AUTOMOBILE NAVIGATION: WHERE IS IT GOING?

Robert L. French
Consultant
Fort Worth, TX 76107

ABSTRACT

Automobile navigation systems based on dead reckoning, map matching, satellite positioning and other navigation technologies are under active development. ''Map intelligent'' systems achieve high relative accuracy by matching dead-reckoned paths with road geometry encoded in a digital map data base that may also serve other functions such as vehicle routing and geocoding. Satellite-based navigation systems achieve high absolute accuracy but require dead reckoning augmentation because of signal aberrations in the automotive environment. Future systems will probably include multiple navigation technologies. Issues influencing the design of future systems include safety concerns regarding the driver interface, and the future availability of comprehensive map data bases, real-time traffic data, and mobile data communication links necessary for on-board generation of optimum routes.

INTRODUCTION

The capabilities and functions of automobile navigation systems in the 1990s will be shaped by important issues encountered in the 1980s.

- Choosing Technology Paths
- Integrating Overall Systems
- Resolving Driver Interfaces
- Providing Map Data Bases
- Coordinating Mobile Communications

This paper reviews each of these issues, and discusses possible scenarios for the future based upon current directions here and abroad. It is a companion piece to an earlier paper which traces the history of automobile navigation and describes contemporary navigation technologies [1].

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Vehicular navigation systems, digital maps, and mobile communications equipment are interrelated product areas that have large potential markets because of their wide applicability to consumer as well as business vehicles. In the United States, for example, there are approximately 150,000,000 automobiles in use, and an additional 10,000,000 are sold each year. U.S. business fleets include 3,400,000 automobiles, 1,600,000 light trucks and vans, 600,000 heavy trucks, and approximately 500,000 buses.

Digital maps and mobile data communications combine synergistically with vehicular navigation to multiply its usefulness and effectiveness, and to enhance the potential market for both consumer and commercial applications. Table I lists system capabilities that may be realized by vehicle navigation alone, by navigation in conjunction with stored digital maps, and in combination with both digital maps and data communications. Clearly, the direction and pace of vehicular navigation system development and deployment will be strongly influenced by the availability of comprehensive digital map data bases and supporting data communications.

Table I. Vehicular System Capabilities

SYSTEM FUNCTIONAL CAPABILITIES	NAVIGATION ONLY	WITH MAP DATA	WITH DATA COMM.
Location Information			
In-Vehicle	X	X	X
Central Dispatch			X
Route Guidance			
Historical		X	X
Dynamic			X

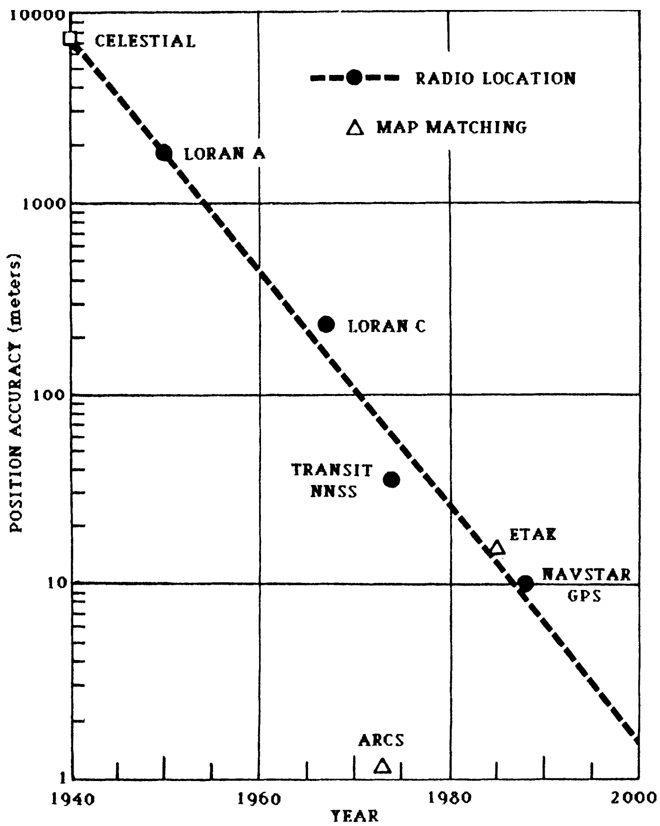

Figure 1. Improvements in Position Accuracy

TECHNOLOGY PATHS

The effectiveness of navigation technology is traditionally rated in terms of position accuracy. Figure 1 shows the improvements in accuracy that have been achieved in recent decades with multi-purpose radio-location technologies as reported by Luse and Malla [2]. The accuracy of celestial navigation in 1940 [2], and the accuracy of recent map matching technologies reported by French and Lang [3] and by Honey and Zavoli [4] are included for comparison.

