

Chapter 2

Outdoor Navigation

2.1 Introduction

In this chapter, the technologies and techniques that are employed in outdoor navigation systems/services along with their features and users are discussed. While the first and second generations of outdoor navigation technology were limited to specific technologies (e.g., only a few geo-positioning sensors were feasible and/or cost effective) and to specific techniques (e.g., routing modules were capable of dealing only with single optimization criterion and there were very few criteria from which users could select), a wide range of technologies and techniques have been available for the third and fourth generations of outdoor navigation technology.

This chapter discusses existing navigation systems/services for outdoor navigation. Despite apparent distinctions among current outdoor navigation systems/services, they are all based on the same fundamental logic and support similar functions/modules. Figure 2.1 depicts the information flow and functions/modules in outdoor navigation systems/services.

As shown in Figure 2.1, in the first step user's current position is determined by: (a) obtaining position data through geo-positioning sensors and (b) applying a map matching algorithm using the obtained position data. It is common practice, in order to improve the accuracy, availability, and reliability of position data in outdoor navigation systems/services, to employ more than one geo-positioning sensors where the acquired position data at each epoch could be filtered (e.g., through a Kalman filter) to find the best position estimate. Once the position data is obtained (directly or filtered), it is input to the map matching algorithm where it uses a map database of the traveling area, which includes spatial and non-spatial data, to find: (a) the road/sidewalk segment on which the user is and (b) the precise location of the user on the segment.

Once user's current location on a road or sidewalk segment is determined, it is highlighted on the map and presented to the user. From this point on, the system/service is on tracking mode, and the user has options to search for POIs or request for optimal routes between pairs of addresses. Upon a route request, the system/service uses such routing criteria as shortest or fastest (often pre-determined by the user)

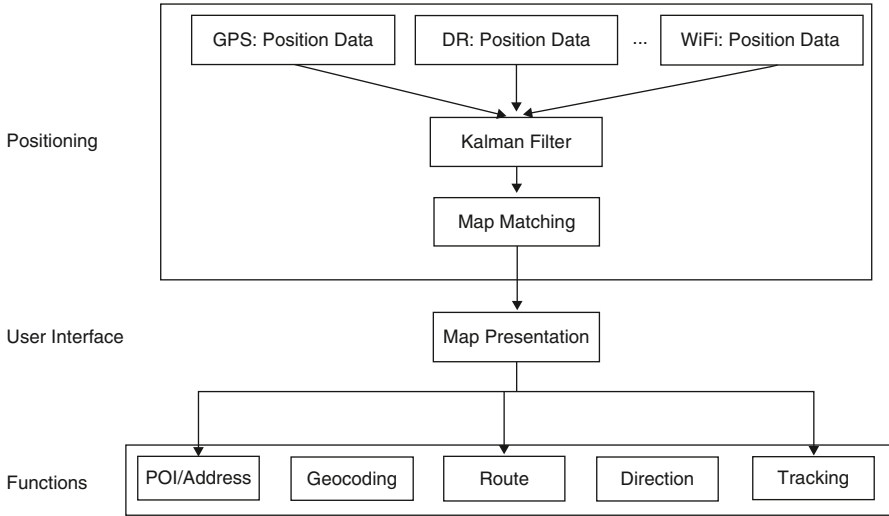


Fig. 2.1 Flow of information in outdoor navigation systems/services

to compute a route between current location, as the origin, and a given address, as the destination. Then the computed route is used to generate a set of turn-by-turn instructions which are presented to the user on the map and/or through voice. While enroute to the destination, the system/service continues obtaining user’s location (using the same sequence of obtaining position data through geo-positioning sensors and applying the map matching algorithm) until the destination is reached. In case the user deviates from the computed route, a new route and a set of new directions are computed (this is commonly known as rerouting) by using the newly acquired position data (i.e., user’s current location), as the origin, to the destination. This process continues until the user arrives at the destination.

2.2 Technologies

The main technologies used in outdoor navigation systems/services include geo-positioning, wireless communication, and database. The main modules in outdoor navigation systems/services are mapping, geocoding, map matching, routing and directions. Depending on several factors including application requirements and cost, navigation system/service vendors decide on the technologies and modules that are feasible and cost effective. However, nowadays navigation system/service vendors are putting more efforts into addressing the needs and preferences of various users in their navigation products. Examples of users’ needs include routes which contain roads with a certain speed limit and roads with two or more lanes. Examples of users’ preferences are routes with shortest distance, fastest travel time,

simple directions, no congestion, scenic sites, and no tolls. Addressing these needs and preferences require the integration of different technologies and techniques in an outdoor navigation system/service. The technologies and techniques suitable for outdoor navigation systems/services are described in the reminder of this section.

2.2.1 Geo-positioning

Geo-positioning sensors provide position data in navigation systems/services. To-day, there are various geo-positioning sensors that are employed in outdoor navigation systems/services and have been the subject of many books and papers where their characteristics and issues, especially accuracy, are discussed. Figure 2.2 shows possible levels of accuracy provided by various geo-positioning sensors that can be implemented in outdoor navigation systems/services. One way to distinguish between these geo-positioning sensors is to characterize the type of positioning technique provided by each sensor (i.e., absolute positioning or relative positioning). Absolute positioning is a technique to calculate the position of an object without using a point of reference. Relative positioning is a technique to calculate the position of an object by using a point of reference. For example, GPS is an absolute positioning technique and Differential-GPS (DGPS) is a relative positioning technique; another example is dead reckoning (e.g., differential odometer) which is a relative positioning technique.

In order to better understand the positioning needs of outdoor navigation systems/services, this section discusses the geo-positioning sensors that are suitable for outdoor navigation systems/services. The existing geo-positioning sensors suitable for outdoor navigation systems/services can be categorized based on three infrastructures: global, wide, and local (Table 2.1). The rationale for this infrastructure-based categorization is that, depending on the underlying infrastructure, each sensor has a different coverage.

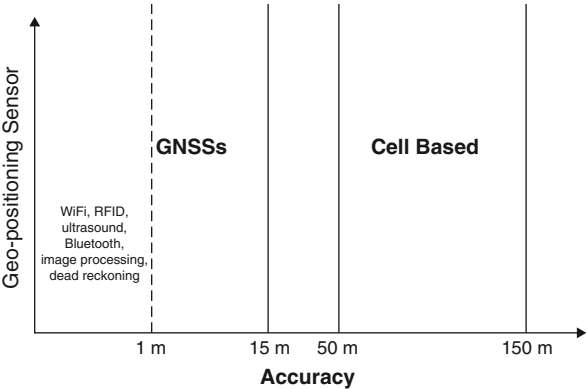


Fig. 2.2 Levels of accuracy provided by geo-positioning sensors

Table 2.1 Geo-positioning sensors suitable for outdoor navigation

Infra-structure	Coverage	Sensor	Accuracy	Latency*	Cost to User
Global	Anywhere on earth	Global Navigation Satellite Systems (e.g., GPS, Galileo, GLONASS, Compass)	Better than 15 m	Slow	Receiver
Wide	City, state, region	Cell based	50-150 m	Medium	Mobile device, service
Local	Campus, city	WiFi, RFID, ultrasound, Bluetooth, image processing, dead reckoning	Centimeters to meters	Fast	Device (HW/SW), service

*Latency: slow (minutes), medium (minute), fast (seconds)

Table 2.2 Sources of errors (in meters) in GPS

Satellite		Receiver		Environment	
Ephemeris	Clock	Measurement	Multipath	Ionosphere	Troposphere
2.5	2.0	1.0	1.0	5.0	0.5

Global infrastructure-based geo-positioning sensors cover everywhere on earth and typically provide better than 15 meters accuracy. GNSS is the best example of global infrastructure-based geo-positioning sensors. The United States NAVSTAR GPS, which is the only operational GNSS as of 2011, is the most prominent GNSS. The three sources of error in GPS are: satellite, receiver, and environment. Table 2.2 shows the sources of errors and the parameters under each source. Each parameter contributes a certain amount of error to the total accuracy in GPS. The two parameters under the satellite source are ephemeris, contributing to around 2.5 m accuracy, and clock, contributing to around 2.0 m accuracy. The two parameters under the receiver source are measurement, contributing to around 1.0 m accuracy, and multipath, contributing to around 1.0 m accuracy. The two parameters under the environment source are ionosphere, contributing to around 5.0 m accuracy, and troposphere, contributing to around 0.5 m to accuracy. Accumulating these errors, the total GPS accuracy is around 12 m.

In addition to GPS, new GNSSs that are under development or deployment are the European Union’s Galileo (scheduled for operation from 2012), the Russian GLONASS (operational since 2010), and the Chinese Compass (planned to be operational from 2020). Usually there is a latency issue with global infrastructure-based geo-positioning sensors as they require time (typically within minutes) to start, known as positioning fix or time-to-first-fix (TTFF), and their cost to the user includes receivers (there is no service charge).

Although each geo-positioning sensor has different sources of errors, the positional error of a location can be roughly estimated as an uncertainty region. For example, Figure 2.3 (a) illustrates an uncertainty region of GNSS positions with accuracy about 10 m (95% confidence), meaning that the estimated point will be

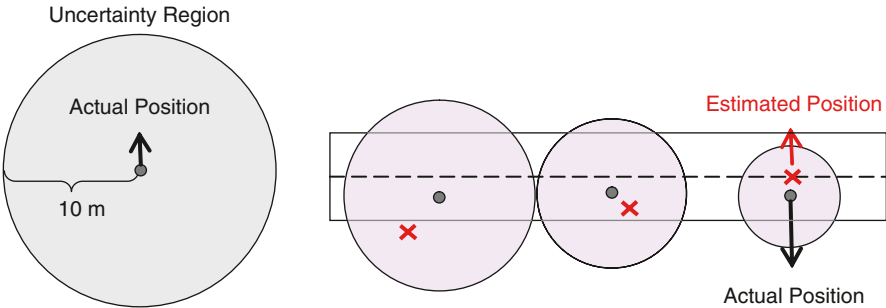


Fig. 2.3 Positional uncertainty. **a** Uncertainty region for an actual position. **b** Estimated positions and uncertainty regions for a moving object

located within 10 m of the actual location. Figure 2.3 (b) illustrates a moving point with different levels of positional accuracy; the cross marks are estimated positions of the vehicle obtained from GNSS while the circle marks are actual positions of the vehicle.

Wide infrastructure-based geo-positioning sensors cover a city, a state, a region and have accuracy ranging between 50 meters to 150 meters. Cell-based systems are the best example of the wide infrastructure-based geo-positioning sensors. The wide infrastructure-based geo-positioning sensors have medium (typically within a minute) latency and their cost to the user includes mobile devices and services.

Local infrastructure-based geo-positioning sensors cover a campus or a city and have an accuracy range of centimeters to meters. Examples of local infrastructure-based geo-positioning sensors are RFID, WiFi, dead reckoning, image processing, ultrasound, and Bluetooth. The local infrastructure-based geo-positioning sensors have the fastest start time (typically within seconds) and their cost to the user includes devices (hardware and software) and services.

Table 2.3 shows the factors that must be taken into consideration for choosing geo-positioning sensors appropriate for outdoor navigation. In the table, the navigation needs of users in outdoors based on their mode of travel (i.e., driving car/motorbike, walking, biking bicycle, or riding wheelchair) are summarized. Each of these modes of travel is analyzed against certain factors (all columns in the table except the last one): speed (possible speed in a given mode of travel); route length (total distance and number of segments a user typically travels in a given mode of travel); structure (environment in which a user would travel); and accuracy (level of positional accuracy suitable for a given mode of travel). The last column of the table highlights ambiguous cases; these are situations in each mode of travel that may cause ambiguity during navigation.

Understanding these factors and their relationships to geo-positioning sensors will have benefits to vendors and users. It will assist vendors in selecting one or a combination of appropriate geo-positioning sensors that address the specific needs of applications and it will assist users in realizing performance and cost issues

Table 2.3 Factors in choosing geo-positioning sensors appropriate for outdoor navigation

Mode of Travel	Speed*	Route Length**	Structure	Accuracy	Ambiguous Cases
Driving Car/ Motorbike	Fast	Long	Road segments	Better than 10 m	Intersections Close parallel roads (within geo-positioning accu- racy range)
Walking (Pedestrian)	Slow	Short	Sidewalk segments	Better than 1 m	Intersections Narrow roads (close side- walks on each side of a road)
Biking Bicycle	Medium	Medium	Road/Side- walk segments	Better than 5 m	Intersections Close parallel roads (within geo-positioning accu- racy range) Narrow roads (close side- walks on each side of a road)
Riding Wheelchair	Slow	Short	Sidewalk segments	Better than 1 m	Intersections Narrow roads (close side- walks on each side of a road)

*Speed: slow < 10 km/h; 10 km/h < medium < 40 km/h; fast > 40 km/h

**Route Length: short (2-3 short segments); medium (3-6 short/long segments); long (6 or more short/long segments)

associated with navigation systems/services. Each of these four factors is described below.

