How car navigation systems have been put into practical use

— Development management and commercialization process —

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Japanese manufacturers have played key roles in developing practical vehicle navigation systems (hereinafter "NAVS"). The NAVS have spread throughout the world and have become extremely useful. The market size in Japan alone is considered to exceed 5 hundred billion yen a year. This system could not have been achieved without the development of a scheme to create a nationwide digital road map, subsequent map creation, methodology to provide traffic information to vehicles, GPS development and its utilization in the United States. Much effort has been directed toward laying down infrastructure comprising these factors. Furthermore, it has been also necessary to develop the required software and hardware for the NAVS including location detection techniques such as map-matching, gyro sensors, displays, memory and microprocessors. The NAVS are presently evolving as onboard information communication systems. This paper describes their development and commercialization, which started even before the requisites for the NAVS developed fully, from a development management perspective.

Keywords **:** Car navigation system, map database, map-matching, gyro sensor, route guidance, VICS, GPS

1 Introduction

In recent years, many automobiles come with a NAVS as a standard feature, even in rental cars and taxis. One of the authors stayed in Germany four years ago and could drive in unfamiliar areas at will without using a map book, because the car he drove had a NAVS. The author did not see a turn-by-turn system simply indicating the next direction on the display, which European engineers had advocated at first. Instead, all the NAVS units were Japanese-style map navigation systems.

The very first navigation system was the south pointing chariot said to be invented by the Yellow Emperor of Yin as related in the *Abridged Eighteen Histories* of China. Centuries later, Honda created a NAVS using a gas rate gyro in 1981. It incorporated a map on a transparent sheet and projected the vehicle's location onto the sheet[1]. Honda's NAVS was followed by some subsequent devices that indicated the route to take based on terrestrial magnetic field. The contemporary NAVS began when Toyota mounted a unit on the Crown that indicated the vehicle's location on a map shown on a display device. This NAVS calculated the cumulative moving distance based on the magnetic field and on a speed sensor output. Although the vehicle location calculated by this NAVS gradually deviated from the true location, this system sparked off a trend towards vehicles provided with NAVS. Toyota's system used a small-scale 1:50000 map (1 cm on the map being equal to 500 m on the ground). In 1989, a NAVS developed by Sumitomo Electric was mounted on the Nissan Cima. This can be said to represent the first practical NAVS in that it displayed the vehicle location on a road map. This paper reviews the NAVS research and development process at Sumitomo Electric and explains key points and difficulties in making a NAVS practical.

2 Road information digitization technology as the foundation for NAVS

The NAVS is a system that displays your vehicle location on a map, suggests a route that leads to your destination along roads on the map, and displays traffic jam conditions. Therefore, to create the complete system, the onboard equipment itself is not sufficient without the development of information technology as part of the road infrastructure. Notably, Japan developed that infrastructure early on.

In Ginza, Tokyo in 1966, traffic management system demonstration tests were conducted, connecting traffic signals and vehicle detectors online and using a computer to detect the traffic and controlling traffic signals[2]. The system proved itself to be effective and was put into practical use. The challenge was to find a way to prevent the rapid increase in traffic accidents and ease traffic jams. In 1973, the then Ministry of International Trade and Industry conducted an experiment using the Comprehensive Automobile Traffic Control System[3] (CACS). In this test, coils were installed under the road at intersections, and as vehicles passed through intersections they received guidance radio waves and routes were displayed on onboard equipment to avoid

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traffic jams. To make the system practical, it was necessary to provide both onboard equipment and an infrastructure. The system was not practical, with development caught in the dilemma of chicken and eggs. However, its usefulness was proven in guiding vehicles to uncrowded roads using traffic information.

Aside from this, the National Police Agency was promoting a patrol car location system[4] (car locator in police terminology) development project to enable the control center to recognize locations of patrol cars and guide them so that the patrol cars could be deployed efficiently.

In these circumstances, already involved in road infrastructure technology, Sumitomo Electric felt the need to develop a NAVS. In 1983, having taken the initiative in traffic management and CACS projects at Sumitomo Electric, Nobuo Yumoto (later Senior Managing Director) found map-matching that was being developed in the US, and realized if it could be incorporated into the NAVS, the system could be made practical. He then began developing a NAVS employing the map-matching system.

Subsequently, the government and the private sector collaborated to develop the technology for the Road and Automobile Information System. In 1984, the Road / Automobile Communication System (RACS) started operation and in 1987, the Advanced Mobile and Traffic Information Communication System (AMTICS) commenced. These systems facilitated acquisition of vehicle information. Meanwhile the NAVS began to be installed in vehicles. There was a growing trend toward introducing a new vehicle information system for mobile units. Consequently, existing members of AMTICS and RACS plus new members established Vehicle Information and Communication System (VICS) in 1991, which later evolved into the Intelligent Transportation System (ITS).