Radio Location

The exponential improvement in radio-location accuracy with time is striking, but it should be noted that the target date of 1988 for Navstar Global Positioning System (GPS) availability will not be met as a result of the presently diminished U.S. capacity for launching satellites. Loran is now gaining some popularity as a means of tracking land vehicle location from a central location [5,6], but its modest accuracy, along with the persisting lack of mid-continent coverage, limits its usefulness for automotive navigation.

Although the absolute accuracy of Navstar GPS has great appeal for future automotive navigation, it is not the panacea inferred by reports following Chrysler's introduction of the CLASS concept at the 1984 World Fair in New Orleans [7] and the investigation of satellite navigation by other automobile manufacturers [8]. GPS signal disruption by buildings, bridges, foliage, etc., may produce positioning discontinuities when GPS receivers are operated in automobiles. Auxiliary dead reckoning subsystems are thus required for effective automotive navigation using GPS.

Other future satellite systems may also offer vehicle navigation as well as mobile data communication services [9]. In addition, there is potential for new radio-trilateration approaches using subcarrier signals from cellular radio transmitters [10].

Dead Reckoning

Dead reckoning is the process of determining a vehicle's location relative to an initial position by integrating measured increments and directions of travel. Most dead reckoning technologies used in automobile navigation systems were developed long before the automobile itself [1]. These include the odometer, the differential odometer, and the magnetic compass. The gyro compass, developed in 1906, has seen only limited use in automobile systems, and inertial systems are presently expensive and ill-suited for the harsh automotive environment.

Dead reckoning accuracy is difficult to quantize because it continuously decreases with time and/or the distance a vehicle is driven. For example, the vehicular odograph, a WW-II military navigation system based on the odometer and compass, accumulated 1 mile of error per 50 to 150 miles driven [11]. Even the most precise dead reckoning navigation systems require periodic reinitialization.

Map Matching

Artificial intelligence concepts may be applied to match dead-reckoned vehicle paths with road maps which are digitized and stored in computer memory. With map matching, sensed mathematical features of the vehicle path are continuously associated with those encoded in a map data base, just as a driver associates observed landmarks and road features with those depicted on a paper map to recognize position. Thus a vehicle's dead-reckoned location may be automatically reinitialized at every turn to prevent accumulation of dead reckoning error.

The first vehicular application of map matching technology was in the Automatic Route Control System (ARCS) which used a differential odometer for dead reckoning [3]. ARCS had an average location accuracy of 1.15 meters (see Figure 1) relative to predetermined routes that were initially digitized by direct field measurements using the ARCS equipment. Since the digital route map data were from replicable field measurements, the 1.15-meter location accuracy is more a measure of the effectiveness of the map matching algorithm rather than the accuracy of the dead reckoning technique or of the map data being matched.

The more recent Etak map-matching system uses a solid state flux-gate compass as well as the differential odometer to dead reckon paths for matching with digitized maps compiled from Census Bureau GBF/DIME files, U.S. Geological Survey topographical maps, and aerial photographs [4]. As shown in Figure 1, the Etak system exhibits an accuracy of approximately 16 meters relative to the digitized maps. The Etak map data base is within 16 meters of ground truth, and has a relative accuracy of 5 meters on each map according to Dial [12].

Interestingly, neither the source nor the magnitude of dead reckoning and map data errors would ...

when map matching is used. As long as the street and road connectivity is accurately defined, the map matching process identifies position relative to the road network as visually perceived by the vehicle driver. The information actually needed by the driver may thus be presented in a customary frame of reference. After all, vehicle location coordinates are of little value to a driver unless used in conjunction with a map [13].

Even relatively crude dead reckoning is sufficiently robust to support map matching when operating on a defined road network. However, good dead-reckoning accuracy is required to achieve reinitialization through map matching upon returning to the road network after off-road operation such as in a parking lot.

Proximity Beacon

This approach uses strategically located short-range transmitters, and the very reception of their location-coded signals infers the receiving vehicle's instantaneous location. Several variations of the proximity approach, some involving two-way communications with equipped vehicles, have been investigated for interactive route guidance [14]. Typically, the driver enters a destination code on the vehicle panel for automatic transmission to a roadside unit as the vehicle approaches an instrumented intersection. The roadside unit, which may be networked with a traffic management system, analyzes the destination code and instantly transmits route instructions for display on the vehicle's panel. Alternatively, the roadside unit may only transmit its location to the vehicle where an on-board computer, using stored road network data, generates the route instructions from the identified location.