Speed. Speed at which a user travels is one factor in determining a geo-positioning sensor suitable for outdoor navigation applications. In order to better understand the impact of speed on navigation in outdoors, mobility of a user can be categorized into slow (less than 10 kilometers per hour), medium (between 10 and 40 kilometers per hour), and fast (over 40 kilometers per hour). For example, a geo-positioning sensor with an accuracy range of 10 meters is not suitable for a mode of travel with slow speed. This is because the precise location of a pedestrian with a speed of 1 meter per second (average walking speed) is unknown within 10 meters, even though the user may have changed his/her location several times.

Route length. Route length is another factor that can assist in understanding the scale of space in which a user can travel. Route length can be categorized into short (2-3 short segments), medium (3-6 short/long segments), and long (6 or more short/long segments). Knowing the number of segments in a route and the length of each segment is important factor affecting the performance of navigation systems/services (number of segments and length of each segment are issues important to map matching algorithms which will be discussed later in this section).

Structure. Structure is a reference to the environment in which the actual physical movements occur. For drivers (cars or motorbikes), structure contains road segments; for pedestrians, structure contains sidewalk segments; for cyclists (bicycles),

structure contains both road segments and sidewalk segments; and for wheelchair users, structure contains sidewalk segments. Each of these structures imposes certain constraints on the use of geo-positioning sensors appropriate for navigation in outdoors. For example, GPS-based navigation systems/services are problematic for wheelchair-bound individuals, with sidewalk segments as structure, as sidewalks are often adjacent to buildings that may obstruct GPS signals leading to accuracy degradation (due to multipath problems) or signal blockage.

Accuracy. Accuracy is a reference to the acceptable level of difference between the estimated position and the true position of the user in a given mode of travel. The accuracy ranges in Table 2.3 are not exact as each application in each mode of travel may require a certain finer range. As mentioned earlier, these accuracy levels are partially a function of speed of user which in turn is a function of mode of travel. For driving, which typically involves fast speed, an accuracy range of better than 15 meters is needed. For walking, which typically involves slow speed, an accuracy range of better than 1 meter is needed. For biking, which typically involves medium speed, an accuracy range of better than 5 meters is needed. For riding wheelchairs, which typically involves slow speed, an accuracy range of better than 1 meter is needed.

The last column in Table 2.3 highlights ambiguous cases where navigation systems/services, based on the mode of travel and structure factors, must resolve. For driving, where road segments are used, intersections and close parallel roads (closer than positional accuracy) may cause ambiguities. For walking, where sidewalk segments are used, intersections and narrow roads (i.e., close sidewalks on each side of a road) may cause ambiguities. For biking, where both road segments and sidewalk segments are used, intersections, close parallel roads (closer than positional accuracy), and narrow roads (i.e., close sidewalks on each side of a road) may cause ambiguities. For riding wheelchairs, where sidewalks are used, similar to walking, intersections and narrow roads (i.e., close sidewalks on each side of a road) may cause ambiguities.

Clearly no single geo-positioning sensor can address all the needs of outdoor navigation. For this reason, an alternative has been taking a hybrid approach, combining two or more geo-positioning sensors for those outdoor navigation applications where a single geo-positioning sensor is insufficient. Determination of a combination of geo-positioning sensors that is appropriate for an application depends on the requirements of the underlying application such as accuracy, availability, reliability, and cost. For example, a common combination is GPS with dead reckoning, where a dead reckoning sensor, such as differential odometer, can augment GPS, especially when GPS signals are unavailable.

2.2.2 *Wireless Communication*

While the first and second generations of outdoor navigation technology did not offer any connection to other systems and resources, the third and fourth genera-

Table 2.4 Wireless communication systems for outdoor navigation

Infrastruc- ture	Coverage	Technology	Band- width	Cost to User
Global	Anywhere on earth	Satellite communication systems	100 Kb/s	Receiver, service
Wide	City, state, region	Cell based	1 Mb/s	Mobile device, service
Local	Campus, city	WiFi	110 Mb/s	Device (HW/SW), service

tions of outdoor navigation technology is able to connect to external systems and resources through wireless communication systems. The availability of a wireless communication system in an outdoor navigation system/service makes it possible for the system/service to access real-time information, such as traffic, weather, and accidents, that can be used in computing optimal routes. One possible use of wireless communication systems in outdoor navigation services is for computing navigation functions remotely (e.g., on remote servers) and transmitting the results to users (e.g., on smartphones); navigation services have become the emerging trend in providing navigation assistance.

Wireless communication systems that can be employed in outdoor navigation systems/services can be divided into three infrastructure categories (Table 2.4): global, wide, and local. Global infrastructure-based wireless communication systems coverage area spans anywhere on the earth. The best example of the global infrastructure-based wireless communication systems is satellite communication systems featuring 100 Kb/s bandwidth. The cost to the user includes receivers and services.

Wide infrastructure-based wireless communication systems coverage area spans cities, states, and regions. Cell-based communication is the best example of the wide infrastructure-based wireless communication systems featuring 1 Mb/s bandwidth. The cost to the user includes mobile devices and services.

Local infrastructure-based wireless communication systems coverage area spans campuses and cities. WiFi communication is the best example of the local infrastructure-based wireless communication systems featuring 110 Mb/s bandwidth. The cost to the user includes devices (hardware and software) and services.

2.2.3 Database

As data for navigation often is not available in one place, a variety of sources are considered to obtain navigation data. Table 2.5 shows geometrical and topological data, along with other data, that a navigation system/service must contain. For navigation in outdoors, depending on mode of travel, two types of databases are needed: road networks and sidewalk networks. A road network database consists of road segments and a sidewalk network consists of sidewalk segments on both side of a road segment. The essential spatial data in navigation systems/services in-

Table 2.5 Characteristics of data and databases for outdoor navigation

Database	Spatial Data (geometry)	Type	Non-Spatial Data	Navigation Data	Database Size	Functions
Road Segment	Series of coordinates on segments making up segment shape	Geometry, vector	Name, length, width, speed limit, number of lanes, one-two way	POI addresses, landmarks	Very large	Retrieval, mapping
Sidewalk Segment	Series of coordinates on segments making up segment shape	Geometry, vector	Name, length, width, surface type, surface condition	Building addresses, ramps, landmarks	Very large	Retrieval, mapping
Road Network	Coordinates of segment end points	Topology (intersec- tions connectiv- ity), vector	Nodes: intersections Links: road segments	Weight on each road segment (e.g., distance and travel time)	Very large	Routing, direction
Sidewalk Network	Coordinates of segment end points	Topology (intersec- tions connectiv- ity), vector	Nodes: intersections Links: sidewalk segments	Weight on each sidewalk segment (e.g., distance and elevation)	Very large	Routing, direction

cludes road/sidewalk segments where each segment contains a series of coordinates representing its shape (geometry). Road/sidewalk networks in navigation systems/services primarily facilitate computation of routes and directions. There are two important points worth mentioning here. One is that a network (road or sidewalk) is needed in navigation systems/services as it represents topology (connectivity) between intersections (nodes of the network) and road/sidewalk segments (links of the network). The second point is that network quality, especially accuracy, is of importance for providing accurate and reliable navigation assistance.

Note that in this table, and throughout this chapter, we make a distinction between non-spatial data and navigation data. By non-spatial data we refer to the types of data that describe road/sidewalk networks and segments and by navigation data we refer to the types of data that are specifically designated for navigation purposes.

Figure 2.4 shows the road network and the sidewalk network within the University of Pittsburgh's main campus. Figure 2.4 (a) shows the road network within the campus, Figure 2.4 (b) shows the pedestrian network within the campus, and Figure 2.4 (c) shows the road network and the pedestrian network within the campus overlaid.

In addition to topological information that a network (road or sidewalk) supports, a road network usually should contain such non-spatial data as road segment name, length, width, speed limit, number of lanes, and right-of-way (one- vs. two-way). Similarly a sidewalk network contains such non-spatial data as sidewalk segment name (really road segment name), length, width, surface type, and surface condition. Navigation data typically associated with road segments include POI (e.g., restaurant, gas station, and landmark). Navigation data associated with sidewalk segments include building address, ramp, and landmark.

Navigation data typically associated with road networks include weight on each road segment (e.g., distance, travel time) and navigation data associated with sidewalk networks include weight on each sidewalk segment (e.g., distance, elevation). Routing algorithms utilize navigation data either directly, as the weight, or indirectly through a weight function to derive other weights for computing optimal routes.

Navigation databases that include road/sidewalk networks, segments, non-spatial data, and navigation data are typically very large requiring large capacity storage devices and efficient algorithms for data retrieval.

In general, road/sidewalk segments and associated non-spatial data and navigation data are used for retrieval and mapping functions and road/sidewalk networks and associated non-spatial data and navigation data are used for routing and direction functions.

Figure 2.5 shows an Entity-Relationship (ER) diagram for navigation databases that provide navigation assistance in outdoors with driving as mode of travel. As shown in the figure, road networks constitute the core of these databases. The main entities in this ER diagram are nodes, points, links, and POIs. Nodes, in road networks, are end points of road segments and are identified by Node_ID. A node is a point which has attributes such as Point_ID and coordinates (e.g., latitude and longitude). A series of points (excluding end points) construct the shape of a road segment. A link (road segment) has a variety of attributes such as Link_ID, length,

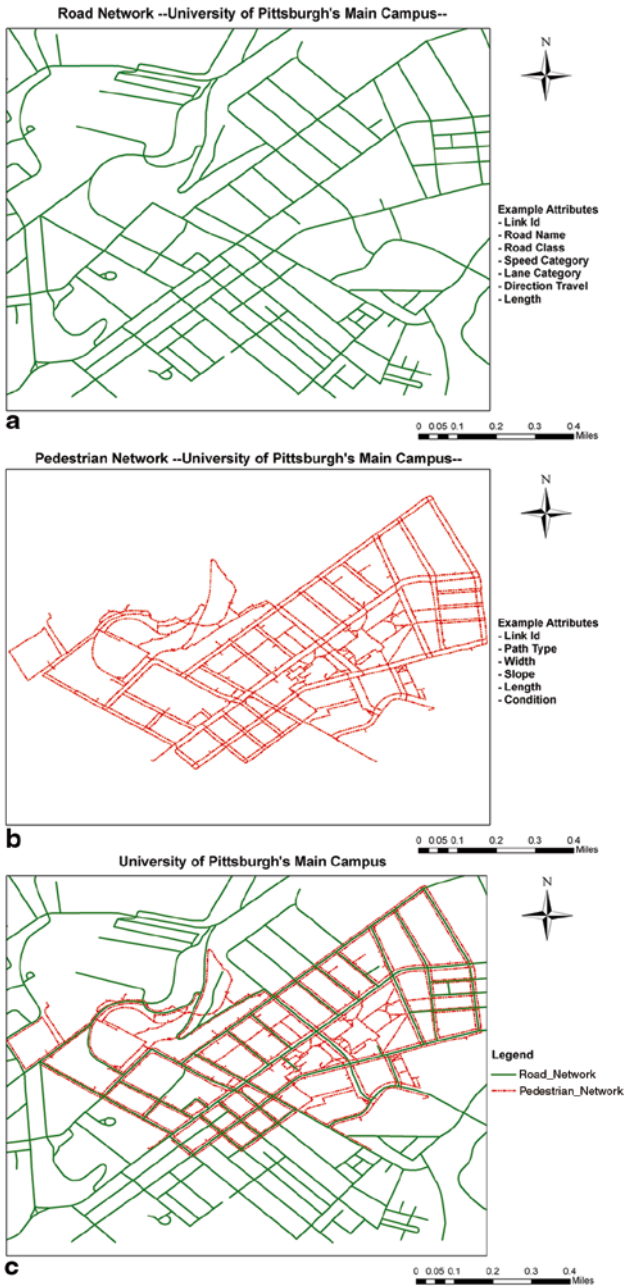


Fig. 2.4 Road and sidewalk networks within the University of Pittsburgh’s main campus. **a** Road network within the University of Pittsburgh’s main campus. **b** Pedestrian network within the University of Pittsburgh’s main campus. **c** Road network and pedestrian network overlaid

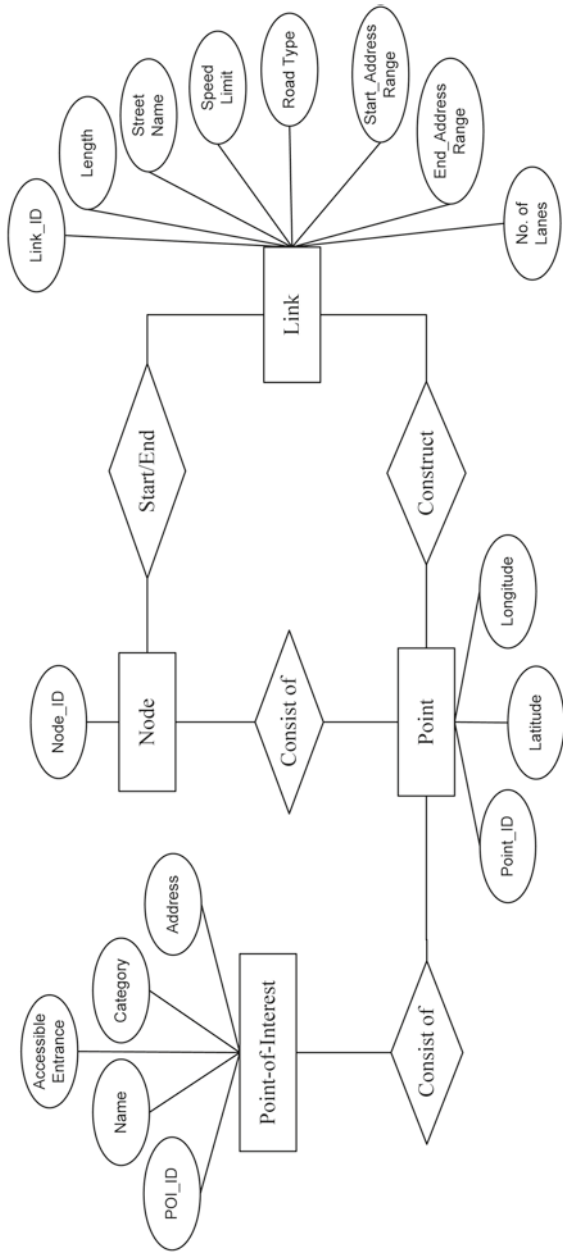


Fig. 2.5 An ER diagram for road networks in navigation databases

street name, path type, slope, surface condition, width, and number of steps. POI is another entity that is a point and has such attributes as POI_ID, name, accessible entrance, category, and address.

