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# Synthesiology

English edition



*Synthesiology* editorial board

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# MESSAGES FROM THE EDITORIAL BOARD

There has been a wide gap between science and society. The last three hundred years of the history of modern science indicates to us that many research results disappeared or took a long time to become useful to society. Due to the difficulties of bridging this gap, it has been recently called the valley of death or the nightmare stage (Note 1). Rather than passively waiting, therefore, researchers and engineers who understand the potential of the research should be active.

To bridge the gap, technology integration (i.e. *Type 2 Basic Research* – Note 2) of scientific findings for utilizing them in society, in addition to analytical research, has been one of the wheels of progress (i.e. *Full Research* – Note 3). Traditional journals, have been collecting much analytical type knowledge that is factual knowledge and establishing many scientific disciplines (i.e. *Type 1 Basic Research* – Note 4). Technology integration research activities, on the other hand, have been kept as personal know-how. They have not been formalized as universal knowledge of what ought to be done.

As there must be common theories, principles, and practices in the methodologies of technology integration, we regard it as basic research. This is the reason why we have decided to publish "*Synthesiology*", a new academic journal. *Synthesiology* is a coined word combining "synthesis" and "ology". Synthesis which has its origin in Greek means integration. Ology is a suffix attached to scientific disciplines.

Each paper in this journal will present scenarios selected for their societal value, identify elemental knowledge and/or technologies to be integrated, and describe the procedures and processes to achieve this goal. Through the publishing of papers in this journal, researchers and engineers can enhance the transformation of scientific outputs into the societal prosperity and make technical contributions to sustainable development. Efforts such as this will serve to increase the significance of research activities to society.

We look forward to your active contributions of papers on technology integration to the journal.

*Addendum to Synthesiology-English edition,*

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*Synthesiology* Editorial Board

**Note 1 :** The period was named "nightmare stage" by Hiroyuki Yoshikawa, President of AIST, and historical scientist Joseph Hatvany. The "valley of death" was by Vernon Ehlers in 1998 when he was Vice Chairman of US Congress, Science and Technology Committee. Lewis Branscomb, Professor emeritus of Harvard University, called this gap as "Darwinian sea" where natural selection takes place.

**Note 2 :** *Type 2 Basic Research*

This is a research type where various known and new knowledge is combined and integrated in order to achieve the specific goal that has social value. It also includes research activities that develop common theories or principles in technology integration.

**Note 3 :** *Full Research*

This is a research type where the theme is placed within the scenario toward the future society, and where framework is developed in which researchers from wide range of research fields can participate in studying actual issues. This research is done continuously and concurrently from *Type 1 Basic Research* (Note 4) to *Product Realization Research* (Note 5), centered by *Type 2 Basic Research* (Note 2).

**Note 4 :** *Type 1 Basic Research*

This is an analytical research type where unknown phenomena are analyzed, by observation, experimentation, and theoretical calculation, to establish universal principles and theories.

**Note 5 :** *Product Realization Research*

This is a research where the results and knowledge from *Type 1 Basic Research* and *Type 2 Basic Research* are applied to embody use of a new technology in the society.

# Synthesiology – English edition Vol.2 No.2 (Oct. 2009)

## Contents

# A study of paleoearthquakes at archeological sites

## — A new interdisciplinary area between paleoseismology and archeology —

**Akira Sangawa**

**[Translation from *Synthesiology*, Vol.2, No.2, p.91-100 (2009)]**

Traces of paleoearthquakes have been found at many archeological sites in Japan. However, most of them have been neglected to date and not considered to be a subject relevant to archeological research. The author has studied these traces since 1988, naming this new study field "Earthquake Archaeology". The field has become popular both in archeology and paleoseismology and many important and useful results have been gradually obtained. These developments will lead to a deeper understanding of the natural and cultural history of the earthquake-prone country, Japan. Most paleoearthquake phenomena present at archeological sites manifest as liquefaction, lateral spreading and landslides. Detailed geological observations may also contribute to a reduction in damage caused by big earthquakes.

*Keywords* : Earthquake archeology, archeological sites, trace of earthquake, active fault, liquefaction, Nankai Trough, Fushimi earthquake, Great Hanshin-Awaji earthquake

### 1 Introduction

The Japanese Archipelago was shaped into its thin, long form as the plates covering the surface of the earth pushed against each other and caused earthquakes. The residents of the Japanese Archipelago have experienced the devastation of earthquakes, and continue to be exposed to their threat. Recently, the Iwate Miyagi Inland Earthquake occurred on June 14, 2008, and the Great Hanshin Awaji Earthquake (official name designated by the Japan Meteorological Agency is "1995 Southern Hyogo Prefecture Earthquake") on January 17, 1995 claimed the lives of 6,434 people.

In the near future, epicenetral earthquake is expected to hit the Tokyo area, and mega-earthquakes such as the Tokai, Tonankai, and Nankai earthquakes are expected to occur during this century in the Pacific region from Kanto to Kyushu.

In Japan, which is one of the most earthquake-prone countries in the world, measures against earthquakes are mandatory, and researches on predictions of place, magnitude, and time of earthquakes, as well as projections of damages and measures to minimize damages are conducted from various perspectives. On the other hand, diffusion of knowledge of earthquakes to the general public is an important issue, since the knowledge of earthquake studies can contribute to the minimization of earthquake damages only when the results are fed back to society.

I have engaged in research to contribute to society by reducing earthquake damages. My area of specialty is the study of active faults that are distributed throughout Japan, and since 1986, I have engaged in research in collaboration with the archaeological discipline that was unrelated to seismology. Specifically, I focused on the traces of earthquakes found during the archaeological excavations. In this paper, I shall describe the process of research and outline the results.

### 2 History of research of active faults

In Japan, research on active faults as cause of inland earthquakes started in the 1960s. I started studying active faults using geomorphological and geological methods from the early 1970s, mainly in the Kansai region. At the time, few active faults were known, and it was an "age of reconnaissance and discovery of active faults" where new faults were identified and their basic attributes were surveyed.

In 1976, about 30 active fault researchers organized the Research Group for Active Faults. The objective of this group was to create a general catalog by investigating the characteristics of active faults that are distributed throughout Japan, using a uniform standard. As a member of the research group, I engaged in the survey of faults in Kinki, Chugoku, and Shikoku regions. Using the 1:40,000 aerial photographs, the positions of the faults were estimated from geomorphological viewpoint, and the presence of faults was checked through geological survey. The result was published in 1980[1].

I joined the Geological Survey of Japan, Agency of Industrial Science and Technology, Ministry of International Trade and Industry in 1979, when the compilation of the "1:500,000 Neotectonic Maps" started. Japan was divided into 15 regions on 1:500,000 scale maps to which geological information and major faults were added. As part of the neotectonic map series, compiled maps of the 15 regions were published from 1982 to 1987[2].

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Through this process, we could now see the overall picture of the active faults in Japan. The researchers were now encouraged to move to the next step from diverse perspectives, such as research on the "mechanism of earthquake occurrence at active faults," "detailed investigation of the characters of individual active faults," and "consideration of fault activities and history of geomorphology."

## 3 New research developments

When the compilation of the 1:500,0000 Neotectonic Maps was almost complete, I started to pay attention to archaeological sites. This happened coincidentally.

I visited a town history library of the Imazu Town Hall, Takashima-gun (currently Takashima City) in spring of 1986 to collect historical materials on Lake Biwa. The excavation of Kitoge Nishikaido Site was being conducted by the Imazu-cho Education Board, and I had an opportunity to talk to the archaeologist who conducted the excavations. He found a strange crack filled with sand at the excavation site, and asked me whether it may be related to past earthquakes.