3 Navigation system development

In its development of the NAVS, which consisted of an onboard NAVS and a patrol car locator, Sumitomo Electric developed common technology and parts for both. This report focuses on the NAVS.

3.1 Current location detection technologies

(1) Technological development of map-matching[5]

The basic technologies for the NAVS are: location detection to determine where the vehicle is, and route computation to calculate the route to the destination and guidance to guide the vehicle along the route.

Location detection, one of the basic technologies, is relatively easy using the GPS satellite-based system. In the early days of our development of the patrol car locator and NAVS, there existed only a few GPS satellites. Moreover, the GPS satellites were still under construction and were not fully usable, being available for only one to two hours a day for location calculations.

1) Development of map-matching

In principle it is possible to identify the current location if the original location, driving distance from that location and driving directions are known. This method is known as dead reckoning. One critical factor in dead reckoning is the accuracy of the sensors used to detect driving distance and directions. Although highly accurate and highly expensive sensors were used in submarines and aircraft, it was not cost effective to use them in automobiles. US-based Etak developed a method to achieve correct location detection without expensive sensors. This method was map-matching which, assuming that the vehicle moves on roads, compares the vehicle's trajectory detected via dead reckoning with a map and corrects the errors, thereby minimizing cumulative errors produced by the sensors and detecting the correct location. Figure 1 shows a schematic for illustrative purposes.

The blue line represents the dead reckoning-based trajectory. Slight deviations in driving distance and direction result in a gradually accumulating error from the true location on the road indicated with the green line. When the vehicle makes a turn at an intersection, map-matching accesses road map data to search for the location of the intersection and corrects the vehicle's current location to the intersection location.

The red line represents the corrected trajectory based on map-matching. The trajectory is corrected to be on the road, which reassures the driver. Sumitomo Electric pondered whether or not to adopt Etak's technology. Differences concerning road density and road configuration between Japan and the United States and other substantial discrepancies that would affect the logic, as well as prospects for future development, made the company develop the required technology in-house.

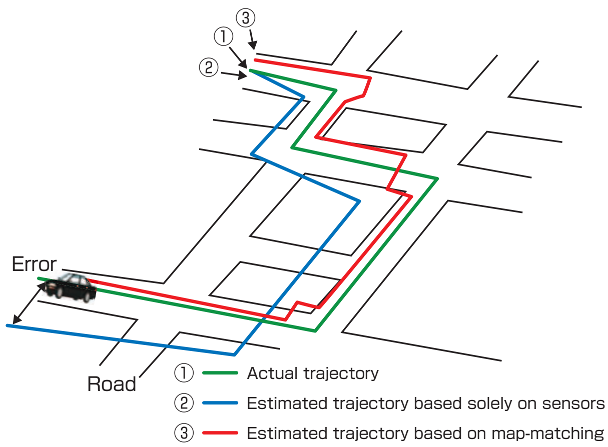

Fig. 1 Principle of map-matching
(Courtesy: Sumitomo Electric Industries, Ltd.)

2) Sensor hardware and software concept
Sensors are required to detect the travel distance and rotation angles. Requirements for use in automobiles include low cost of the order of hundredths to thousandths of the cost of sensors for submarines or aircraft, relatively good accuracy, no need for servicing, and ruggedness during the service life of the vehicle which is some ten years.

Travel distance and rotation angles are determined based on the average number of revolutions of both wheels and the differences between them. Since Sumitomo Electric manufactured anti-lock braking systems (ABS), we were familiar with ABS wheel speed sensors and asked automakers to allow us to use them as travel distance and rotation angle sensors. Since rotation angle sensors are incapable of indicating the absolute direction, a magnetic field sensor was also incorporated. Wheels slip, so the number of revolutions of a wheel differs from the actual travel distance. Magnetic field sensors are subject to substantial errors depending on the location, such as a point close to a DC-driven electric train. Thus, it became critically important to develop software to correct these errors by map-matching. To test the software, we drove actual vehicles on various courses and conducted simulations using data acquired from the actual driving. Nonetheless, it had turned out through the test driving and simulation that the accuracy of the rotation angles determined from the difference between both wheels was inadequate. Eventually, we developed an optical fiber gyro[6], which will be discussed later. Other components were selected for automotive use from those used widely in automobiles and that were sufficiently reliable and durable under vibration and high and low temperature conditions. To display a map and the optimal route, we first used a six-inch CRT (some vehicles already had them installed). Maps were recorded on a CD-ROM. In 1989, a NAVS incorporating these systems was adopted for the Cedric and Cima (Fig. 2). Today, the CRT and CD-ROM have been replaced by an LCD unit and either a DVD or a hard disk.

Fig. 2 Vehicle navigation system
(Courtesy: Nissan Motor Co., Ltd.)

NAVS produced around 1990 used six-inch CRTs. The NAVS was positioned where audio and air-conditioner controls had been previously installed. Audio and air-conditioner control functions were included in NAVS features.