The proximity beacon approach, inactive in the U.S. since Congress mandated termination of the ERGS project in 1970 [15], has been the subject of further development and testing in Japan [16] and West Germany [17] where the task of instrumenting the road networks is less formidable. For example, the ALI-SCOUT proximity beacon system, which uses dead reckoning and map matching techniques between beacons which download updated map and traffic data, is nearing testing in West Berlin [18].

FUTURE INTEGRATED SYSTEMS

What configurations will prevail in automobile navigation systems of the future? Patterns already set in the design of other automotive systems, as well as computer and entertainment systems, suggest commonality and modularity as likely system characteristics.

Figure 2 is one concept for the type of general purpose systems likely to appear in the next 15 years. It represents a composite of state-of-the-art developments, provides the modularity necessary for adaptation to specific applications, and leaves room for vendor differentiation.

Distance and heading sensing will be included even if precise location sensing, such as Navstar GPS, is available. Distance and heading sensing may be accomplished by differential odometry using input signals from existing antilock braking systems, or in combination with software compensated flux-gate magnetic compasses. The fibre optics

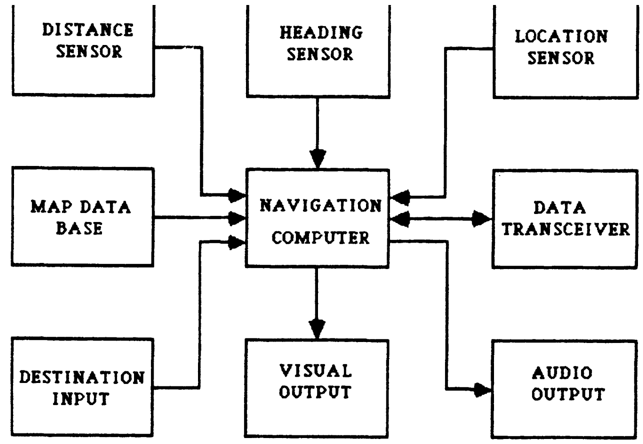

Figure 2. Future System Configuration

gyroscope [19] also shows potential as an inexpensive and rugged means for accurately sensing heading changes.

Digitized maps are as essential to the automotive navigation systems of the future as paper maps and charts were to the professional maritime navigators of the past. Large capacity storage is required for useful amounts of map data. Cooke estimates that 60 percent of the U.S. population lives on about one million streets represented in the Census Bureau's GBF/DIME files [20]. Assuming 120 to 150 bytes per street, simple extrapolation allowing for rural areas suggests that a nationwide digital map would fit on one 500 MByte CD-ROM disk.

Map matching systems based upon dead reckoning alone can become confused if digital maps are not current, or from extensive driving off the defined road network. Thus absolute location sensors, such as satellite positioning or proximity beacons, will be required if occasional manual reinitialization is to be avoided.

Data communications will also be a feature of future systems in countries that integrate traffic management with in-vehicle route guidance to enhance the benefits. One-way communication from the infrastructure to the vehicle is the most useful link. However, additional system benefits would be provided by vehicle-to-infrastructure data communications. This could provide destination information to central traffic management systems for planning optimal traffic flow or, as in the case of the ALI-SCOUT [18], eliminate the need for traffic sensors by reporting recent travel experience to the central traffic management system.

The lower three blocks of Figure 2 comprise the driver interface, an important and controversial topic which is discussed separately.

DRIVER INTERFACES

The approach to the interface between an on-board navigation system and the vehicle operator must take into account ergonomics and safety considerations as well as functional requirements. Most systems proposed or developed to date use detailed map displays or some combination of symbolic graphics, alphanumeric messages, and audio signals.

There is considerable information available to automotive systems design engineers on display and control surface location, display brightness, contrast, color, font type, character density, analog vs digital representation, and many other signal properties have been well defined as a result of many years of intensive aerospace research. Good sources of data are also available that specifically relate to automobile and traffic control device designs. However, considerably less information is available on when to present information to motorists; priorities for presentation of different types of information; temporal, spatial, and modal redundancy; and resolution of apparent conflicts in information derived from outside and inside the vehicle [21].