The Kitoge Nishikaido Site was identified as the cemetery of the Jomon to Yayoi periods. I immediately visited the site, and observed a crack of about 1 m width, running straight and filled with sand. By digging the ground and looking at the cross section of the geological layers, it was found that the sand emerged from the underlying sand layer that rose and filled the crack. This was a trace left when the area was hit by a strong seismic tremor, the underground sand layer liquefied, the layers covering it were ripped apart, and a sand boil erupted onto the ground surface.

As shown in Fig. 1, the old graves from the Jomon Period were ripped apart while the new graves were dug into the sand boils. The ripped graves were built before the earthquake, while graves on top of the sand boil were built after the earthquake. There were two kinds of graves found at the site: *dokoubo* (hole grave) where bodies were buried in holes dug into the ground, and *dokikanbo* (earthenware coffin grave) where the bodies were placed in coffin jars and buried. The graves were dated using the earthenware buried with the body and the coffin jars. Based on these informations, the earthquake occurred in the Late Jomon Period or Shigasato "a" Period according to archaeological sequencing, or about 3,000 years ago[3].

I found great interest in the fact that the traces of earthquake was found in an archaeological excavation and that I was able to identify an earthquake occurrence that was not recorded in writing, and decided to look for earthquake traces in other archaeological sites. When I made an inquiry to the Kyoto Prefecture Research Center for Archaeological Properties, I obtained information that similar formations were found at the Kizugawa Riverbed Site in Yawata City, Kyoto, where excavations were being carried out at the time.

Large-scale liquefaction had occurred at the Kizugawa Riverbed Site, and cracks (sand vein) of about 1 m width crisscrossed the ground surface (Fig. 2). The sand boil that erupted from the cracks tore the layers of Nanbokucho and Muromachi periods, but was covered by the Edo Period layer. Therefore, these were traces of an earthquake that occurred at the end of the 16th Century.

In fact, there are many written records of Keicho Fushimi Earthquake that occurred on September 5, 1596 (5th year of Bunroku, leap month July 13 of 1st year of Keicho) and caused great damages to Kyoto. It is written that the houses were leveled in the villages of Yawata where the Kizugawa Riverbed Site is located. Hence, I was able to find physical evidence of a recorded earthquake at the Kizugawa Riverbed Site[4].

Japan was enjoying steady economic growth in 1986, and transportation network and residences were constructed actively. The cultural properties buried underground would be destroyed due to these developments, and many archaeological surveys were conducted prior to construction. In the course of this process, archaeological materials were accumulated, sequencing of artifacts such as pottery progressed, and it

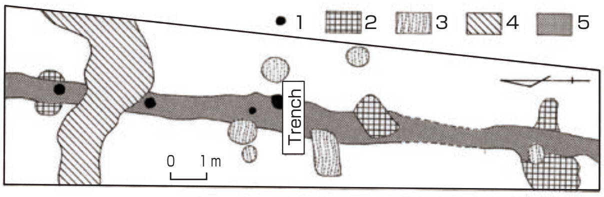


**Fig. 1 Traces of earthquake found at the Kitoge Nishikaido Site (information added to Reference[3]).**

1. Modern stake marks. 2. *Dokoubo* (hole-shaped grave). 3. *Dokikanbo* (coffin jar grave). 4. Remains from the Yayoi Period. 5. Sand vein.
The area marked "trench" was excavated to reveal that this was a trace of liquefaction.

**Fig. 2 Traces of liquefaction at the Kizugawa Riverbed Site.**

The white line that stretches diagonally is the sand vein (excavation of Kyoto Prefecture Research Center for Archaeological Properties, photography by Sangawa).

became possible to identify the dates of individual artifacts fairly accurately.

Hardly any attention was paid to the “traces of earthquakes” that must have been found in the process of the archaeological excavations. Even if the earthquake traces showed up, most were neglected as items unrelated to archaeology, without knowledge that they were products of earthquakes. Even if the archaeologist noticed that they might be related to earthquakes, the survey methods were unaltered and the traces remained untouched, except in very few cases.

In July, 1987, I moved from the Tsukuba Science City to the Geological Survey Osaka that was located in the government building of Chuo-ku, Osaka. Many archaeological excavations were conducted in the Kansai area, since this was the seat of central government in ancient and medieval periods, and public interest in archaeology was high. I frequently visited the archaeological sites where the earthquake traces were found and participated in the excavation. I learned the survey methods and dates of artifacts from the archaeologists in charge of the excavation, and in exchange, taught them the basic knowledge of earthquakes.

In November, 1987, I presented the case studies and the basic survey methods of earthquake traces in a lecture of the Kodaigaku (Ancient Study) Research Group, Osaka[5]. Many participants enthusiastically reported that they had come across earthquake traces in past excavations. Immediately after, with advice from an archaeologist, I named this study “earthquake archaeology,” and officially declared its establishment at the Japanese Society for Scientific Studies on Cultural Property and the Japan Archaeological Association in spring of 1988[6][7]. In the following year, I presented the basic survey methods for earthquake archaeology in the journal of the Society of Archaeological Studies[8].

By using the name “earthquake archaeology,” people involved in the archaeological excavations became aware that earthquake traces were subjects of archaeology. There increased the number of cases where the dates were narrowed down and the effects of earthquakes on the people were investigated when earthquake traces were found in the course of an archaeological excavation. It became routine to include a detailed description of earthquake traces in the archaeological site reports[9].

At the Nara National Research Institute for Cultural Properties (currently part of the National Institutes for Cultural Heritage), there is a system of training new research methods for archaeologists in charge of excavations from local governments and research centers for buried cultural properties throughout Japan. From 1989, I started lecturing on the survey methods for earthquake traces.

## 4 Characteristic of the study

Areas with rich traces of people’s existence buried underground and buildings (such as *kofun* or mound tomb) valuable as cultural heritages are designated “archaeological or historical sites” based on the Law for the Protection of Cultural Properties established in 1950. An archaeological site contains abundant remains such as residences and structures as well as artifacts such as plates, bowls, burial goods, and agricultural tools. When a site is to be destroyed by development, archaeological excavation is conducted prior to the construction.

In Japanese archaeology, date sequencing for remains and artifacts has been studied thoroughly so that when an earthquake trace is found in an archaeological excavation, the date of the earthquake that left the trace can be narrowed down by looking at the sequential relationship of the remains and artifacts for which the dates have been confirmed. Particularly, archaeological sequencing through remains and artifacts as well as absolute dating are well-established for the 2,000 years after the Late Yayoi Period, and narrowed-down dates of the earthquake traces can be obtained.

Since the Japanese Archipelago is subject to severe tectonic activities, the submerging areas are covered by sediments carried by rivers and ocean, and plains and basins are formed. Our ancestors set up residence in flat places close to the water, and majority of the archaeological sites are concentrated in plains and basins. Older remains and artifacts are buried in the lower layers.

When a major earthquake strikes, the area with weak foundation suffers most, and traces of liquefaction are seen in Kitoge Nishikaido and Kizugawa Riverbed sites. Liquefaction drew attention when a modern city suffered great damages in the Niigata Earthquake that occurred in 1964, and severe damages occurred to lifelines in the Great Hanshin Awaji Earthquake of 1995. When sand is carried up to the surface with underground water due to liquefaction, sand boils are formed.

In the soft sand layer deposited underground, there are spaces between the sand grains, and with strong tremors, the sand grains juggle around to reduce the space, which in turn compacts the sand layer. The underground water in the space is compressed, resulting in increased water pressure, and water spews out onto the surface along with sand as they tear the layers above. Figure 3 is a schematic diagram of a trace of sand boiling, and the layer torn by the sand boil was deposited before the earthquake while the layer covering the sand boil was deposited after the earthquake. The dates of the two layers are determined by the remains and artifacts in each layer. As in this figure, assuming that the topmost layer torn by the sand boil (before the earthquake) is dated to the

7th century and the lowest layer covering the sand boil (after the earthquake) is of the 8th century, it can be known that this sand boil is a trace of a major earthquake that occurred from the 7th to 8th centuries.

