_{yx} are the covariances. The error ellipse can be derived as

$$a = \hat{\sigma}_0 \sqrt{\frac{1}{2}\left(\sigma_x^2 + \sigma_y^2 + \sqrt{(\sigma_x^2 - \sigma_y^2)^2 + 4\sigma_{xy}^2}\right)}$$

$$b = \hat{\sigma}_0 \sqrt{\frac{1}{2}\left(\sigma_x^2 + \sigma_y^2 - \sqrt{(\sigma_x^2 - \sigma_y^2)^2 + 4\sigma_{xy}^2}\right)}$$

$$\phi = \frac{\pi}{2} - \frac{1}{2}\arctan\left(\frac{2\sigma_{xy}}{\sigma_x^2 - \sigma_y^2}\right)$$

where a is the length of the semi-major axis of the ellipse, b is the length of the semi-minor axis of the ellipse, ϕ is the orientation of the semi-major axis of the ellipse relative to North (Figure 4.3), and $\hat{\sigma}_0$ is the a posteriori variance of unit weight, also known as the expansion factor. Assuming that the distribution of measurement errors is a standard normal distribution, the standard ellipse ($\hat{\sigma}_0 = 1$) corresponds to a 39% confidence region. The dimensions of the ellipse can be scaled to represent various confidence levels. In the 2D case, an expansion factor $\hat{\sigma}_0$ of 2.15 can be used to obtain the 95% confidence level, and 3.03 can be used to obtain a 99% confidence level.

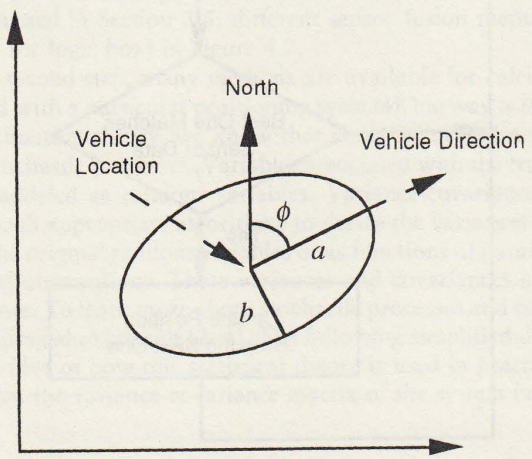


Figure 4.3 Error ellipse.

If the data received [illegible] matching error ellipse, we can [illegible] the outputs of the GPS receiver, [illegible] we can substitute A_{11}^{-1} for σ_x^2, [illegible] the cofactor matrix P discussed in [illegible] invoking the Position/Status/Data [illegible] GPS receiver manuals may allow the user [illegible] under different names.

For multisensor-based map-matchi[illegible] have also been developed to define the [illegible] probability (CEP) [6], and vehicle locatio[illegible] the CEP algorithm in further detail later i[illegible] E) is used for sensor integration and fus[illegible] becomes easier. Because the variance-co[illegible] product of the filter computations, this i[illegible] the error region (ellipse) as noted before.

Note that it is very common to multi[illegible] (confidence) factor. There may be other u[illegible] Map databases could have errors due to e[illegible] errors, processing mistakes, and so on. T[illegible] have been slightly different from the actu[illegible] within the width of a particular segment [illegible] the uncertainty, so expansion of the erro[illegible]

To implement the third step in Figur[illegible] region. Since ellipses are inconvenient for [illegible] generally used. To ensure that the error re[illegible] candidate segments, an expansion factor [illegible] the ellipse to a higher confidence level be[illegible] region. The Cyrus-Beck clipping algorith[illegible] the region [8]. This algorithm uses the [illegible] rectangular boundaries and vectors from a[illegible] on each boundary to determine whether [illegible] clipping region.

As for the fourth step in Figure 4.2[illegible] previous step. The segment that most clos[illegible] be at the top of this list. Appropriateness [illegible] criterion. Because of the many uncertaint[illegible] heading, a threshold is used to allow the a[illegible] headings are close to the sensor-detected [illegible] segment is connected with the old segment[illegible] on in the previous computation cycle. S[illegible] should have lower priority on the list. If t[illegible]

Petitioner Honda Ex-1038, 0018

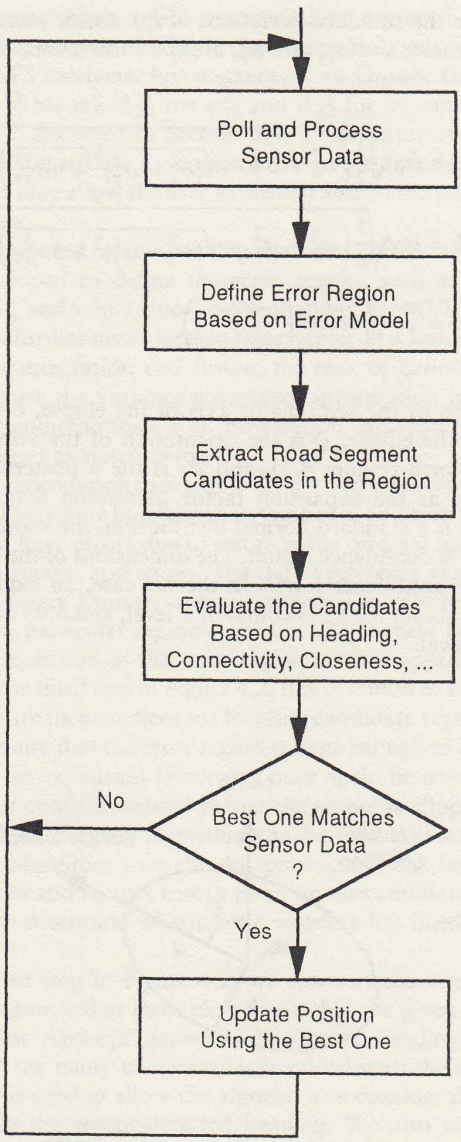


Figure 4.2 A simplified conventional map-matching algorithm.