Insights on the driver interface issue may be gained by reviewing approaches that have been tried or proposed here and abroad.

United States

Some of the most serious research on driver interfaces was in connection with the ERGS project of the late 1960's [22]. The ERGS vehicle unit back-illuminated various combinations of arrows and words on a guidance panel. Tests were also conducted with "heads up" displays which projected simple combinations of arrows and words on the windshield so that the driver did not have to remove his eyes from the road [23].

Safety concerns about automotive use of CRT displays and elaborate control panels more typical of aircraft are exemplified by those of Zwahlen [24]. He points out the potential for visual overload leading to impairment of lateral steering control.

In the early 1970s, ARCS, an automatic route control system developed for operation over programmed newspaper routes, used prerecorded audio route guidance instructions during extensive operational tests [3]. This approach worked well, but tape recorded audio instructions were awkward to prepare and control, and systhesized speech was not yet available. Therefore, an improved version used a plasma display panel to give route guidance in the form of shaped arrows along with street names, etc. [25]. Subsequent research reported by Streeter [26] established that drivers who listened to directions drove to destinations in fewer miles, less time, and with about 70 percent fewer errors than drivers using customized route maps.

The next generation of systems development in the United States used CRT displays for the driver interface. These include satellite-based navigation systems demonstrated by Ford [27], General Motors [28], and Chrysler [7], all of which displayed detailed map images. The Etak Navigator, the only advanced automotive navigation system actually on the market in the U.S., carries the trend a step further by displaying a map that rotates to match vehicle heading [4].

Europe

European automobile navigation system designs seldom use elaborate visual displays for the driver interface. The principal exception is the Philips CARIN system [29] which includes a color CRT map display for showing vehicle location relative to the surroundings. CARIN includes synthetic voice for conveying instructions to the driver when operating in the route guidance mode.

The earliest example of a route guidance system incorporating automatic route generation using on-board digital maps was "Micropilot" developed in England in 1981 [30]. This system used an audio interface in the form of digitized voice — not speech synthesis — with a vocabulary of twenty six words.

West German designs invariably use simplified visual displays, sometimes in combination with audio messages, for conveying route instructions to the driver. Virtually all West German systems to date use some combination of short visual messages, symbolic graphics, and/or voice.

One example is the route guidance system described by Haeussermann in a 1984 paper [31]. When on highway networks, this system uses a 2-line LCD display with 16 characters per line to give the next route point and remaining distance. When on city streets, an alternate LCD display with a pointer indicates the direction of the destination, and shows numerals to indicate the remaining distance.

The first generation EVA system developed by Bosch-Blaupunkt also uses simplified graphics to convey route instructions [32]. The original prototype includes differential odometer, map data base with map matching, and route search software to generate explicit route guidance instructions. The main display includes a vertical LCD panel for graphics and a small horizontal LCD strip for character display. Voice capability is included, and is used to confirm destination entries. Turns at complicated intersections, lane changes, etc., are specified to the driver in the form of simplified diagrams which show lane boundries and use arrows to indicate the path to be taken.

Bosch-Blaupunkt also provides the interface equipment for the ALI-SCOUT system, a joint project of the West German Government, Siemens, Volkswagen, Blaupunkt and others. ALI-SCOUT is also a route guidance system, but rather than being autonomous, it depends upon the reception of area road network data and recommended route data broadcast from strategically located IR beacons [18]. Driving directions are presented much the same way as in EVA, but with an additional feature similar to the "Wolfsburg wave" [33]. The Wolfsburg wave is essentially a bar graph that, in this application, gives a "count down" to the exact point where the vehicle is to turn, thus clearly delineating among closely spaced turns.

Destination input, as well as system control, for the next generation of ALI-SCOUT (which will be subjected to large scale user tests in West Berlin starting next year) will be via a hand held wireless remote control unit with shift keys for alphanumeric information. Thus initializing the system for a trip will be much like remotely programming a VCR, and may be done by anyone in the automobile.

Japan

Current driver interface approaches for Japanese automobile navigation systems seem to align more with those of the U.S. than with Europe. However, Japan's first major step toward route guidance was the CACS (Comprehensive Automobile Traffic Control System) project [16] of the 1970s which was patterned after the U.S. ERGS (Electronic

Route Guidance System) project of the late 1960s [22]. Like ERGS, CACS used simple combinations of direction indicators and descriptors to indicate routes to be taken.