In Japan, there are written records for the past thousand or more years, and there are many references to damages by earthquakes. After the Noubi Earthquake of 1891, the Imperial Earthquake Investigation Committee was created, and the collection of earthquake records was started as one of its activities. This work continues to the present[10]-[12], and interdisciplinary research on historical earthquake materials are done by the Society of Historical Earthquake Studies. Since many of the disaster records include the time and date of the earthquakes, the time at which the earthquake traces were left can be obtained by comparing the written records against the traces at the sites.

When the earthquake traces are confirmed, the records of temples and shrines and the diaries of aristocrats which mention the earthquakes are also confirmed. In the periods before the Edo Period when there is markedly less number of written records, great earthquakes may not have been documented, but the gaps in history can be filled through earthquake traces at the archaeological sites. Also, before the Kofun Period where there is no written record, the earthquake traces lead to discovery of earthquakes.

By comparing the records of historical earthquakes, the accuracy of dates of earthquake traces is increased. In turn, presence of earthquake traces raise the reliability of historical earthquakes in written records, and the history of earthquakes can be traced to periods without written records.

## 5 Outline of research results

Majority of the archaeological excavation in Japan are conducted due to development, and therefore, where and what kind of earthquake traces are found is dominated by chance. Progress of research depends on the discovered traces. I shall describe some of the results obtained so far[13]-[16].

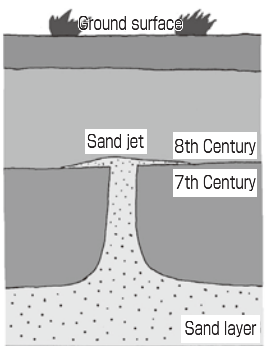


**Fig. 3 Schematic diagram of liquefaction trace.**
The yellow part in the diagram is the sand.

### *5.1 Earthquakes in periods without written records*

As an example where an earthquake in periods without written records was found, I shall describe the region around Lake Biwa. As mentioned before, earthquake traces of the Jomon Period was found at the Kitoge Nishikaido Site. After this find, the Shiga Prefecture Cultural Properties Protection Association conducted an excavation of the Hariehama Site, which is a lake-bottom site, 250 m off the coast of Shinasahi-cho, Takashima-gun, located in the northwestern area of Lake Biwa. When the lake bottom was dug for about 1 m, the ground on which the people of Middle Yayoi Period lived was revealed, and remains of furrows, agricultural tools, and fallen willow trees were found. This ground was covered by a sand boil that poured out from the underground sand layer. It is thought that the land on the lakeshore submerged due to an earthquake, and liquefaction occurred due to severe seismic tremors. In the alluvial lowlands around Lake Biwa, traces of liquefaction thought to have occurred in the same period were found at several sites (Fig. 4), and it is highly likely that a great earthquake during the middle of the Yayoi Period caused part of the lakeshore to submerge as the area around Lake Biwa was shaken severely.

### *5.2 Earthquakes described in the Nihonshoki*

The word "*jishin* (earthquake)" appears for the first time in the *Nihonshoki* (Chronicles of Japan). In the "7th Year of the Reign of Emperor Tenmu (679 AD)," there is a specific description of the damages caused by the Tsukushi Earthquake: "The earth was torn and the width of the rift was about 2 *jo* (about 6 m) and the length more than 3,000 *jo* (about 10 km), and many houses fell in all villages." However, the *Nihonshoki* contains several alterations of historical facts and imitations of Chinese history, and verification was necessary for the reference to the Tsukushi Earthquake.

Since the birth of earthquake archaeology in 1988, traces of

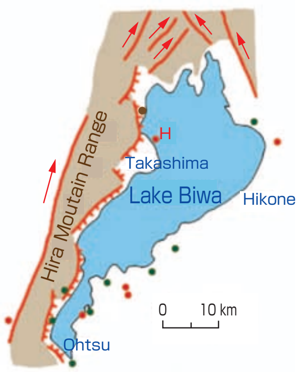


**Fig. 4 Traces of earthquakes around Lake Biwa.**
The red lines represent active faults (the hatching sides are relatively submerged, while the arrows show the direction of lateral shift). Green dots represent the sites from which medieval to modern (Edo period) earthquake traces were found. Red are sites from which earthquake traces of Yayoi Period were found. Brown is the Kitoge Nishikaido Site where the Jomon Period earthquake trace was found. H is Hariehama Site.

earthquakes were reported in the sites around Kurume City, Fukuoka Prefecture, including the archaeological site of the ancient Tsukushi Capital. Their dates were limited to the late 7th century, and this corresponded with the Tsukushi Earthquake described in the *Nihonshoki*. In 1992, a trace of fault activity during this period was found in the survey of Maekawa Maeda Site located right on top of the Minou Fault Zone that runs east-west along the east of Kurume City. Thus, it was verified that a great earthquake occurred due to the activities of Minou Fault Zone in 679, and this event was recorded in the *Nihonshoki*.

Also, in the *Nihonshoki*, the earthquake of 684 (13th Year of the Reign of Emperor Tenmu) is described in details: "Great earthquake occurred at around 10 o'clock at night, and men and women throughout the country screamed and ran. Mountains collapsed and rivers flooded. Government buildings, people's houses, warehouses, temples, and shrines in the provinces were damaged, and many people and cattle were injured or died. The hot springs of Dogo Spa of Iyo stopped. In the province of Tosa (Kochi Prefecture), about 500,000 *shiro* or 1,000 *choho* (about 10 km$^2$) of farmland submerged and became ocean. Waves rushed to the shores and ships for carrying tributes were swept away."

Severe tremors in a wide area including Kinai, stopping of the hot springs of the Dogo Spa, submersion of Kochi Plain, and tsunami along the Pacific coast are characteristics of the Nankai earthquake that occurs at the "Nankai Trough" which is on the plate boundary of the Pacific Ocean bottom. Therefore, it can be seen that a Nankai earthquake occurred in 684.

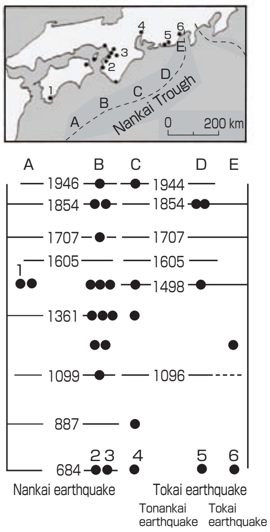


**Fig. 5 Timetable for great earthquakes of the Nankai Trough (additions to Reference[13]).**

The years shown in Western calendar years are occurrences of earthquakes known from written record. ● represent sites from which earthquake traces were found.

1. Azono Site. 2. Kawanabe Site. 3. Sakafuneishi Site. 4. Tadokoro Site. 5. Sakajiri Site. 6. Kawai Site.

### 5.3 Great earthquakes in the Nankai Trough

Figure 5 shows the timetable of mega-earthquakes in the Nankai Trough. The Trough is divided into 5 segments, A~E. A to B cause the Nankai earthquake, and C to E cause the Tokai earthquake. After the Showa Period, the latter is divided into C and D for Tonankai earthquake and E for postulated Tokai earthquake. In Fig. 5, the western calendar years are dates of occurrences that can be determined from written records such as the Nankai earthquake of 684.

After the Edo Period where there are abundant historical materials, most major earthquakes were recorded in writing. In contrast, the absolute quantity of historical materials decreases significantly before the Edo Period, and records may not exist for earthquake occurrences. This is the reason the number of earthquakes after the Edo Period increases in the western calendar timetable in Fig. 5.