Petitioner Honda Ex-1038, 0019

If the data received from a GPS receiver alone are used to define the map-matching error ellipse, we can obtain the variances and covariances directly from the outputs of the GPS receivers. For instance, if an Oncore GPS receiver is used, we can substitute A_{11}^{-1} for σ_x^2, A_{22}^{-1} for σ_y^2, and A_{12}^{-1} for σ_{xy} and σ_{yx}, where A^{-1} is the cofactor matrix P discussed in Section 3.4. These parameters are available by invoking the Position/Status/Data Extension Message command [5]. Consulting other GPS receiver manuals may allow the user to identify similar output variables, possibly under different names.

For multisensor-based map-matching systems, different statistical methods have also been developed to define the error region, such as contours of equal probability (CEP) [6], and vehicle location probability area (VLPA) [7]. We discuss the CEP algorithm in further detail later in this chapter. If a Kalman filter (Appendix E) is used for sensor integration and fusion, the task of defining the error region becomes easier. Because the variance-covariance information is available as a by-product of the filter computations, this information can readily be used to derive the error region (ellipse) as noted before.

Note that it is very common to multiply the derived error region by an expansion (confidence) factor. There may be other uncertainties in addition to the sensor errors. Map databases could have errors due to errors in the original sources, measurement errors, processing mistakes, and so on. The initial reference vehicle position might have been slightly different from the actual position. The vehicle could be anywhere within the width of a particular segment or lane. All of these factors contribute to the uncertainty, so expansion of the error region is often appropriate.

To implement the third step in Figure 4.2, it is common to first modify the error region. Since ellipses are inconvenient for locating candidate segments, a rectangle is generally used. To ensure that the error region is large enough to include all potential candidate segments, an expansion factor can once again be used to further enlarge the ellipse to a higher confidence level before the ellipse is clipped to a rectangular region. The Cyrus-Beck clipping algorithm can be used to locate the segments in the region [8]. This algorithm uses the dot products of the inner normals of the rectangular boundaries and vectors from a point on the candidate segment to a point on each boundary to determine whether the segment lies inside or outside of the clipping region.

As for the fourth step in Figure 4.2, we can sort the segments found in the previous step. The segment that most closely matches the given sensor data should be at the top of this list. Appropriateness of the segment heading is a very important criterion. Because of the many uncertainties involved with the sensor and segment heading, a threshold is used to allow the algorithm to consider the candidate whose headings are close to the sensor-detected heading. We also need to check if the segment is connected with the old segment that the vehicle was most likely traveling on in the previous computation cycle. Segments far away from the old segment should have lower priority on the list. If the vehicle was following a predetermined

Petitioner Honda Ex-1038, 0020

route during route guidance (Chapter 6), the segments along this route should be strong candidates for matching considerations. All this checking will likely identify the best matching segment. If an off-road situation (such as a parking lot) is detected, more computations are required in order to include candidate segments within a gradually growing region of the vehicle vicinity. It uses similar matching criteria to determine when and where the vehicle returns to the road network.

Finally, this best matching segment is presented to the system along with a most probable matching point on the segment. If there are no good candidates available, if the sensor-determined position coincides with the current vehicle position, or if there is an ambiguity, nothing will be reported, provided the algorithm is designed to do so. The vehicle must then rely on the sensor data alone to determine its position.

To save on computation time, a rectangular trial-and-error region rather than an error ellipse may be defined. The drawback of this method is that the error region will never be associated with the positioning errors. A statistically defined error region can be expanded and shrunk at each cycle of the algorithm while the trial-and-error region would stay at the same size all the time. As an example, we will see below how a probabilistic algorithm, which follows the basic procedures in [6] closely, works.

This probabilistic algorithm interrupts the main system program approximately once per second to provide the current vehicle position for display. During each cycle, it first updates the old dead-reckoned or map-matched position to the current dead-reckoned position, on the basis of sensor-measured data, as discussed in Section 3.2. As in the second step of Figure 4.2, the update accuracy is estimated in terms of the CEP, which defines an error region. This region encloses an area with a certain probability of containing the actual position of the vehicle.

The basic idea is to use a 3D probability density function (PDF) to define a set of equal-probability contours (Figure 4.4). Each contour is generated by an XY horizontal plane slicing through the PDF at some level and encloses an area with a percentage of the probability density, such as 50%, 60%, and so on. The peak of the PDF is directly above the current dead-reckoned position. By projecting these contours onto the XY plane, we obtain a set of ellipses, each with an equal probability of including the actual position of the vehicle. For instance, the 90% CEP encloses an area that has a 0.9 probability of including the actual position of the vehicle. In actual implementation, one of the ellipses is selected as the error region and is approximated by a rectangle. Reference [6] contains a set of equations used to define the four corners of the rectangle based on the error models of the fluxgate magnetic compass and the differential odometer. The area of the CEP is normally proportionately larger than the area determined by the matching point (discussed shortly) from the last cycle to reflect the accumulated error and the resulting reduction in the accuracy of the current dead-reckoned position.

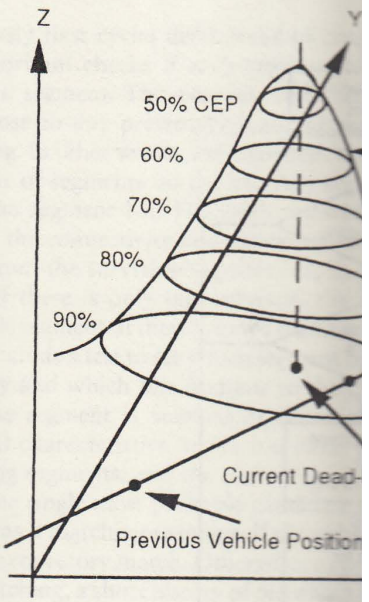


Figure 4.4 Position error regions defined by a proba

Once the error region has been define
of the steps shown in Figure 4.2, except f
matching road segment. This segment is th
the vehicle to contain a point more likely tha
of the vehicle to be the current vehicle po
each of these steps (between the second ar
provided in Figure 4.5.

