Proposal for technology architecture analysis

— Application of an analysis method to the development of car navigation systems —

Toshihiko NOMI[1,2]* and Hirosaka IKEDA[3]

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Product development involves many element technologies, so methods that analyze the integration process are important for R&D management. This paper proposes a new method to analyze *technology architecture*: i.e., a method for determining how to combine element technologies, which takes into account relations between product function and element technologies, and the complementary or substitutive relations among these element technologies. We applied this method to the case of development of car navigation systems, where the combination of element technologies changed several times. From this example application of our method, we obtained important insights into the analysis of technology architecture.

Keywords : Innovation, R&D management, element technologies, complementary or substitutive relation, technology architecture, car navigation system

1 Introduction

Important points for innovation are not only developing element technologies but also developing a new way to integrate them. While the former is purely a technical subject, the latter is closely related to R&D management, and affects competitiveness of finished products. This brings the following questions. How should we select a technology from candidate technologies? How should we develop the way to integrate many element technologies? In order to reply to these questions, it is important to study the past innovation cases, and to accumulate those case studies.

This paper analyzes the way to combine element technologies as "technology architecture." The word "architecture" has been used in the field of system engineering as a technical term which expresses fundamental structures of the relation of functions or performance of a total system and sub-systems composing it or relation among the sub-systems. These days, the term is also used in business administration studies[1] and is attracting attention in technological management studies. However, attention has not been paid to the fact that the way to integrate element technologies is a management issue to be selected artificially in the process of R&D. We propose a new method for illustrating and examining the technological relation of a total system (a finished product) and element technologies, and the technological relation among element technologies, by using the new word "technology architecture." Moreover, we apply this method to the case of development of car navigation systems by Sumitomo Electric Industries Ltd. (hereinafter "Sumitomo Electric"). Sumitomo Electric was a leading company in the changing of generations of car navigation systems in the beginning, especially in developing the current location detection technologies. From this application example of our method, we obtained important insights into the analysis of technology architecture.

This paper describes the authors' views and is not the official views of the organization to which the authors belong.

2 Prior research and issues of this study

Technological methods changed in the development of car navigation systems as shown later. For such innovation, we should keep in mind the fact that technological issues change in the life cycle of technology or industry. Abernathy and Utterback pointed out that product innovations were essential in the early stage of new industry where many types of products came onto the market by using many types of technologies, but product design gradually shifted to a "dominant design," and process innovation became main after the dominant design appeared.[2][3] Foster said that technologies developed along an S curve, and a new type of technology was needed to break through the limit when old types of technology matured and came close to the limit of performance.[4]

Although innovations are often divided into the two types of incremental and radical innovations, Henderson and Clark categorized them into four types using two axes, depending on whether core concepts were reinforced or overturned and whether linkages between core concepts and components were unchanged or changed,[5] as shown in Fig. 1. Although

1. Ministry of Economy, Trade and Industry 1-3-1 Kasumigaseki, Chiyoda-ku 100-8901, Japan, 2. Research Institute of Economy, Trade & Industry (RIETI) 1-3-1 Kasumigaseki, Chiyoda-ku 100-8901, Japan * E-mail: nomi-toshihiko@meti.go.jp, 3. Kyushu University Innovation Plaza 2F, 3-8-34 Momochihama, Sawara-ku, Fukuoka 814-0001, Japan

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in the "modular innovation" type in the figure, components using new technology substitute the old, in the "architectural innovation" type, core concepts of components do not change but the architecture of product design changes, and it means that changes of the relation among components make an innovation even though we use old components. They pointed out that "architectural innovation" changes the technical paradigm citing the semiconductor lithography industry as an example, and emphasized the importance of this type of innovation because change of the technical paradigm brings about the change of the competitive company from one to another as shown by Tushman and Anderson.[6] Their study has similarities with this paper in terms of focusing on "architecture." However, they think "radical innovation" is different from "architecture innovation," although examining architecture is indispensable for planning radical innovation. In this paper, we analyze the technology architecture including the case of radical innovation without being concerned with the classification of Fig. 1. Moreover, we analyze what technology architecture is appropriate and how to examine it, as we think these issues are important.

On the other hand, there is much research on "product architecture" in the field of business administration.[1][7]-[10] They classify products into two types, "modular architecture" where one module bears one function and "integral architecture" where it does not, and analyze competitiveness of firms or appropriate strategies based on this typology. But, issue awareness of this paper is different from the above approach.

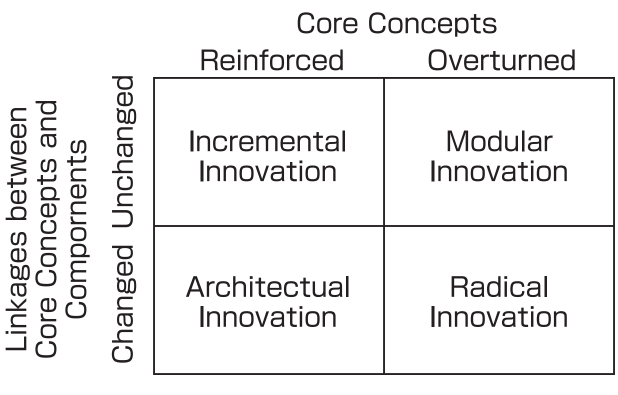


Fig. 1 Typology of Innovation by Henderson and Clark[5]

"Technology architecture analysis" in this paper is a method to examine the way to integrate element technologies which researchers or engineers need for arranging R&D plans of new products. "Technology architecture" is not fixed technologically, but is to be designed and selected by researchers or engineers. It is related to the studies on business administration, because the result of the selection affects relations among firms and competitiveness of firms. However, how to examine technology architecture is an independent research topic.

3 Method to illustrate technology architecture

Performance of a system product can be broken down to some functions necessary to the performance, and each function is realized by one or several element technologies. When several element technologies are needed for realizing one function, these element technologies have complimentary relations with each other. When there are several candidate element technologies to realize a function and any one candidate technology can realize it, these element technologies have substitutive relations or competitive relations. Only one element technology is selected from these candidates when development of a new product is completed. However, which substitutive element technology should be selected is an important issue for management when planning R&D. Therefore, this paper analyzes substitutive element technologies explicitly. We use logic symbols "AND" and "OR" to illustrate complimentary and substitutive relations among element technologies, as shown in Fig. 2.

Moreover, products often evolve as time goes by, and their element technologies also change. One type of change is brought about by an addition of a new function, and a new element technology is also added for that purpose. This change can be illustrated by using "AND" and "OR" as shown in Fig. 3 a). However, this is complicated. It would be better to illustrate it as Fig. 3 b) by bringing in a new symbol "ADD↓." Additionally, another type of change of element technology is replacement by a different element technology which has a substitutive relation with the old technology due to technological progress. Although this type of change is basically a phenomenon within the relation shown by "OR," we illustrate it by introducing a new symbol "OR↓" as in Fig. 4, when we stress change with time. As mentioned above,

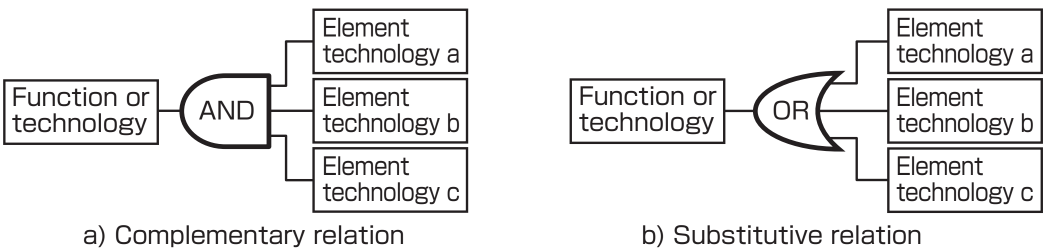


Fig. 2 Complementary and substitutive relations among element technologies

this paper illustrates the technology architecture basically by using logic symbols “AND” and “OR,” with additional new symbols “ADD↓” and “OR↓.” When considering chronological changes in a product or element technologies, there is only “AND,” not “AND↓” for a line of AND, “OR” and “OR↓” for a line of OR, and there is “ADD↓,” not “ADD” for a line of ADD.