3) Commercialization concept
We used ABS sensors as wheel speed sensors for our NAVS. Accordingly, our NAVS could be installed only in vehicles that had an ABS system, while at that time, few consumer vehicles were equipped with ABS. Requirements concerning the magnetic field sensor included: erasing magnetic effects of the iron body by the automaker during production; recording sensor constants by revolving and checking the magnetic orientation; and subsequent automatic correction by wheel speed sensor readings and map-matching.

In location detection by map-matching, it is basically necessary to set a starting point. In addition, the actual road may differ from the map and the vehicle location may be lost during driving. On such an occasion, it becomes necessary to re-input the starting point where the vehicle location is identifiable. Since this would have to be carried out by the user, it was necessary to reduce the frequency of such occasions and to make operation simple.

To meet these requirements, it was necessary to make displayed information easy to read and the starting point setting operation simple. Consequently, in addition to the software for vehicle location detection and route navigation guidance, the software for information display and NAVS operations gained monumental importance.

This NAVS system required a digital road map for map-matching in addition to a map for display. Since such a map did not exist, we decided to develop one ourselves (explained later).

In addition, the NAVS display played an important role as a vehicle information display unit. Software was developed to display vehicle information. Target prices were roughly ¥50,000, ¥100,000 and ¥200,000. Using a large color display, no significant cost reduction could be expected. Basically, the NAVS was an expensive commodity. Although aftermarket units were available, their inexpensive yet small displays were subject to poor readability. They were not suitable to be marketed as original equipment manufacture (OEM) systems that needed to ensure safety, and therefore we excluded them from the options.

(2) Developing orientation detection gyros
1) Developing an optical fiber gyro[6]
Regarding sensors used to measure vehicle rotation angles, the accuracy of determining the difference in the number of revolutions between both wheels is not precise enough. Because of this problem, early NAVS frequently got lost, with

map-matching capacity limits being exceeded. We believed it was necessary to improve the accuracy of the rotation angle sensors. Thus, we explored the ways to reduce production costs of the optical fiber gyro (sample priced at millions of yen) that had been developed at Sumitomo Electric at that time for robots used to work in adverse conditions, and to remodel this gyro into one for the NAVS. Fortunately, we ourselves could produce most parts required for the optical fiber gyro. We mass-produced each part at a low cost and lowered precision to reduce the cost to a level acceptable for NAVS applications. A double digit cost reduction was somehow achieved, and it became possible to install it in the vehicle. The introduction of the optical fiber gyro contributed to improved performance to a level where the NAVS would get lost only once or so per 200 km driving.

2) Vibration gyro[7]

The GPS became available for NAVS in 1990. Since then, optical fiber gyro-level accuracy has not been highly required for rotation angle sensors. Instead, lower-cost sensors have been in demand. As vibration gyros designed to prevent camera shake emerged on the market, we explored the possibility of using them for NAVS. Vibration gyros designed for cameras were aimed at detecting hand motion, with no consideration given to offset drifts occurring over an extended period of time. We drew up specifications and requested sensor suppliers to develop a vibration gyro for NAVS. It has turned out that Murata Manufacturing Co., Ltd. was able to produce an almost satisfactory gyro sensor, enabling us to replace the optical fiber gyro with a vibration gyro. We did not solely rely on the performance improvement of the vibration gyro itself, but also provided the gyro-handling software with additional functions such as offset drift estimation during driving and estimation of the drift amount by gyro temperature measurement. Because of these software capabilities, the vibration gyro we employed was smaller and less expensive than the optical fiber gyro, yet was five times greater in zero offset.

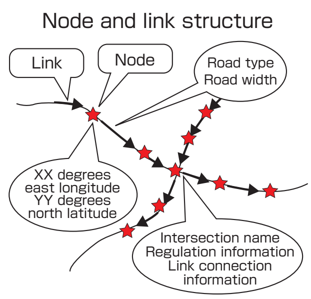

Fig. 3 Road configuration data
(Courtesy: Sumitomo Electric Industries, Ltd.)

Fig. 4 Plotting example of actual roads
(Courtesy: Sumitomo Electric Industries, Ltd.)

3.2 Development of route calculation and guidance technologies

Since accurate detection of the current location was achieved, there were demands for capabilities to determine the optimal route up to the destination and to guide the vehicle to turn right or left during driving. Route computation algorithms were developed largely in academic laboratories. Prerequisites to route computation were often huge memory and map data storage allowing for fast readout. In contrast, with NAVS it was necessary to quickly compute 500 km routes between Tokyo and Osaka using the base speed of CD-ROM and lowest cost memory. We made route computation fast, spending only 30 seconds, instead of the 30 minutes required by the conventional method.

3.3 Development of digital road maps

(1) Providing a map database

Map-matching requires digitized map data, in the configuration of which an intersection and section between intersections are referred to as a node and a link, respectively. Map-matching data contains road connection relations, one-way traffic regulations and other information. Thus, it is far more elaborate data than map data structured solely for display purposes.