The algorithm extracts candidate roa
by examining all segments in the neighbo
segments are fetched from the digital map
determine if its direction is parallel to the veh
If it passes the direction test, this segment is t
the CEP (error region), which probably c
initial tests, the segment is added to the segm
to the top and fetches another segment for th
is not the last one in the neighborhood.

The algorithm tests each segment ad
closeness. The connectivity test checks if

Petitioner Honda Ex-1038, 0021

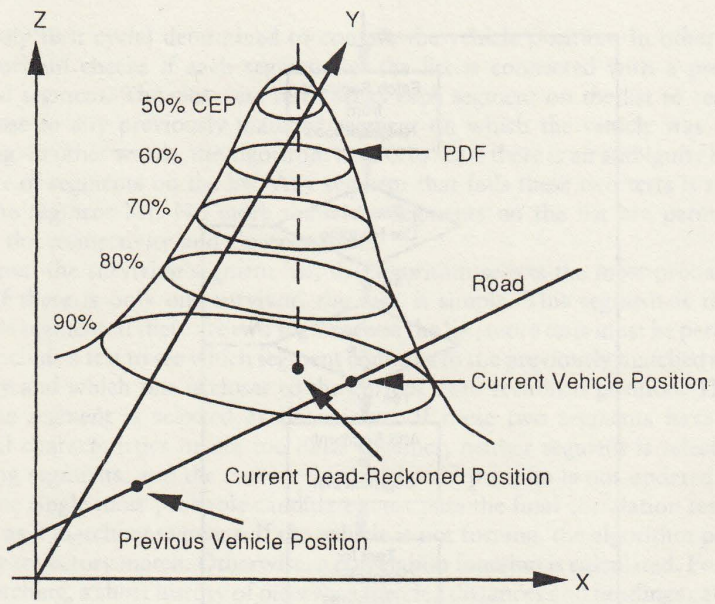


Figure 4.4 Position error regions defined by a probability density function (PDF).

Once the error region has been defined, the algorithm performs the remainder of the steps shown in Figure 4.2, except for the last update step, to find the best matching road segment. This segment is the most likely candidate in the vicinity of the vehicle to contain a point more likely than the most recent dead-reckoned position of the vehicle to be the current vehicle position. A more detailed description for each of these steps (between the second and the last steps in Figure 4.2) has been provided in Figure 4.5.

The algorithm extracts candidate road segments (segments in the error region) by examining all segments in the neighborhood of the vehicle in sequence. The segments are fetched from the digital map database. Each segment is first tested to determine if its direction is parallel to the vehicle heading within a specified threshold. If it passes the direction test, this segment is then examined to determine if it intercepts the CEP (error region), which probably contains the vehicle. After passing these initial tests, the segment is added to the segment list. Otherwise, the algorithm returns to the top and fetches another segment for the same test provided the current segment is not the last one in the neighborhood.

The algorithm tests each segment added to the list for its connectivity and closeness. The connectivity test checks if the segment connects to the segment

Petitioner Honda Ex-1038, 0022

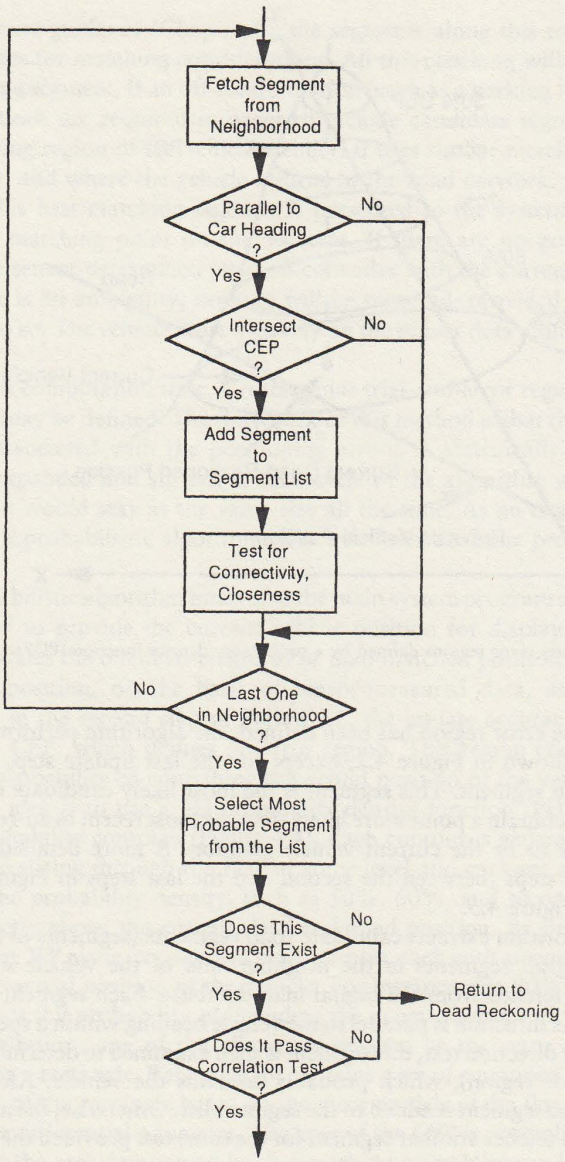


Figure 4.5 Finding a best matching segment within a confined region in a probabilistic algorithm.

previously (last cycle) determined to con
the algorithm checks if each segment o
matched segment. The closeness test che
very close to any previously matched se
traveling. In other words, the algorithm ch
any pair of segments on the list. Any seg
from the segment list. No more than tw
survive the connectivity and closeness tes

From the surviving segment list, the
ment. If there is only one survivor, the
probable segment. If there are two segment
These include a test to see which segment c
properly and which one is closer to the c
probable segment is selected as the win
identical characteristics or are too close
matching segments, and the current dead-

The single most probable candidate
eligible as a matching segment. If the vehi
a simple trajectory match. Otherwise, a co
tory matching, a short history of piecewise
from sensor outputs are kept in memory
are used to compare against the vehicle ro
headings from the same period. If a matc
to which the current dead-reckoned posi
matching segment. For correlation functi
the function between the vehicle trajectory
probable segment and the segments con
thresholds, the most probable (correlation
calculation is saved for later use in upda
Obviously, the segment that contains thi
segment. If this most probable candidate
dead-reckoned position is not updated, in
Figure 4.5.