Furthermore, the direction from left to right in the figures means breakdown from the whole to the element. The figures have a holonic structure, and they can be used in more detailed element analysis, or analysis of large whole systems.

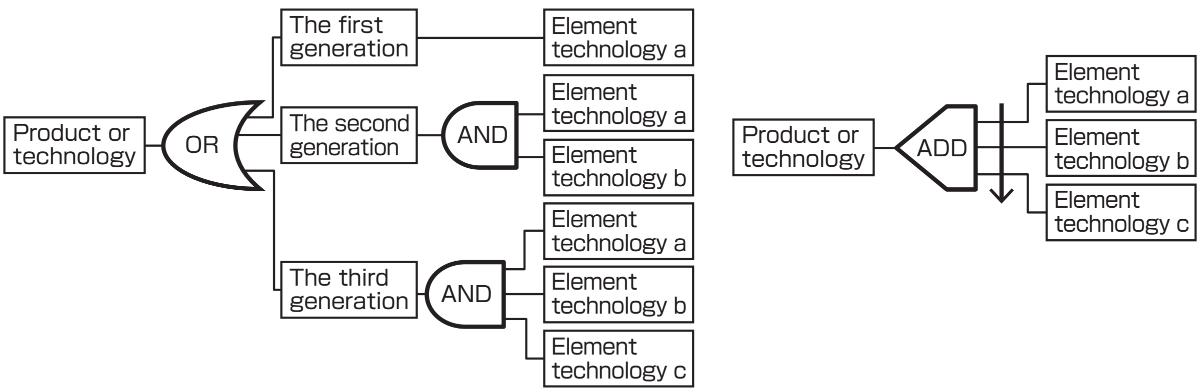
4 The case of car navigation system development by Sumitomo Electric

4.1 R&D issues in developing car navigation systems

Navigation systems detect current locations of vehicles correctly (the first fundamental function) and provide guides to destinations (the second fundamental function).[11] They have been used for ships from old times, and are used widely for aircraft in modern times. However, they had not been used for automobiles before 1980, because requirement for technology to detect current locations in automotive use was much more demanding than in marine or flight use. Concretely speaking, firstly, the margin of error in detecting current locations must be very small, because accurate locations, such as of intersections or gateways of expressways, are critical. Secondly, the price of equipment for automobile use must be very low compared to those of gyroscopes for military planes which vary from several millions to several tens of million yen.[12] Thirdly, operation must be easy for automobile drivers, unlike professional pilots for marine and flight use.

Meanwhile, there are two types of technology systems for navigation in marine and flight equipment, which are self-contained[Term 1] and heteronomy[Term 2] navigations. Self-contained navigation is a method that measures the distance and direction of locomotion, and the current location is reached by adding these measurements to the starting position and direction (Fig. 5). Heteronomy navigation is radio navigation[Term 3] from a station on the ground which transmits location information when a vehicle comes close to it. However, no station on the ground with this function existed then for automobiles.[13]

As explained above, high-performance and low-cost were required for car navigation systems although its technological seeds were limited, and they were not realized for a long time. However, the feasibility of its business emerged by the advance of relevant technologies in the 1980s. An important technological advancement was the invention of “map-matching technology,[Term 6]” which was developed in 1983 by ETAK, a venture business company in the U.S. This is a technology to correct an error on software by comparing detected trajectory and current location with roads on a map assuming that cars must run on roads. Although the self-contained navigation needed high-precision sensors because measurement errors were accumulated as moving distance increased, the requirement for precision of sensors was moderated by this technology.[13] In addition, some small-



a) Adding functions or element technologies by generation change

b) Symbol for adding functions or technologies

Fig. 3 Symbol “ADD↓”

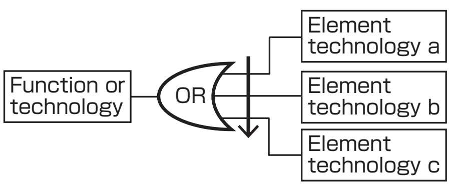


Fig. 4 Change among substitutive element technologies with time (OR↓)

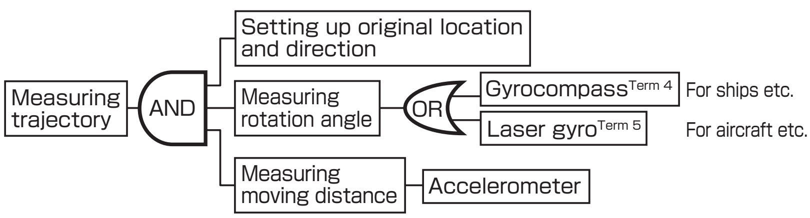


Fig. 5 Former method to measure trajectory by self-contained navigation

sized and highly-efficient information appliances, such as CD-ROMs and 16bit-CPUs, were developed in the 1980s.

Some companies had started to develop car navigation systems. There are three generations in car navigation systems. The first generation detects only the current location, the second generation additionally provide route guides to destinations, and the third generation provide route guides by receiving real-time information, such as traffic jams, road repairs and traffic accidents, from outside (Fig. 6). Car navigation systems have evolved through these changes of generations. This paper analyzes the birth and changes in the technology architecture of car navigation systems as follows.

In order to develop a car navigation system, R&D of current location detection technologies is necessary, as well as that of hardware and software to control the system. There are a variety of current location detection technologies such as self-contained navigation, GPS, radio navigation from a ground station, and a combination of these systems.[14] In the case of self-contained navigation using map-matching technology, sensor technologies and digital road maps are indispensable. Detailed R&D issues are arranged in order in Fig. 7. This figure describes the fundamental structure of the technology architecture including new technology types which had not been developed in the beginning of the 1980s, which are explained later, because we arranged them in retrospect. R&D issues on hardware including sensors are indicated in Fig. 8, and it was decided that many components would be supplied from the outside. Regarding software, R&D on software was needed for displaying the road map,

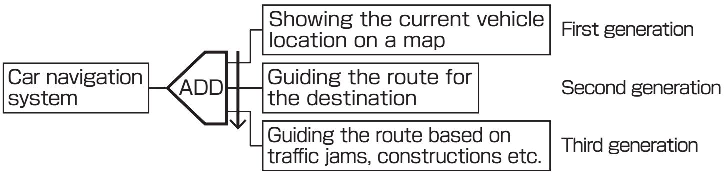


Fig. 6 First-third generations of car navigation systems

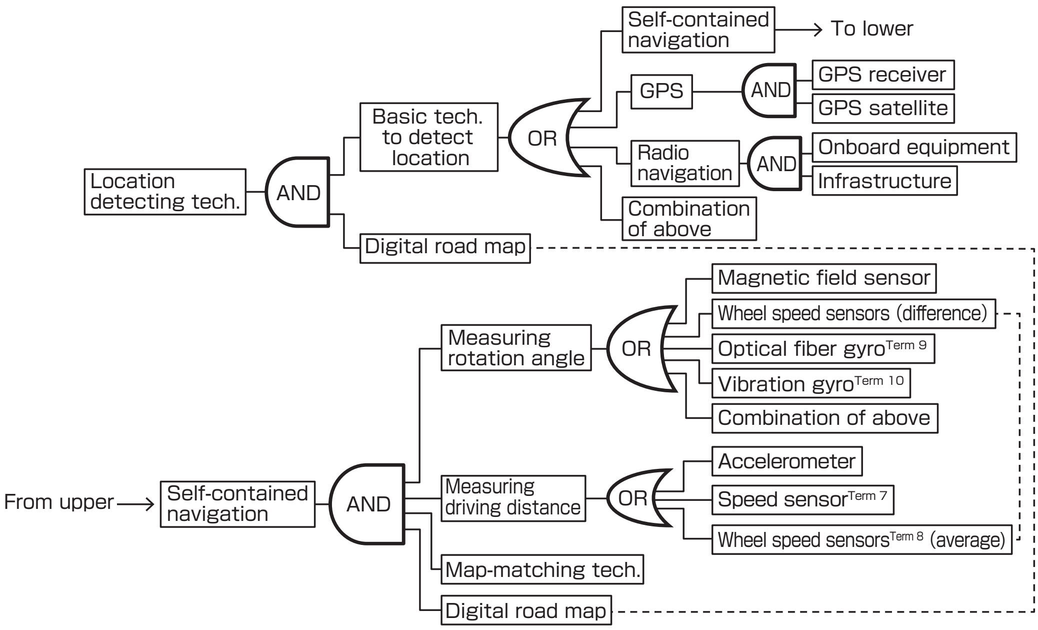


Fig. 7 R&D issues for detecting current location of car navigation systems (Technology architecture)