In the survey of Sakajiri Site in Fukuroi City located east of Lake Hamana, Shizuoka Prefecture, the residential remains from the mid 7th century were torn by many sand boils. Since government buildings were built in early 8th century on top of the sand boil, it could be seen that the Tokai region was severely shaken in the late 7th century. Moreover, traces of liquefaction in the same period were discovered in the Kawai Site in Shizuoka City and the Tadokoro Site of Aichi Prefecture. Therefore, there is high possibility that a Tokai earthquake occurred at the same time as the Nankai earthquake of 684 described in the *Nihonshoki*. For the Nankai earthquake of 684, corresponding earthquake traces

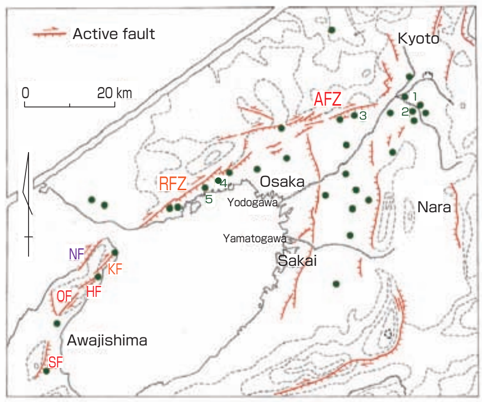


**Fig. 6 Traces of earthquake that are thought to be left by the Fushimi Earthquake (additions to Reference[16]).**

● represent the sites from which traces of the Fushimi Earthquake were found.

1. Kizugawa Riverbed Site. 2. Uchisato Haccho Site. 3. Imashirozuka Tomb. 4. Sumiyoshi Miyamachi Site. 5. Nishimotomezuka Tomb.

The fault that was active in the Great Hanshin Awaji Earthquake of 1995: NF Nojima Fault.

Ones that were active in the Fushimi Earthquake of 1596: AFZ Arima-Takatsuki Fault Zone, HF Higashiura Fault, OF Nodao Fault, and SF Senzan Fault.

Ones that are speculated to have been active in the Fushimi Earthquake: RFS Rokko Fault Zone and KF Kusumoto Fault.

were found at the Kawanabe Site in Wakayama City and the Sakafuneishi Site of Nara Prefecture.

On the other hand, there are some records of the Tokai earthquake in 1498, but no historical record of the Nankai earthquake exists. However, after 1989, the traces of liquefaction attributed to about the 15th century were found one after the other at the Azono Site, Shimanto City, Kochi Prefecture of Shikoku as well as at sites in Itano-cho, Tokushima Prefecture[9][17], and it can be seen that there was a Nankai earthquake that rocked the entire island of Shikoku.

When the earthquake traces of both earthquakes are entered into the timetable along with the dates of earthquakes known from written records, it can be seen that the great earthquakes of the Nankai Trough occur at fairly regular intervals at the same time or in sequence.

### *5.4 Investigating the total picture of the Keicho Fushimi Earthquake*

On the other hand, many traces of inland earthquakes were found around the Osaka Plain. Because the majority of the traces show that the medieval layers were torn but were covered by layers of the Edo period, they are suspected to be due to the Keicho Fushimi Earthquake of 1596, as in the Kizugawa Riverbed Site (Fig. 6). There are several types of earthquake traces. Traces of large-scale liquefaction can be seen in the alluvial lowlands with high groundwater level in southern Kyoto Basin, as in Kizugawa Riverbed Site and Uchisato Haccho Site (Fig. 7). Also, at Sumiyoshi Miyamachi Site in the southern foot of the Rokko Mountain Range, traces of lateral flow in which the ground slid sideways due to liquefaction were found. In the Imashirozuka Tomb of Takatsuki City and the Nishimotomezuka Tomb of Kobe City, although the mounds were deformed due to landslides, from the date of the layer covered by the soil from the collapsed mound, it was known that the trace was of the Keicho Fushimi Earthquake.

For this earthquake, the chronicles of temples and shrines and aristocrats' diaries describe that the tower of the Fushimi Castle collapsed in Kyoto, the temples Toji, Daikakuji, Tenryuji, and Nisonin were destroyed, houses of Osaka and Sakai were damaged, and the fires consumed the fallen buildings in Hyogo (current Kobe). As will be described later, from the trench excavation of active faults, it was found that this earthquake was caused by the Arima-Takatsuki Fault Zone and the active faults of Awajishima.

In the case of the Keicho Fushimi Earthquake, the active fault was identified and the damages to castles, temples, and houses were determined from written records. Adding the ground disaster that could be learned from earthquake traces at the archaeological sites, the overall picture of the earthquake can be seen from three perspectives.

### *5.5 New findings on liquefaction*

Since the Niigata Earthquake of 1964, liquefaction came into the spotlight, as sand boils that pour out on to the surface can be observed by anyone immediately after the earthquake. However, there was lack of knowledge about the original sand layer that supplied the sand boils, as well as for the mechanism of sand boil rising to the ground. Knowledge was limited to speculations based on results of underground boring. However, when liquefaction traces were found at archaeological sites, observation of the cross section of layers could be made by excavating the ground, and the following basic facts that were unknown before were clarified.

For example, the depth of the sand layer that supplied sand to the sand boil when liquefaction occurred was only tens of cm to 2 m deep, and it was shallower than originally thought. Also, liquefaction was thought to occur in the sand layer, but many cases were found where the gravel layer containing large proportions of gravel liquefied and rose through the sand vein. Figure 8 shows the trace of liquefaction observed at the Hariehama Site at the bottom of Lake Biwa. Liquefaction occurs in the sand layer containing plenty of

**Fig. 7 Traces of liquefaction of the Uchisato Haccho Site (excavation of Yawata City Education Board, photography by Sangawa).**

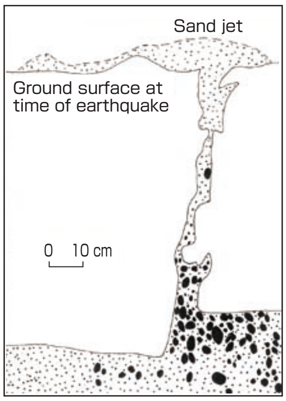


**Fig. 8 Traces of liquefaction at the Hariehama Site.**
The liquefaction occurred in the gravel layer, but large gravels did not reach the ground surface.

gravel, but large pebbles are left behind when sand and gravel rise with the underground water. In this case, looking only at the surface, it seems that liquefaction occurred in the sand layer without gravel, but that is not the actual case. Basic knowledge can be obtained by sequential observation of the flow in the layer when liquefaction occurs up to the arrival of the sand boil to the surface.

## 6 The Great Hanshin Awaji Earthquake

The Hanshin Awaji Earthquake of January 17, 1995 was caused by the activity of the Nojima Fault shown in the "Akashi" section of 1:50,000 Geological Map published in 1990 by the Geological Survey of Japan[18]. The position and the movement of this fault was correctly described in the map manual, but at the time of its writing, the information was not at the level that allowed predictions of the scale of earthquake damages to be caused by future activities of the faults.

After the Hanshin Awaji Earthquake, the importance of active faults was recognized, and the Headquarter for Earthquake Studies Promotion was established in the Agency for Science and Technology (current Ministry of Education, Culture, Sports, Science and Technology). The national project was started to study the accurate positions and activities of major active faults throughout Japan, to predict statistically the future fault activities by investigating the history of their activities, and to project the scale and spread of the seismic movement caused by their activities. The survey was conducted as joint efforts of the Geological Survey of Japan, Agency of Science and Technology, as well as the local governments and universities throughout Japan.

Many active faults stretch from the southwestern area of the Kyoto Basin, passing by the north rim of the Osaka Plain, and traveling all the way to Awajishima. The Hanshin Awaji Earthquake was caused mainly by the movement of the Nojima Fault (labeled NF in Fig. 6). Immediately after the earthquake, there was worry that a larger earthquake may occur in the near future in connection with this earthquake if there were other faults that were inactive for long periods and their energy was being accumulated. Many people living in the northern part of Osaka Plain became worried.

