HISTORICAL OVERVIEW OF AUTOMOBILE NAVIGATION TECHNOLOGY

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ABSTRACT

Sophisticated automobile navigation systems are becoming feasible largely because of low-cost computer technology. Computer technology is used to add artificial intelligence to dead reckoning navigation techniques that have been around for as long as 2000 years, and to automate radio frequency navigation concepts dating back to WW-II. This paper outlines the history of navigation technologies applicable to automobiles, and discusses their integration in various systems approaches ranging from the mechanical route guides of the early 1900's to the high-technology systems now beginning to appear.

INTRODUCTION

Navigation is an applied science that uses a variety of techniques and procedures to determine present position, heading, and/or direction and distance to a destination. For centuries, navigation technology centered on the use of celestial observations and compass readings to fix the position and set the course of ships at sea. Similar techniques were adapted for aircraft navigation, and were soon joined by radio direction finding, triangulation, inertial guidance, and satellite positioning systems.

However, except for a brief period of activity starting around 1910, automobile navigation had received little attention compared to sea, air and space navigation prior to the recent flurry of engineering projects, concept car showings, and media reports. Recent developments include a pioneering map matching system that is already on the market in California, as well as Ford and Chrysler concept cars with satellite navigation. General Motors has recently launched institutional advertising foretelling "electronic navigation systems that tell you where you are and how to get where you're going." In addition, there are international developments that, in some ways, outpace the

Key developments relating to vehicle navigation are listed in Table 1, and are discussed by category below. 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 guidance. Subsequent sections describe system concepts and functions, and give examples of both early and emerging automobile navigation systems.

Table I. Vehicle Navigation Developments

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

DEAD RECKONING TECHNIQUES

Dead reckoning is the process of determining a vehicle's location and heading relative to an initial position by integrating measured increments and directions of travel. A vehicle's current position in rectangular (x,y) coordinates is given by

$$x = x_o + \int \cos\phi(\ell)\,d\ell \qquad (1)$$

$$y = y_o + \int \sin\phi(\ell)\,d\ell \qquad (2)$$

where x_o, y_o are the initial coordinates, $d\ell$ is the travel increment, and $\phi(\ell)$ is the vehicle heading associated with the distance increment.

Most dead reckoning technologies used in automobile navigation systems were developed long before the automobile itself. These include the odometer, the compass. The gyrocompass, developed in 1906, has seen only limited usage in automobile systems.

Odometer

Descriptions of odometers started appearing in both western and Chinese literature approximately 2000 years ago (1). One early model described by Hero of Alexandria recorded distance travelled by dropping a stone into a receptacle at periodic intervals. An early Chinese odometer struck a drum at distance intervals of approximately 500 yards, and rang a bell at every 10th interval.

The odometer was the basis for a wave of mechanical road guides beginning around 1910 as a proliferation of automobiles created a demand for routing information before adequate road signs and maps were generally available. Among the first was the Jones "Live Map" (2). This mechanical road guide consisted of a turntable driven by a gear train and flexible shaft connected to one of the vehicle wheels. Individual routes were "programmed" on paper discs with a scale of miles printed around their perimeter. The discs were mounted on the turntable beneath a glass cover with a fixed pointer, and printed road directions keyed to specific distances from the beginning of the route came into view under the pointer at the time for execution.

One of the most sophisticated mechanical route guides of the era was the Chadwick Road Guide (3). Routes were programmed by holes punched in a metal disk, and signal arms and a bell were activated by the punched holes as each maneuver point was approached. One of ten signal arms bearing color-coded symbols indicating the action to be taken would appear behind a window and the bell would sound to attract the driver's attention.

Conventional mechanical odometers for automobiles are usually driven by flexible shafts attached to the drive train, and display distances to the nearest 0.1 mile. Electronic odometers, which can measure travel increments as small as one inch, are often used in automobile navigation systems. These provide sensor signals from a rotating shaft or wheel and apply a conversion factor to obtain distance travelled.