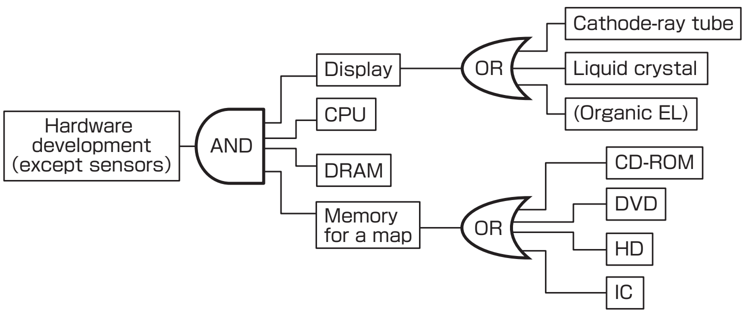


Fig. 8 Element technologies for hardware development

for controlling the car navigation system by a driver, as well as for detecting the current location. Software to calculate the route was also necessary after the second generation.

4.2 The first development of a car navigation system by Sumitomo Electric (The first half term of the first generation)

Sumitomo Electric focused on the map-matching technology developed by ETAK, and considered introducing the technology. However, it launched R&D on a car navigation system by itself in 1983 because technology in the U.S. was not conformed to the traffic conditions in Japan. The company set its target on a total system in which measurement errors should be within several tens of meters and should not miss a road, and the price should be around 300-400 thousand yen.

For the fundamental current location detection technology, only self-contained navigation was a realistic choice because GPS was not available due to the small number of GPS satellites, and radio navigation was also not possible because there were no ground stations. The basic strategy was to use map-matching technology for self-contained navigation, because target performance mentioned above was very difficult in those days. Additionally, sensors had to be very accurate, and digital road maps had to contain detailed road information in order to realize correct map-matching.

Rotation angle sensors and travel distance measuring sensors were necessary as sensor technologies, and there was not a wide range of alternatives in those days as shown in Fig. 9, except for extremely expensive sensors. Sumitomo Electric used a magnetic field sensor for measuring the rotation angle, but, using it solely was insufficient because disorder occurred near large constructions or DC drive trains. Sumitomo Electric, which was manufacturing anti-lock braking systems (ABS), knew that luxury cars had wheel speed sensors,[13] got an idea that rotation angle could be measured by the difference between numbers of revolutions of right and left wheels, and decided to develop a system using wheel speed sensors for combined use with a magnetic field sensor. The reason for combining two kinds of sensors is to use two kinds of information complementally, because with wheel speed sensors, errors caused by wheel slip or change of tire inflation pressure also occurred. It was decided that information about travel distance would be obtained from the average speed of both wheels.

For developing a digital road map, there were two choices of 1:25,000 maps or 1:2,500 maps. The former maps for the whole of Japan could be obtained all together, because the Geospatial Information Authority of Japan had them. However, they did not include information about community roads. Sumitomo Electric decided to use 1:2,500 maps in three metropolitan areas, because high precision maps were important for the map-matching technology. Local governments of cities, towns and villages had 1:2,500 maps for urban planning, therefore Sumitomo Electric negotiated with them, such as the 23 wards of Tokyo, to use the maps. However, some of these maps had old information because they were issued a long time ago. Therefore, it decided to also use the detailed maps for cables or pipe construction owned by power companies and gas companies. It digitalized information of these road maps with a large amount of labor by using a great deal of money.

For necessary hardware excepting sensors, such as displays, CPUs, memories for digital road maps and DRAMs, it decided to procure good ones from other companies. Concretely speaking, it decided to use around 6 inch cathode-ray tubes for displays, CD-ROMs for road map memories, and it used cushioning rubber for CD-drive to bear the vibration of automobiles.

Some software was also necessary, such as software to control information from wheel speed sensors, magnetic field sensors, and information about travel distance, and to conduct map-matching by combining the information with a digital road map, software to show calculated current location on the display, and software to give current location set up by a driver feedback to the system. Thus data processing was very complicated, and on-board CPU needed much time for processing. However, the target time in which the system should display the vehicle location on the display was set as within 0.3 seconds. For this purpose, the arrangement of road map data was changed to quicken readout time, a good calculation method for map-matching was sought, and an original OS to increase the data processing speed was

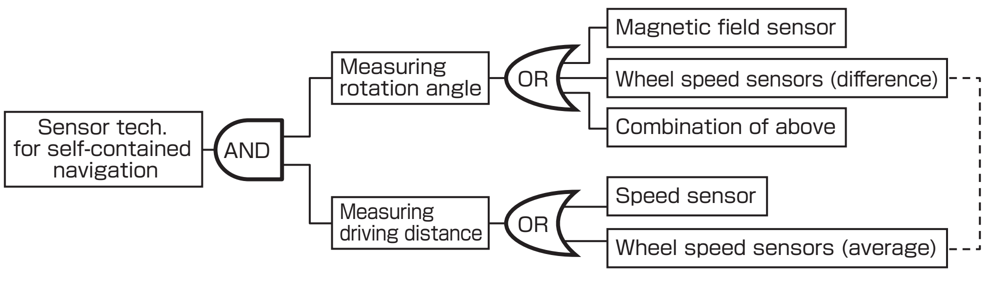


Fig. 9 The choice for sensor technologies in the first development of a car navigation system

developed. Finally, it cleared the target time. Additionally, a car navigation system needed software to control and display air-conditioners and car-audio systems, because large displays of car navigation systems would be installed at the place where switches and displays of air-conditioners and car-audio systems used to be.

Technology architecture mentioned above is shown in Fig. 10. After developing element technologies, Sumitomo Electric made a trial product that integrated element technologies, attached it to a real vehicle, and conducted experiments by a running vehicle. The most difficult problem with integrating element technologies into a total system was calculations of the current location in a condition that there was no absolutely reliable information, because sensors had measurement errors which were very large sometimes, and information of road maps was old and sometimes different from actual roads. In order to solve this problem, it decided to stochastically use all information from each sensor, a digital road map, and trajectory information up to that time, and set the extent of credibility of such information individually within the software. For this purpose, it repeated trials and errors, i.e. extracted problems by a real running vehicle test, refined the software, and conducted tests again. However, it used computer simulation in the laboratory frequently by using data collected from real running vehicle tests after the first test. It improved the accuracy of detecting the current location by the cycle of refining, testing a trial product, and extracting problems. This sequence yielded its own map-matching technology within Sumitomo Electric.[13]

The car navigation system as a result of such R&D put map-matching technology into practical use for the first time. The system became so reliable that frequency for a driver to reset the current vehicle location on the system when it missed a road was decreased to once per 40-50 km drive. This system had the best performance in the world those days, and was adopted by Nissan Motor Corp., and put into practical use by being installed in the 1989 model of Nissan Cedric and Cima.

On the other hand, drivers became to trust the car navigation system, therefore they began to complain about mistakes in current locations. The mistakes were mainly caused by insufficient accuracy of the measuring rotation angle. Even though the accuracy of wheel speed sensors was of a high level, it became clear that it was lower than the market needs.