However, traces of the Keicho Fushimi Earthquake in 1596 were found from many archaeological sites in the Keihanshin and Awaji regions (Fig. 6), and based on these evidences, the active faults in question were active in the earthquake 399 years ago. Moreover, in the trench survey of active faults conducted by the Geological Survey in 1995, it was found that many faults in the north rim of the Osaka Plain to the east coast of Awajishima, such as Arima-Takatsuki Fault Zone (labeled AFZ in Fig. 6) were active in the Keicho Fushimi Earthquake[19]. Together with the result of the trench survey that the activity of the Arima-Takatsuki Fault Zone prior to this occurred about 3,000 years ago[19], people were relieved of their worry that "a giant earthquake capable of annihilating the Keihanshin region will follow the Hanshin Awaji Earthquake."

On the other hand, many cultural properties such as Buddhist sculptures were damaged when the temples and shrines collapsed, as well as the archaeological artifacts that were on display during the Hanshin Awaji Earthquake. Demands were raised for measures against earthquakes for cultural properties and for support activities after the earthquake in the fields of history and archaeology.

Although swift recovery measures were needed in the Hanshin and Awaji regions that were hardest hit by the disaster, the construction work for recovery destroyed buried cultural properties, and the number of excavation surveys of archaeological sites increased sharply. As emergency measures, many archaeologists of the local governments throughout Japan were dispatched to the Hyogo Prefecture to support the excavations, and joined the survey with local archaeologists[20].

The archaeologists dispatched from around Japan had first-hand observation of the earthquake damages, and learned the basic knowledge of earthquakes. Moreover, in the process of excavating the sites of the Hanshin Awaji regions, many traces of the Keicho Fushimi Earthquake were discovered[21], and people who were unfamiliar with earthquake traces were able to learn the basic survey methods.

With the increased interests in earthquake traces, the archaeologists of Japan took part to edit and publish the *Excavated Traces of Earthquake*, a catalog of earthquake traces[22]. The journal *Kodaigaku Kenkyu* started a section for collecting earthquake traces in each issue, and this continues to the present[17][23].

In the aforementioned 1:500,000 Neotectonic Map series, the "Kyoto" region which became the center of attention in the Hanshin Awaji Earthquake was revised totally, and the second edition was published. In the "Paleoearthquake Data Map," the traces of Keicho Fushimi Earthquake and the mega-earthquakes from the Nankai Trough are shown in different colors to indicate the corresponding earthquakes[24].

## 7 In preparation for the earthquakes in the 21st century

Immediately after the Hanshin Awaji Earthquake, I spoke with many people of the disaster regions, and was shocked to find that most people had believed, "There will be no earthquake in the Kansai area." In reality, there are many active faults in this area, and great disaster befell in the Keicho Fushimi Earthquake about 400 years ago. At the same time, I felt strongly that if the knowledge of earthquakes known to researchers were widely known to the general public, perhaps the damages might have been decreased.

According to the timetable (Fig. 5) compiled from the written records and earthquake trace materials for the great earthquakes from the Nankai Trough, it is almost inevitable that a Nankai and Tokai (Tonankai) earthquakes will occur in the middle of the 21st century. Moreover, it is highly likely that these great earthquakes will occur simultaneously or sequentially. In addition, there is a period of increased earthquakes (active period) several decades prior to the Nankai earthquake, and it is believed that the active period started after the Hanshin Awaji Earthquake[25].

In the new century, measures against earthquakes are becoming important, and both research institutes and governments are working on them. I think it is particularly effective to utilize the earthquake traces in archaeological sites to diffuse the knowledge to the general public.

As an example, I shall mention the Takamatsuzuka Tomb in Asuka, south of Nara. In 1972, the colorful wall paintings of the beauties of Asuka Period were found in the stone chamber of this tomb, and public interest in archaeology increased. In the recent survey, many fissures were found in the mound of the Takamatsuzuka Tomb, and some fissures reached the stone chamber[26]. These were caused by the great earthquakes that occurred repeatedly at the Nankai Trough. In 2006, the stone chamber was disassembled to prevent the deterioration of the wall paintings, and the results of the excavation done at the time were covered widely by the newspapers and television. In addition, traces of the earthquake that damaged the Takamatsuzuka Tomb was reported, and many people learned that “ great earthquakes of the Nankai Trough is approaching, and a broad area including Asuka will be shaken.”

The general public holds the impression that the mechanism of earthquakes is difficult to understand. However, by looking at the earthquake traces at the archaeological site, they can easily understand that in the past, a great earthquake struck the area they reside and left markings. When an archaeological excavation is done, public viewings are held, and in some cases tens of thousands of people visit the site. Since the establishment of earthquake archaeology, earthquake traces have also become subjects of viewing and are reported each time by the media. Their effectiveness as educational tools is great.

I have several opportunities to talk about earthquakes to the general public at lectures and events. On such occasions, referring to archaeological sites and history eases diffusion of knowledge to people who are not particularly interested in earthquakes. Recently, there are increased opportunities for earthquake education to elementary school students, and using earthquake traces of well-known archaeological sites improves educational value.

About 20 years have passed since I started this study, and the awareness to take up earthquake traces found at archaeological surveys as subjects of research has diffused widely among archaeologists, along with basic survey methods. In this sense, my initial objective has been achieved. I have written books for the general public on this subject. Particularly, in the book published in 1992[13], I described the research results and survey methods of the earthquake traces in archaeological sites, and many readers adopted interest in earthquake archaeology. I also introduced the history of earthquakes in Japan since the Jomon Period[16].

The consciousness that archaeological sites, which may seem unrelated, may become subjects of research has spread to researchers of various earthquake-related fields such as geology and engineering, and research from new perspectives are being started.

I worked as visiting professor at the Institute of Industrial Sciences, the University of Tokyo, as well as at the Disaster Prevention Research Institute, Kyoto University, and am conducting research in collaboration with researchers of earthquake engineering and geotechnical engineering.

As one example, as in the aforementioned Hariehama Site, at the Motojima Site of Shizuoka Prefecture, traces where only sand rose out from the gravel layer in liquefaction were observed[27]. Various other findings on liquefaction obtained from the sites are becoming widely known among engineering researchers[28].

Also, in the Imashirozuka Tomb where the sliding and moving of the soil of the mound in a landslide could be observed sequentially, joint research including mathematical analysis was conducted[29]. Also, traces of landslide and fissures are being studied with engineers at the Nishimotomezuka Tomb and Takamatsuzuka Tomb[30]-[32].

In the future, I hope studies using archaeological sites will progress further, and I shall continue to work on the diffusion of this knowledge.

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## Author

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Completed doctorate course at the Graduate School of Science, Tohoku University in March 1979 (Doctor of Science). Joined the Geological Survey of Japan, Agency of Industrial Science and Technology, Ministry of International Trade and Industry in April 1979. Chief researcher of AIST from April 2001. Visiting researcher of AIST from April 2007. Also served as visiting professor at the Institute of Industrial Sciences, the University of Tokyo from April 2002 to March 2004, and visiting professor at the Disaster Prevention Research Institute, Kyoto University from April 2005 to March 2008. Engages mainly in research on active faults, and has been engaging in interdisciplinary research with archaeology since declaring earthquake archaeology in 1988. Received the Award of the Minister of Agency of Science and Technology in 2000.

## Discussion with Reviewers

### 1 Activities to diffuse "earthquake archaeology"

**Question and Comments (Eikichi Tsukuda, Research Coordinator, AIST)**

The research of Dr. Sangawa is widely known throughout society, has received the attention of the mass media, and I think much contribution was made in reducing earthquake disasters. Earthquake study is rapidly advancing in recent years, but for the results to be returned to society as *Full Research*, and to actually reduce earthquake damages, increased understanding of the general public about earthquakes is necessary, and it must result in both long-term activities (earthquake resistant residences) and short-term activities (immediately after an occurrence of an earthquake). I think Dr. Sangawa's research, as a *Full Research*, is an extremely important contribution in the field of earthquake disaster reduction. Can you please provide comments about the diffusion activity through your experience in collaboration with the mass media?