Figure 2.6 shows an ER diagram for navigation databases that provide navigation assistance in outdoors with walking as mode of travel. As shown in the figure, sidewalk networks constitute the core of these databases. The main entities in this ER diagram are nodes, points, links, and POIs. Nodes, in sidewalk networks, are end points of sidewalk segments and are identified by such attributes as Node_ID and curb. A node is a point which has attributes such as Point_ID and coordinates (e.g., latitude and longitude). A series of points (excluding end points) construct the shape of a sidewalk segment. A link (sidewalk segment) has a variety of attributes such as Link_ID, length, street name, path type, slope, surface condition, width, and number of steps. POI is another entity that is a point and has such attributes as POI_ID, name, accessible entrance, category, and address.

Road and sidewalk network data are collected, maintained, and disseminated by different providers. Table 2.6 shows the providers of data for road and sidewalk networks which are government agencies or non-profit organizations, commercial mapping companies, and community mapping volunteers. An example of a government agency that provides data for road networks in the United States is Census Bureau; TIGER (Topologically Integrated Geographic Encoding and Referencing system) is one product by the Census Bureau that contains data for navigation purposes. An example of a non-profit organization that provides data for road network data is Pennsylvania Spatial Data Access (PASDA) in Pennsylvania, U.S. Examples of commercial mapping companies that provide data for road networks are NAVTEQ and Tele Atlas. Examples of community mapping volunteers are OpenStreetMap and Wikimapia. The data for sidewalk networks are often provided by local government agencies, such as county and city. Examples of commercial mapping companies that provide data for sidewalk networks in some cities are NAVTEQ and Tele Atlas. An example of a community mapping volunteers is OpenStreetMap.

As for data collection approaches by government agencies and non-profit organizations, satellite imagery, GPS data collection, mobile mapping systems, field survey and paper map digitization and scanning are common. These same approaches are also taken by commercial mapping companies. However, possible data collection approaches by community mapping volunteers are GPS data collection and online manual map digitization.

Advancements in satellite imagery and availability of high-resolution spatial and temporal satellite images have made image processing, to extract data/objects of interest, an attractive and active field of study in the geospatial community. Satellite imagery has become an essential source of data for GIS databases and navigation systems/services. Through automated and semi-automated techniques, data for road and sidewalk network databases can be extracted from satellite images. As shown in Table 2.5, governments, organizations, and commercial companies routinely utilize satellite imagery to collect geospatial data for road and sidewalk network databases. In particular, high-resolution images which provide details at the level appropriate for data in navigation systems/services play a dominant role in collecting and

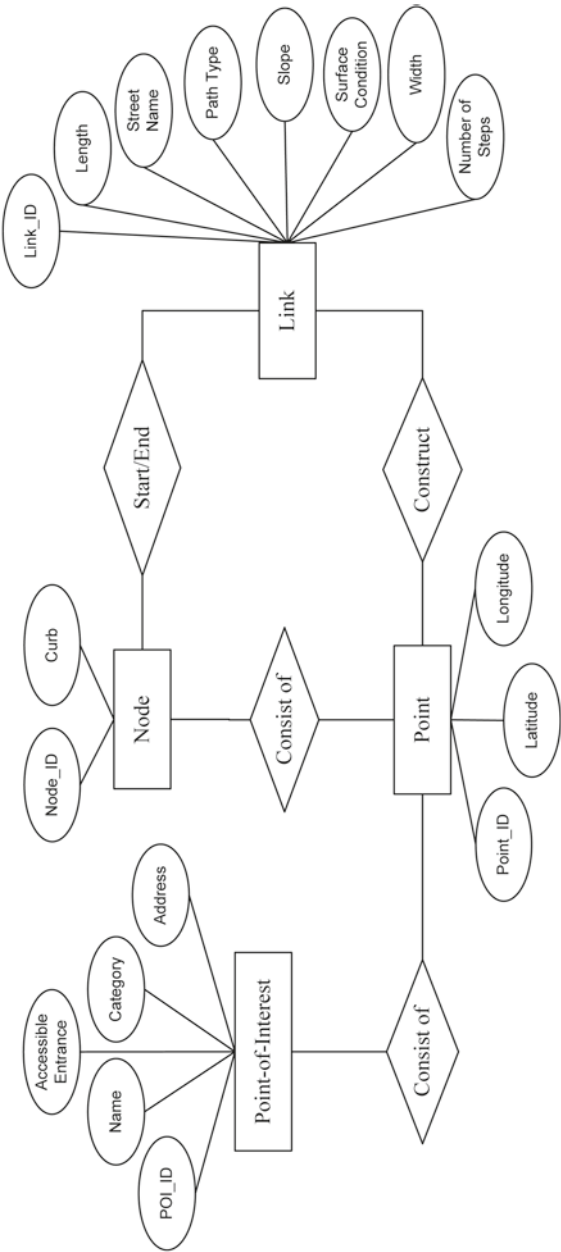


Fig. 2.6 An ER diagram for sidewalk networks in navigation databases

Table 2.6 Map data providers for road and sidewalk networks

Data Providers	Road Network	Sidewalk Network	Data Collection
Government Agencies	E.g., U.S. Census Bureau's TIGER	Local government agencies: county, city	Satellite imagery; GPS data collection; Mobile Mapping Systems; Field survey; Paper map digitization and scanning
Non-Profit Organizations	E.g., Pennsylvania Spatial Data Access (PASDA)		
Commercial Mapping Companies	E.g., NAVTEQ, Tele Atlas	E.g., NAVTEQ (some cities), Tele Atlas (some cities)	Satellite imagery; GPS data collection; Mobile Mapping Systems; Field survey; Paper map digitization and scanning
Community Mapping Volunteers	E.g., OpenStreetMap, Wikimapia	E.g., OpenStreetMap (some areas)	Online GPS data collection; Online manual map digitization

updating road and sidewalk network databases. Figure 2.7 (a)¹ shows an example of a 1 m resolution satellite image and Figure 2.7 (b)² shows an example of a 0.3 m resolution satellite image for the same area.

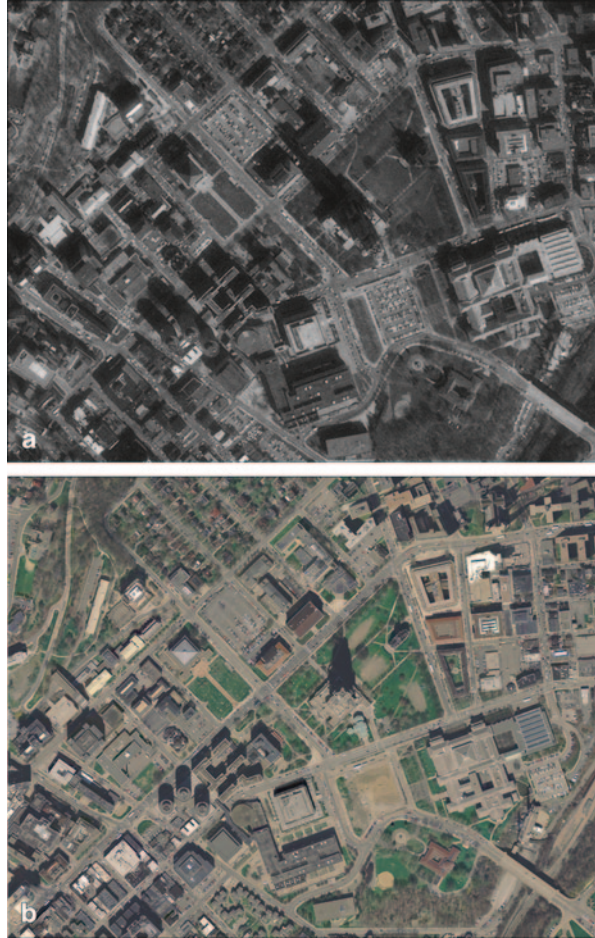
Quality of a road network or a sidewalk network is crucial in the operation of an outdoor navigation system/service as such networks constitute the foundation for many data processings and computations in navigation systems/services. Due to availability of various methods for collecting road data and of various techniques to generate a road network database, different map providers may provide map databases with significantly different qualities. Figure 2.8 shows two examples of road network data, obtained through three different sources (PASDA, TIGER/Line, and NAVTEQ), overlaid and verified with 0.305 m pixel resolution natural color orthoimages obtained from the United States Geological Survey. The accuracy of orthoimages is estimated not to exceed 3 m root mean square error (RMSE). TIGER/Line has the lowest positional accuracy as shown in the figure where some street centerlines intersect buildings. NAVTEQ has a higher resolution and positional accuracy (e.g., for representation of cul-de-sac features) than the other two sources as shown on the right image in Figure 2.8.

Table 2.7 shows the different types and sources of uncertainties in road and sidewalk networks. Three general sources of uncertainties are: geometry, topology, and attribute. Uncertainties associated with geometry in road and sidewalk networks are of three types: accuracy, completeness, and resolution. Uncertainties associated with topology in road and sidewalk networks are of two types: accuracy and com-

¹ http://www.pasda.psu.edu/uci/MetadataDisplay.aspx?entry=PASDA&file=doq99_pa.xml&dataset=1

² http://www.pasda.psu.edu/uci/MetadataDisplay.aspx?entry=PASDA&file=pittsburghpa2005a_orthoimagery.xml&dataset=603

Fig. 2.7 Example high-resolution satellite images. **a** 1 m resolution. **b** 0.3 m resolution

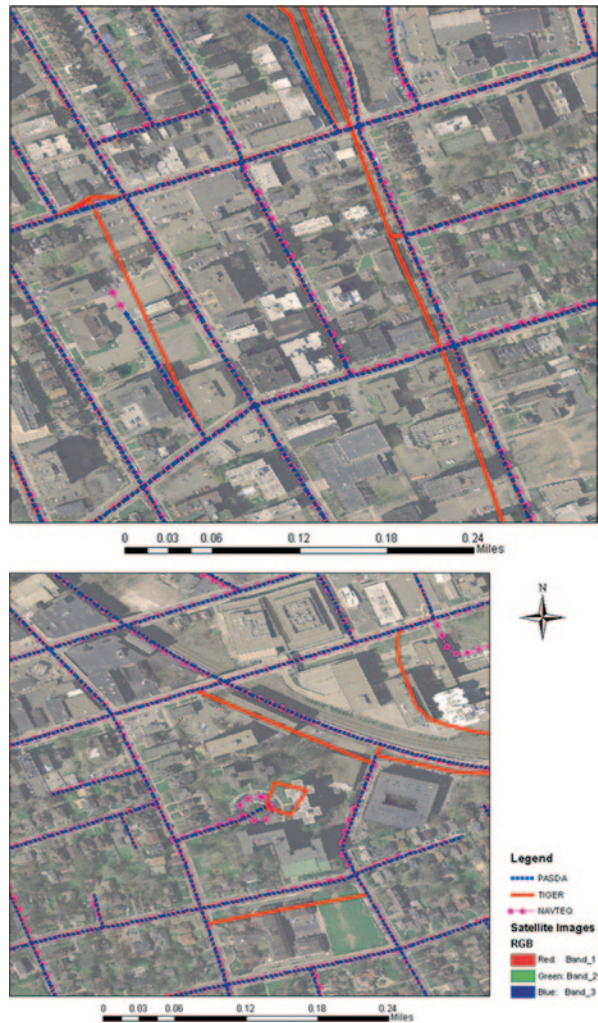


pleteness. Uncertainties associated with attribute in road and sidewalk networks are of two types: accuracy and completeness.