4.3 Development in the latter half term of the first generation by using an optical fiber gyroscope

Sumitomo Electric launched plans to develop the next system just after the development of the system in 1989. The most important challenge was to develop a more accurate rotation angle sensor than the wheel speed sensors. In those days, Sumitomo Electric had developed an optical fiber gyroscope by itself, whose accuracy in measuring the rotation angle was very high, however its sample price was some million yen, which had to be reduced to 10-20 thousand yen for automobile use. Sumitomo Electric reconsidered one by one its element technologies, such as materials of the parts, the process technologies, and finally it realized this price. While the technology architecture of this system was basically the

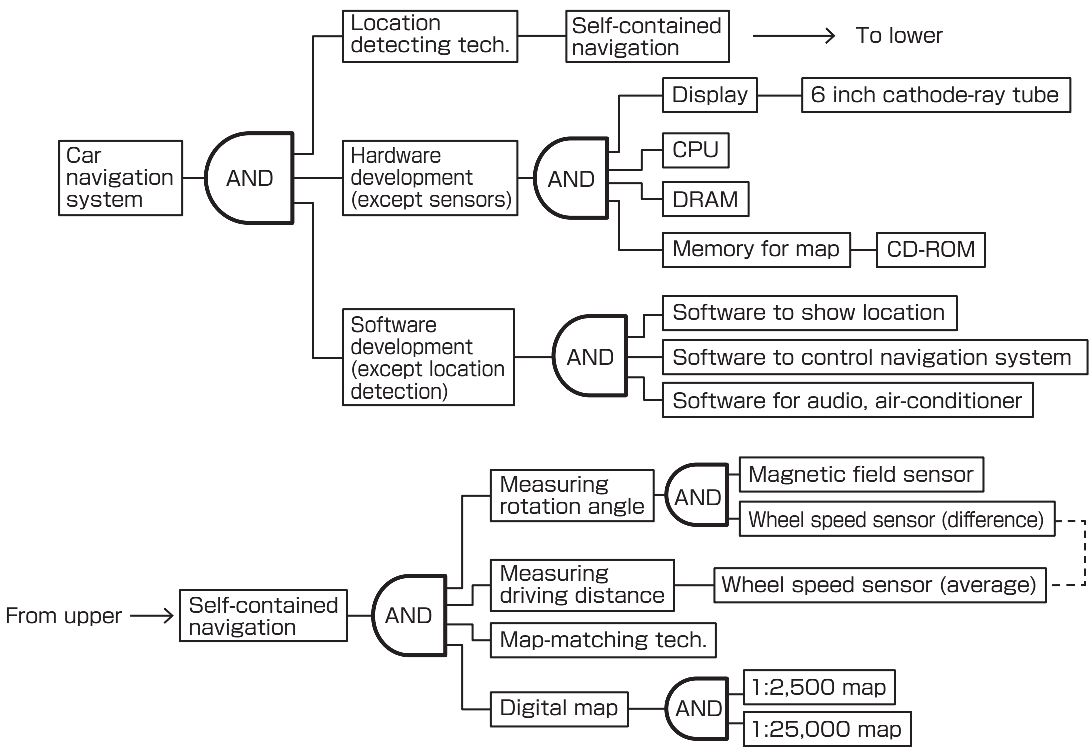


Fig. 10 Technology architecture when the first car navigation system was finished (1989 model)

same as the previous system, the combination of sensors for self-contained navigation was changed as shown in Fig. 11.

On the other hand, except for the design on the display, it used the digital road map developed by the Japan Digital Road Map Association established in 1988, which was developing the digital road map associated with related government offices and companies concerned.

The car navigation system of the latter model of the first generation, which was developed as explained above, was installed into the 1991 models of Nissan Cedric and Cima. Although other companies followed Sumitomo Electric in the production of car navigation systems by using map-matching technology, the optical fiber gyroscope, which was not installed into other companies' products, became the source of competitive advantage of the Sumitomo Electric's product, which decreased the frequency of reset of current vehicle location by a driver into once per about 200 km drive.

4.4 Development of the second generation which became the dominant design

One of the next challenges was to add the function of guiding toward a destination (the second fundamental function of navigation) on the previous function of detecting the current vehicle location. Another company preceded in the development of such a second generation car navigation system, therefore Sumitomo Electric also had to follow. Then, it was necessary to develop software to calculate the route guide, and to add traffic control information such as one-way streets or no right turns and road connection information such as connecting roads to expressways on the digital road map. Many universities had published algorithms for calculation software, however a large memory capacity and high speed read-out capacity were needed. Sumitomo Electric developed its own route guide software in order to calculate the route at high speed by a small memory capacity,

Additionally, other challenges were to incorporate the fruits of technology progress in the relevant fields; one of these was GPS. The designers of car navigation systems were looking for a way to know the absolute position, because offset of position which resulted in missing a road could not be avoided entirely even when map-matching technology was used. However, GPS made it possible, which is the technology to know the absolute position of a vehicle by receiving positioning signals from 4 GPS satellites of the 24 GPS satellites located in orbit.[15][16] After its launch in 1978, although the number of GPS satellites was small in the 1980s, it became large enough for practical use in the 1990s.[17] Another company put a car navigation system using GPS into practical use in 1990, therefore Sumitomo Electric decided to use GPS. Issues for R&D were mainly to develop software for map-matching using information from GPS, because GPS receivers were already distributed in the market. (Thereafter, establishment of GPS was announced in 1993, and its full-scale service was started in 1995.) Although GPS had problems that it was not available in tunnels or behind buildings, and that its margin of error was 100m at maximum because the U.S. Department of Defense lowered its precision intentionally as selective availability (S.A.) measures, combined with self-contained navigation, problems in practical use could be avoided.

Another technology incorporated from the fruits in the relevant field was a vibration gyroscope which was used for measuring the rotation angle. This is based on the principle that inertia of solids of revolution (Coriolis effect) is also effective against oscillating bodies, and the technology to refine its sensibility to the practical level was developed in 1988. Downsizing and cost reduction was also achieved later.[12] This technology began to spread for use in hand-shake prevention systems of cameras. Sumitomo Electric took note of this, and decided to use a small and low-cost vibration gyroscope for its car navigation system, although its accuracy was lower than the optical fiber gyroscope, because accuracy required for a rotation angle sensor became lower when used jointly with GPS. A magnetic field sensor was no longer needed. However, a vibration sensor had a problem of zero-point temperature drift where the sensor displays a rotating signal even when it is not rotating caused mainly by temperature. Although this was not a problem for camera use, temperature correction was needed for a car navigation use. Therefore, Sumitomo Electric requested Murata Manufacturing Co. Ltd. a vibration gyroscope manufacturer, to reduce the drift, and the company achieved this[13] (as shown in Fig. 12).

Thus, the second generation of car navigation systems, whose cost reduction and downsizing were realized through

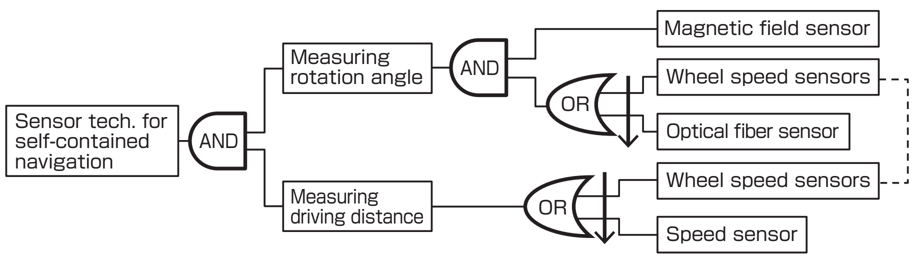


Fig. 11 Change of sensors from 1989 model to 1991 model

the development mentioned above, was adopted in the 1992 model of Diamante of Mitsubishi Motors. Thereafter, the mode to use GPS and a vibration gyroscope jointly in a car navigation system diffused among other manufacturers, and this style became the industry-wide standard, i.e. the dominant design around 1993.

4.5 Development of the third generation of car navigation system and the withdrawal of Sumitomo Electric

In the 1990s, car navigation systems diffused widely. The technology progress brought about the third generation, which gave route guides by taking into account traffic information such as traffic jams, accidents and road constructions. For this generation, it was necessary for real-time traffic information to be offered from the outside (the ground stations) to vehicles running on the road. Therefore the Vehicle Information and Communication System Center (VICS[Term 11] center) was established in 1995, after careful consideration from 1990. This center collects traffic information from the police and road administrators, and offer the information to car navigation systems on-board by optical beacons[Term 12] or radio wave beacons.[Term 13] It started the infrastructure development i.e. installation of the stations on the roads to offer the information, launched the service in Tokyo and Osaka metropolitan areas from 1996, and expanded the service area thereafter. From the beginning of this service, the car navigation systems of Sumitomo Electric also evolved into the third generation, and used VICS information. VICS information was also useful for detecting the current location, and it was used jointly with GPS and a vibration gyroscope (as shown in Fig. 13).