In Fig. 3, nodes are intersections and curves on roads and come with information such as coordinates, intersection names and connected links. Links are vector data in which nodes are connected by straight lines, containing information such as road attributes and widths.

Figure 4 shows an example of actual roads. Roads connecting to an expressway constitute many links that imitate actual curves. Figure 5 shows a displayed map, which contains water systems, building shapes, place names, facility names and other information for readability.

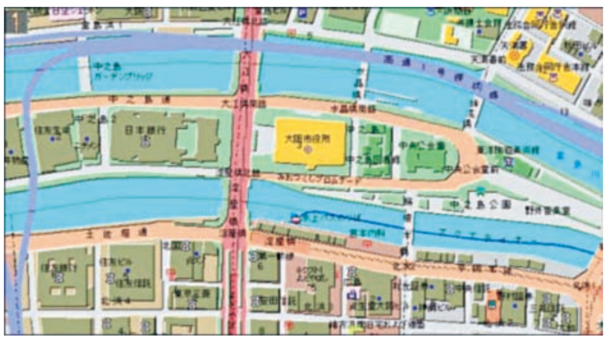

Fig. 5 Example of map data display
(Courtesy: Sumitomo Electric Industries, Ltd.)

At first, each NAVS supplier independently began data development. Sumitomo Electric developed data for the three metropolitan regions based on detailed map data such as 1:2500 urban planning maps issued by power companies, gas companies and municipalities. This process required permissions from municipalities. Our development staff branched out and visited municipal governments to obtain permission.

(2) Japan Digital Road Map Association[8]
Independently-developed map data was sufficient to meet early metropolitan application requirements. As there were growing trends toward wider use of the NAVS, however, each supplier became aware that map data should not be developed separately by private businesses, spending a large number of man-hours and large expense. Accordingly, we worked on interested sectors. Our efforts led to establishing the Japan Digital Road Map Association to develop digital road maps, with the then Ministry of Construction taking the initiative. Key issues in founding the association were specifications (standardization) and members (user attraction). One major achievement was that automakers decided to cooperate in the domain of surveys and editing for the industry's sake while leaving the domain of designing how information is displayed for the competition. Participants from the then Ministry of Construction were the Road Bureau and the Geospatial Information Authority of Japan. Although shared use of map data implied loss of differentiation, private businesses took part in the association, providing funds and member fees and sending engineers, in anticipation of cost reductions.

Meanwhile, functional requirements for map data have changed with the advance of the NAVS. Simply displaying the current location, the first generation was required to ensure network accuracy. The second generation, which displayed a route to the destination, met the needs for information on regulations, such as one-way traffic, right/left turns and presence/absence of a median strip. The third generation, displaying traffic information, was required to ensure consistency with traffic jam data management units. Since then, the Digital Road Map Association has provided data to sustain the NAVS in Japan. Route navigation was achieved by combining the original map data with the no-right/left turn and other traffic regulation data administered by the police.

3.4 Receiving traffic information

Japan makes optimal use of traffic networks constructed on its narrow land. Road traffic management in Japan is the most advanced in the world. Traffic jam conditions have been monitored by numerous vehicle sensors[9], image sensors and intersection-monitoring cameras installed on roads. Traffic jam information was provided to NAVS via multiple media: FM broadcasting administered by the then Ministry of Posts and Telecommunications; radio wave beacons[10] on expressways administered by the then Ministry of Construction; and optical vehicle detectors[11] (optical beacons) on general roads under the control of the National Police Agency. The Vehicle Information and Communications System[12] (VICS) Center was founded through the efforts of interested parties. Information collected at the VICS Center was sent to NAVS via each media center. This scheme enabled NAVS to obtain information on nationwide traffic jam conditions. Thanks to the efforts of involved parties from the business sector, we were able to overcome the challenge of integrating the different mediums and were able to develop a uniform format for shared data sent via radio waves.

Again, data processing software was important for receiving data from the beacon. It was necessary under any display conditions for the NAVS to instantly display simple graphic data unique to a specific location, sent from a beacon, as with handling an interrupt. Receiving beacon data at times of high CPU or memory load, as when changing to a different display scale or route re-searching, resulted in heavy demands on internal processing.

In providing traffic information, it was necessary to ensure correspondence among expressions of map data containing traffic jam information, data at the VICS Center, and data on onboard NAVS units. A solution was developed thanks to the efforts of interested parties.

In Fig. 6, green and red arrows on the map represent uncrowded and crowded roads, respectively. In 1973, CACS envisioned coordination between onboard equipment and infrastructure. A coordinated system was finally achieved in 1996 when NAVS had become popular and VICS was established.