In road networks, examples of uncertainties associated with geometry under accuracy type include inaccurate coordinates of nodes (e.g., the represented location of an intersection is very far from its true location) and inaccurate coordinates of points representing links (e.g., mismatch between the points forming a road segment and the true location of the road segment); examples of uncertainties associated with geometry under completeness type include missing nodes (e.g., an intersection is not stored in the database) and missing links (e.g., a road segment is not stored in the database); an example of uncertainties associated with geometry under resolution type is insufficient points representing segments (e.g., the small number of points on a road segment do not represent the true shape of the road segment).

In road networks, an example of uncertainties associated with topology under accuracy type is incorrect connectivity at junctures (e.g., an intersection does not have

Fig. 2.8 Digital road network data obtained through three different sources



the correct connection to road segments); and an example of uncertainties associated with topology under completeness type is missing nodes (e.g., an intersection is not stored in the database).

In road networks, examples of uncertainties associated with attribute under accuracy type are inaccurate name of a road segment, type of a road segment, and number of lanes in a road segment; examples of uncertainties associated with attribute under completeness type are missing road segment, road segment type, and number of lanes in a road segment.

In sidewalk networks, an example of uncertainties associated with geometry under accuracy type include inaccurate coordinates of nodes (e.g., a decision point is located in a wrong place) and inaccurate coordinates of points representing links

Table 2.7 Types and sources of uncertainties in road and sidewalk networks

Network	Geometry			Topology		Attribute	
	Accuracy	Completeness	Resolution	Accuracy	Completeness	Accuracy	Completeness
Road	Inaccurate coordinates of nodes (junctions); inaccurate coordinates of points representing links (segments)	Missing nodes (junctions); Missing links (segments)	Insufficient points representing segments	Incorrect connectivity at junctions	Missing nodes (junctions)	Inaccurate name, type, number of lanes	Missing name, type, number of lanes
Sidewalk	Inaccurate coordinates of nodes (junctions); inaccurate coordinates of points representing links (segments)	Missing nodes (junctions); missing links (e.g., footpath)	Insufficient points representing segments	Incorrect connectivity at junctions	Missing nodes (junctions)	Inaccurate name, side, type	Missing name, side, type

(e.g., the points representing a sidewalk segment do not match the true location of the sidewalk segment); examples of uncertainties associated with geometry under completeness type are missing nodes (e.g., a decision point is not stored in the database) and missing links (e.g., a footpath is not included in the database); an example of uncertainties associated with geometry under resolution type is insufficient points representing segments (e.g., the small number of points on a footpath do not represent the true shape of the footpath).

In sidewalk networks, an example of uncertainties associated with topology under accuracy type is incorrect connectivity at junctures (e.g., a decision point does not have the correct connection to sidewalk segments); an example of uncertainties associated with topology under completeness type is missing nodes (e.g., a decision point is not stored in the database).

In sidewalk networks, examples of uncertainties associated with attribute under accuracy are inaccurate name of sidewalk segment, side of the road to which sidewalk segment belongs and type of sidewalk segment; examples of uncertainties associated with attribute under completeness are missing name of sidewalk segment, side of the road to which sidewalk segment belongs and type of sidewalk segment.

2.3 Functions

An outdoor navigation system/service performs a variety of functions, some are obvious to users and some are performed in the background. Table 2.8 shows the main functions performed by most outdoor navigation systems/services.

Retrieval. The retrieval function is responsible for retrieval of data from the database which contains spatial and attribute data. The input to the retrieval function is usually a POI name and the output, depending on the input, could be a location of an intersection or a POI address.

Map creation. The map creation function is responsible for creating a map using the centroid of an area (e.g., city), a POI location, or current location (obtained through geo-positioning sensors). This function needs all data including road/sidewalk networks, road/sidewalk segments, and attribute data.

Mapping. Once a map is created, the user is able to perform mapping functions. The mapping function allows user to zoom in, zoom out, and pan the created map. Similar to the map creation function, the input to the mapping function could be the centroid of an area (e.g., city), a POI location, or current location and the output is a new map. All available data including road/sidewalk networks, road/sidewalk segments, and attribute data are needed for this function.

Geocoding. The geocoding function is responsible for computing the coordinates of an address or a POI. The input to the geocoding function often is a POI address and the output is the location of the POI address on the map. The geocoding process in most cases involves an interpolation scheme whereby spatial information about the end nodes of road/sidewalk segments (i.e., coordinates of end points), the geometry of the segment (i.e., series of coordinates forming the shape of the

Table 2.8 Main functions performed by outdoor navigation systems/services

Computation	Input	Process	Output	Database
Retrieval	POI name	Retrieve spatial, non-spatial data	Location of intersection, address of POI	Spatial, attribute
Map Creation	Centroid location, POI location, current location	Clip spatial and non-spatial data	Map	Road/sidewalk segments, attribute
Mapping	Centroid location, POI location, current location	Zoom in, zoom out, pan	Map	Road/sidewalk segments, attribute
Geocoding	Address	Interpolation	Location on map	Road/sidewalk segments, attribute
Routing/ Rerouting	Origin-Destination addresses (current location for rerouting)	Optimal routing	Route on map	Road/sidewalk networks
Tracking	Position data	Map match position data on road/sidewalk segments	Current location on map	Road/sidewalk networks, road/sidewalk segments, attribute
Direction	Route	Compute distance and search for landmarks	A set of instructions to navigate from origin (or current location) to destination	Road/sidewalk networks, road/sidewalk segments, attribute

segment), and the address ranges on both sides of the segment (i.e., start and end addresses on each side of the segment) are used to estimate the location of a given address. The data needed for the geocoding function includes POI address, road/sidewalk segments, and attribute data.

Geocoding is a common function in outdoor navigation systems/services as well as other applications and services such as Web Mapping Services (WMSs), e.g., Google Maps, that provide navigation assistance. Results of geocoding by different WMSs are illustrated in Figure 2.9. Figure 2.9 (a) shows a geocoded location from Google’s street geocoding service where the geocoded point is on the side of the building’s main entrance. Figure 2.9 (b) shows multiple locations of an address geocoded through different geocoding services.

A reference database upon which a geocoding algorithm geocode addresses, through interpolation, plays an important role in the process. Street centerlines con-

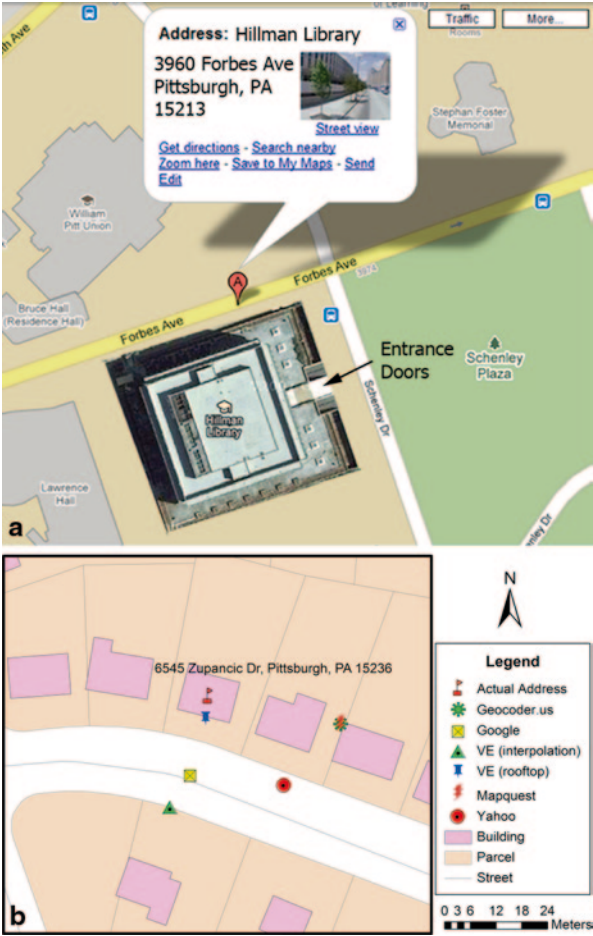


Fig. 2.9 Example geocoding results by different services.
a Geocoding by Google.
b Geocoding by multiple services

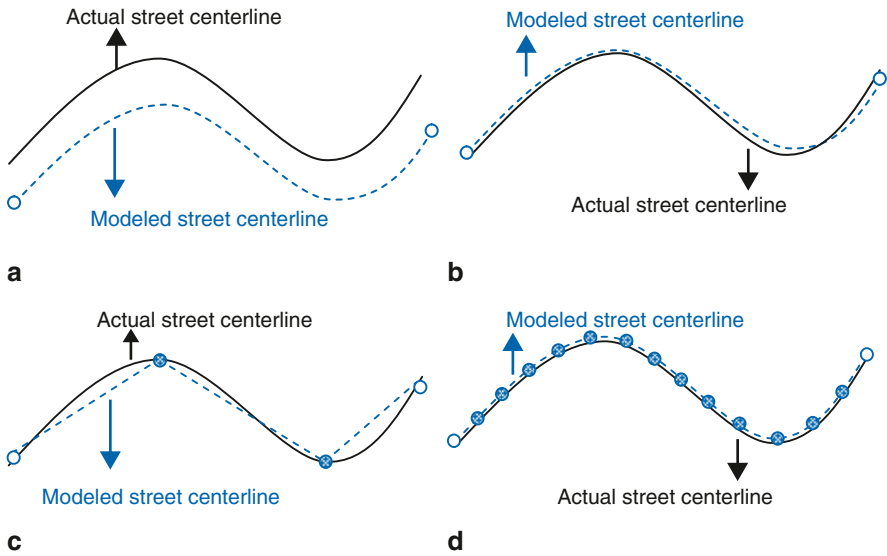


Fig. 2.10 Example street centerline modeled at different levels of accuracy and resolution. **a** Low accuracy **b** High accuracy **c** Low resolution **d** High resolution

stitute the core of such reference databases. Geometrical accuracy of street centerlines directly influences positional accuracy of geocoded points since coordinates along street centerlines are used for calculating street length and interpolating addresses. Figures 2.10 (a) and (b) illustrate a street centerline with low and high accuracy, respectively. Street resolution, which is the sampling frequency of shape points along each segment, is another source of errors. Low-resolution sampling results in a coarse representation of the actual street and a rough estimate of the total length of the segment, as shown in Figure 2.10 (c), while high-resolution sampling results in lines close to actual streets, as shown in Figure 2.10 (d). Low-resolution reference databases are susceptible to higher errors compared to high-resolution reference databases.

Geocoding addresses using street information is called street geocoding, which is the technique in most current geocoding software and tools. An alternative geocoding technique is called rooftop geocoding where coordinates of centroids of buildings and monuments are used to geocode addresses. However, since rooftop geocoding requires as many centroids as possible in the geographic extent of interest which are currently unavailable in GIS databases, most existing applications, including navigation, are based on street geocoding. In general, rooftop geocoding produces less matched (due to lack of available centroid coordinates in GIS databases) but more accurate (due to preciseness of centroid coordinates) results than street geocoding where it produces more matched (due to availability of street information in GIS databases) but less accurate (due to impreciseness of information on streets) results.

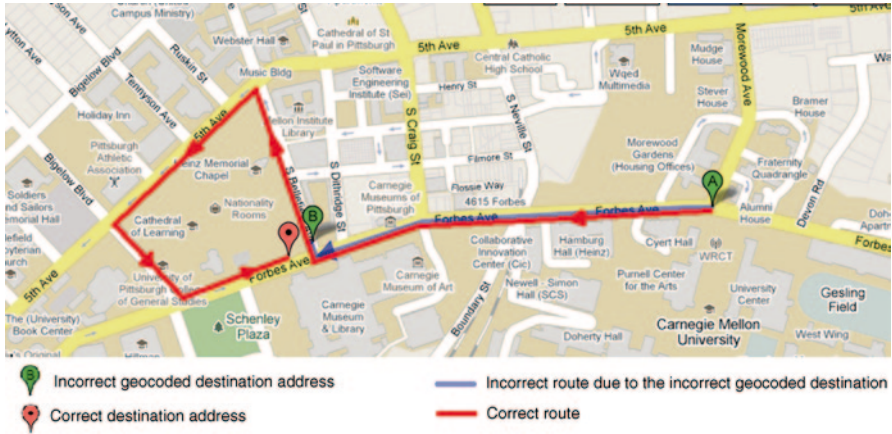


Fig. 2.11 Two routes from single origin to two different locations

Destinations in navigation systems/services can be obtained through on-the-fly geocoding or previously geocoded and stored data, thus susceptible to errors due to uncertainties in geocoding process and map database. Incorrect geocoding, on-the-fly or stored, results in wrong locations of addresses as destinations and undesired routes. Figure 2.11 shows two routes, one from origin A to the correct location of a destination, and another from origin A to an incorrect location of the destination estimated by geocoding.