Last, the algorithm updates the vehi
step in Figure 4.2. If the vehicle is turnin
matching point determined during the cor
it is updated to a most probable constant-co
Once the current position has been update
of the CEP will be proportionally reduce
accuracy of the vehicle position. Again, se
new corners of this rectangular error regio
the vehicle has just finished a turn, the dist

Petitioner Honda Ex-1038, 0023

previously (last cycle) determined to contain the vehicle position. In other words, the algorithm checks if each segment on the list is connected with a previously matched segment. The closeness test checks each segment on the list to see if it is very close to any previously matched segment on which the vehicle was actually traveling. In other words, the algorithm checks to see if there is an ambiguity between any pair of segments on the list. Any segment that fails these two tests is removed from the segment list. No more than two segments on the list are permitted to survive the connectivity and closeness tests.

From the surviving segment list, the algorithm selects the most probable segment. If there is only one survivor, the task is simple. This segment is the most probable segment. If there are two segments on the list, more tests must be performed. These include a test to see which segment connects to the previously matched segment properly and which one is closer to the current dead-reckoned position. The most probable segment is selected as the winner. If these two segments have almost identical characteristics or are too close together, neither segment is selected as a matching segments, and the current dead-reckoned position is not updated.

The single most probable candidate must pass the final correlation tests to be eligible as a matching segment. If the vehicle is not turning, the algorithm performs a simple trajectory match. Otherwise, a correlation function is calculated. For trajectory matching, a short history of piecewise traveled distances and headings calculated from sensor outputs are kept in memory temporarily. These vehicle trajectory data are used to compare against the vehicle route data of piecewise segment lengths and headings from the same period. If a match exists, the sole survivor is the segment to which the current dead-reckoned position can be updated and is saved as the matching segment. For correlation function computation, the algorithm calculates the function between the vehicle trajectory and certain segments (including the most probable segment and the segments connected to it). If the results pass certain thresholds, the most probable (correlation) point on the segment derived during the calculation is saved for later use in updating the current dead-reckoned position. Obviously, the segment that contains this matching point becomes the matching segment. If this most probable candidate fails the correlation tests, the current dead-reckoned position is not updated, indicated as a rightward pointing arrow in Figure 4.5.

Last, the algorithm updates the vehicle position, which is similar to the last step in Figure 4.2. If the vehicle is turning, the vehicle position is updated to the matching point determined during the correlation function calculation. Otherwise, it is updated to a most probable constant-course position along the matching segment. Once the current position has been updated to the map-matched position, the area of the CEP will be proportionally reduced to reflect the resulting increase in the accuracy of the vehicle position. Again, see [6] for the equations used to derive the new corners of this rectangular error region. Finally, the sensors are recalibrated. If the vehicle has just finished a turn, the distance sensor is recalibrated. If the vehicle

Petitioner Honda Ex-1038, 0024

is not turning, the heading sensor is recalibrated. The turning condition of the vehicle can be easily determined either using the heading sensors or during the map-matching process. The update steps in this algorithm are shown in Figure 4.6.

We know that the probabilistic method makes no assumption that the vehicle is always on the road network. It handles off-road conditions much better than the semi-deterministic method. However, unlike traveling on a known road network, map-matching adjustments cannot prevent the accumulation of dead-reckoning errors while the vehicle is off-road. There may be considerable uncertainty in vehicle position, which could lead to incorrect conclusions when matching against the surrounding road segments. The further the vehicle travels off-road, the greater the uncertainty in the estimated position. Many possible approaches have been proposed to eliminate this problem. For instance, an absolute sensor can be used as a sanity-checking sensor to bound the absolute accuracy of the system as briefly mentioned in Section 4.4.

4.3 FUZZY-LOGIC-BASED MAP MATCHING

As discussed in preceding sections, the vehicle trajectory generated by a positioning module alone is often distorted or different from the actual route due to sensor and processing errors as well as imperfections of the database resulting from digitization.

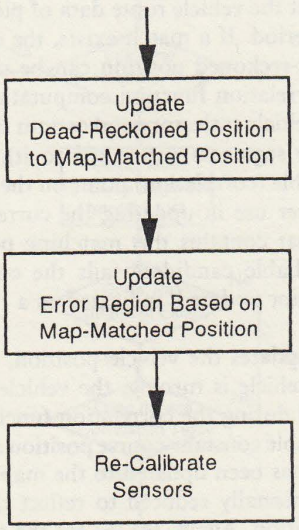


Figure 4.6 Final detailed update steps of the probabilistic algorithm.

This often causes some difficulty in the m
based vehicle is traveling in a city downto
matching the trajectory reported by the p
It may be difficult to distinguish precisely
traveling. Rather, the system may conclud
on certain streets, and "less likely" to be o
of the vehicle can be determined only whe
tion is provided to compare against the di
to be resolved if an accurate location and
techniques for dealing with qualitative ter
map-matching process.

Fuzzy logic has been demonstrated a
involve qualitative terms, linguistic vaguen
use of fuzzy sets (Appendix F), linguistic te
mathematically. Expert knowledge and ex
Furthermore, inferences can be drawn thr
which simulates human reasoning capabiliti
decision-making process involving a degr
development of fuzzy-logic-based map-ma
logic can also be used in other modules
matching module. Readers can refer to [9]

4.3.1 Fuzzy-Logic-Based Algorithms

In this section, we discuss how to apply
constructing a simple rule set for a map-ma
who are not familiar with the concept of f
As discussed in that appendix, a fuzzy logic
parts: the fuzzifier, the inference engine, and

Our discussion of this fuzzy-logic-base
method is based on the approximate reason
assign truth values from zero to one for each
and then make decisions based on the assig

Figure 4.8 shows a flowchart for this
rithm. To save space, "road" has been used
The rules are numbered to correspond with
of them consist of more than one sub-rules.