Differential Odometer

A differential odometer is essentially a pair of odometers, one each for wheels paired on opposite sides of the vehicle. When the vehicle changes heading, the outer wheel travels further than the inner wheel by an amount (ΔD) that is equal to the product of the change in heading ($\Delta\phi$) and the vehicle's width (W):

$$\Delta D = W\Delta\phi. \quad (3)$$

Thus, by measuring the differential travel of opposite wheels, a vehicle's path and heading relative to its starting point may be computed using algorithms based on Equation 3.

The differential odometer principle was used in a direction-keeping device by the Chinese approximately 200 - 300 A.D., perhaps earlier (1). The device was in the form of a horse-drawn two-wheel cart bearing a turntable-mounted statue with an outstretched arm. It was called the "south-pointing carriage" because the statue's arm always continued to point in its original direction regardless of which way the carriage turned as it travelled. When changing heading, a gear train driven by the south-pointing carriage's outer wheel automatically engaged and rotated the horizontal turntable (bearing the statue) to offset the vehicle's change in heading.

The differential odometer was tested as a basis for automobile navigation by Meyer in 1971 (4). He used the differential odometer and a mechanical dead-reckoning computer to keep track of vehicle coordinates and heading. Test results indicated heading errors averaging approximately 20 degrees per mile of travel. At about the same time, French developed and tested an electronic version of the differential odometer in an automatic route guidance system which included a map-matching algorithm to maintain much higher accuracy (5).

Magnetic Compass

The magnetic compass's well-known accuracy problems due to anomalies in the earth's magnetic field become more severe when installed in an automobile because of induced fields depending upon vehicle heading. In addition, an automobile may have a permanent magnetic field of its own, and sub-permanent magnetism may be acquired or lost when hitting bumps.

Nonetheless, magnetic compasses have long been used as heading indicators for automobiles, and modern versions of the compass are now frequently used as a component in integrated navigation systems for automobiles. Whereas the compass first appeared around the 11th century in the form of a magnetic needle floated on a liquid surface (6), current versions include compact solid state flux-gate compasses with software algorithms for compensating errors due to both permanent and induced magnetism of the vehicle.

Perhaps the earliest use of a magnetic compass in an integrated vehicle system was the vehicular odograph, a self-contained navigation system for U. S. Army vehicles developed during WW-II (7). An electro-mechanical system drove a stylus to automatically plot vehicle course on a map of corresponding scale. An odometer provided a distance input which was resolved into x,y components using servo-driven input from a photo-electrically-read magnetic compass.

Gyrocompass

The gyrocompass, which was patented in Germany in 1906 by Auschütz-Kämpfe, uses the gyroscopic inertia principle to maintain a constant reference alignment in space. One of the few examples of the gyrocompass being incorporated in an automobile navigation system is the Lunar Roving Vehicle (LRV) used on the moon where a magnetic compass would be useless. The LRV, driven on the moon's surface during Apollo Missions 15, 16, and 17, had a dead reckoning navigation system which continuously measured direction and distance travelled, and periodically calculated vehicle position. Using gyrocompass reference heading and magnetic odometer inputs, the system could return the astronauts to within 100 yards of their origin after a 20-mile journey (8).

MAP MATCHING TECHNIQUES

Navigation of an automobile from one location to another differs considerably from sea and air navigation because the automobile is essentially constrained to a finite network of streets and roads. This makes it possible to apply artificial intelligence pattern recognition concepts to match a vehicle's dead reckoned course with a mathematically mapped route or route network to compensate dead reckoning error and to determine vehicle location with great accuracy.

Map Modeling

Graph theory is used as a conceptual framework for mathematically modeling maps of roads and streets as internodal vectors. Each vector is the combination of distance and direction representing the road between two nodes defined by their coordinates. Thus, a particular route from a given initial location may be defined as a unique sequence of vectors.

The most extensive body of vector-encoded map data is the GBF/DIME (Geographic Base File/Dual Independent Map Encoding) System developed by the 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. Although a useful resourse, this map data base has numerous errors in segment connectivity, and represents the street network in 1977 (9).

Since existing map data bases may not be used without extensive correction and revision, commercial map publishers are positioning to supply special map data bases for vehicular navigation (10). One automobile navigation systems company, Etak, Inc., has undertaken development of a special digital map data base for the entire U.S. (11).