Routing/Rerouting. The routing function is responsible for computing optimal routes, based on a pre-determined criterion, between pairs of origin-destination addresses. The origin could be entered by the user or current user's location obtained through geo-positioning sensors. The output is the computed route highlighted on the map. The main data needed for the routing function is the road/sidewalk network within the geographic extent of interest (this can be determined by the area that covers both origin and destination locations) which provides the topology of the network, a requirement by all routing algorithms. Today's navigation systems/services allow different routing criteria such as shortest distance, fastest travel time, least intersections, and no tolls among others. An extension to the routing function is rerouting which, depending on the situation (e.g., deviation from the computed route), re-computes a new route from user's current location, as the origin, to the destination.

In general, routes in navigation systems/services could be computed through exact algorithms or heuristic algorithms. Exact algorithms are those algorithms that consider all possible options between pairs of origin and destination addresses to find optimal solutions. Heuristic algorithms are those algorithms that are based on rule-of-thumbs (shortcuts) to find good solutions between pairs of origin and destination addresses. In other words, exact algorithms consider the entire solution space (i.e., all possible routes) to find optimal solutions and heuristic algorithms consider a portion of the solution space (i.e., a subset of all possible routes), to find solutions



Fig. 2.12 An optimal route computed by an exact algorithm and a non-optimal route computed by a heuristic algorithm

which may not necessarily be optimal. Factors affecting choice of exact or heuristic algorithms for navigation systems/services include acceptable response time, networks size, and computational power. Acceptable response time is an important factor in navigation systems/services for computing routes, especially rerouting that is typically computed in real time while the vehicle is moving. Network size is determined by the total number of nodes (e.g., intersections) in a network. In general, the larger the number of nodes, the longer the computation will be. Computational power of a navigation device is another factor that impacts performance of routing and rerouting. Figure 2.12 illustrates an example of an optimal route (in blue) computed by an exact algorithm and an example of a good (non-optimal) route (in red) computed by a heuristic algorithm. In this example, the strategy by the heuristic algorithm is to trim the entire network (solution space) to a smaller network (a window around the origin and destination locations as shown in Figure 2.12). By using the sub-network (the network within the window), the heuristic algorithm only considers some of the routes surrounding the origin A and the destination B locations to find a solution, which may be acceptable but not optimal.

Other than incorrect geocoded destination addresses, which are of geometrical errors, topological errors and attribute errors in networks result in incorrect routes as well. Figure 2.13 shows an example where the computed shortest route (in blue) is different and longer, due to topological errors (e.g., a road segment is incorrectly stored as dead-end), than the actual shortest route (in red). Figure 2.14 shows an example where attribute errors (e.g., incorrect road segment orientation, one- or two-way) result in a route which is different and longer than the actual shortest route.

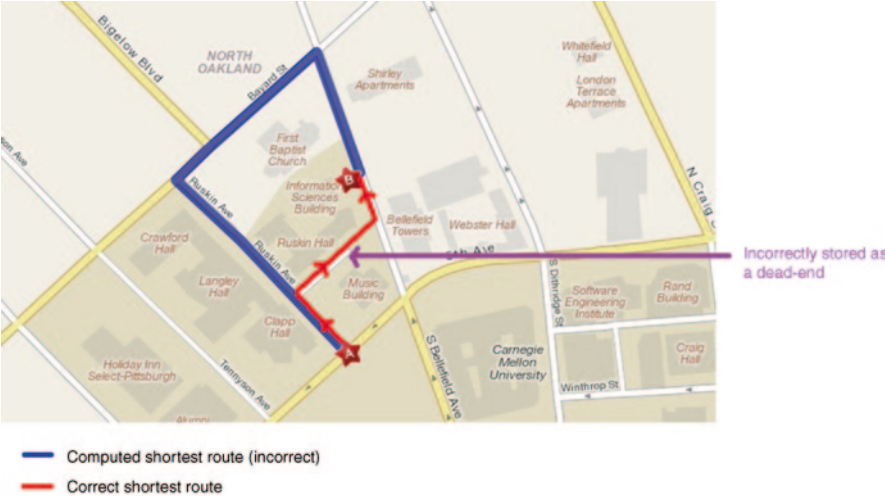


Fig. 2.13 An example of an incorrect route due to topological errors

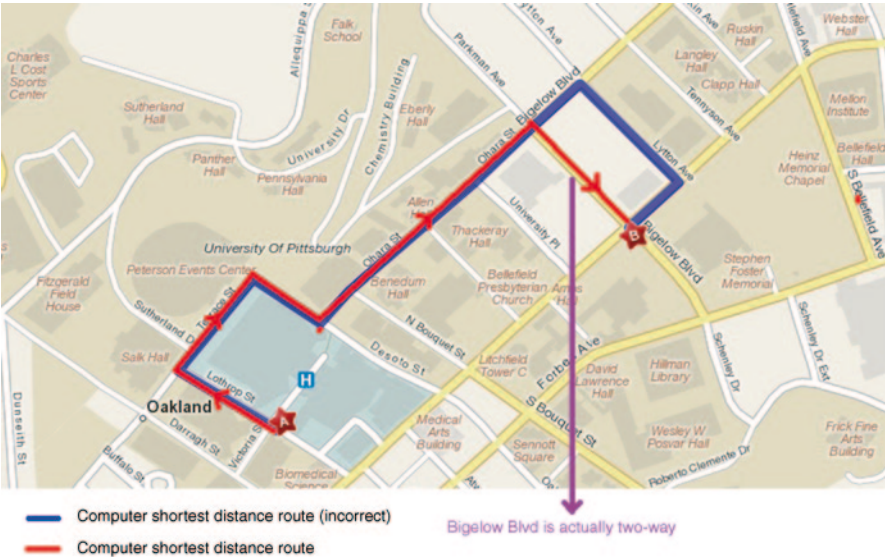


Fig. 2.14 An example of an incorrect route due to attribute errors

Tracking. The tracking function is responsible for the continuous monitoring of user’s location in real time. The input to the tracking function is the position data acquired continuously from geo-positioning sensor(s) at a fixed interval (time or distance) where it is used for map matching. The output is the real-time location of the

user displayed on the map traveling, on a road segment or sidewalk segment. The data needed in the tracking function include road/sidewalk networks, road/sidewalk segments, and attribute data. The key to the tracking function is the map matching algorithm which performs two tasks: (a) finding the segment (road/sidewalk) on which the user is and (b) finding the precise location of the user on the segment. There are many map matching algorithms, but they all are based on one of the three fundamental approaches: point-to-point, point-to-curve, and curve-to-curve. There are advantages and disadvantages with each of these approaches and map matching algorithms based on these approaches tend to exploit their advantages while overcoming their disadvantages.

For illustrative purposes, in Figure 2.15 results of two map matching approaches, point-to-point and point-to-curve, are highlighted. It is assumed in this figure that a vehicle is travelling on segments AB and BD and the position data obtained from

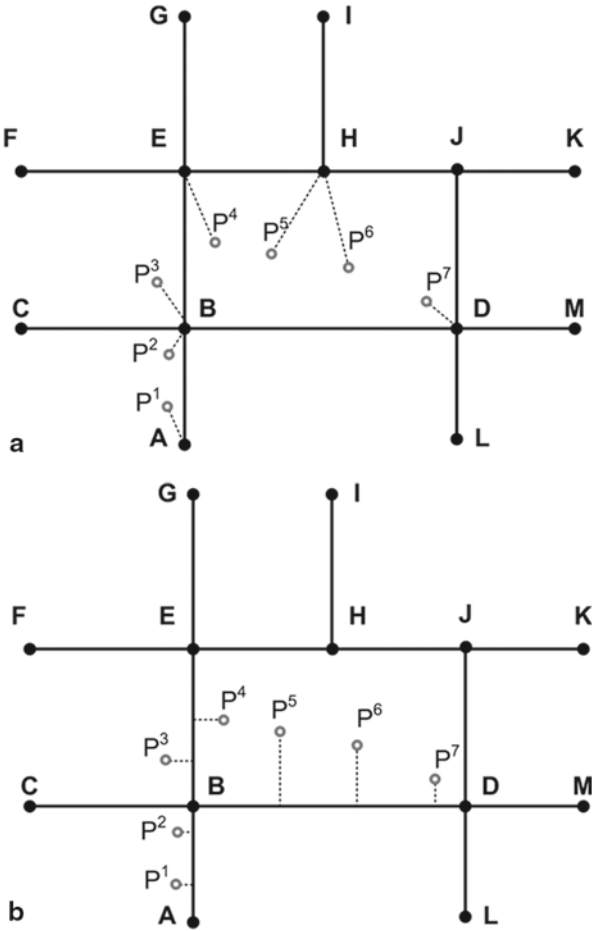
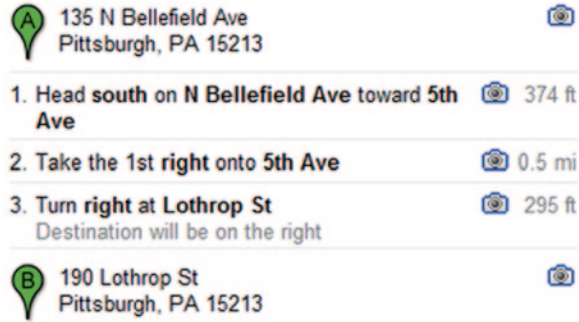


Fig. 2.15 Examples of map-matched results using different algorithms. **a** Point-to-point map matching. **b** Point-to-curve map matching

Fig. 2.16 Example direction generated between a pair of addresses



geo-positioning sensors are indicated by P^1 to P^7 . The map-matched results of the point-to-point approach in Figure 2.15 (a) show that the vehicle travels from AB to BE to EH and to BD. The map-matched results of the point-to-curve approach in Figure 2.15 (b) show that the vehicle travels from AB to BE and to BD. Both algorithms produce incorrect results for P^3 and P^4 .

Direction. The direction function uses the computed route to provide instructions on how to travel from the origin to each segment of the route to reach the destination. The input to the direction function is a route and the output is a set of instructions to navigate on the route displayed on the map and/or presented through voice. The set of instructions basically utilizes information on intersections, distances on road segments, and landmarks. The input to the direction function includes road/sidewalk networks, road/sidewalk segments, and attribute data.

Direction generation refers to the process of generating step-by-step instructions for a given route, which involves two main steps. First, instructions are generated for the entire route from origin to destination. This information is usually delivered to the user as text. Figure 2.16 shows an example of such directions. Second, the instructions generated in the first step are presented to the user turn-by-turn in real time, using the tracking function, based on vehicle's position.

In general, navigation, and consequently directions, could be simple or complex. Factors impacting directions to be simple or complex include navigation environment (structure and density), route length, route complexity in terms of decision points, and user's familiarity with the navigation environment. Figures 2.17 (a) and (b) show examples of routes and directions on them. In Figure 2.17 (a) direction is simple as only one road segment exists in the computed route, whereas in Figure 2.17 (b) direction is complex as there are many decision points where the user must make decision.