As Figure 4.8 indicates, this algorith
membership functions associated with each
discussion of the rules, we assume that the
headings is used as the heading error to dete

Petitioner Honda Ex-1038, 0025

This often causes some difficulty in the map-matching process. If a map-matching-based vehicle is traveling in a city downtown area, there may be many road patterns matching the trajectory reported by the positioning sensors at any given moment. It may be difficult to distinguish precisely on which particular street the vehicle is traveling. Rather, the system may conclude that the vehicle is "more likely" to be on certain streets, and "less likely" to be on some certain other streets. The location of the vehicle can be determined only when sufficient additional trajectory information is provided to compare against the digital map database. This ambiguity needs to be resolved if an accurate location and navigation system is desired. Therefore, techniques for dealing with qualitative terms such as likeliness are required in the map-matching process.

Fuzzy logic has been demonstrated as an effective way to deal with tasks that involve qualitative terms, linguistic vagueness, and human intervention. By making use of fuzzy sets (Appendix F), linguistic terms with vague concepts can be defined mathematically. Expert knowledge and experience is represented by a set of rules. Furthermore, inferences can be drawn through an approximate reasoning process, which simulates human reasoning capabilities. Because map matching is a qualitative decision-making process involving a degree of ambiguity, this suggests that the development of fuzzy-logic-based map-matching algorithms may be useful. Fuzzy logic can also be used in other modules or subsystems in addition to the map-matching module. Readers can refer to [9] for these potential application areas.

4.3.1 Fuzzy-Logic-Based Algorithms

In this section, we discuss how to apply fuzzy logic in a navigation system by constructing a simple rule set for a map-matching module. Background for readers who are not familiar with the concept of fuzzy logic can be found in Appendix F. As discussed in that appendix, a fuzzy logic inference process consists of three main parts: the fuzzifier, the inference engine, and the defuzzifier, as shown in Figure 4.7.

Our discussion of this fuzzy-logic-based algorithm follows [10,11] closely. This method is based on the approximate reasoning in fuzzy logic. It uses fuzzy logic to assign truth values from zero to one for each of the sensor signals and road segments and then make decisions based on the assigned truth values.

Figure 4.8 shows a flowchart for this fuzzy-logic-based map-matching algorithm. To save space, "road" has been used for "road segment" in this flow chart. The rules are numbered to correspond with the logic boxes in the flow chart. Some of them consist of more than one sub-rules.

As Figure 4.8 indicates, this algorithm uses eight rules. Some of the fuzzy membership functions associated with each rule are given next. In the following discussion of the rules, we assume that the root mean square error of the past five headings is used as the heading error to determine if the heading has become steady.

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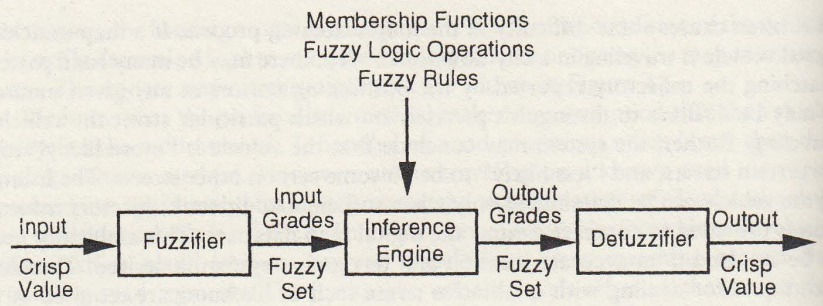


Figure 4.7 Fuzzy logic system structure.

Rule 1: IF Δheading is small
THEN resemblance of the route is high

where "Δheading" is defined as the difference between the direction of the road segment and the heading of the vehicle. The membership functions "small," "large," and "high" for "Δheading" and "resemblance" are defined in Figure 4.9.

Rule 2: IF Δheading is almost 180° AND heading error is zero
THEN possibility of U-turn is high

where, as described in Appendix F, AND is a min (minimal) operator. Membership functions of "almost 180°" for "Δheading" and "zero" for "heading error" are defined in Figure 4.10. The membership function for "possibility of U-turn" being "high" is defined the same as "resemblance" in Figure 4.9.

Rule 3.1: IF Δdistance is large
THEN necessity to retrieve successive segments is high
Rule 3.2: IF Δheading is large and heading error is zero
THEN necessity to retrieve successive segments is high

where "Δdistance" is defined as the difference between the segment length and the distance the vehicle has traveled on that particular segment. The membership function of "large" for "Δdistance" is defined in Figure 4.11. The membership functions of "large" for "Δheading" and "high" for "necessity" (same as "resemblance") are defined in Figure 4.9.

Rule 4: IF the heading errors and the root mean square errors for the vehicle speed are small
THEN the motion is steady
Rule 5: IF the truth value of the previous candidate road pattern is high
AND

