AUTOMOBILE NAVIGATION IN THE PAST, PRESENT, AND FUTURE

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ABSTRACT

One of the first automobile navigation systems appeared around 1910 in the form of route instructions printed on a turntable-mounted disk driven by an odometer mechanism in synchronization with distance travelled along the route. Instructions keyed to specific distances from the beginning of the route came into view under a pointer at the time for execution. Proximity beacon navigation, first researched in the United States during the 1960s, has largely given way to autonomous map-matching systems and to advanced radio-location systems in the 1980s. Autonomous systems achieve high relative accuracy by matching observed mathematical features of dead-reckoned vehicle paths with those of road networks encoded in a map data base, but occasionally require manual resetting to a known location. Satellite-based navigation systems offer high absolute accuracy, but require dead-reckoning augmentation because of signal aberrations in the automotive environment. Thus future systems are likely to incorporate multiple navigation technologies. The main developments yet to come are in the information and institutional areas. Private sector investments will be required for the development and maintenance of comprehensive digital map data bases, and coordination among public sector organizations will be required for collecting, standardizing, and communicating real time information on traffic and road conditions.

INTRODUCTION

Industry leaders are beginning to take it for granted that sophisticated navigation systems for automobiles will become commonplace by the end of the 1990s (Rivard 1986). The stage is being set by high-technology systems developed and tested (and, in some cases, marketed) during the 1980s. But few are aware of the surprisingly rich history of what had been accomplished in vehicular navigation long before the present decade. In fact, as we enter an era of high technology automobile navigation, we find relatively little underlying technology that is basically new, other than the on-board digital computer. The computer enables advanced radio-location schemes, and it makes map matching possible, thus breathing new life into dead-reckoning technologies that are ancient compared to the automobile itself. This paper describes the past, present and future of automobile navigation in terms of developments prior to 1980, those of the present decade, and those that may be expected beyond 1990.

AUTOMOBILE NAVIGATION IN THE PAST

Early developments relating to vehicle navigation technology are listed in Table 1. Virtually all high-technology automobile navigation systems use on-board computers to integrate and automate two or more of these technologies to provide vehicle location, heading, routing, or step-by-step route guidance. A historical overview of automobile navigation technology is given in an earlier paper (French 1986). Highlights are summarized below.

Table I. Vehicle Navigation Milestones

DATE	TECHNOLOGY
<60 AD	Odometer
200-300	Differential Odometer
1100-1200	Magnetic Compass
1906	Gyrocompass
1910	Programmed Routes
1940	Loran Positioning
1964	Satellite Positioning
1966	Proximity Beacon
1971	Map Matching

South Pointing Carriage

The South Pointing Carriage is the earliest known example of a land vehicle navigation system. This direction-keeping device is a Chinese invention dating back to 200 - 300 A.D., possibly earlier. Chinese literature confused the south-pointing carriage with the magnetic compass (invented almost 1000 years later) so thoroughly that historical research has only recently established that the south-pointing carriage had nothing to do with magnetism. Instead, it was based on the principle (now called "the differential odometer") that for a given change in vehicle heading, a vehicle's outer wheels travel a mathematically-predictable distance farther than the inner wheels. When changing heading, a gear train driven by a south-pointing carriage's outer wheel automatically engaged and rotated a horizontal turntable to exactly offset the change in heading. Thus a figure with an outstretched arm mounted on the turntable always pointed in the original direction regardless of which way the carriage turned.

Jones Live-Map

Among the first U. S. devices for car navigation was the Jones Live-Map introduced in 1909. This mechanical road guide consisted of a turntable driven by a gear train connected by flexible shaft to one of the vehicle wheels. Paper discs for individual routes had a scale of miles printed around their perimeter and were mounted on the turntable beneath a glass cover with a fixed pointer. Printed road directions keyed to specific distances from the beginning of a route came into view under the pointer at the time for execution. An advertisement for the Jones Live-Map claimed "You take all the puzzling corners and forks with never a pause. You never stop to inquire ...."