However, GPS receivers, vibration gyroscopes, and VICS receivers no longer were competitive advantages for a car

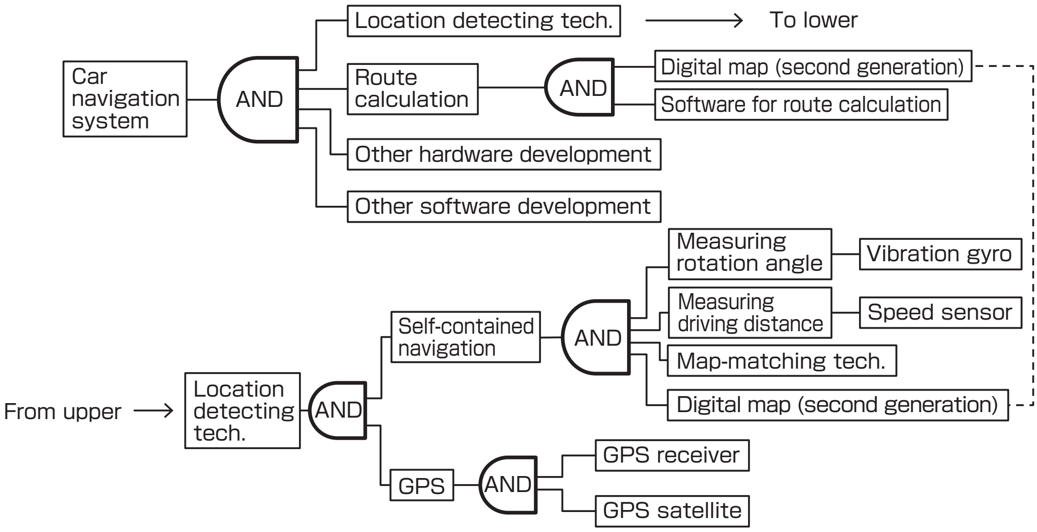


Fig. 12 Technology architecture of 1992 model (second generation)

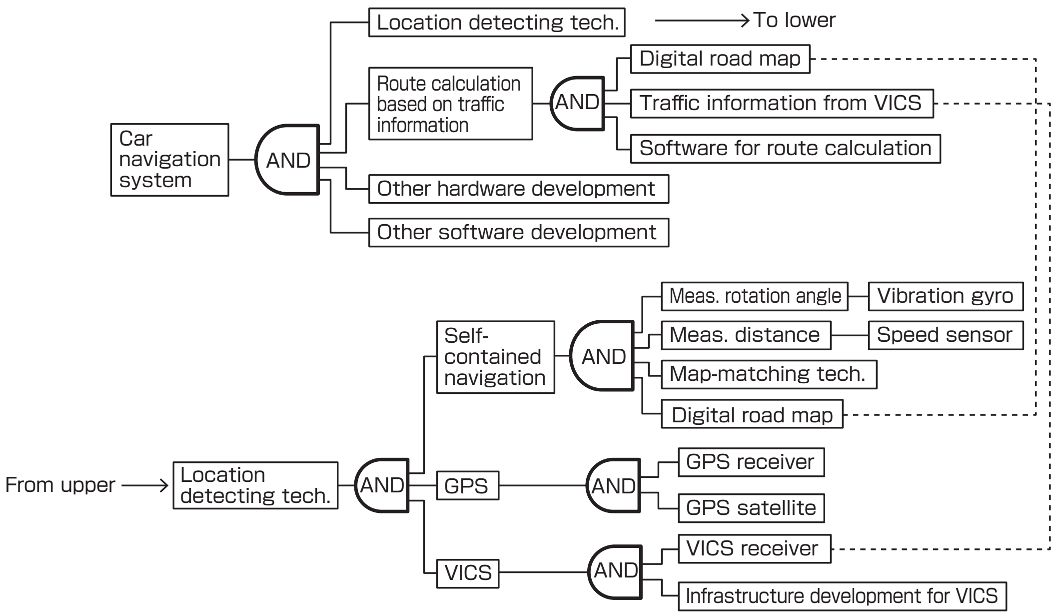


Fig. 13 Technology architecture of the third generation of car navigation systems

navigation system manufacturer, because anyone could purchase them from companies specializing in making these pieces of equipment. As a result, the number of companies entering the car navigation system business increased to twenty or more by mid-1990s, and their product prices dropped. Sumitomo Electric also became caught up in the competition for lower prices. On the other hand, the expansion of the functions to be processed by software led to sharp increase in the scale of software, manpower for its development and development cost. Original OS introduced for speeding up data processing in the beginning of the development of the car navigation system also enhanced this tendency, and brought a disadvantage in the competition with companies who used a general-purpose OS. Owing to continual deficits in the business, Sumitomo Electric was forced to withdraw from the car navigation system business in 2000 following a decision made in 1999.

5 Analyses of technology architecture from a short term perspective and innovations over a long time frame

In the previous chapter, this paper explained the facts of how Sumitomo Electric made the selection of element technologies in the period of the emergence and the generation change of car navigation systems. This story can be interpreted not only as four short-term cases of 4 R&D projects, i.e., the first half term of the first generation, the latter half of the first generation, the second generation and the third generation, but also as one long-term case of the evolution process of car navigation systems. Therefore, this chapter focuses on the examination from these two viewpoints.

5.1 How to examine an R&D plan of a new product in each generation

The examining process is a focal point when planning R&D of new products from a short-term perspective. In the case of car navigation systems, Sumitomo Electric examined ① system configuration of how the total system consists of sub-systems, i.e. element technologies, ② broad search of candidate technologies to realize each sub-system, ③ appropriate selection of technologies by comparison of candidate technologies, ④ deciding between in-house development and acquisition from the outside for each adopted technology. This means that the following 4 processes are examined in the technology architecture analysis, i.e. ① examination of complementary technologies, ② quest for substitutive technologies, ③ selection of substitutive technologies, ④ examination of the ways to obtain element technologies. When considering R&D plans, it is important to draw up a figure of technology architecture according to these 4 processes, and to examine the 4 processes deeply by using the figure. Additionally, the following knowledge about examination of these 4 processes have been gained from the case of car navigation development.

Firstly, it is important to examine both complementary technologies and substitutive technologies as element technologies. The technology architecture for a finished product, such as Fig.10, 12 or 13, is written by only “AND,” because a finished product does not include an unnecessary element, and consists of only complementary technologies. However, this is the result after selecting element technologies to be adopted. When examining an R&D plan, it is important to specify substitutive technologies as candidates as shown in Fig.7 or 9, and to select appropriate technologies. Actually, Sumitomo Electric had competitive advantage because it selected suitable element technologies such as map-matching technology with wheel speed sensors or an optical fiber gyroscope by taking product differentiation into account.

Secondly, it is critical to collect a wide variety of information about substitutive technologies to be listed up as candidates. The information about rotation angle sensors in the car navigation case was of 4 types, i.e. original idea for wheel speed sensors, in-house technology for an optical fiber gyroscope, information from a competitor for GPS, and information from other industry (camera industry) for a vibration gyroscope. Although generally, there is an argument on which is more important, exploration for candidate technologies or exploitation of existing technologies, Sumitomo Electric carried out exploration appropriately.[19] Some research on dynamic capability of companies also points out the importance of sensitivity for detecting new opportunities.[20]

The third point concerns the standard in selecting element technologies. An element technology should be selected not only by performance and cost of the technology, but also by the competitiveness of the finished product with the technology installed, or, in other words, the relation between the whole and elements. For example, the reason for adopting an expensive optical fiber gyroscope in the 1991 model was to respond to the market needs for the product. On the other hand, sometimes complementary technologies used together affect the selection of element technologies, in other words, the relation among elements. For example, detailed road information from 1:2,500 maps was input into digital maps in the 1989 model in order to bring out the best in map-matching technology. A vibration gyroscope was adopted instead of an optical fiber gyroscope in the second generation system because requirement for the accuracy of a rotation angle sensor was relaxed by the use of GPS.