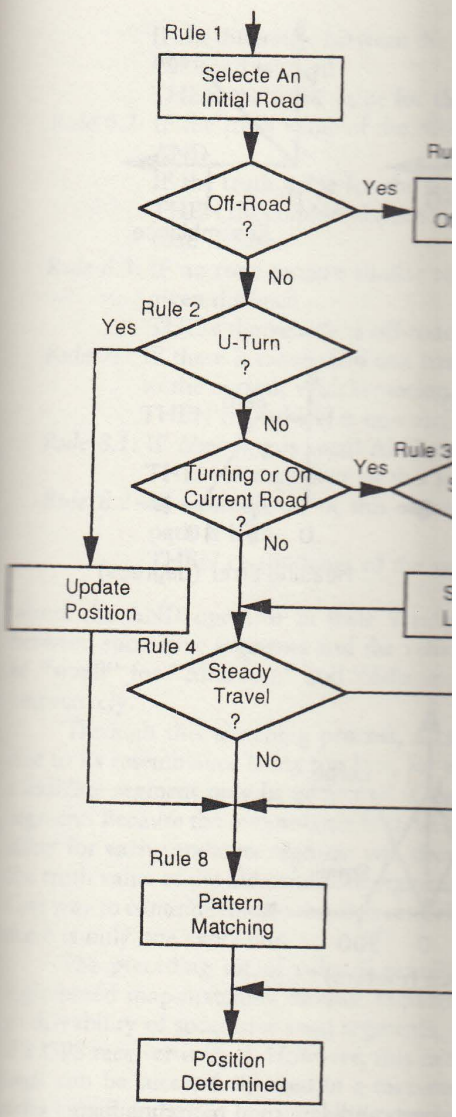


Figure 4.8 A fuzzy-logic-based map-matching algorith

Petitioner Honda Ex-1038, 0027

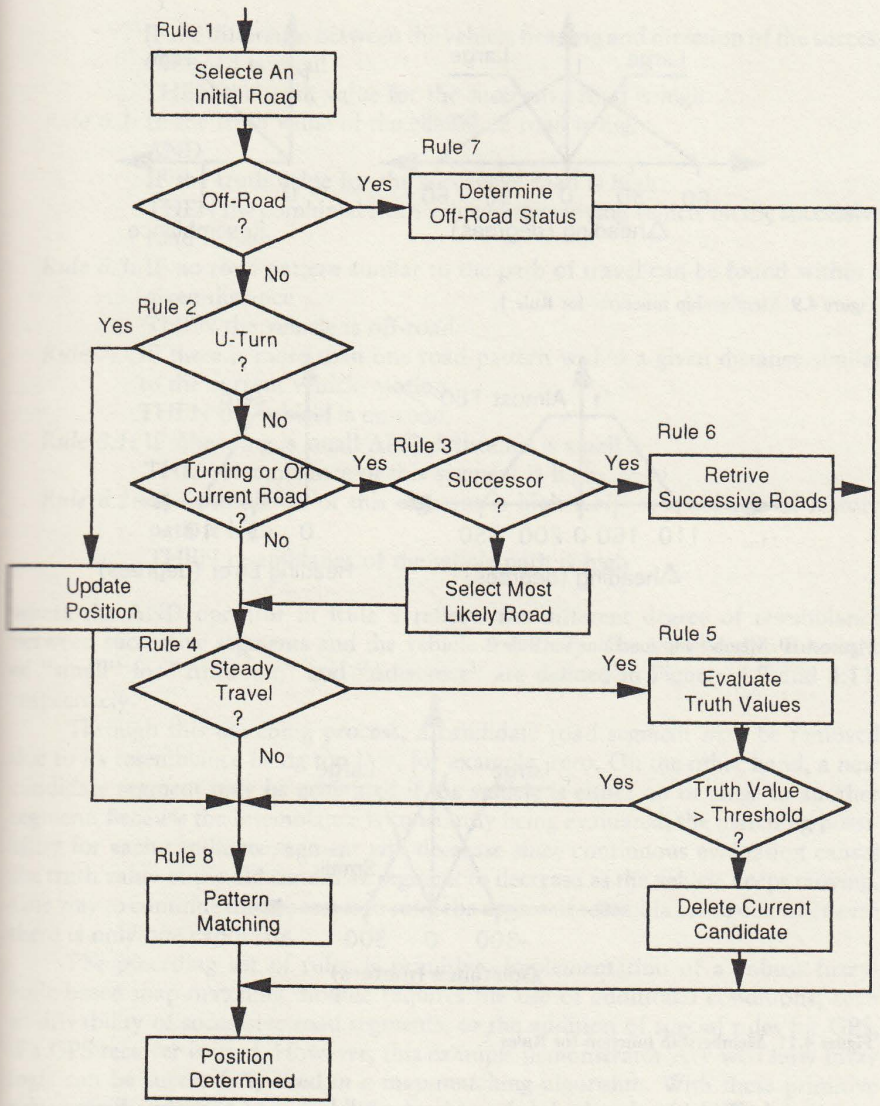


Figure 4.8 A fuzzy-logic-based map-matching algorithm.

Petitioner Honda Ex-1038, 0028

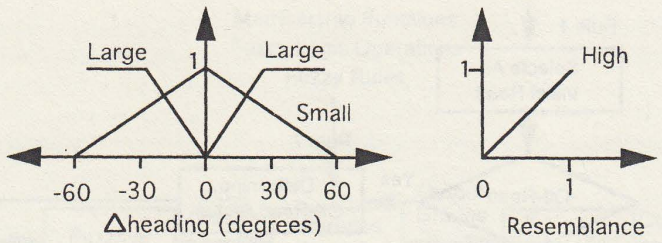


Figure 4.9 Membership functions for Rule 1.

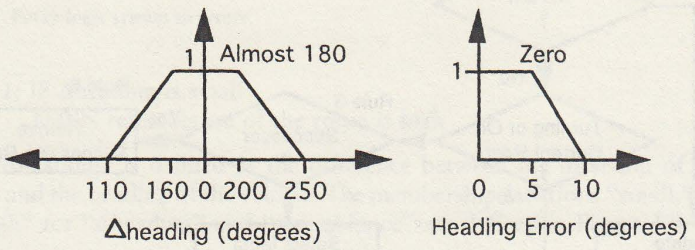


Figure 4.10 Membership functions for Rule 2.

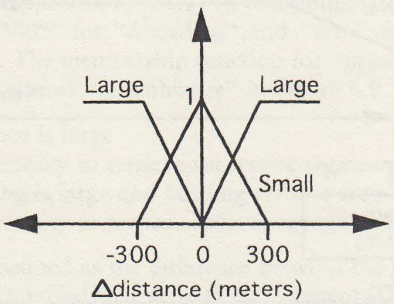


Figure 4.11 Membership function for Rules 3.