3.5 Development of other core components

The NAVS was required to perform map-matching and show computation results of a route up to the destination and route navigation in real time over the map on the display. This resulted in a need for large memory, software size and computational power previously unseen with conventional onboard equipment. Semiconductor memory in the initial phase of development was far below the required level of capacity to store display and map-matching maps within the

Fig. 6 Map displayed with traffic jam information

practical scope of applications. We selected CD-ROMs even though the media was seldom used in vehicles at that time. In employing CD-ROMs, we introduced CD drive suppliers to an oil damper developed by Tokai Rubber Industries, an affiliate of Sumitomo Electric, so that CD drives could withstand vibrations in the vehicle.

Furthermore, ROM was selected as program memory to store programs up to 1 Mbyte. For map operation memory, we selected DRAM, although it was also rarely used for automotive purposes. We employed these devices with automotive environmental testing and reliability considerations in mind.

The United States started refining the GSP for military purposes in around 1988, and the system has been permitted to be used by civilians with intentionally reduced accuracy. GPS made it possible to determine the current location without the aforementioned sensors in vehicles, only requiring the provision of a receiver. In around 1990, GPS NAVS emerged on the market, which were mostly off-the-shelf NAVS because they were easy to install. At first, since there were not a sufficient number of satellites in the sky required for positioning, GPS NAVS became useless in tunnels and in the shade of buildings where no satellite was in view. In around 1995, however, GPS NAVS became almost practically useful. When the effect of accuracy degradation was removed in 2001, they easily reached the practical level.

3.6 Promoting sales to customers

Sumitomo Electric developed digital road maps of Osaka and the surrounding areas, tested the NAVS and began appealing to automakers six months after we independently started developing the NAVS in 1983. Our project was highly regarded by Nissan. Mass production of map-matching NAVS incorporating wheel speed sensors, a magnetic field sensor and a 1:2500 map commenced in 1989 with a planned monthly output of 1000 units for the Cima and Cedric, although the unit needed to improve in positioning accuracy. In 1991, we offered optical fiber gyro-equipped NAVS for the Cedric and Cima. Subsequently, however, Nissan founded Xanavi Informatics Corporation jointly with Hitachi as an attempt to develop NAVS in-house. Thereafter, although our systems were selected by customers excluding Toyota, a substantial amount of man-hours required to meet customized requirements resulted in huge deficits, and this became problematic in terms of business operations.

Meanwhile, audio manufacturers and other suppliers began offering aftermarket NAVS, which gradually became predominant. Although we speculated that OEM NAVS would go mainstream as a driving assist system in the future, we entered into a competition in the aftermarket against the will of some of our employees because we considered that gaining a reputation in the aftermarket was indispensable to our survival in the business. While many GPS NAVS displayed current locations away from roads or even on a lake according to GPS-detected coordinates, our positioning accuracy and quick route computation, achieved with OEM onboard NAVS, were well-received.

4 NAVS business: development and withdrawal

4.1 Development cost burden and business profitability

As we worked on NAVS hardware development, along with improvements in location detection, view for the map, route computation and route guidance, and paying costs of nationwide map development and updating, it was impossible to continue the NAVS business without successful prospects for business profitability. To recover these costs, required NAVS sales were at least 20,000 units per month.

Vehicles equipped with an OEM NAVS at that time numbered some thousands per month at each automaker, although the number was very large at Toyota, to which Sumitomo Electric was not shipping. We received orders totaling less than 10,000 units per month even during busy periods. At that time, we thought that the NAVS market would explode and our sales volume would soon reach a profitable level. Contrary to our expectations the market growth halted after the burst of the bubble economy, and our business was constantly underperforming. One cause of the failure of our NAVS business model was that we could not develop a scheme in which automakers would pay the heavy costs of map data and software development.

Consequently, to somehow improve profitability, we collaborated with our competitors in map database construction and even in NAVS development.

4.2 Onboard NAVS software development problems

After entering the aftermarket, we still worked with multiple automakers on developing OEM NAVS. With them it was necessary to enable audio and air conditioner controls to be displayed on the same screen. Different vehicle families came with different instrument panel designs and the number of switches installable on the instrument panel would also change. The presence or absence of one switch necessitated a substantial software revision, as in the case where use of a different cell phone model entails a substantially changed feel of operation. After 1995, in addition to adapting the NAVS to different vehicle families, we implemented novel major software features such as VICS reception and access to the Internet. In order to launch new features such as VICS support and Internet connections ahead of competitors in such a period it was important to standardize the software so that the functions could be simply expanded.

To ensure that the above-mentioned adaptation and launch of new features met multiple automakers' requests, we needed highly capable development staff, which resulted in software development costs dragging the business down.

Nonetheless, Sumitomo Electric was then developing our original NAVS operating system aiming to boost the performance of NAVS. Our aftermarket NAVS launched in 1995 was highly regarded due to its fast operation. On the other hand, specialized operating system and application software necessitated operating system upgrading for adaptation to different vehicle families of individual automakers and for implementing novel functions. To provide access to the Internet, it was necessary to develop a new original browser. These difficulties in providing new features incurred huge software development costs and man-hours. As a result, by necessity, we requested automakers to give up implementing some features.