Pattern Matching

In map matching, the pattern of the vehicle's path is analyzed and defined as a sequence of vectors deduced from any of a variety of dead reckoning processes. As the vehicle travels, its measured vector sequence is continuously compared with the mapped vector sequence. Each time a turn is executed whose sense, magnitude, and location approximate those of a mapped turn, the vehicle is presumed to be at the mapped location. The matching process thus removes any dead reckoning error accumulated since the last turn.

Vector map matching was demonstrated in 1971 by French (5). An on-board computer analyzed differential odometer signals to deduce a delivery vehicle's path and match it with programmed routes. An average location accuracy of 4 feet was maintained during extensive testing of the map matching process.

Error Compensation

In addition to correcting dead reckoning errors, map matching may be used to continuously fine tune differential odometer calibration factors used in computing distance increments (12). When an adjustment is necessary to make the perceived location of a turn conform with the programmed location, the difference may be used to calculate revised calibration factors which are weighted and combined with the prior factors for subsequent use.

RADIO FREQUENCY TECHNIQUES

Numerous navigation schemes, including triangulation, phase and pulse trilateration, Loran, proximity beacons, and satellite approaches, involve the use of radio signals in determining position. The later two have received the most attention as the basis for vehicle location and navigation systems using radio signals.

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. The widest application of proximity technology is for automatic vehicle location (AVL) monitoring systems such as those used for monitoring the location and status of transit buses from a central dispatch office (13). An on-board system receives and stores a location code as the vehicle passes a proximity beacon or "electronic signpost". Upon periodic polling, the last beacon location and the distance or time since passing the beacon are automatically radioed to the dispatch computer.

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 instrumented intersections. The roadside unit, which may operate autonomously, or 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, will generate the route instructions from the identified location.

Proximity beacon navigation was researched in the United States starting with DAIR in the mid-1960's. DAIR (Driver Aided Information and Routing System), which used roadbed arrays of magnets arranged in binary code to communicate location to passing vehicles, was the subject of limited development and testing by General Motors (15). It was followed by ERGS (Electronic Route Guidance System), a Federal Highway Administration project of the late 1960's which promulgated radio communication between vehicle and roadside units (16). ERGS was discontinued in the early 1970's, largely because of the expensive infrastructure required, but similar approaches have subsequently been tested in West Germany and Japan.

Satellite

Satellite positioning has received considerable attention as a basis for automobile navigation systems. The "Transit" satellite system, which was implemented by the U. S. Navy in 1964 (17), was the basis for the Ford "Concept 100" car in 1983 (18). Transit receivers determine location by Doppler analysis of signals from a passing satellite. The satellites are in polar orbit at a height of approximately 1,000 kilometers, and are longitudinally spaced to give worldwide, although intermittent, coverage. Since a Transit satellite is not always in range, the Ford system included a dead-reckoning subsystem (based on odometer and magnetic compass inputs) for determining position between satellite passes. Selectable CRT displays showed vehicle heading, map location, etc.

The Navstar Global Positioning System (GPS), which is still in the implementation stage with the last of 18 satellites to be launched within the next few years (17), has been considered as a basis for automobile navigation by all of the major U.S. motor companies (18, 19, 20). When the satellite constellation is complete, any point on earth will always be within range of at least four Navstar satellites.

A GPS receiver could determine its three position coordinates by analyzing the travel time of signals from only three satellites if the receiver's clock was precisely synchronized with the atomic clocks that time the satellite signals. However, given the timed signals from four satellites, the GPS receiver solves a system of four equations for its three position coordinates (P_x, P_y, P_z), and for the bias (C_B) of its less precise quartz clock:

$$(x_1-P_x)^2+(y_1-P_y)^2+(z_1-P_z)^2 = (R_1-C_B)^2 \quad (4)$$

$$(x_2-P_x)^2+(y_2-P_y)^2+(z_2-P_z)^2 = (R_2-C_B)^2 \quad (5)$$

$$(x_3-P_x)^2+(y_3-P_y)^2+(z_3-P_z)^2 = (R_3-C_B)^2 \quad (6)$$

$$(x_4-P_x)^2+(y_4-P_y)^2+(z_4-P_z)^2 = (R_4-C_B)^2 \quad (7)$$

where x_n, y_n, z_n, are position coordinates of the nth satellite based on ephemeris carried by its signal, and R_n is the range to the nth satellite.