The fourth point is the possibility of using substitutive technologies complementarily. Although a magnetic field sensor and wheel speed sensors are substitutive for rotation angle sensors, they were used complementarily in the 1989 model in order to compensate the different defects of each technology. The relation between GPS and self-contained navigation was the same as above.

The fifth point is the variety of ways to obtain element technologies. There were in-house developments, purchase of hardware such as information appliances from other companies, and a request to another company for the development of vibration gyroscope. Introduction of map-matching technology from a venture company and technology transfer of route guide software from universities was also considered, although they were not realized in the end.

The sixth point is that not only examination before R&D but also tests and improvements after development of element technologies and trial production of a total system are important, and these processes should be prearranged in an R&D plan. There is possibility of some omissions of complementary technologies in an R&D plan, although it should include all necessary complementary technologies. There is also possibility that a total system cannot achieve its designed performance when all element technologies are combined. In the case of car navigation, repeating trials and errors brought out much improvement in the performance when testing a trial car navigation system installed on a real running vehicle.

The first, second and third points above are deemed to be especially important. Although these points are critical for deciding element technologies, element technologies are not necessarily to be decided uniquely by technology architecture analysis. For example, one set of element technologies is not always to be extracted when functions of a product are broken down to element technologies from the first viewpoint. Therefore, examination from many angles would be necessary.

5.2 Innovations of technology architecture over a long term

Interpreting this story as one long-term process from the emergence of a car navigation system business until the appearance of its dominant design, innovations of the technology architecture can be drawn as Fig.14.

There are two types of innovation of the technology architecture as shown in Fig.14. One type is expanding the functions of the product, and adding necessary element technologies. When a car navigation system converted from the first generation which had only the function to show the current vehicle location on a road map to the second generation which had a function to guide the way to a destination too, software to calculate the route and traffic control information such as one-way streets and no right turns in a digital road map became necessary. Moreover, when changing to the third generation which took account of traffic information such as traffic jams and road constructions, transmitting and receiving real-time information through VICS between the onboard navigation

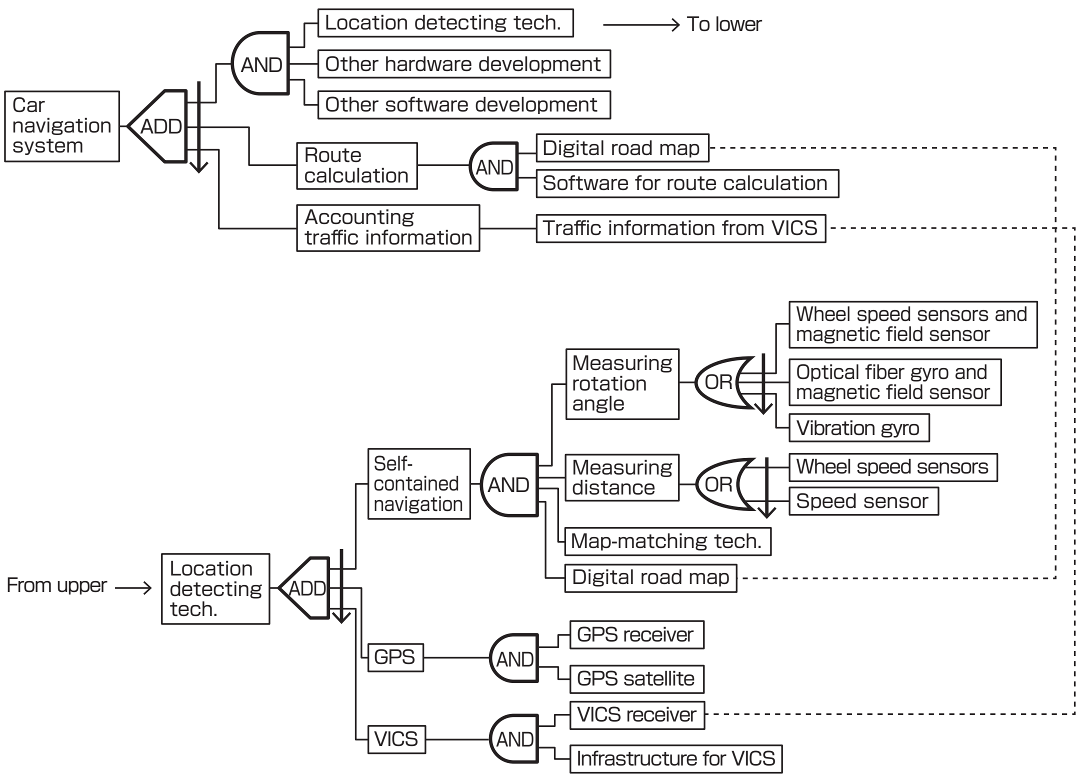


Fig. 14 Innovations in technology architecture of car navigation systems

system and infrastructure outside the vehicle became necessary. The symbol “ADD↓” shows this type in Fig.14. Another type is innovation of technology architecture replacing technology seeds or technology types. For example, the rotation angle sensor changed from joint use of wheel speed sensors and a magnetic field sensor to joint use of an optical fiber gyroscope and a magnetic field sensor, and then to a vibration gyroscope. The symbol “OR↓” shows this type in Fig.14.

A characteristic in the innovation of car navigation systems is that the direction of technology evolution depended on the relation between product performance and market needs. In concrete terms, performance of the rotation angle sensors was more important than their cost in the early period of the business, for example the wheel speed sensors were used in addition to a magnetic field sensor, or the expensive optical fiber gyroscope was used. On the other hand, the cost was more important than the performance of the sensors in the period of the second generation which used GPS, as shown in the adoption of a small and low-cost vibration gyroscope in spite of its lower performance. This story is similar to the “destructive innovation” of the hard disk drive industry in which 8 inch drive, which was the mainstream in the market, shifted to lower performance products such as 5.25 inch drive or to 3 inch drive.[21][22]

Additionally, there would be differences in the details to be studied of the R&D plan between a long-term viewpoint (Fig.7) and a short-term viewpoint (Fig.9). In 1983 when Sumitomo Electric launched R&D on a car navigation system, the use of GPS was not realistic, because the infrastructure of GPS, i.e. enough number of GPS satellites, was not yet arranged although its plan had been announced. At the time, the use of radio navigation was neither realistic, because the infrastructure of VICS was not planned although its technology was well known. Therefore, it was rational to narrow the study down to R&D plans on a self-contained navigation and its sensors from a short-term viewpoint as shown in Fig.9. However, from a long-term viewpoint, the technology architecture of car navigation systems changed at once when a breakthrough occurred to remove bottlenecks of technologies or social conditions. Fig.7 is the figure of the technology architecture containing wide-range substitutive technologies including candidate technologies mentioned above. As one hypothesis, it would be useful to identify bottlenecks of technologies and to simulate the change of technology architecture when the bottlenecks are eliminated. In the simulation, it is not necessary to know the specific way for breakthroughs. Through this simulation, companies could become sensitive to risks and chances that emerge in long-term technological changes, and could react positively to the changes thereafter.

In the case of car navigation, there was a change in the competitiveness of companies along with the change of technology architecture as shown in Fig.15. In concrete terms, the sensor technology owned by Sumitomo Electric lost its competiveness, and capabilities to develop software became a key in the competition among companies after the current vehicle location could be detected by a GPS receiver and a vibration gyroscope purchased from other companies. Industry shifts from a birth period to a maturing period through a growth period when many companies enter the industry and their competition becomes severe. A successful company in the maturing stage is not necessarily a leader company in the beginning,[23] If a company could anticipate the changes of technology architecture based on the above hypothesis, it would be useful for a long-term technology management, although this is a future research theme.

6 Conclusion

This paper proposed the methods to illustrate and analyze technology architecture, and applied them to the case of the innovation of car navigation systems by Sumitomo Electric. It showed that this illustrating method could express technology architecture objectively, and could express changes in element technologies in past innovations. For example, although it is difficult to understand the whole structure with many element technologies related to the current vehicle location detection in the case study, relations among element technologies become clear by illustration as shown in Fig.7. A prior examination on an R&D plan would become easier by this means. This is the fundamental function of technology architecture analysis.