**Answer (Akira Sangawa)**

As you indicated, I think diffusion through the mass media is important. Although lectures and writings by researchers can transmit specialized knowledge to the general public, there is an enormous difference in the capacity to reach many people through newspapers, TV, and radio. In that sense, the mass media plays the role as a bridge between the researchers and the general public, and is important in widely publicizing the research results. When there is coverage, I try to provide sufficient explanation so my intent is communicated accurately, and specialized knowledge is explained where needed to make the contents of coverage as high quality as possible. I think the people of AIST, particularly of the Geological Survey, who are involved in earthquake research, respond very carefully to news interviews.

As long as we live in Japan, there is a chance that our lives may be lost due to an earthquake, and it is necessary for all Japanese citizens to have at least some knowledge of earthquakes. However, not too many people seek this knowledge actively. I think it is important to engage in diffusion to people who think earthquakes are too difficult for them to understand. As one method, I talk in terms of subjects that the general public find interesting. It is more effective if earthquakes are coupled with cultural properties such as tombs and famous historical events.

### 2 Synthetic process of "earthquake archaeology"

**Question and comment (Akira Ono, Vice President, AIST)**

I think this is an excellent research where archaeology and seismology were fused to successfully create a new discipline. Can you please explain, using diagrams if possible, how a new fused discipline was created from two different disciplines?

**Answer (Akira Sangawa)**

I created Fig. a. Although it is a fusion of archaeology and seismology, seismology mainly utilizes geologic methodology, so I added "geology" in small type under seismology in the figure on the left.

In the survey of archaeological sites, excavation is done from the ground surface downward to dig up the remains and artifacts, dates are figured out using archaeological methods, and comparisons made with ancient records and writings. As a result, new findings can be added to the history of the region.

In seismology, the fields involved and methodologies are diverse, so I listed the research subjects in Fig. a. The subjects are: places where the earthquake occurs like plate boundaries and active faults; also, events that occur due to an earthquake such as liquefaction and landslides. Advancements of both researches are necessary for earthquake prediction and damage reduction.

Earthquake archaeology begins when a trace of an earthquake is found at an archaeological site. The date of the earthquake trace is obtained using the dates of remains and artifacts, and such materials are accumulated to build a history of earthquakes. Recently, the study of the history of active faults has progressed, and we find many earthquake traces that correspond to fault activities. Each earthquake history of plate boundaries and active faults becomes basic material for predicting future occurrences. On the other hand, observation of sand flow and movement brings new findings about liquefaction. The traces of landslide in structures whose original shape are known, as in a tomb, help clarifying the mechanism of landslides.

In archaeology, earthquake traces used to be meaningless, mysterious things. Some of the mysteries of archaeology, such as the disappearance or the decline of a village after the date earthquake traces were left, the discovery of remains that show evidences of residences from lake bottoms, and the presence of strangely shaped tombs can now be solved by introducing the concept of earthquakes. In the case where there are abundant earthquake traces and the overall picture of earthquakes can be readily seen, as in the Tsukushi Earthquake of 679 and the Keicho Fushimi Earthquake of 1596, the earthquake traces provide exact dates and help refine archaeological dating.

### 3 Traces of earthquakes other than liquefaction

**Question and comment (Akira Ono)**

In this paper, liquefaction is mainly described as a trace of great earthquakes on archaeological sites, but are there other kinds of traces?

**Answer (Akira Sangawa)**

In archaeological surveys, many traces of liquefaction in particular are found readily. Liquefaction occurs in the soft sand layer with abundant underground water. Our ancestors lived mainly in the plain with abundant water supply, so the traces of liquefaction can be found in the residences. Also, the traces of sand boils that poured out onto the surface by liquefaction allow dating the earthquake. Other than this, tombs that were built on slightly higher grounds show traces of landslides and fissures due to seismic movements. In the Tsukushi Earthquake of 679, excavations were done right on top of the active fault that caused the earthquake, and we were able to observe direct evidence of the fault activities.

### 4 Estimation of magnitude of earthquakes

**Question and comment (Akira Ono)**

Figure 5 shows the past great earthquakes of the Nankai Trough, but what was the magnitude of the earthquakes that could be estimated by the earthquake archaeology methods?

**Answer (Akira Sangawa)**

When earthquake traces are found in some archaeological sites, I can estimate the scale of the tremor at that place. When the earthquake traces of the same earthquake are found in multiple points in a widespread area, I can see the range of the region that was hit by a severe tremor, and can estimate the magnitude of the earthquake. In case of the great earthquake in the Nankai Trough, there are plenty of written records of damages, and I can estimate the magnitude based on such materials. Recently, there are advances in the studies of traces of tsunami, and the history of the occurrence of great earthquakes can be seen from tsunami traces. I think it is good to observe from both aspects of tremors and tsunamis.

### 5 Application to foreign earthquakes

**Question and comment (Akira Ono)**

Do you think it is possible to apply earthquake archaeology to earthquakes that occurred abroad? What are the points that differ from Japan?

**Answer (Akira Sangawa)**

In Japan, a great number of excavations have been done, and archaeological sequencing is very refined. The population density was high, and the life cycle of artifacts used were short because houses were made of wood and people used easily breakable earthenware and pottery, and this enables fine sequencing. Also, there are written records for the past thousand or more years, and the accuracy of archaeological sequencing is increased through comparison with written records. Of course, Japan is one of the most earthquake-prone countries in the world, and people lived in the plains with abundant water supply, so there are many traces of liquefaction. Therefore, it is a land most suited for studying the history of earthquakes in conjunction with archaeology. Although it may not be the same as Japan, any country can adopt the perspective of studying earthquakes through archaeological sites, and I think it is possible to devise methods that suit the situation of the country.

### 6 Fusion of fields of sciences and humanities

**Question and comment (Akira Ono)**

Earthquake archaeology is a fused discipline that handles the fields of humanities and sciences that are quite a distance apart. Wasn't reading ancient documents a difficult factor for a scientific researcher? Please comment on other points in fusing humanities and sciences.

**Answer (Akira Sangawa)**

I think reading ancient writings and records can be a very difficult process for scientific researchers. However, in Japan, collection of old records on earthquakes has been done actively after the Meiji Era, and the documents are available in modern type, so one can read them fairly easily. I like archaeology as well as Japanese literature and Japanese history, so reading old writings and records is quite enjoyable. However, I am handicapped because I am not specially trained, but I feel my understanding has deepened as I read more. At any rate, for fusion of science and humanities, the essential condition is that you fall in love with the other discipline.