In the meantime, the NAVS released in 1997 underwent specification changes, which in part caused software development man-hours to increase from the initial estimate of some 200 man-months to 1000 man-months at the time of completion, resulting in a substantial cost increase. Moreover, the software had so many bugs, which were detected after the release, which raised maintenance costs and substantially increased the deficit. This was one major factor in our pulling out of the NAVS market.

Meanwhile, "concentration on core competence" became a keyword in the business sector. Sumitomo Electric decided to withdraw from the NAVS business because it had run up huge deficits and had no prospects of improvement.

5 Summary

The NAVS has been successfully developed not simply by NAVS software development, but through synergetic effects of developing substantial infrastructure and related technologies, such as a map database, traffic information, communication modes and various hardware units. Today's widespread use of NAVS has been achieved through cooperation among persons concerned at the then Ministry of Construction, the then Ministry of Posts and Telecommunications and the National Police Agency; Toyota, Honda, Nissan and other automakers; many NAVS suppliers including Denso, Mitsubishi Electric, Alpine and Pioneer; Panasonic, Hitachi and other infrastructure developers; and component suppliers involved in developing small vibration gyros, GPS, display units and other components.

Figure 7 shows technologies and components employed in NAVS as well as related infrastructure in chronological order. Accordingly, the NAVS is complete, consisting of a number of technologies, combinations of components and software that ensures efficient use of them.

Map data evolved from proprietary data possessed by individual companies to shared data. Sensors technology saw the emergence of vibration gyros. When GPS was developed, it became simple to detect the current location with high accuracy. As display devices, the price of LCDs fell. Trends in the area of functional enhancement were improved performance of CPUs, increased memory size, and advances from CD-ROM to DVD or HDD.

Another factor contributing to the widespread use of NAVS was the simultaneously developed infrastructure. The Japanese Intelligent Transport System (ITS) emerged as NAVS became popular and has now become essential to automobiles. Subsequently, the development of the electronic toll collection system followed.

The NAVS plays the role of an information center in a vehicle, displaying images of onboard cameras and various other pieces of information. Integration between the NAVS and driving control is advancing, as exemplified by automatic deceleration before the intersection at which the vehicle is to make a turn. Meanwhile, portable navigation devices (PNDs) are becoming popular abroad at a remarkable pace. NAVS are expected to be more ubiquitous in the future, becoming polarized into high-end OEM NAVS and affordable PNDs.

Acknowledgments

The development of NAVS for practical use has been achieved through the efforts and contributions made by many involved parties from the industrial, governmental, and academic sectors. We hereby recognize their achievements and express our gratitude to them. We need to mention that former Sumitomo Electric executives Nobuo Yumoto

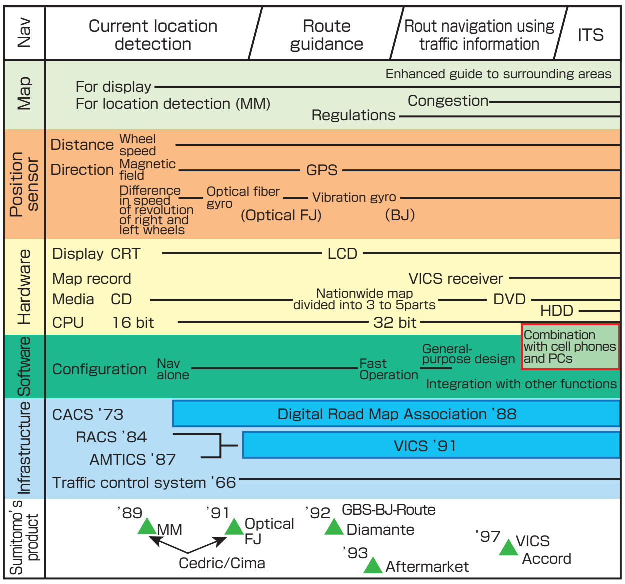

Fig. 7 Correlations in development of car navigation system

and Kunihiko Mito contributed to solving many problems involved in developing NAVS. We would like to express our thanks to Mr. Mito for his support in preparing this paper. We have promoted the development, commercialization, onboard installation, and other plans for the NAVS. However, the project turned out to be unsuccessful as a business, and we had no choice but to withdraw from the NAVS business. In conclusion, as the individuals responsible for the project, we would like to express our heartfelt regret for having caused a great deal of inconvenience to many involved parties over the period of the project.

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Kazuo Hirano

Graduated in 1974 from the Department of Applied Mathematics and Physics, Faculty of Engineering, Kyoto University. Joined Sumitomo Electric in 1974. Began to work on wiring harness electronics and NAVS development in 1981. Took the post of Manager, Automotive Electrical & Electronics Div. in 1996. Moved to the post of Deputy Director, Automotive Technologies Laboratories. and then to the present post of Manager, Strategic Planning Div., Automotive Business Unit. In this paper, Hirano was principally in charge of onboard NAVS software development and VICS construction.