Chadwick Road Guide

The Chadwick Road Guide, another odometer-driven device introduced in 1910, had signal arms and a bell activated by punched holes in a programmed route disc. As each maneuver point was approached, one of ten signal arms bearing color-coded symbols indicating the action to be taken appeared behind a window and the bell sounded to attract the driver's attention. A Chadwick advertisement read:

> "The Chadwick Automatic Road Guide is a dashboard instrument which will guide you over any highway to your destination, instructing you where to turn and which direction. You will be warned upon your approach to rough roads, railroad tracks, speed traps. The names of the city or town through which you are passing and the name of the street will appear on your Chadwick Road Guide. Model B - $55.00, Model C - $75.00."

Short of automatically maintaining synchronized position, the Chadwick Road Guide is strikingly similar to modern concepts for real-time route guidance.

Vehicular Odograph

The vehicular odograph, a self-contained navigation system for jeeps and other U. S. Army vehicles, was developed during WWII (Faustman 1945). An electromechanical system drove a stylus to automatically plot vehicle course on a map of corresponding scale. An odometer provided a distance input measurement which was mechanically resolved into x,y components using servo-driven input from a photo-electrically-read magnetic compass. The vehicular odograph, the first example of an automated system for determining and showing vehicle location on a map, is a precursor of state-of-the-art systems for CRT display of vehicle location on a digital map. A post-WWII publication (McNish and Tuckerman 1947) speculated about the potential for civilian automobile use of the vehicular odograph:

> "One is inclined to wonder if cost would prove an important limitation if a cheaper model of the odograph were manufactured by the millions, and maps of cities and of tourist routes, drawn to the proper scale for use with the odograph, were available at every filling station."

Driver Aided Information and Routing (DAIR) System

Proximity beacon navigation, which uses strategically positioned short-range location-coded signals, was first researched in the United States starting with DAIR in the mid-1960's. DAIR, which used roadbed arrays of magnets arranged in binary code to communicate location to passing vehicles and was the subject of limited development and testing by General Motors, was a forerunner of ERGS.

The Electronic Route Guidance System (ERGS)

ERGS, which was researched by the Federal Highway Administration during the late 1960's as a means of controlling and distributing the flow of traffic (Rosen, et al. 1970), is based upon automatic radio communication with roadside equipment to provide equipped vehicles with individual routing instructions at decision points in the road network. An in-vehicle console with thumbwheel switches permits the driver to enter a selected destination code. The code is transmitted when triggered by a roadside unit as approaching key intersections. The roadside unit immediately analyzes routing to the destination and transmits instructions for display on the vehicle console panel. Although technically sound, ERGS required expensive roadside infrastructure and the development effort was terminated by Congressional mandate in 1970.

Automatic Route Control System (ARCS)

Networks of roads and streets may be modeled as internodal vectors in a digital map data base, and a particular route may be "programmed" as a unique sequence of mathematical vectors. As demonstrated in 1971 (French and Lang 1973), an on-board computer may be programmed to analyze dead-reckoning inputs and match the deduced vehicle path with programmed routes to automatically remove position discrepancies that would otherwise build up. The automatic route control system (ARCS) used a differential odometer for dead reckoning and a map-matching algorithm to correlate each sequentially measured vector with its data base counterpart. The vehicle's location along the route was confirmed, and pre-recorded audio route guidance instructions were issued where appropriate. A second version issued visual route instructions on a plasma display panel (French 1974). ARCS yielded an average location accuracy of 1.15 meters during extensive tests over newspaper delivery routes which were originally "mapped" by driving an ARCS-equipped vehicle over them while operating in a data acquisition mode.

STATE-OF-THE-ART SYSTEMS

A variety of automobile navigation systems have appeared during the 1980s. Most state-of-the-art systems fall within the following classifications:

Dead Reckoning

A dead-reckoning system called "City Pilot" is now on the European market. Developed by VDO Adolf Schindling AG, it uses an earth magnetic field sensor and an odometer distance sensor (Gosch 1986). Prior to a journey, the driver uses a light pen to read bar-coded starting and destination coordinates on a special map. Using the sensor inputs and destination coordinates, a microcomputer calculates the direction and line-of-site distance to the destination. LCD arrows show the driver which general direction to take, while numerals indicate the distance. Test results reveal that drivers using the system reach their destinations with an accuracy of 97 percent (i.e., within 3 percent of the distance travelled).