Each step of direction generation introduces some uncertainties, mainly associated with road attributes, to the resultant directions. The main sources of errors in the first step of direction generation are segment name and segment length. The sources of errors in the second step of direction generation are associated with vehicle's position determination at each time epoch using map matching and distance

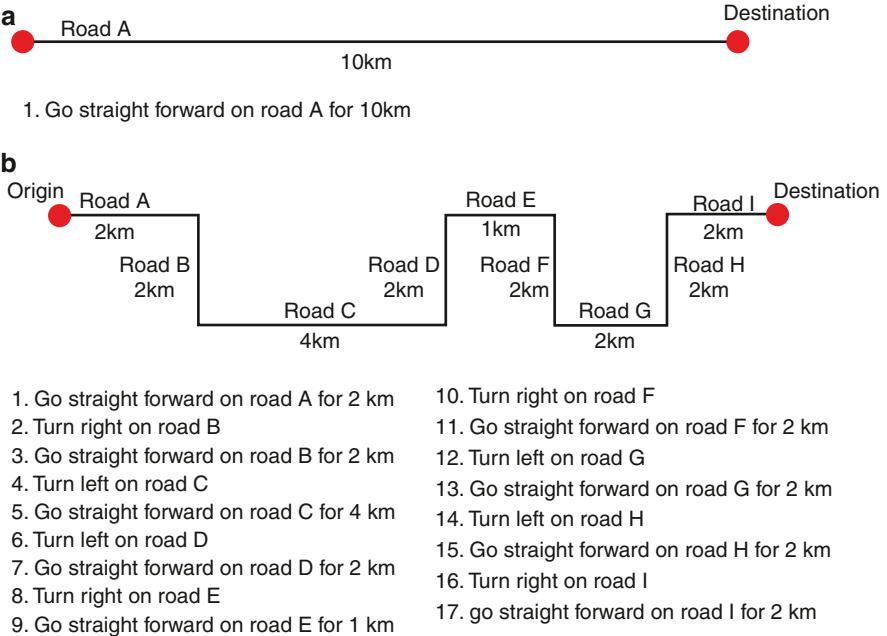
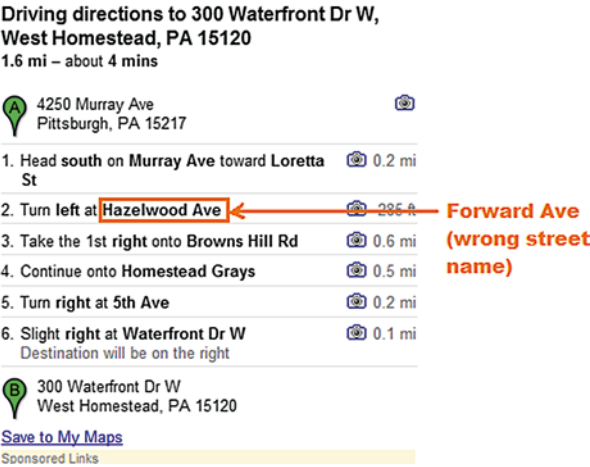


Fig. 2.17 Example directions. **a** Simple directions. **b** Complex directions

Fig. 2.18 An example of direction errors due to incorrect street name



estimation to the next decision point based on vehicle’s position, speed, and current road segment length. Figure 2.18 shows an example of generated directions with an incorrect street name.

2.4 Static and Dynamic Navigation

Outdoor navigation systems/services can operate either in static mode or in dynamic mode. In static mode (or stand-alone mode), the navigation system/service uses only the data stored in its database and it has no access to real-time information such as traffic, weather, or accidents. Rerouting in static mode occurs only when the user deviates from the computed route, in which case the new location of the user is used to compute a new route to the destination.

In dynamic mode, in addition to the stored database the navigation system/service has access, through a wireless communication system, to remote resources. Such remote resources could be real-time weather information, real-time traffic updates, real-time road accidents, among others, within the traveling range. Rerouting in dynamic mode may occur when the user deviates from the computed route or when new real-time information affecting the travelling route is made available to the system/service. In this case, the navigation system/service uses the current location of the user to compute a new route (which may contain a portion of the original route computed at the start of the trip) by taking into account the newly acquired real-time information. For example, if user's preference for routes is least congested, then the navigation system/service capable of dynamic mode will continually check for traffic information on the upcoming segments of the original computed route. If the information it receives indicates congestion on the segments that the user is about to reach, it re-computes a new route to the destination, replaces it with the original computed route and presents it to the user.

2.5 User

The technologies and techniques that are appropriate for outdoor navigation were discussed in the previous sections. In this section, we focus on usability, another important aspect of navigation systems/services. Usability in outdoor navigation systems/services is defined as the accessibility of navigation functions and features by its users. Given that outdoor navigation systems/services can benefit from a wide range of hardware and technologies and that the demand for navigation systems/services is continually increasing, navigation vendors are paying more attention to the usability aspect of their products. For an outdoor navigation system/service to be able to provide appropriate guidance, it is required that it supports various features such as map representation, navigation situations, purpose of trip, and user preferences. Table 2.9 shows the usability features for different modes of travel in outdoor navigation systems/services.

In Table 2.9 users are categorized based on mode of travel, (i.e., car/motor driver, pedestrian, bike rider, and wheelchair rider). For each group, map presentation, navigation situation (static or dynamic), purpose of trip, and user preferences with respect to POI, route, and map presentation are analyzed and described below.

Table 2.9 Usability features in outdoor navigation systems/services

Mode of Travel	Navigation Situation		Purpose of Trip	User Preferences		POI	Map Presentation
	Map Presentation	Static		Dynamic	Route		
Driver/Motor rider	Streets; Roads; Landmarks	Safety; Toll	Commute	Traffic; Weather; Time;	Shortest path; Fastest time;	Office; School; Home; Library	Voice/text directions; Color; Brightness; Screen size; Font size; Map scale; Selected POIs
				Accident;	Least intersections; Avoid tolls; Least left turns; Safe route; Low congestion		
				Route under construction			
Pedestrian	Sidewalk; Buildings; Landmarks	Safety	Emergency		Low congestion	Hospital; Clinic; Pharmacy	Voice/text directions; Color; Brightness; Screen size; Font size; Map scale; Selected POIs
					Scenic route; Avoid tolls; Safe route; Low congestion		
Bike Rider	Streets; Roads; Sidewalks; Buildings; Landmarks	Safety; Toll	Commute	Weather; Time; Route under construction	Shortest path; Safe route	Office; School; Home; Library	Voice/text directions; Color; Brightness; Screen size; Font size; Map scale; Selected POIs; Unsafe neighborhood
					Safe route; Scenic route		
Wheelchair Rider	Streets; Roads; Sidewalks; Buildings; Landmarks; Inaccessible routes	Safety; Toll	Commute	Weather; Traffic; Time; Accident; Route under constructions	Shortest path; Least intersections; Least left turns; Route with feasible slope; Safe route	Office; School; Home; Library	Voice/text directions; Color; Brightness; Screen size; Font size; Map scale; Selected POIs; Unsafe neighborhoods
					Least intersections; Least left turns; Route with feasible slope; Safe route; Scenic route		
Wheelchair Rider	Sidewalk; Buildings; Landmarks; Inaccessible routes	Safety; Slopes; Curbs; Steps	Commute	Traffic; Weather; Safety; Obstacles	Shortest path; Least left turns; Route with feasible slope; Safe route; Avoid obstacles; Avoid curbs; Avoid steps	Office; School; Home; Library	Voice/text directions; Color; Brightness; Screen size; Font size; Map scale; Selected POIs; Unsafe neighborhoods; Inaccessible routes

Map presentation: Maps play a major role in an outdoor navigation system/service as they are the media with which users interact the system/service. A map for navigation purposes must provide the right amount of information, as both incomplete and excessive information may confuse the user; present the orientation dynamically in the direction of travel; and display each set of different objects in a different color. These parameters may be computed and presented differently for each mode of travel. For example, for car/motor drivers, road networks along with relevant objects (e.g., landmarks) on or around road segments that assist in navigation are appropriate. For pedestrians, sidewalk networks and relevant objects (e.g., buildings and landmarks) on or around sidewalk segments are appropriate. For bike riders, since the user may ride on both roads and sidewalks, the presentation may include both road networks and relevant objects on road segments and sidewalk networks and relevant objects on sidewalk segments. In areas where bike riders are required to bike only on designated paths, the presentation must include only such paths and relevant objects on them. For wheelchair riders, sidewalks, buildings, landmarks, and accessible routes must be presented. Due to the impediments in passing inaccessible routes, such as curbs, steps, obstacles, and slopes with more than a specific amount, by wheelchair riders, the map either must not present them at all or present them in such a way that are not confusing to wheelchair riders.

Building a navigation system/services that is capable of representing maps appropriate for each mode of travel as discussed above is complex, which is why most current navigation systems/services are designed for one mode of travel, though new navigation systems/services that are multi-modal are emerging.

Navigation situation: One way to analyze navigation situations for each mode of travel is categorizing them into one of two groups: static and dynamic. Static navigation situations are situations which affect user preferences and do not change over time. Dynamic navigation situations are those which are temporary (i.e., changing over time). For drivers and motor riders, safety and tolls are considered as static situations, whereas weather, accidents, roads under construction, and road side development are considered as dynamic situations. For pedestrians, safety is considered as static navigation situation, and weather, time of day, sidewalks under construction are considered as dynamic situations. For bike riders, since they can ride on both roads and sidewalks, navigation situations are the combination of those for drivers/motor riders and pedestrians. For wheelchair riders, safety, slopes, curbs, and steps are considered as static navigation situations, and traffic, weather, safety, and obstacles are considered as dynamic situations.

Purpose of trip: User's preferences usually vary based on purpose of trip. One may prefer to take a different route while commuting than a route between the same origin and destination locations when purpose of trip is leisure. For instance, consider a restaurant next to a user's office. The user drives from his/her house to the office everyday, a specific time, which may be during rush hours, impacting his/her preferences with respect to fastest, shortest or least congested route. However, when going to the restaurant next to his/her office during the weekend, his/her preference might be a scenic route which could be even a longer route.

User’s preferences can be categorized (see Table 2.6) based on three different purposes of trip for drivers/motor riders (i.e., commute, emergency, and leisure), two purposes of trip for pedestrian and bike riders (i.e., commute and leisure), and one purpose of trip for wheelchair riders (i.e., commute). For each purpose of trip, user’s preferences for routes and POIs are identified. For drivers and motor riders there are several preferences such as shortest, fastest, least turns, non-toll, least left turns, safest, or least congested route when commute is purpose of trip. Typical everyday POIs include office, school, home, and library. In emergency situations, since time is of the essence, shortest, fastest, and least congestion routes are usually preferred. Typical emergency POIs include hospital, clinic, and pharmacy. In addition, preferences for trips chosen as leisure are determined as scenic, non-toll, safest, and least-congested routes. Typical leisure POIs include restaurant, bar, and shopping mall.

Likewise, as Table 2.6 shows, preferences for pedestrians, bike riders, and wheelchair riders are determined based on purpose of trip. However, these preferences are not confined to those aforementioned, and also may vary user by user. The complexity of an outdoor navigation system/service is affected by different needs and preferences they address.

User’s preferences presented on maps are usually independent of purpose of trip. These preferences are roughly the same for each mode of travel with minor differences. Regardless of mode of travel and purpose of trip, each user has some preferences for receiving directions (via voice or text) and presenting color and brightness, font size, map scale, and screen size of the device. However, for presenting upcoming POIs and landmarks, users often prefer to be notified of the ones which are related to their purpose of trip (e.g., parks in leisure and hospitals in emergency situations). Moreover, for pedestrians, bike riders, and wheelchair riders presenting unsafe neighborhoods and inaccessible routes for wheelchair riders would be useful.



Fig. 2.19 Computed route on a road network



Fig. 2.20 Computed route on a sidewalk network

Figure 2.19 shows an example of a route for outdoor navigation. In this figure the computed route between A and B locations are highlighted on a road network of the navigation environment.

Figure 2.20 shows an example of a route for outdoor navigation. In this figure the computed route between A and B locations are highlighted on a sidewalk network of the navigation environment.

Table 2.10 shows a sample of navigation systems/services currently in the market. Navigation vendors featured in this table are Garmin, TomTom, Magellan, and Pioneer. In this table, the products by each navigation vendor along with their general characteristics are highlighted.

2.6 Summary

In this chapter, characteristics, technologies, and techniques of outdoor navigation systems/services are discussed. The main technologies in navigation systems/services are geo-positioning, wireless communication, and database. Of the possible geo-positioning sensors, GNSS, currently GPS, is the main geo-positioning sensor for outdoor navigation. GPS and its uncertainty are described. Wireless communication systems and their use in outdoor navigation systems/services are discussed. Road and sidewalk networks, composed of road/sidewalk segments, constitute the core of data in outdoor navigation systems/services. The main functions performed by today’s modern outdoor navigation systems/services are POI retrieval, map creation, geocoding, routing/rerouting, and tracking. Static and dynamic navigation, users, and routing options in outdoor navigation systems/services are described.