Discussions with Reviewers

1 General

Comment (Akira Kageyama, Research and Innovation Promotion Headquarters, AIST)

The content of the paper is suitable for *Synthesiology*, as it concisely describes extensive elemental technologies used in car navigation systems (NAVS). The paper makes it clear that a wide range of technologies is required to launch a product to the market. At the same time, it describes what technologies are employed or dismissed in order to achieve a goal, and how a specific technology is combined with those in other fields. The paper is of great value in providing an example of corporate research and development management.

Furthermore, despite its limited number of pages, the paper mentions the establishment of the Japan Digital Road Map Association, collaboration with other corporations, and cooperation with government agencies as important elements of research and development management. This makes the paper a representative one on *Synthesiology*.

2 General perspective on combining individual elemental technologies

Comment (Akira Kageyama)

The paper refers to: (A) location detection, (B) route calculation and (C) route guidance as key elemental technologies and, beginning with map-matching, introduces. the reader to candidate technologies usable for the completion of (A), several technologies suited to the completion of (B) and a few technologies needed to complete (C). I think the paper can include an illustration or a list of elemental technologies used to complete NAVS as a practical technology, in order to help readers unfamiliar with the subject field understand the topic. Such an illustration or list would facilitate reader understanding of the need of a lot of technologies in producing NAVS.

Comment (Motoyuki Akamatsu, Human Technology Research Institute, AIST)

If a figure is provided showing how course changes were made when selecting technologies regarding each individual major technological element, such as map-matching, location identification, digital map and route calculation, depending on new factors of the time (GPS, CPU and storage devices), readers would immediately understand that the development scenario underwent dynamic changes to keep up with technology trends.

Answer (Hirosaka Ikeda)

We inserted Fig. 7 in “5. Summary” to show relationships among elemental technologies.

3 Importance of software technology development for unified control of diverse hardware technologies

Comment (Akira Kageyama)

The paper states that not only sensor technology, but also software technology is important. I think it is better to place more emphasis on the importance of OS and other software research and development. Software appears to play a critical role in combining sensor technology and digital maps, location correction and processing of data received from radio-wave or optical beacons.

Answer (Hirosaka Ikeda)

A NAVS is an onboard device in which software technology plays an important part, as you point out. Its software size is far larger than those of other onboard devices. The paragraph on vibration gyros in subchapter 3.1 of the paper now has an additional description about software improvement needed for the use of vibration gyros, since they are poorer than optical fiber gyros in performance of the hardware itself, specifically in drift amount. Regarding beacon data reception, the paper describes the need for complex internal processes due to intensive loads, such as switching to an interruption screen after receiving beacon data.

4 Technological development process

Question (Akira Kageyama)

The paper states that a huge increase in software development cost necessitated the withdrawal of Sumitomo Electric Industries, Ltd. from NAVS business. Sumitomo Electric’s withdrawal is very regrettable, since the company led the industry in the early days of NAVS. Nonetheless, could you please, from an engineering or industrializing perspective, summarize key technological or management points that enabled NAVS and ETC to later develop into high growth industries?

Answer (Hirosaka Ikeda)

(1) Key points that led to high industrial growth

1) One key technological point is that the NAVS is, as with television, a commodity that is used repeatedly. Once a customer tries it, he or she cannot go without it. Take the example of television in the early days; people argued, from an educational point of view, that they had no need for television in their homes, as it would lead to home environment degradation. Today, multiple television sets are found in every home.

The NAVS was in a similar situation in its early days. Most staff at automakers’ electronics divisions said that automobiles did not need navigation systems. One said: “What are you doing, Mr. Ikeda, at this busy time? You should stop fiddling with NAVS development.” He later took the post of NAVS development manager and said: “Mr. Ikeda, I was wrong.” At that time, market surveys showed that few people wanted a NAVS in their cars. On the other hand, interestingly, one automaker executive did not trust so-called marketing approaches. He said: “Mr. Ikeda, it’s meaningless to ask customers whether they want a product that is not yet on the market. They have no idea.” Professional taxi and company drivers said that they needed no NAVS, that looking at a map would be sufficient. The NAVS has now become a necessity for them. In this sense, the NAVS is a driving assistance system. Derivative words from NAVS are now used in other fields, proving the wide acceptance of NAVS.

2) Few automotive parts cost more than ¥10,000, and even fewer exceed ¥100,000. However, the NAVS has proven that expensive onboard equipment can be viable. Moreover, the NAVS involves extensive supporting industries. For instance, there is a market even for onboard LCD alone.