Other recent examples of dead-reckoning systems include the Nissan "Driver Guide", the Honda "Electro Gyro-Cator", and the Daimler-Benz "Routenrechner". The Nissan system (Mitamura , et al. 1983) uses magnetic compass and odometer signals to continuously compute the distance and direction to a destination whose coordinates are input by the driver. A display comprised of an array of symbolic indicator lights shows the current direction to the destination, and a bar graph shows remaining distance.

The Honda system (Tagami, et al. 1983) uses a helium gas-rate gyro and odometer to compute the vehicle's path relative to its starting point. The path is displayed on a CRT screen behind a transparent map overlay of appropriate scale. Provision is included for manually adjusting the map position to keep it in registration with vehicle path.

The Daimler-Benz system has two modes, one for city and one for highway driving (Haeussermann 1984). The city mode operates much like the Nissan system, using magnetic compass and odometer inputs to compute and display distance and direction to a driver-specified destination. In the highway mode, the system makes use of stored digital map data for the highway network. The driver inputs origin and destination, and the system computes the optimum highway route and prompts the driver step-by-step over the route. The next route point and its distance is continuously shown on a small alphanumeric display. Only odometer input is used in the highway mode; the driver must manually correct any distance error when arriving at route points.

Proximity Beacon

This approach, now inactive in the U. S., has been the subject of further development and testing in Japan and West Germany. The major new development in proximity systems is ALI-SCOUT, a joint project of the West German Government, Siemens, Volkswagen, Blaupunkt and others (von Tomkewitsch 1986). ALI-SCOUT is a route guidance system that receives area road network data and recommended route data from strategically-located IR beacons. Simplified graphic driving directions to the input destination are presented in real time on a dashboard LCD. Destination input, as well as system control, is via a hand-held wireless remote-control unit. ALI-SCOUT will be subjected to large-scale user tests in West Berlin starting this year.

Map Matching

The first commercially available automobile navigation system based on map-matching technology is the Etak Navigator™ now marketed in California. The Etak system uses a flux-gate magnetic compass as well as differential odometry and uses 3.5-MByte tape cassettes to store digital-map data (Honey and Zavoli 1985). The vehicle's location relative to its surroundings is continuously displayed on a CRT map which may be zoomed to different scales. A fixed symbol below the center of the CRT represents the vehicle position, and points to the top of the display indicating vehicle heading. As the vehicle is driven, the map rotates and shifts about the vehicle symbol accordingly. Input destinations are also shown on the Etak screen.

A map-matching system developed for testing and demonstration by Philips features the compact disc (CD-ROM) for storage of map data bases (Thoone and Breukers 1984). Called "CARIN", this system includes a route-search algorithm and provides step-by-step route guidance. A color CRT map display shows vehicle location relative to the surroundings, and voice instructions prompt the driver when operating in the route guidance mode.

Bosch-Blaupunkt has developed a map-matching system called "EVA" which uses a differential odometer and includes route-search software to generate explicit route-guidance instructions (Pilsak 1986). Turns at intersections, lane changes, etc. are specified on an LCD in the form of simplified diagrams which show lane boundaries and use arrows to indicate the path to be taken. Voice capability is included, and is used to confirm destination entries. A CD-ROM version is under development.

Satellite

The Transit navigation system, implemented by the U. S. Navy and operational since 1964, was the basis for a Ford concept car navigation system (Gable 1984). Several Transit satellites in polar orbits at a height of approximately 1,075 kilometers are longitudinally-spaced to give worldwide, albeit intermittent, coverage. Each satellite transmits information which, in combination with measured Doppler characteristics, permits calculation of receiver location by iterative solution of a set of equations. Since a Transit satellite is not always in range, the Ford system included dead reckoning for continuous determination of position between satellite passes. The vehicle speedometer and a flux-gate magnetic compass software-compensated for magnetic variations provided dead-reckoning inputs. A touch-screen color CRT provided alternative displays, including vehicle heading in several formats and a map display with cursor tracking of vehicle position.