Additionally, we learnt many lessons on prior examination for short-term R&D projects from this case study, and could present one hypothesis on the method to apply to long-term R&D management which included generational changes of products. Technology architecture is a subject for researchers or engineers to design and choose, therefore this method is expected to be used in prior examination of R&D plans. This method would be useful for examining what functions finished products should have, and what element technologies

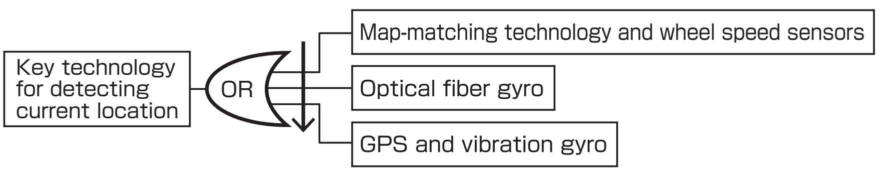


Fig. 15 Change of key element tech. for detecting current location

should be developed therefor, for example, in development of intelligent transport systems (ITS)[Term 14] which is an advanced form of car navigation systems, or in development of robots which are used in real-life settings such as nursing care, or in the field of agriculture, forestry and fishing.

Furthermore, it would be meaningful when management and researchers/engineers exchange opinions about strategies for a technology choice or about possible expansion of products/technologies in the future, to illustrate technology architecture and to show various routes connecting a finished product and element technologies including substitutive technologies that may look impractical in a short-term.

Technology architecture analysis also has possibility to be helpful in discussions with management on business strategies considering market size and profitability as well as technology strategies which are also important. A technology strategy for a technology choice or for the way to obtain parts or element technologies has possibility to influence the industrial structure in the future, and profitability depends on the industrial structure such as price bargaining power with user companies or suppliers and the new entry by competitors after industrialization. Hence, an integrated framework to examine technology architecture, a technology strategy, future industrial structure and a business strategy might be possible, and this is a future research theme. Moreover, technology architecture might be related to a path for evolution of element technologies or to core technology strategies. These are also subjects for future research. Therefore, it is important to apply technology architecture analysis to various cases in the future, and to accumulate the knowledge.

Terminologies

Term 1. Self-contained navigation: One kind of navigation technique to detect the current location by only equipment installed in vehicles such as automobiles. For that purpose, dead-reckoning technique is usually used. It detects the current location by adding the measured rotation angle and the driving distance of the vehicle to the original or starting location and direction.

Term 2. Heteronomy navigation: One kind of navigation technique different from self-contained navigation. A vehicle detects the current location by receiving information transmitted from the station on the ground etc.

Term 3. Radio navigation: One kind of heteronomy navigation. The vehicle detects the current location by receiving radio wave information from a station, when a vehicle comes close to a station.

Term 4. A gyrocompass: A device to know the direction by using the nature of a fast-spinning object, which keeps the rotation axis in the original direction.

Term 5. A laser gyroscope: A device to measure the angular velocity of rotation using a characteristic of lasers that the propagation velocity changes by rotation, which has a laser oscillator structure with ring-like optical waveguide consisting of several mirrors.

Term 6. Map-matching technology: Technology to correct differences between road map information and running trajectory calculated from the measurement by self-contained navigation etc. as a measurement error, which can prevent the accumulation of measurement errors.

Term 7. A speed sensor: A sensor to measure revolving speed of gears in a transmission to express automobile speed. All cars have this sensor.

Term 8. Wheel speed sensors: Sensors to measure revolving speed of wheels on right and left side independently. Luxury cars have these sensors.

Term 9. An optical fiber gyroscope: A device to measure angular velocity of rotation by emitting laser light from both ends of a rolled up optical fiber. This is based on a characteristic of lasers that the propagation velocity changes by rotation.

Term 10. A vibration gyroscope: A device to measure Coriolis force caused by rotation of a round pillar etc. which is vibrated by piezoelectric elements. This is based on the principle that Coriolis force on a rotating object is also effective on a vibrating object.

Term 11. VICS (Vehicle information and Communication System): A System that provides on-board car navigation systems real-time traffic information such as traffic jams, locations of road constructions and traffic restrictions. It transmits information owned by the police or road administrators by means of optical beacons or radio wave beacons set up along roads.

Term 12. Optical beacons: Devices to transmit information of VICS to on-board car navigation systems by near infrared rays. They are set mainly on ordinary roads for car navigation.

Term 13. Radio wave beacons: Devices to transmit information of VICS to on-board car navigation systems by radio waves. They are set mainly on expressways for car navigation.

Term 14. ITS (Intelligent Transport System): System to transmit and receive information among persons, automobiles and roads, and solve various problems such as traffic jams, environmental problems, safety measures. Systems such as car navigation, VICS and ETC have been put into practical use up to now, and R&D on more advanced systems is ongoing for support of safe driving by inter-vehicle communication, and more efficient distribution of goods by appropriate management of the roads, etc.

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Authors

Toshihiko NOMI

Graduated from the Graduate School of Engineering, Kyoto University in 1981. Received Ph.D. in Engineering, from Tohoku University in 2005. Joined Ministry of International Trade and Industry (MITI) in 1981. Was Director of Technology Research and Information Office, Professor at Kobe University etc. and presently Senior Analyst for Industry-Academia-Government Cooperation Promotion, METI. Working concurrently as Consulting-fellow in RIETI. Belonging to the Society for Science Policy and Research Management, Japan Society for Intellectual Production, the Academic Association for Organizational Science and Japan MOT Society. In this paper, Nomi proposed technology architecture analysis, applied it to the case of car navigation systems.

Hirosaka IKEDA

Graduated from the Department of Applied Chemistry, Faculty of Engineering, Kyushu University in 1964. Received Doctor of Engineering from Mie University in 2010. Joined Sumitomo Electric in 1964. Oversaw automotive wire harness development, vehicle electronics and NAVS. Became President at AutoNetworks Technologies, Ltd. in 1995, and Managing Director in 1999. Became Special-Appointment Professor at the Innovation Training Program Center for R&D and Business Leaders of Kyushu University in 2008, and presently Advisor at Industry-University-Government Collaboration Management Center of Kyushu University from 2014. In this paper, Ikeda was in charge of all the facts of development of car navigation systems and the way of thinking in its management.

Discussions with Reviewers

1 Overview

Comment (Naoto Kobayashi: Center for Research Strategy, Waseda University)

This paper analyzes mainly how to combine elemental technologies by studying car navigation systems whose R&D and commercialization was conducted by Sumitomo Electric, and discusses new knowledge on the methods or strategies in the new product development. The methodology to combine elemental technologies makes the basis of synthesiology, and therefore, this paper is suitable for *Synthesiology.*

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

This paper studies the history and the method of R&D of car navigation systems as a case study, and illustrates them by re-analyzing and re-arranging them from a viewpoint of management of technology. I understood it to be an attempt to build a general method to construct technology architecture. It has been revised to a more rational and refined paper after discussions with the reviewers. Hence, this paper could be expected to diffuse its effect for improving the probability of R&D plans of new products in companies and others.

2 Meticulousness in the logical structure

Question and comment (Akira Kageyama)

In the papers of *Synthesiology*, it is required to argue the following points, (A) and/or (B).

(A) To describe the thinking or examining process i.e., the idea, hypothesis or discussions, by or through which a certain technology was narrowed down, when there were several candidate technologies for carrying out one function.

(B) To describe by what thought or examination a group of elemental technologies was combined when several technologies in different technological fields were needed for achieving a certain purpose.

This paper attempts to systematize a method of how to combine element technologies in R&D of system products and presents technology architecture which uses a logical structure using symbols such as AND, OR and ADD. It is a challenging study in which Sumitomo Electric carrying out R&D and business expansion of car navigation systems is given as a concrete example. However it includes some explanations which have leaps in logic. Therefore, please reconsider those points.

Considering the history of developing car navigation systems in about 15 years from 1980s to 1990s, an argument including time axis would be necessary. In concrete terms, there were changes, for example, new technological seeds sprouted with time, and availability of new technologies for cost reduction grew by innovation or technology improvements in other industries. Logic symbol ADD introduced by the authors would be very useful for illustrating the changes of technology architecture with time. Could you show the effect of ADD more clearly?