3) NAVS software was the largest embedded automotive software. Since its quality and reliability requirements were far higher than those in other industries, including the PC industry, NAVS software improved noticeably. As with hardware, software quality requirements are high in the automotive industry. Users would immediately notice defects. General IT companies would not be able to take part in genuine brand NAVS production. Company distinction was created in that business sector, according to quality. The sector was characterized in that zero bug tolerance was a fundamental requirement. But this was a trap that Sumitomo Electric fell into when conducting its development management.

(2) Software breakthrough

When you build software, you need to think about both functional differentiation through pursuit of your originality, as well as ease of expandability provided by commonality. In my view, Sumitomo Electric was preeminent above all others in NAVS performance. However, in the years following 1995, it became necessary to add major features such as compatibility with VICS and support for the Internet. We should have been aiming for commonality at that time. Nonetheless, Sumitomo Electric took the course of developing its proprietary OS in order to achieve functional differentiation and fast operation. As a result, the company had no choice but to provide major additional features by itself. We revised the paper to include this information.

5 Information on Etak’s NAVS

Question (Motoyuki Akamatsu)

Etak, the company that released the world’s first map-matching technology, launched a NAVS in 1985, while the paper states that Mr. Yumoto became interested in map-matching technology in 1983. Did he learn about the technology because there were some papers on map-matching published before Etak commercialized it?

Answer (Hirosaka Ikeda)

When Yumoto, then working for Sumitomo Electric, visited

America on a business trip, he got information from Dr. Robert French, a NAVS trailblazer, and tried Etak's prototype NAVS. Incidentally, the map used for that NAVS was a simple one.

6 International comparison of NAVS proliferation

Question (Motoyuki Akamatsu)

Concurrently with Gyrocator, developed by Honda Motor Co., Ltd., Electro Multi Vision by Toyota Motor Corporation and Sumitomo Electric's system, US-based Etak developed and launched their NAVS. Eventually, NAVS came into widespread use in Japan. Why the difference, do you think?

Also, I would like to hear your view on why the Japanese industrial sector was highly motivated and why the Japanese government showed a positive attitude toward NAVS.

Answer (Hirosaka Ikeda)

(1) Differences in NAVS proliferation

In the United States, cities have streets and avenues neatly arranged in a grid pattern. Access points to inter-city roads are numbered and easy to follow, reducing the need for NAVS. For route guidance in America, itemized information is more often used than maps, further reducing the need for map-based NAVS.

In Europe, by contrast, city states of long history have winding roadways that are extremely difficult to follow. In such places, the NAVS is readily accepted, as in Japan.

Japanese people are generally early adopters. In addition, the country had advanced technologies for NAVS, including gyro sensors, displays, CD-ROM drives, semiconductors and traffic information communication systems.

(2) In the motivated industrial sectors, NAVS system and map development was promoted by automotive, car electronics, audio, electric and map manufacturers. Parts suppliers worked on gyro sensors, GPS, semiconductors including microprocessors, CD/DVD/HD drives and displays. Moreover, many emerging IT companies entered the market as a new field for them and provided embedded NAVS software.

(3) The government, I think, was interested in NAVS as a new industrial sector involving infrastructure.

7 Distinction from review papers

Comment (Akira Kageyama)

Readers of this paper may have the impression that it is a review of the technological development of NAVS, or a research and development history. Therefore, it is recommended that it be stated why a specific technology was selected from among a set of candidate technologies for research and development, and in what aspects the selected technology was superior to the other candidate technologies, by providing semiquantitative data or something similar.

Answer (Hirosaka Ikeda)

Regarding the optical fiber gyro, we inserted a sentence: "The introduction of the optical fiber gyro contributed to improved performance to a level where the NAVS would get lost only once or so per 200 km driving." For the vibration gyro, the following has been added: "We did not solely rely on the performance improvement of the vibration gyro itself, ... Because of these software capabilities, the vibration gyro we employed was smaller and less expensive than the optical fiber gyro, yet was five times greater in zero offset."

8 On *Synthesiology* paper

Question (Motoyuki Akamatsu)

Your present paper is on NAVS development and commercialization. Could you please mention specific information that you have provided for the first time in the *Synthesiology* paper and may not have included in other papers for conventional journals?

Answer (Hirosaka Ikeda)

In the paper we could write:

(1) Process behind the NAVS development at Sumitomo Electric
(2) Process behind the optical fiber gyro development conducted to improve positioning accuracy
(3) Process behind the creation of an unprecedented digital map database
(4) Relationships with automakers
(5) Development of aftermarket NAVS
(6) Business profitability and development cost issues
(7) Software defect issues

What we could not write was considerable, including:

(1) Inter-government agency coordination issues
(2) Difficulty associated with parts procurement
(3) Marketing to approach customers
(4) Responses to various relevant events (From a business promotion perspective, it was not necessarily wise to actively participate in events.)
(5) Objections from members of Sumitomo Electric
(6) Relationships with competitor manufacturers
(7) Alliances