IF the truth value of the current candidate road pattern is high
THEN the truth value of the correspondence is high

Rule 6.1: IF the difference between the distance traveled along the current candidate road and the length of the candidate road is small
AND

IF the difference between the
sive road is small
THEN the truth value for th

Rule 6.2: IF the truth value of the can
AND
IF the truth value for the suc
THEN the combined truth va
road is high

Rule 6.3: IF no road pattern similar to
given distance
THEN the vehicle is off-road

Rule 7: IF there is more than one roa
to the current vehicle motion
THEN the vehicle is on-road

Rule 8.1: IF Δheading is small AND Δ
THEN resemblance of this se

Rule 8.2: IF resemblance of this segme
path is high
THEN resemblance of the wh

where the AND operator in Rule 8 refle
between successive segments and the vehic
of "small" for "Δheading" and "Δdistanc
respectively.

Through this matching process, a ca
due to its resemblance being too low, for e
candidate segment may be generated if the
segment. Because the resemblance is constan
bility for each candidate segment will decr
the truth value of the old candidate segment
One way to continue the process is to reset th
there is only one candidate.

The preceding set of rules is primiti
logic-based map-matching module requires
as drivability of successive road segments, o
if a GPS receiver is used. However, this exa
logic can be successfully used in a map-ma
rules as a foundation, one can easily develo
fuzzy-logic development tools are available
tested using these tools. Users can either u
computer language code directly for integr
own fuzzy inference engine to be embedded

Petitioner Honda Ex-1038, 0029

IF the difference between the vehicle heading and direction of the successive road is small
THEN the truth value for the successive road is high

Rule 6.2: IF the truth value of the candidate road is high
AND
IF the truth value for the successive road is high
THEN the combined truth value of the moving vehicle on the successive road is high

Rule 6.3: IF no road pattern similar to the path of travel can be found within a given distance
THEN the vehicle is off-road

Rule 7: IF there is more than one road pattern within a given distance similar to the current vehicle motion
THEN the vehicle is on-road

Rule 8.1: IF Δheading is small AND Δdistance is small
THEN resemblance of this segment is high

Rule 8.2: IF resemblance of this segment is high AND resemblance of history path is high
THEN resemblance of the whole path is high

where the AND operator in Rule 8 reflects the different degree of resemblance between successive segments and the vehicle trajectory. The membership functions of "small" for "Δheading" and "Δdistance" are defined in Figures 4.9 and 4.11, respectively.

Through this matching process, a candidate road segment may be removed due to its resemblance being too low, for example, zero. On the other hand, a new candidate segment may be generated if the vehicle is either on or close to another segment. Because the resemblance is constantly being evaluated, the matching possibility for each candidate segment will decrease since continuous evaluation causes the truth value of the old candidate segment to decrease as the vehicle keeps moving. One way to continue the process is to reset the degree of resemblance to one whenever there is only one candidate.

The preceding set of rules is primitive. Implementation of a robust fuzzy-logic-based map-matching module requires the use of additional conditions, such as drivability of successive road segments, or the addition of special rules for GPS, if a GPS receiver is used. However, this example demonstrates very well how fuzzy logic can be successfully used in a map-matching algorithm. With these primitive rules as a foundation, one can easily develop a good map-matching module. Many fuzzy-logic development tools are available. New rule sets can be developed and tested using these tools. Users can either use the tool to generate the embedded computer language code directly for integration with the system, or design their own fuzzy inference engine to be embedded in the system [12].

Petitioner Honda Ex-1038, 0030

The basic principles of the conventional and fuzzy-logic-based map-matching algorithms are the same. Both algorithms try to identify the road segment on which the vehicle is traveling and precisely determine the position of the vehicle on this segment to update the dead-reckoned position. The main difference is that one approach determines this matching segment by probabilistic reasoning and the other does it via a fuzzy-logic inference process. More specifically, the conventional algorithm defines the sensor error models relative to the candidate segments in probabilistic terms. The fuzzy-logic-based algorithm, on the other hand, uses membership functions to describe the sensor error models in relation to the candidate segments. The matching processes for both algorithms are essentially the same. A possibility is associated with each candidate segment. These possibilities increase or decrease according to similarity. Candidates with low possibilities are discarded and the one with the highest possibility is presented to the system. However, different methods can be used to evaluate the possibility. This leads to the interesting conclusion that other inference methods besides the two methods discussed here can also be used in map-matching algorithms.

4.4 OTHER MAP-MATCHING ALGORITHMS

Map matching is basically a pattern recognition process. Therefore, many pattern recognition methods could be used. One such candidate method is based on a neural network. As mentioned in Section 3.5, neural networks consist of many layered nodes (neurons) that are interconnected. A neural network is a dynamic system and must be trained to rearrange the layers and interconnections to model the real-world application. Besides different pattern recognition methods, centralized, decentralized, or hybrid approaches can be used to work with positioning sensors. In the centralized approach, the integrated and fused multisensor data are matched with the map. In the decentralized approach, each individual sensor or group of sensors is matched with the map separately. In the hybrid approach, the centralized and distributed methods are applied sequentially to obtain a better matching result. Although there are many variations on this technique, the underlying principle is the same: A digital map is used to filter out vehicle sensor errors and to determine the best position. As examples of these variations, we show some typical map-matching methods used with GPS receivers in Figure 4.12.

Because of the popularity of GPS receivers, many applications have been developed on the basis of this satellite-based radio navigation technology. There is no question that a map-matching process can also help improve the accuracy of the receiver output as shown in Figure 4.12(c), especially, when selective availability (SA) is on (see Section 3.4.2).