Table 2.10 Sample navigation services

Company	Product Name/Model	General Characteristics	URL
Garmin	nüvi® 3790T	Map coverage: North America; Europe; Australia;	https://buy.garmin.com/shop/shop.do?cID=134&pID=63940
	Versions: nüvi® 3790T nüvi 3790T, Europe, Premium traffic nüvi 3790T, Europe, Premium traffic nüvi 3790T, Australia and New Zealand, Premium traffic nüvi 3790T, Russia nüvi 3790, Arabic	New Zealand; Middle East 4.3" diagonal multi-touch glass display Dual orientation (horizontal, vertical) nüRoute technology with traffic-Trends& MyTrend 3D Building & terrain view Lane assist with junction view Hands-free calling Subscription-free traffic alert Voice command Navigate city transit Calculate more fuel-efficient route Track fuel usage Measurement & currency conversions Emergency locator Anti-theft Nearly 6 million POIs	
TomTom	GO 950 LIVE	Map coverage: Western & central Europe, USA, Canada Hands-free calling Enhanced positioning technology (uninterrupted navigation even in tunnels, etc.) IQ Routes technology Advanced lane guidance Local search with Google Live snapshots QuickGPSfix Speed Cameras Weather condition and forecast 4.3" touchscreen Map Share technology to correct maps & benefits from other users' corrections Provide real-time traffic Compute fuel-efficient routes Provide latest fuel price Emergency menu	http://www.tomtom.com/en_gb/products/car-navigation/go-950-live/index.jsp

Table 2.10 (continued)

Company	Product Name/Model	General Characteristics	URL
Magellan	RoadMate 3065	Map coverage: USA, Canada, Puerto Rico 4.7" touchscreen Hands-free calling Life-time free traffic Highway lane assist Built-in AAA TourBook Multi-destination routing Include millions of POIs Automatic night view	http://www.magellangps.com/products/product.asp?seglID=354&prodID=2327
Pioneer	AVIC-Z120BT	In-car navigation system Map database: TeleAtlas Map coverage: US, Canada, & Puerto Rico 7" touchscreen Inputting destination addresses by voice Including more than 12 million POIs Estimate fuel cost of trip Estimate vehicle's CO2 emission Log and archive driving data and analyze driving habits for generating different reports and suggestions for improving fuel efficiency	http://www.pioneerelectronics.com/Products/CarAudioVideo/In-Dash/GPS-Navigation-Systems/AVIC-Z120BT

Further Readings

- Abdel-Hafez MF (2010) The autocovariance least-squares technique for GPS measurement noise estimation. *IEEE Transactions on Vehicular Technology* 59:574-588.
- Abdel-Hafez MF (2010) On the GPS/IMU sensors' noise estimation for enhanced navigation integrity. *Mathematics and Computers in Simulation*.
- Ali J, Ullah Baig Mirza MR (2010) Performance comparison among some nonlinear filters for a low cost SINS/GPS integrated solution. *Nonlinear Dynamics* 1-12.
- Allain DJ, Mitchell CN (2010) Comparison of 4D tomographic mapping versus thin-shell approximation for ionospheric delay corrections for single-frequency GPS receivers over North America. *GPS Solutions* 14:279-291.
- Alnaqbi A, El-Rabbany A (2010) Precise GPS positioning with low-cost single-frequency system in multipath environment. *Journal of Navigation* 63:301-312.
- Andersson E, Supej M, Sandbakk O, Sperlich B, Stöggl T, Holmberg HC (2010) Analysis of sprint cross-country skiing using a differential global navigation satellite system. *European Journal of Applied Physiology* 1-11.
- Arias J, Lázaro J, Zuloaga A, Jiménez J, Astarloa A (2007) GPS-less location algorithm for wireless sensor networks. *Computer Communications* 30:2904-2916.
- Bączyk R, Kasiński A (2010) Visual simultaneous localisation and map-building supported by structured landmarks. *International Journal of Applied Mathematics and Computer Science* 20:281-293.

- Bai L, Wang Y (2010) A sensor fusion framework using multiple particle filters for video-based navigation. *IEEE Transactions on Intelligent Transportation Systems* 11:348-358.
- Bai L, Wang Y, Fairhurst M (2010) Multiple Condensation filters for road detection and tracking. *Pattern Analysis and Applications* 1-12.
- Balaebail RA, Ariyur KB (2010) Motion estimation and navigational drift correction with LiDAR data. In: *NATO/SPS International Technical Meeting on Air Pollution Modelling and its Application*, vol. 1, pp 337-345 Torino, Italy.
- Barabanova LP (2010) Minimization of GNSS geometric factors. *Journal of Computer and Systems Sciences International* 49:310-317.
- Batista P, Silvestre C, Oliveira P (2010) Optimal position and velocity navigation filters for autonomous vehicles. *Automatica* 46:767-774.
- Bétaille D, Toledo-Moreo R (2010) Creating Enhanced Maps for Lane-Level Vehicle Navigation. *IEEE Transactions on Intelligent Transportation Systems*.
- Cao W, Hauschild A, Steigenberger P, Langley RB, Urquhart L, Santos M, Montenbruck O (2010) Performance evaluation of integrated GPS/GIOVE precise point positioning. vol. 2, pp 710-722.
- Cappelle C, Najjar MEBE, Pomorski D, Charpillat F (2010) Intelligent geolocalization in urban areas using global positioning systems, three-dimensional geographic information systems, and vision. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations* 14:3-12.
- Cesetti A, Frontoni E, Mancini A, Zingaretti P, Longhi S (2010) A Vision-based guidance system for UAV navigation and safe landing using natural landmarks. *Journal of Intelligent and Robotic Systems: Theory and Applications* 57:233-257.
- Chang CL (2010) Using fuzzy logic controller with adaptive detection scheme for fast acquisition of satellite navigation signals. *Journal of the Chinese Institute of Engineers, Transactions of the Chinese Institute of Engineers, Series A/Chung-kuo Kung Ch'eng Hsueh K'an* 33:367-378.
- Chen YH, Juang JC, Kao TL (2010) Robust GNSS signal tracking against scintillation effects: A particle filter based software receiver approach. vol. 2, pp 797-805.
- Cheng PC, Lee KC, Gerla M, Härri J (2010) GeoDTN+Nav: Geographic DTN routing with navigation prediction for urban vehicular environments. *Mobile Networks and Applications* 15:61-82.
- Chien YH (2010) Effects of three hypermedia topologies on users' Navigational performance. *Asian Journal of Information Technology* 9:72-77.
- Choi KH, Park SY, Kim SH, Lee KS, Park JH, Cho SI (2010) Methods to detect road features for video-based in-vehicle navigation systems. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations* 14:13-26.
- Dilello J (2010) A hybrid GNSS integrity design leveraging a priori signal noise characteristics. *Journal of Navigation* 63:513-526.
- Duckham M, Winter S, Robinson M (2010) Including landmarks in routing instructions. *Journal of Location Based Services* 4:28-52.
- Duric Z, Goldenberg R, Rivlin E, Rosenfeld A (2002) Estimating relative vehicle motions in traffic scenes. *Pattern Recognition* 35:1339-1353.
- Dutta G, Mullur H, Roh JC, Rao S, Hosur S (2008) Improving user experience in assisted land navigation using sub-optimal sensor configuration installed on a cell phone. In: *21st International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2008)*, vol. 4, pp 1901-1906.
- Fang J, Gong X (2010) Predictive iterated kalman filter for INS/GPS integration and its application to SAR motion compensation. *IEEE Transactions on Instrumentation and Measurement* 59:909-915.
- Fantino M, Molino A, Nicola M (2010) N-Gene: A complete GPS and Galileo software suite for precise navigation. In: *ITM - NATO/SPS International Technical Meeting on Air Pollution Modelling and its Application*, vol. 2, pp 1245-1251 Torino, Italy.
- Fröhlich P, Schatz R, Leitner P, Baldauf M, Mantler S (2010) Augmenting the driver's view with realtime safety-related information.

- Geng T, Zhao Q, Liu J, Li G (2010) Regional orbit determination of navigation satellite based on global priori information. *Wuhan Daxue Xuebao (Xinxi Kexue Ban)/ Geomatics and Information Science of Wuhan University* 35:491-494.
- Georgy J, Noureldin A, Korenberg MJ, Bayoumi MM (2010) Low-cost three-dimensional navigation solution for RISS/GPS integration using mixture particle filter. *IEEE Transactions on Vehicular Technology* 59:599-615.
- Goldberg L (1996) Vision-based vehicle navigation system uses artificial vision to plug GPS's 'blind spots'. *Electronic Design* 44:35-36.
- Golledge R (1995) Path Selection and Route Preference in Human Navigation: A Progress Report. In: *Spatial Information Theory-A Theoretical Basis for GIS*, vol. 988 (Frank, A. and Kuhn, W, eds), pp 207-222: Springer/Berlin.
- Groves PD, Mather CJ (2010) Receiver interface requirements for deep INS/GNSS integration and vector tracking. *Journal of Navigation* 63:471-489.
- Guo Z, Miao LJ, Shen J (2010) Adaptive control of rotary position system in inertial navigation. *Beijing Ligong Daxue Xuebao/Transaction of Beijing Institute of Technology* 30:552-556+572.
- Gupta RA, Masoud AA, Chow MY (2010) A delay-tolerant potential-field-based network implementation of an integrated navigation system. *IEEE Transactions on Industrial Electronics* 57:769-783.
- Haala N, Böhm J (2003) A multi-sensor system for positioning in urban environments. *ISPRS Journal of Photogrammetry and Remote Sensing* 58:31-42.
- Han S, Wang J (2010) Land vehicle navigation with the integration of gps and reduced ins: Performance improvement with velocity aiding. *Journal of Navigation* 63:153-166.
- Hile H, Vedantham R, Cuellar G, Liu A, Gelfand N, Grzeszczuk R, Borriello G (2008) Landmark-based pedestrian navigation from collections of geotagged photos. In: *Proceedings of the 7th International Conference on Mobile and Ubiquitous Multimedia (MUM'08)*, pp 145-152.
- Hilton J (2010) Ford motor company and telenav to launch connected in-vehicle GPS navigation system. *Automotive Industries* AI 190.
- Huang C, Liao Z, Zhao L (2010) Synergism of INS and PDR in self-contained pedestrian tracking with a miniature sensor module. *IEEE Sensors Journal* 10:1349-1359.
- Islam A, Iqbal U, Langlois JMP, Noureldin A (2010) Implementation methodology of embedded land vehicle positioning using an integrated GPS and multi sensor system. *Integrated Computer-Aided Engineering* 17:69-83.
- Jeon YW, Daimon T (2010) Study of in-vehicle route guidance systems for improvement of right-side drivers in the Japanese traffic system. *International Journal of Automotive Technology* 11:417-427.
- Jin J, Bian S (2010) Analysis of inertial navigation system positioning error caused by gravity disturbance. *Wuhan Daxue Xuebao (Xinxi Kexue Ban)/ Geomatics and Information Science of Wuhan University* 35:30-32+41.
- Jirawimut R, Pragoonwit S, Cecelja F, Balachandran W (2003) Visual odometer for pedestrian navigation. *IEEE Transactions on Instrumentation and Measurement* 52:1166-1173.
- Jirawimut R, Pragoonwit S, Cecelja F, Balachandran W (2003) Visual odometer for pedestrian navigation. *IEEE Transactions on Instrumentation and Measurement* 52:1166-1173.
- Jo BC, Kim S (2010) Multipath interference cancellation technique for high precision tracking in GNSS receiver. *IEICE Transactions on Communications* E93-B:1961-1964.
- Jong GJ, Horng GJ (2010) Heterogeneous Vehicle Navigation Platform Combined with Mobile RFID Using MIMO System. *Wireless Personal Communications* 1-12.
- Karimi HA (1996) Real-time optimal-route computation: a heuristic approach. *Journal of intelligent transportation systems* 3 (2):111-127.
- Karimi HA, Conahan T, Roongpiboonsopit D (2006) A methodology for predicting performances of map-matching algorithms. In: *6th International Symposium on Web and Wireless Geographical Information Systems (W2GIS 2006)*, Hong Kong, 4-5 December 2006. Springer, pp 202-213.