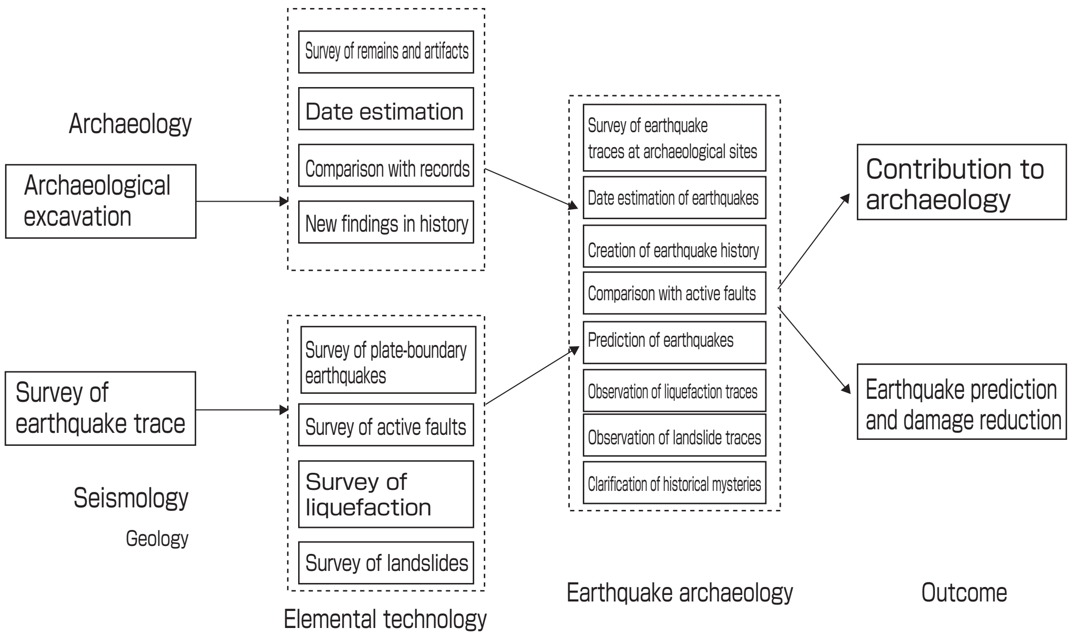


**Fig a. Process of synthesis in earthquake archaeology**

# High accuracy three-dimensional shape measurements for supporting manufacturing industries

## — Establishment of the traceability system and standardization —

**Sonko Osawa***, **Toshiyuki Takatsuji and Osamu Sato**

**[Translation from *Synthesiology*, Vol.2, No.2, p.101-112 (2009)]**

Digital engineering technique has widely been used for speedy and effective manufacturing of industrial products. Coordinate measuring machines (CMM) are being used for measuring three-dimensional shapes of products and taking an important role to keep the quality of the products high. National Metrology Institute of Japan (NMIJ/AIST) has established the traceability system of CMM, that is, measurement results by CMM are traceable to the national standards of length. To achieve this objective, not only calibration techniques have been developed, but industrial standards (ISO and JIS) and guidelines to which accredited laboratories should conform were documented. In addition, to raise the calibration capabilities of prefectural laboratories and to contribute to the local industries, technical supports have been provided by NMIJ.

*Keywords* : Three-dimensional coordinate measurement, coordinate measuring machine, measurement standard, metrological traceability, digital engineering

## 1 Introduction

Japan became a wealthy country by developing its industry after World War Ⅱ. Particularly, manufacturing, represented by the automobile industry, is the center of Japanese economy. In manufacturing, a product is produced by designing, manufacturing, and assessment. Recently, manufacturing is done using digital data for design, manufacturing, and assessments as shown in Fig. 1. After designing using CAD (computer aided design) and CAE (computer aided engineering), the data is sent to CAM (computer aided manufacturing) for manufacturing. The manufactured product is measured using CAT (computer aided testing), and the measurement data are fed back to the design and manufacturing processes. The analysis and design based on real data as well as the manufacturing process are improved, and this completes the cycle of the manufacturing process. Through the development of the manufacturing system using digital data, it is possible to significantly reduce the days required for manufacturing prototypes. In such digital manufacturing system, coordinate measuring machines (CMM) are often used to assess the shape of the product. CMM is also called the universal measuring machine, and is capable of measuring various three-dimensional shapes (position, size, and geometrical features including straightness, roundness, cylindricity, and squareness).

Here, the functions of a CMM will be outlined. As shown in Fig. 2, the CMM consists of a probing system to measure the coordinates by contacting the surface of the workpiece, a guide to linearly transfer the probing system along the X, Y, and Z axes that run at right angles to each other, a scale to measure the distance of transfer, and a computer to control the coordinate transformation and the measuring machine. In the CMM, the range in which the probe (stylus) attached to the probing system can move is its measurement space. It is also possible to calculate not only the distance between two points, but also the feature quantity of geometrical shape of the workpiece (for example, diameter, roundness, and center coordinate of a circle) using the least-square fitting from measured points.

Conventionally, CMMs were expensive and required advanced skills to operate, and they were installed only in prototype and quality control divisions of large corporations. However, they are currently installed in manufacturing lines and small factories because of the need to adapt to digital manufacturing, demand for high quality control for products, and for differentiation against products of other Asian countries. By installing the workpiece and building

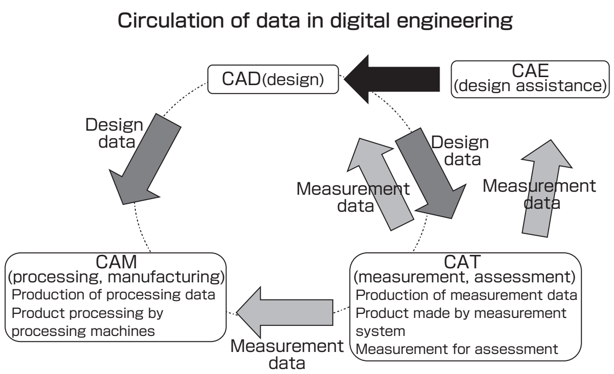


**Fig. 1 Digital data manufacturing.**

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the measurement program on the first run, the measurements thereafter on the CMM can be done by computer control. Therefore, some companies simply assign measurement personnel to only conduct routine work, and depend on the manufacturer of the measuring machine to do the complex programming to cut the cost of measurements. However, it is known that there is a distinct difference between the measurements by a person with specialized knowledge of CMM and someone without such knowledge. This is because the difference in the knowledge and the ability to deal with factors such as positioning of the workpiece and temperature of the environment may affect measurements. To increase the reliability of three-dimensional measurement, it is most important to create a system where the skill of the operator can be improved without requiring profuse knowledge or prolonged training.

Previously in Japan, the manufacturing process was perfected within the consolidated company group, and the system for maintaining reliability of the product was relatively well established within the companies. However, as more less-expensive, good-quality parts are obtained inside and outside Japan, and as production overseas is increased to cut the cost of labor, globalization of parts procurement increases and the system for maintaining reliability within a corporate group is collapsing. For example, flaws in assembly may become a problem because the size of parts delivered by Company A and the size of parts from Company B are slightly different. Therefore, some kind of official support has become necessary to replace the system of maintaining reliability that had been established within the consolidated company group.

The aim of this research is to develop technology necessary to increase reliability of three-dimensional shape measurement, which is one of the most basic technologies that support manufacturing, and to create an official system to diffuse such system to the sites of production.

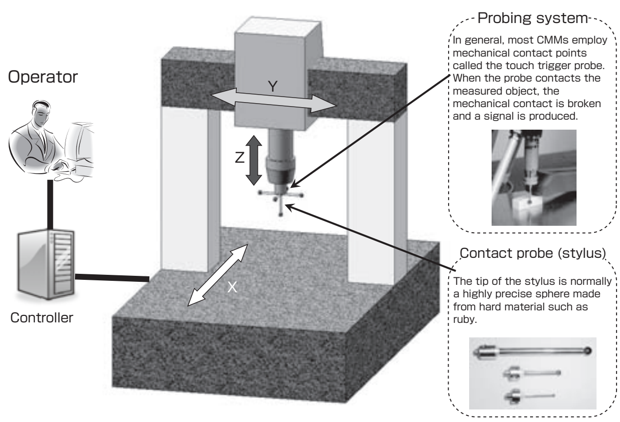


**Fig. 2 Outline of CMM.**

## 2 Scenario

### *2.1 Scenario for improving reliability*

For the dissemination of AIST's research results to a wide range of industries, it is necessary to create a system for delivering the results to the site of production. A scenario for wide dissemination to sites of production was drafted in advance, starting with the establishment of a high-precision national measurement standard. Figure 3 shows the scenario drafted to improve the reliability of three-dimensional shape measurement.