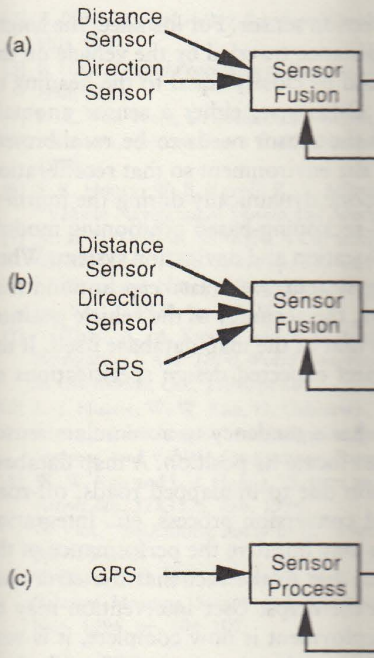


Figure 4.12 Variations of map-matching algo
(b) as one of integrated sensors, a

4.5 MAP-AIDED SENSOR CALIBR

Map data elements (attributes) can b
angular sensors. These may be done
sensors in Chapter 3. For instance, s
detected and corrected using the map
segment can be compared against the
direction of a road segment can be co
direction sensor. When the vehicle trav
threshold will be detected and the cor
performed.

Assume that the map database
traveling on a specific road segment
positioning module. The system can
segment. If the segment is long enoug

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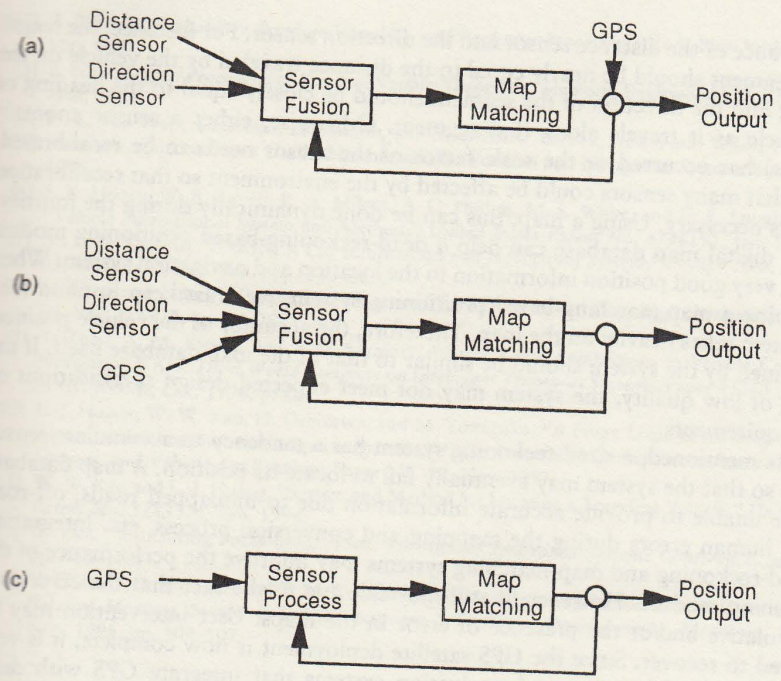


Figure 4.12 Variations of map-matching algorithms used with GPS: (a) as a sanity-checking sensor, (b) as one of integrated sensors, and (c) as the only sensor.

4.5 MAP-AIDED SENSOR CALIBRATION

Map data elements (attributes) can be used to calibrate both distance sensors and angular sensors. These may be done during a trip as briefly discussed for certain sensors in Chapter 3. For instance, sensor blunders (short-term anomalies) can be detected and corrected using the map-matching results [13]. The length of a road segment can be compared against the distance measured by the distance sensor. The direction of a road segment can be compared against the direction measured by the direction sensor. When the vehicle travels on this segment, any errors above a certain threshold will be detected and the corresponding corrections and calibration can be performed.

Assume that the map database is accurate and the fact that the vehicle is traveling on a specific road segment can be confirmed by a map-matching-based positioning module. The system can record the starting and ending points of the segment. If the segment is long enough, a comparison can be done to monitor the

Petitioner Honda Ex-1038, 0032

performance of the distance sensor and the direction sensor. For instance, the length of the segment should be nearly equal to the distance traveled by the vehicle on the segment and the direction of the segment should be closely equal to the heading of the vehicle as it travels along that segment. Otherwise, either a sensor anomaly (blunder) has occurred or the scale factor of the sensor needs to be recalibrated. Recall that many sensors could be affected by the environment so that recalibration becomes necessary. Using a map, this can be done dynamically during the journey.

A digital map database can help a dead-reckoning-based positioning module present very good position information to the location and navigation system. When developing a map-matching-based positioning system, we must keep in mind that this system relies heavily on the map. Therefore, the accuracy of the vehicle position determined by the system should be similar to that of the map database itself. If the map is of low quality, the system may not meet expected design specifications or user requirements.

As mentioned, a dead-reckoning system has a tendency to accumulate sensor errors, so that the system may eventually fail to locate its position. A map database may be unable to provide accurate information due to unmapped roads, off-road travel, human errors during the mapping and conversion process, etc. Integration of dead-reckoning and map-matching systems may improve the performance of the positioning module. However, it still may fail due to the fact that the errors are accumulative and/or the presence of error in the maps. User intervention may be required to recover. Since the GPS satellite deployment is now complete, it is very common to find location and navigation systems that integrate GPS with dead reckoning and map matching to boost the self-recovery ability, and to provide system reliability. Besides, as a source of independent position, direction, and velocity information for the vehicle, GPS can help to calibrate the dead-reckoning sensors and detect sensor blunders dynamically. On the other hand, GPS receivers can occasionally generate suspicious position and velocity information or even no solution at all because of satellite signal blockage and multipath reflection. Dead-reckoning sensors and the map can detect GPS blunders and fill voids by erratic satellite signals. As we shall see in Section 10.2, similar map-matching techniques can also be used to assist terrestrial-radio-based positioning or other systems. By complementing each other, these systems provide much better performance than systems that do not use these matching techniques (Table 10.1).

In conclusion, let us consider an interesting question. During the segment matching process, how can you determine which is the best matching candidate when a road forks into almost parallel roads with very small differences in road direction?

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