- Karimi HA, Durcik M, Rasdorf W (2004) Evaluation of uncertainties associated with geocoding techniques. *Computer-Aided Civil and Infrastructure Engineering* 19 (3):170-185.
- Karimi HA, Liu S (2004) Developing an automated procedure for extraction of road data from high-resolution satellite images for Geospatial Information Systems. *Journal of Transportation Engineering* 130 (4):621-631.
- Karimi HA, Sutovsky P, Durcik M (2008) Accuracy and performance assessment of a window-based heuristic algorithm for real-time routing in map-based mobile applications. *Map-Based Mobile Services*:248-266.
- Kasemsuppakom P, Roongpiboonsopit D, Karimi H (2010) Current trends and future direction in GIS. In: Karimi H, Akinci B (eds) *CAD and GIS Integration*. Auerbach Publications, Boca Raton, FL, pp 23-49.
- Ki Lee J, Jekeli C (2010) Neural network aided adaptive filtering and smoothing for an integrated INS/GPS unexploded ordnance geolocation system. *Journal of Navigation* 63:251-267.
- Kray C, Elting C, Laakso K, Coors V (2003) Presenting route instructions on mobile devices. In: *Proceedings of the 8th international conference on Intelligent user interfaces* Miami, Florida, USA
- Leandro RF, Santos MC, Langley RB (2010) Analyzing GNSS data in precise point positioning software. *GPS Solutions* 1-13.
- Lee WC, Ma MC, Cheng BW (2010) Field comparison of driving performance using a portable navigation system. *Journal of Navigation* 63:39-50.
- Lee YL (2010) The effect of congruency between sound-source location and verbal message semantics of in-vehicle navigation systems. *Safety Science* 48:708-713.
- Lehmann F (2009) Deterministic particle filtering for GPS navigation in the presence of multipath. *AEU - International Journal of Electronics and Communications* 63:939-949.
- Li C (2006) User preferences, information transactions and location-based services: A study of urban pedestrian wayfinding. *Computers, Environment and Urban Systems* 30:726-740.
- Li C, Wang Q, Zhu Z, Guan Z (2007) Study on the GPS/MM navigation method based on the vehicle kinematic model. *Yi Qi Yi Biao Xue Bao/Chinese Journal of Scientific Instrument* 28:150-153.
- Li G, Lu H (2010) Visual recommendation knowledge service based on intelligent topic map. *Information Technology Journal* 9:1158-1164.
- Li J (2010) Improving the accuracy of GPS positioning with an exponential stochastic model. In: *2010 Second International Conference on Networks Security, Wireless Communications and Trusted Computing*, vol. 2, pp 162-165 Wuhan, Hubei.
- Li JZ, Wu MQ (2010) Three satellites positioning algorithm based on AGPS structure and realization. *Dianzi Keji Daxue Xuebao/Journal of the University of Electronic Science and Technology of China* 39:372-375+424.
- Li T, Yang D, Geng H, Liu W, Zhang T, Lian X (2010) Spider-web road network model for in-vehicle navigation digital maps. *Wuhan Ligong Daxue Xuebao (Jiaotong Kexue Yu Gongcheng Ban)/Journal of Wuhan University of Technology (Transportation Science and Engineering)* 34:439-442.
- Lin CT, Wu HC, Chien TY (2010) Effects of e-map format and sub-windows on driving performance and glance behavior when using an in-vehicle navigation system. *International Journal of Industrial Ergonomics* 40:330-336.
- Liu W, Xu H, Zhang J (2010) Study of high precision and MINS/GPS integrated navigation systems. *Wuhan Daxue Xuebao (Xinxi Kexue Ban)/ Geomatics and Information Science of Wuhan University* 35:160-163.
- Liu ZL, Shi ZK (2010) A dynamic route planning strategy based on road network changes. *Jiaotong Yunshu Xitong Gongcheng Yu Xinxi/Journal of Transportation Systems Engineering and Information Technology* 10:147-152.
- Ning XL, Ma X (2010) Analysis of filtering methods for satellite celestial navigation. *Kongzhi Lilun Yu Yinyong/Control Theory and Applications* 27:423-430.
- Paetzold F, Franke U (2000) Road recognition in urban environment. *Image and Vision Computing* 18:377-387.

- Pang G, Chu MH (2007) Route Selection for Vehicle Navigation and Control. In: The 33rd Annual Conference of the IEEE on Industrial Electronics Society (IECON 2007), pp 2586-2591 Taipei, Thailand.
- Pang GaC, M.H. (2007) Route Selection for Vehicle Navigation and Control. In: Industrial Electronics Society (IECON 2007), pp 2586-2591 Taipei, Thailand.
- Panga GKH, Takashib, K., Yokotab, T., and Takenagab, H. (2002) Intelligent route selection for in-vehicle navigation systems. *Transportation Planning and Technol* 25:175-213.
- Panzieri S, Pascucci F, Ulivi G (2001) An outdoor navigation system using GPS and inertial platform. In: Proceedings of IEEE/ASME International Conference on Advanced Intelligent Mechatronics, pp 1346-1351 Como, Italy.
- Park B, Kee C (2010) The compact network RTK method: An effective solution to reduce GNSS temporal and spatial decorrelation error. *Journal of Navigation* 63:343-362.
- Park SK, Suh YS (2009) Gait state classification by hmms for pedestrian inertial navigation system. *Transactions of the Korean Institute of Electrical Engineers* 58:1010-1018.
- Patino-Studencka L (2010) Approach for detection and identification of multiple faults in satellite navigation. In: IEEE PLANS, Position Location and Navigation Symposium, pp 221-226 Indian Wells/Palm Springs, California.
- Patino-Studencka L, Rohmer G, Thielecke J (2010) Researches on the new system of aids to navigation. In: IEEE PLANS, Position Location and Navigation Symposium, pp 221-226 Indian Wells/Palm Springs, California.
- Peeta SaY, J.W. (2005) A Hybrid Model for Driver Route Choice Incorporating En-Route Attributes and Real-Time Information Effects. *Networks and Spatial Economics* 5:21-40.
- Petrovski I, Okano K, Ishii M, Torimoto H, Konishi Y, Shibasaki R (2003) Pedestrian ITS in Japan: Pseudolites and GPS. *GPS World* 14:33-37.
- Polat E, Yeasin M, Sharma R (2003) A 2D/3D model-based object tracking framework. *Pattern Recognition* 36:2127-2141.
- Ren C, Pan Y, Liu J, Teng Y (2010) Study on multi-information fusion system to improve the vehicle's position and satellite tracking accuracy. *Yingyong Jichu yu Gongcheng Kexue Xuebao/ Journal of Basic Science and Engineering* 18:358-367.
- Rizos C, Grejner-Brzezinska DA, Toth CK, Dempster AG, Li Y, Politi N, Barnes J, Sun H, Li L (2010) Hybrid positioning a prototype system for navigation in GPS-challenged environments. *GPS World* 21:42-47.
- Roongpiboonsopit D, Karimi H (2010) Comparative evaluation and analysis of online geocoding services. *International Journal of Geographical Information Science* 24 (7):1081-1100.
- Roongpiboonsopit D, Karimi H (2010) Quality assessment of online street and rooftop geocoding services. *Cartography and Geographic Information Science* 37 (4):301-318.
- Roongpiboonsopit D, Karimi HA (2009) A multi-constellations satellite selection algorithm for integrated GNSSs. *Journal of Intelligent Transportation Systems* 13 (3):127-141.
- Sabatini AM (2008) Adaptive filtering algorithms enhance the accuracy of low-cost inertial/ magnetic sensing in pedestrian navigation systems. *International Journal of Computational Intelligence and Applications* 7:351-361.
- Sadeghian P, Kantardzic M, Lozitskiy O, Sheta W (2006) The frequent wayfinding-sequence (FWS) methodology: Finding preferred routes in complex virtual environments. *International Journal of Human-Computer Studies* 64:356-374.
- Saeed G, Brown A, Knight M, Winchester M (2010) Delivery of pedestrian real-time location and routing information to mobile architectural guide. *Automation in Construction* 19:502-517.
- Santa J, Toledo-Moreo R, Zamora-Izquierdo MA, Úbeda B, Gómez-Skarmeta AF (2010) An analysis of communication and navigation issues in collision avoidance support systems. *Transportation Research Part C: Emerging Technologies* 18:351-366.
- Schmid A, Neubauer A, Ehm H, Weigel R, Lemke N, Heinrichs G, Winkel J, Angel Ávila-Rodríguez J, Kaniuth R, Pany T, Eissfeller B, Rohmer G, Overbeck M (2005) Combined Galileo/GPS architecture for enhanced sensitivity reception. *AEU - International Journal of Electronics and Communications* 59:297-306.

- Schmid F (2008) Knowledge-based wayfinding maps for small display cartography. *Journal of Location-based Services* 2:57-83.
- Schwagten B, Witsenburg M, De Groot NMS, Jordaens L, Szili-Torok T (2010) Effect of Magnetic Navigation System on Procedure Times and Radiation Risk in Children Undergoing Catheter Ablation. *American Journal of Cardiology* 106:69-72.
- Serrano L, Kim D, Langley RB (2010) Multipath adaptive filtering in GNSS/RTK-based machine automation applications. In: *Position Location and Navigation Symposium (PLANS)*, 2010 IEEE/ION, pp 60-69 Indian Wells, CA, USA.
- Shen Z, Georgy J, Korenberg MJ, Noureldin A (2010) FOS-based modelling of reduced inertial sensor system errors for 2D vehicular navigation. *Electronics Letters* 46:298-299.
- Shi W, Shen S, Liu Y (2009) Automatic generation of road network map from massive GPS vehicle trajectories. In: *12th International IEEE Conference on Intelligent Transportation Systems (ITSC '09)*, pp 48-53 St. Louis, MO.
- Shin DH, Joo BY (2010) Design of a vision-based autonomous path-tracking control system and experimental validation. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 224:849-864.
- Sivaraman S, Trivedi MM (2010) A general active-learning framework for on-road vehicle recognition and tracking. *IEEE Transactions on Intelligent Transportation Systems* 11:267-276.
- St. Amant R, Long T, Dulberg MS (1998) Experimental evaluation of intelligent assistance for navigation. *Knowledge-Based Systems* 11:61-70.
- Stentz A, Hebert M (1995) A complete navigation system for goal acquisition in unknown environments. *Autonomous Robots* 2:127-145.
- Stirling R, Fyfe K, Lachapelle G (2005) Evaluation of a new method of heading estimation for pedestrian dead reckoning using shoe mounted sensors. *Journal of Navigation* 58:31-45.
- Stophor P, FitzGerald C, Zhang J (2008) Search for a global positioning system device to measure person travel. *Transportation Research Part C: Emerging Technologies* 16:350-369.
- Sugimoto C, Nakamura Y, Hashimoto T (2008) Pedestrian-to-vehicle communication system for improving road safety using cellular phones. In: *Proceedings of INSS 2008 the 5th International Conference on Networked Sensing Systems*, p 226.
- Terradellas E, Téllez B (2010) The use of products from ground-based GNSS observations in meteorological nowcasting. *Advances in Geosciences* 26:77-82.
- Tideman M, van der Voort MC, van Arem B (2010) A new scenario based approach for designing driver support systems applied to the design of a lane change support system. *Transportation Research Part C: Emerging Technologies* 18:247-258.
- Toledo-Moreo R, Pinzolas-Prado M, Cano-Izquierdo JM (2010) Maneuver prediction for road vehicles based on a neuro-fuzzy architecture with a low-cost navigation unit. *IEEE Transactions on Intelligent Transportation Systems* 11:498-504.
- Toledo-Moreo R, Zamora-Izquierdo MA (2010) Collision avoidance support in roads with lateral and longitudinal maneuver prediction by fusing GPS/IMU and digital maps. *Transportation Research Part C: Emerging Technologies* 18:611-625.
- Tsuge M, Tokunaga M, Nakano K, Sengoku M (2010) On Estimation of Link Travel Time in Floating Car Systems. *International Journal of Intelligent Transportation Systems Research* 1-13.
- van Eijk O, Roeloffs M (2010) Forensic acquisition and analysis of the Random Access Memory of TomTom GPS navigation systems. *Digital Investigation* 6:179-188.
- Vasconcelos JF, Cardeira B, Silvestre C, Oliveira P, Batista P (2010) Discrete-Time Complementary Filters for Attitude and Position Estimation: Design, Analysis and Experimental Validation. *IEEE Transactions on Control Systems Technology*.
- Wang QT, Hu XL (2010) Improved Kalman filtering algorithm for passive-BD/SINS integrated navigation system based on UKF. *Xi Tong Gong Cheng Yu Dian Zi Ji Shu/Systems Engineering and Electronics* 32:376-379.
- Won SHP, Melek WW, Golnaraghi F (2010) A kalman/particle filter-based position and orientation estimation method using a position sensor/inertial measurement unit hybrid system. *IEEE Transactions on Industrial Electronics* 57:1787-1798.

- Wu Q, Duan F, Shi L, Li J (2010) Design and implementation of a vehicle multimedia navigation terminal software. *Wuhan Ligong Daxue Xuebao (Jiaotong Kexue Yu Gongcheng Ban)/Journal of Wuhan University of Technology (Transportation Science and Engineering)* 34:573-576.
- Xiang L, Liu Y, Su B (2008) New nonlinear filter for GPS/DR integrated navigation system. *Dongnan Daxue Xuebao (Ziran Kexue Ban)/Journal of Southeast University (Natural Science Edition)* 38:27-31.
- Xiang L, Liu Y, Su BK (2010) Improved particle filter algorithm for INS/GPS integrated navigation system. *Kongzhi Lilun Yu Yinyong/Control Theory and Applications* 27:159-163.
- Xu H, Liu H, Tan CW, Bao Y (2010) Development and application of an enhanced kalman filter and global positioning system error-correction approach for improved map-matching. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations* 14:27-36.
- Xu Z, Li Y, Rizos C, Xu X (2010) Novel hybrid of LS-SVM and kalman filter for GPS/INS integration. *Journal of Navigation* 63:289-299.
- Yanqing W, Deyun C, Chaoxia S, Peidong W (2010) Vision-based road detection by Monte Carlo method. *Information Technology Journal* 9:481-487.
- Zhou J, Knedlik S, Loffeld O (2010) INS/GPS Tightly-coupled integration using adaptive unscented particle filter. *Journal of Navigation* 63:491-511.
- Zhou Z, Shen Y, Li B (2010) A windowing-recursive approach for GPS real-time kinematic positioning. *GPS Solutions* 1-9.
- Zhu W, Boriboonsomsin K, Barth M (2010) Defining a freeway mobility index for roadway navigation. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations* 14:37-50.



<http://www.springer.com/978-1-4419-7740-3>

Universal Navigation on Smartphones

Karimi, H.A.

2011, X, 157 p., Hardcover

ISBN: 978-1-4419-7740-3