Locations may thus be determined with an accuracy of approximately 50 feet using Navstar GPS P-Code signals intended for Department of Defense applications. Less precise C/A-Code signals intended for commercial use will permit location determination to within 300-500 feet.

Although Navstar GPS will provide continuous coverage when the satellite constellation is completed, vehicle location determination may be impaired at times due to signal attenuation or reflection by buildings, foliage, terrain features, etc. Therefore, as in the case of Transit, auxiliary dead reckoning is required for GPS automobile applications.

Other RF Techniques

Of the various other radio-frequency based approaches that have been proposed or tested for vehicle location monitoring (21), Loran (LOng RAnge Navigation) probably has the most potential for automobile navigation because of its relatively wide coverage. Invented in 1940 by Loomis, Loran is a hyperbolic navigation system using multiple pairs of ground-based master-slave transmitters. U. S. coverage is complete along all coasts and most inland areas except for a band from Texas to North Dakota (22).

The master transmitter emits a sequence of electromagnetic pulses which are received by a widely separated slave station and retransmitted on a slightly different frequency. The Loran user's receiver picks up both signals and analyses the difference in arrival time to establish a hyperbolic line-of-position associated with the time delay. Repetition of the procedure for a different master-slave pair yields the longitude and latitude of the receiver at the intersection of two hyperbolae.

The availability of microprocessor-controlled receivers with improved performance at lower cost may make Loran C an attractive alternative to proximity beacon AVL in some cases (22, 23, 24). But Loran has not been pursued extensively as the basis for automobile navigation systems, perhaps due to incomplete geographic coverage as well as location inaccuracies typically on the order of 600 feet. One known use of Loran in a U.S. automobile is a General Motors test system which also includes GPS positioning (19). Loran is also used in a Nissan delivery vehicle navigation system currently being tested in Japan (25).

SYSTEMS ENGINEERING

Navigation and positioning techniques outlined above may be integrated in various combinations for automobile systems providing a wide range of functions.

Navigation Functions

Automobile navigation system functions are broadly categorized according to whether they provide the driver with location information only, with other information useful in routing selection, or with explicit real-time route guidance.

Location Vehicle location information has several possible forms. A popular concept is to indicate vehicle location by the position of a cursor on a map display panel. Another concept is to display street name and to give position in terms of address range or distance to the next cross street. Vehicle coordinates *per se* are generally not provided.

Routing A variety of other information may be useful to the vehicle driver in selecting a route to a particular destination. Examples include vehicle heading, direction to destination, distance to destination, location of destination on map display, highlighted thoroughfares on map display, etc. An approach used in a few cases displays the route travelled to the present location by plotting it on a map.

Guidance Real-time route guidance prompts the driver turn-by-turn over an appropriate route to his destination. Once the driver specifies destination and routing criteria (fastest, shortest, scenic, etc.), the system makes all navigation decisions, freeing the driver to concentrate on driving safely. Explicit route guidance may be in the form of spoken instructions, displayed symbols (e.g., arrows shaped according to the maneuver), and/or displayed messages.

System Concepts

Although the wide range of domestic and foreign systems approaches for automobile navigation defies precise categorization, it is convenient to use the classifications characterized in Table II for discussing major system concepts.

Table II. Automobile Navigation Systems

CLASSIFICATION	TYPICAL CHARACTERISTICS
Dead Reckoning	
	Low Vehicular Expense
	Autonomous Operation
	Accuracy Degrades with Travel
	Requires Manual Updates
Proximity Beacon	
	Low to Moderate Vehicular Expense
	Requires Costly Roadway Equipment
	Dead Reckoning between Beacons
	Accuracy Updated at Beacons
Satellite Positioning	
	High Vehicular Expense
	Requires Satellite Service
	High Accuracy when Reception Good
	Dead Reckoning Backup Required
Map Matching	
	Moderate Vehicular Expense
	Requires Map Data Base
	High Accuracy when Map Correct
	Compensates Dead Reckoning Error

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