Autonomous navigation systems started appearing in Japan in the early 1980s. The Nissan Driver Guide System [34] displayed information in a simplified graphical form "in order to make the bearings and distance to the destination easily viewable while driving." Directional arrows showed the direction to the destination, and a bar graph indicated the fractional distance remaining.

Appearing about the same time was the Honda "Electro Gyro-Cator" navigation system [35] which used a CRT display to show a plot of the vehicle's path. Location could be established by using a transparent map overlay.

Subsequent systems shown in Japan incorporate color CRT map displays. These include systems displayed by several automobile manufacturers at the October 1985 Tokyo Auto Show [36]. Another example of current directions is a Loran-based Nissan delivery truck system which also uses a color CRT map display [37].

A new integrated systems approach currently under joint development by Japanese industry and government groups potentially includes an on-board computer, CRT display, compact disk with road network data, dead reckoning sensors, roadside electronic signposts for location confirmation as equipped cars pass within range, and map matching to augment dead reckoning between signposts [36].

MAP DATA BASES

"Not since cartographer Gerardus Mercator started mapping the world as round instead of flat in the 16th century has the science of map making been as stirred up." Thus observed the *Wall Street Journal* in an April 18, 1985 article on the impact of digital maps on cartography. Indeed, the introduction of the computer to map making is being hailed as a revolution that might be comparable to the development of the printing press. The market for computer mapping systems is expected to grow from $250 million to $1 billion during the last half of this decade [38].

Irrespective of the progress being made in preparing and using maps in digital form, a major barrier to widespread implementation of vehicular navigation systems will be the lack of comprehensive map data bases to support advanced navigation functions such as route guidance. Developing and maintaining the large amounts of map data required are costly tasks that are difficult to justify commercially until enough map data is available for realistic feedback on the demand [13].

The most extensive body of vector-encoded map data is the GBF/DIME (Geographic Base File/Dual Independent Map Encoding) System developed by U.S. Census Bureau for virtually all Standard Metropolitan Statistical Areas (SMSA). GBF/DIME includes street names and address ranges between nodes, as well as a variety of information not relevant to vehicle navigation. This map data base has numerous errors and represents the street network as of 1977 [20]. Nonetheless, it is a highly useful resource as it provides an established map encoding approach which is applicable to digital maps for use with vehicular navigation systems.

In particular, graph theory is used as a conceptual framework for mathematically defining the location of all intersections and the interconnecting streets or roads, thus reducing conventional road map information to computer files. Road geometry is modeled in terms of nodes and segments with nodes representing the location of intersections, turns, etc., and connecting segments representing increments of road.

In order to discuss map data requirements for vehicular navigation systems it is necessary to consider the functions to be performed [13]. The driver presumably needs a user friendly road map for trip planning, vehicle location, orientation, etc. Digitized map data is also needed for map matching regardless of what location technique is used. A third use of digital map data is for automatic routing, an especially demanding application which requires that the map data base include information on traffic directions, turn restrictions and other ephemeral data. Other digital map uses relating to vehicle navigation include geocoding (what is the location of a specific address?) and location directory (where is the nearest garage?).

Standards for digital map data bases are not yet available although the newly organized Automotive Navigational Aids Subcommittee of the Society of Automotive Engineers (SAE) has formed a task group to address the need for map data base standards. Nonetheless, one automobile navigation systems company, Etak, Inc., has undertaken development of a proprietary digital map data base for the entire U.S. [4]. The Etak map data base will support navigation systems which display vehicle location, destination, etc., relative to the road network, as does Etak's own system and the version being developed under license by General Motors for introduction in 1989. Systems which automatically generate an appropriate route to an input destination will require a map data base containing additional attributes as described above.

MOBILE DATA COMMUNICATIONS

Major potential roles for data communications in future automobile navigation systems will be to provide current updates (road additions, closures, detours, etc.) for on-board map data bases, and to provide real-time information on traffic conditions for systems that include on-board route generation. Mobile data communications offer additional advantages for commercial vehicles using navigation systems, including centralized vehicle location monitoring and dispatch control.

Mobile cellular radio offers great potential for two-way data communications with vehicles equipped with navigation systems. As the public adopts the idea of the "mobile office", there will be considerable demand for cellular radio for the transmission of data as well as voice. The necessary modems are already beginning to appear on the market [39].

For one-way data communications with vehicle navigation units, an alternative area broadcast approach such as the Radio Data System (RDS) proposed by the European Broadcasting Union [40] may be advantageous. This enables digital information to be superimposed on the normal broadcasts of FM radio stations by means of sub-carrier modulation

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