Answer (Toshihiko Nomi)

The symbol of "↓" has been attached to the symbol "ADD" for distinguishing the base technology and the technologies added later. The new symbol "ADD↓" means that the technology written in the lower position of "↓" is added on the base technology written in the upper position of "↓," and illustrates that a technology is added with time. Additionally, a new technology sometimes substitutes an old technology as another type of technological change with time, therefore a new symbol "OR↓" has been introduced for illustrating this type of change. This means that the technology written in the lower position of "↓" substitutes the technology written in the upper position of "↓." By using these symbols of "ADD↓" and "OR↓," we drew the figure of technology architecture, Fig. 14 in chapter 5, additionally, and illustrated how elemental technologies have changed in the evolution process of the car navigation systems.

In addition to the illustration of the changes of the technology architecture during the 15 years in Fig.14, we conducted a new analysis. Although in the beginning period when the performance was lower than the market needs, serious consideration was paid more to the technological performance than the cost. The cost became more important in the technology architecture after the performance for detecting current locations of vehicles was improved by the introduction of GPS. Furthermore, we showed a hypothesis that it might be useful in handling technological changes in long-term R&D management to draw a figure of technology architecture (Fig.7) containing a wide-range of substitutive technologies including candidates deemed unrealistic, and to simulate in advance how the technology architecture would change when a breakthrough occurs in a technological bottleneck.

3 Technology architecture

Question and comment (Naoto Kobayashi)

In chapter 1 "Introduction," the authors describe that they analyze "the way to combine elemental technologies" as "technology architecture." Is this term used for the first time in this paper? If so, this term should be explained in detail. If the term has been already used in other papers, its source should be given clearly. This term seems to be the core concept of this paper, and is very important.

Answer (Toshihiko Nomi)

The term, "architecture," is used frequently in system engineering etc., and recently "product architecture" or "business architecture" is used in business administration. However, "technology architecture" is a term used for the first time in this paper. Therefore, we explained the term of "architecture" and "technology architecture" in detail in chapters 1 and 2. In prior research, because the term of "architectural innovation" used by Henderson & Clark is similar to our use of the term, we explained this term in detail, and the difference between this and "technology architecture" as well.

Comment (Akira Kageyama)

Could you explain the hypothesis of the method to construct technology architecture in more detail? For example, could you do as follows:

(1) draw a figure of technology architecture including some working hypotheses at the beginning,

(2) clarify "AND technologies" and "OR technologies" in the above figure, and "ADD technologies" from a long-term viewpoint,

(3) select methods to manage technologies, such as in-house development, licensing or procurement from other companies or joint-development with other companies.

By conducting these processes as one methodology, the following would become possible: ① visualizing necessary technologies, ② sharing information and a sense of value within a development project team and ③ checking validity of various decisions etc.

Answer (Toshihiko Nomi)

It would be important when considering long-term changes of technology architecture to draw a figure including unrealistic substitutive technologies with some bottlenecks as mentioned in the paper, because technological systems to be adopted sometimes change through development of unexpected new technologies or changes of social conditions.

And, because there are various paths connecting elemental technologies and a product, a selected course sometimes changes in response to the progress of elemental technologies. A figure of technology architecture is expected to serve as a map to overview the whole including various courses. This would be useful for examining technological paths or technology road maps to improve performance or functions of a product through its generational changes.

Additionally, technology architectural figure including a wide range of substitutive technologies would be useful for considering impacts, i.e. risks and chances for the businesses by the development of new technologies in the future. Managers and researchers/engineers could hold discussions, and examine business strategies and R&D strategies integrally by using this figure.

4 Possibility for future development or research

Comment (Akira Kageyama)

Although this paper points out the advantage for prior consideration of an R&D plan at the end of chapter 5, could you show "some examples as hypotheses"? Two or three examples to which figures of technology architecture are applicable would make readers understand this analysis better, and motivate them to draw such a figure, even if the examples are not so detailed as in the case of car navigation systems.

Answer (Toshihiko Nomi)

Car navigation systems analyzed in this paper are about to be developed further toward intelligent transportation systems (ITS), therefore the technology architecture analysis would also be useful for examining the R&D plan of ITS, for example, examining what functions the total systems should have, or what elemental technologies should be developed for those functions. Moreover, as there is an increasing trend to use robots in daily life such as in nursing care, or in the field of agriculture, forestry and fishing, the technology architecture analysis would be useful for examining the R&D plans of robots, such as examining what functions robots should have, what technological issues should be derived from the breakdown of those functions, or what technological seeds would be needed. Therefore, we added these examples at the end of chapter 6.

5 Generational changes in car navigation systems

Comment (Naoto Kobayashi)

There are explanations that the first generation of car navigation systems has the function “to detect current locations,” the second generation the function “to route guide to destinations” and the third generation the function “to route guide by taking into account additional information.” Please inform us whether the researchers made the initial R&D plan with an awareness of these generations, or whether characteristics of generations emerged as a result of the changes of the development goals according to the technology advancement and changes of the market needs.

Answer (Hirosaka Ikeda)

Sumitomo Electric was aware of possible future development up to the “third generation of car navigation systems” from the beginning of the R&D of car navigation systems, and it proceeded with the development. Because the usefulness of a car navigation system “was proven in guiding vehicles to uncrowded roads using traffic information” by a test in a large-scale R&D project the “Comprehensive Automobile Traffic Control System” started in 1973 as mentioned in reference [13], the company set the goal to put this system into practical use.

For this purpose, it proceeded with the necessary development of car navigation systems, elemental technologies and social systems simultaneously, and realized them according to the time order of steps 1, 2 and 3 according to the order of possibility for commercialization. Actually, the company approached the National Police Agency, the Ministry of Construction, and the Ministry of Post and Telecommunication, which resulted in the establishment of the Japan Digital Road Map Association and the Vehicle information and Communication Systems Center, and traffic information began to be distributed. Although Sumitomo Electric made efforts to develop such social infrastructures for car navigation systems, it could not reflect its efforts to its business. This was one of the reasons for its withdrawal from the car navigation business.

6 Future development of the world market of car navigation systems

Comment (Naoto Kobayashi)

Although Japan had about 100 % of the share in the world market of car navigation systems in 2004, its share dropped steeply to 20 % in 2007. One reason is said to be because portable navigation devices (PND) whose prices were overwhelming low diffused, and grabbed the market share of Japanese companies which were producing high-performance and high-price types of products installed in cars. This means that cost (price) was selected in the choice of performance and cost. On the other hand, there is another possibility that car navigation systems would be upgraded more and more in the future equipped with many sensing and acting functions for automatic driving systems of cars. Please show the global strategy of Japanese companies for car navigation systems of the future, if possible.

Answer (Toshihiko Nomi)

It is said that there is a trend for bipolarization of high-performance products installed in cars and low-cost portable navigation devices (PNDs) in the market of car navigation systems. Although car navigation systems which showed the current vehicle location on a road map didn’t exist in the market other than Japan in the past, a low-cost portable navigation device (PND) developed by a Dutch company diffused explosively in the European and the U.S. markets, and then expanded its sales rapidly in the Chinese market. For that reason, Japanese companies dropped their global share in unit sales. However, this did not mean the decrease of sales of Japanese companies. Many Japanese companies have entered into the PND business in the Japanese market. On the other hand, car navigation systems installed in cars have advanced toward high-performance by introducing voice recognition technology, an on-board camera and a head up display, to say nothing of integration with a car audio. In addition, it is said that the sales number of PNDs in the global market decreased in 2011 because the function of navigation was added to smart phones. Recently, the issue is the choice between low-price products which only show navigation information from a connected smart phone on a display and high-price products installed in cars.

Additionally, car makers are examining strategies, such as to use big data by connecting a car navigation system with the Internet, or to realize automatic driving by using the route guide function of a car navigation system. It is also said that Google intends to develop automatic driving technology, and to get its de facto standard. In the advance of car navigation systems, various industries and various companies are contemplating their own strategies, and the future course of events is very fluid.