The Navstar Global Positioning System (GPS), which is being implemented by the Department of Defense, has been considered as a basis for automobile navigation systems by both Ford and General Motors (Gable 1984), and was the basis for CLASS, the Chrysler Laser Atlas and Satellite System, a concept displayed at the 1984 World's Fair in New Orleans (Lemonick 1984). CLASS included a nationwide set of maps stored in image form on a video disc, and software for automatically selecting and displaying on a color CRT the map area incorporating the vehicle's current location as indicated by a cursor.

Still in the implementation stage, the Navstar GPS system will be completed in the early 1990s when the last of 18 satellites are orbited. The 18 satellites are being spaced in 12-hour orbits such that at least four will always be in range from any point on earth. Using timed signals from four satellites, the receiver's computer automatically solves a system of four simultaneous equations for its three position coordinates and a time bias signal for synchronizing the receiver's quartz clock with the satellites' precise atomic clocks. The signals are modulated with two pseudo-random noise codes: P, which provides position accuracies as close as 10 meters, and C/A which is about one tenth as precise. Use of the P code may be restricted to authorized applications.

Although GPS has great potential accuracy and will provide continuous coverage, auxiliary dead reckoning is required in automobile applications to compensate for signal aberrations due to shadowing by buildings, bridges, foliage, etc. A recent evaluation of GPS for land vehicles notes that, because of differing ellipsoidal reference systems, the task of melding GPS location with local maps is formidable (Mooney 1986). Hence map matching technologies may be useful with GPS as well as with dead reckoning.

AUTOMOBILE NAVIGATION IN THE FUTURE

Figure 1 shows elements and functions likely to appear in automobile navigation and information systems during the balance of this century. Dead reckoning will be included even though precise location sensing, such as Navstar GPS, will probably be available at acceptable cost. Distance and heading sensing may be accomplished by differential odometry using input signals from anti-lock braking systems, or in combination with software compensated flux-gate magnetic compasses. The fiber-optics gyroscope also shows potential as an inexpensive and rugged means for accurately sensing heading changes.

Map matching, an artificial intelligence process, will have a role in many future systems. Map matching based upon dead reckoning alone occasionally fails if digital maps are not current, or from extensive driving off the defined road network. Thus absolute location means, such as satellite positioning or proximity beacons, will be required if manual reinitialization is to be avoided. Although it appears unlikely that the proximity-beacon approach will be pursued again in the United States in the foreseeable future, proximity beacons may provide additional navigation inputs in some countries.

Large capacity storage, such as the CD-ROM, is required for useful amounts of map data. A nationwide digital map would fit on one 500-MByte CD-ROM disc. However, future systems will also allocate large amounts of storage to "yellow pages" or other directory information to aid drivers in performing personal errands and business functions.

Data communications will be a feature of future systems in countries that integrate traffic management with in-vehicle route guidance to enhance the benefits. One-way communications from the infrastructure to the vehicle is the most useful link. However, additional 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 (von Tomkewitsch 1986), eliminate the need for traffic sensors by reporting recent travel experience to the central traffic management system.

Driver inputs and system outputs are provided through a driver interface, an important and controversial system element which must take into account ergonomics and safety considerations as well as functional requirements. Most U. S. systems proposed or developed to date use detailed

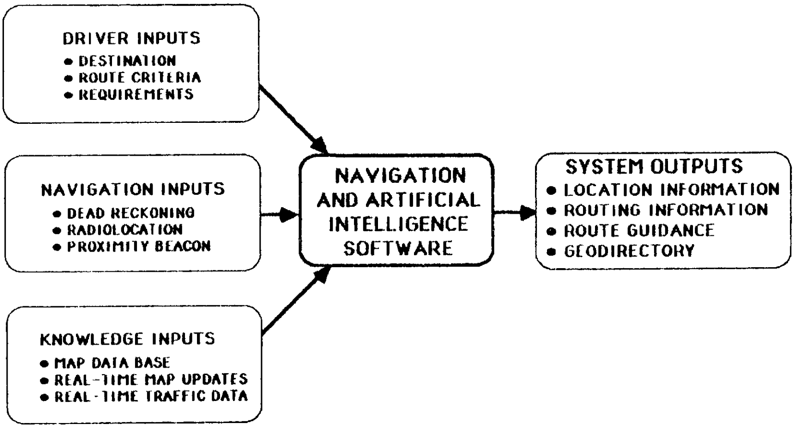

Figure 1. Future Navigation System

map displays, whereas most European systems use some combination of symbolic graphics, alphanumeric messages, and audio signals. Future systems will probably have multiple modes of operation and some will have "heads up" displays for route guidance. Driver input, presently by key pad or touch screen means, will eventually include voice recognition.

Long-term scenarios for car navigation and information system development and deployment are projected by ARISE (Automobile Road Information System Evaluation), a 1985 feasibility study performed by the Swedish consulting firm ConNova:

1990 - Autonomous, vehicle-born navigation systems are available. The main market is for commercial vehicles.

1995 - Navigation devices in commercial vehicles (e.g., trucks, taxis and limousines) have become commonplace.

2000 - New integrated road information systems give route and navigation assistance, and road traffic is flowing more smoothly.

2010 - Integrated road information systems are now fitted in half of all road vehicles, and is becoming standard equipment in new cars.

CONCLUSIONS

Car navigation based upon dead reckoning alone is limited in both accuracy and application. These limitations may be alleviated by map matching, but map matching requires digital maps. Advanced radio-location technology has good potential for high absolute accuracy, but requires dead-reckoning augmentation. Proximity beacons for navigation also provide good accuracy but require extensive roadside infrastructure. Interactive car navigation and route guidance requires integration with traffic management systems

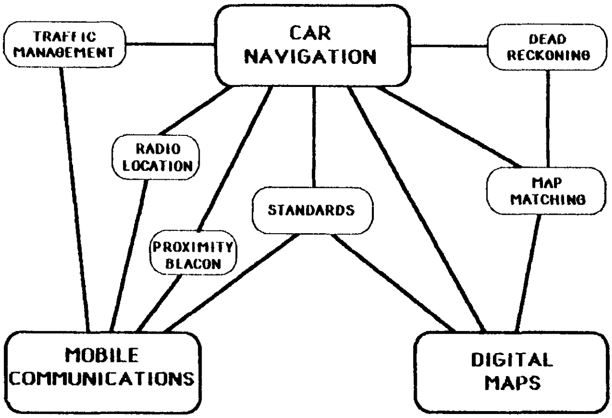

Figure 2. Navigation, Maps and Mobile Communications

which, in turn, requires data communications. Finally, car navigation, digital maps, and mobile data communications all require effective standards. Figure 2 illustrates some of the more important interrelationships.

Practical technologies for future automobile navigation and route-guidance systems have already been developed, or are within reach. Digital maps, vital to advanced automobile navigation and information systems, are becoming available, but early versions define little more than basic road geometry, street names, address ranges, and road classification. Maps for in-vehicle systems that compute best routes and provide automatic route guidance also require traffic regulation and other attributes that may influence route choice. Systems developers and map firms have been reluctant to undertake comprehensive digital map development before the market becomes better defined. However, standardization efforts by the new SAE Automotive Navigational Aids Subcommittee provide encouragement.

A remaining obstacle to advanced car navigation systems in the United States is the lack of established means for collecting and communicating real-time traffic data, as well as updated map data, for use in dynamic routing. Although mobile data communications will be essential to advanced car navigation and route-guidance systems, the U.S. public sector, unlike other developed countries, has no coordinated effort to bring about the necessary standardization.

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