To organize the national standard, AIST develops the standards and their calibration methods, and also will engage in the development of next-generation standards with higher precision. The reliability of three-dimensional measurement is improved by using such developments to calibrate the CMMs at the site of production. The equivalency of the established national standard will be checked by conducting international comparisons that involve the comparison of measured values with the national metrology laboratories of other countries, and the consistency of measured values based on that standard will be recognized worldwide. To diffuse the established standard in Japan, an accreditation system of calibration service is constructed, and the standard is introduced into the site of production through the service provided by the calibration service. To increase the competitiveness of local small and medium companies, training and technical support for high-precision measurement are provided to public research laboratories of each prefecture. Also, the reliability of three-dimensional shape measurement is raised at the site of production by standardizing the CMM assessment methods and the new three-dimensional shape measurement methods, and by developing a remote calibration technology to allow calibration of the CMM on-site using a simple procedure. To support Japanese companies that operate in developing countries, technical support is provided to national metrology laboratories of the developing countries. By establishing the scenario, our objective was to improve the international competitiveness of the Japanese manufacturing industry.

### *2.2 Maintenance of traceability and goals of development*

Objective demonstration of the reliability of three-dimensional shape measurement can be achieved by establishing the traceability to the national standards. For over ten years, AIST has been engaging in technological development to establish the traceability system of three-dimensional measurement. Figure 4 shows the technological developments of the traceability system for length. For three-dimensional measurement, the system is traceable to the iodine stabilized He-Ne laser that is the national standard for length. The shape of the product manufactured is assessed by a CMM; this CMM is calibrated with a standard called gaugeblock or ball plate, which is calibrated with a laser distance meter using stabilized He-Ne laser; and this laser distance meter is calibrated with the iodine stabilized He-Ne laser that is the national standard of length. Hence, the standards are linked seamlessly to the higher-level standards.

For practical operation of such traceability system at the sites of production, the following four items must be newly developed: (1) a calibration system of the standard, (2) an accreditation system for private calibration services, (3) standardization of CMM assessment method using standards, and (4) a training system to improve the skills of measurement personnel. To establish the traceability system for three-dimensional measurement, *Full Research* was conducted with the objective of developing these four subsystems. The researches conducted by AIST to develop these subsystems included the following three research topics:

1. Development of standards to calibrate and assess the CMM (construction of metrology standard)
2. Technological development for constructing the traceability system for three-dimensional measurement (construction of a calibration service accreditation system and standardization of calibration methods)
3. Development of high-precision three-dimensional shape measurement technology (advancement of metrological technology)

All three are developments that improve the reliability of three-dimensional shape measurement required in manufacturing, and are basic technologies to maintain reliability of measurements at the site of production. In chapters 3 to 5, specifics of the above technological developments will be described. Chapter 6 will be a description of the activities currently conducted at AIST for three-dimensional shape measurement technology, activities to diffuse the metrological standards to sites of production, and future developments.

## 3 Standard for assessing CMM

### *3.1 Error in three-dimensional measurement*

Although CMM is a convenient and useful measuring device, there are the following issues concerning its reliability:

1. Measurement error is likely to occur because the probe that detects the position of the workpiece does not match

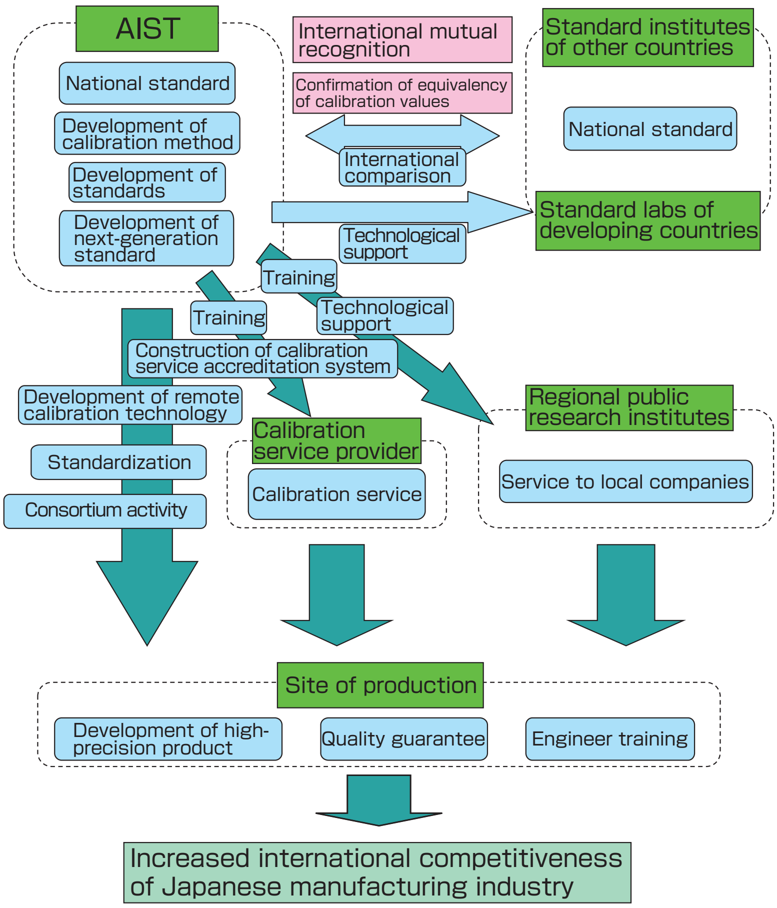


**Fig. 3 Scenario for improving reliability of three-dimensional shape measurement.**

the baseline length of the scale (that is, position of the probe is separated from the scale itself) (in technological terms, it “does not fulfill Abbe’s Principle”).
2. There are several other factors of error, and assessment of uncertainty of measurement data is difficult.

Although Issue 1 is a major problem in conducting high-precision measurement, the effect is kept small by allowing correction by software[1], by improving repeatability through increased rigidity of the machine itself. Most of the current CMMs have software correction functions, and it is necessary to obtain accurate correction data in advance to conduct effective correction. Specifically, there are two types of correction data. One is the correction data for the probing system. By measuring a calibration sphere, for which the value of the diameter has been precisely measured in advance and which has extremely small shape error (with 50 nm or less deviation from circularity), the diameter, deflection, and characteristic of this probing system of the spherical tip of the probe (stylus) used can be calculated (specifically, when the cross-section of the sphere is measured with a CMM, the shape may not turn out circular, but may be triangular or square depending on the characteristic of the probing system). The other type of correction data is the movement error of the instrument including scale error (of attachment of the scale), squareness error (orthogonality among each axis), straightness error (distortion in each axis guide), and rotational error (error due to changes in position). The errors of scale, squareness, straightness, and rotation are called geometrical errors[2] that can be calculated using various standards. Standards for CMM are necessary to obtain precise measurements of the two types of correction data, as described in the next section.

Issue 2 refers to the difficulty in assessment of uncertainty because CMM has multiple factors of error, and also because of complicated processing where the measurement data is calculated by concentrating the discretely distributed measurement points into one factor. We looked at a new calculation method for uncertainty using software simulation, and conducted research to solve this problem. This will be explained in detail in section 4.2.

### *3.2 Development of standards for CMM*

#### *3.2.1 Step gauge*

To check the measurement accuracy of the CMM or to obtain the data for software correction, various standards such as gaugeblocks and ball plates that can be traced to higher-level national standards (iodine stabilized He-Ne laser) are used. Unless calibration of these standards is conducted accurately, highly precise assessment of CMMs that is in the lower level of the traceability system cannot be done. Therefore, development of standard calibration technology is important, and the metrology labs of other countries are engaging in the development of calibration technology and calibration services.

AIST has been engaging in the development of a standard calibration system for about 10 years. In Japan, end measures (gaugeblock or step gauge) are generally used in the precision assessment of CMMs. For assessment of CMM, a step gauge (see Fig. 5), where short gaugeblocks are lined up and used as standards for varying lengths, is used more often than the gaugeblock. In major national metrology labs, step gauges are calibrated using a special instrument that combines a laser interferometer and a moving stage[3]. AIST developed a system for calibrating the step gauge by combining the CMM and the laser interferometer[4]. Figure 6 shows the developed system. In this system, by using a four optical path interferometer, the measured length shows the distance between the center of the sphere at the tip of the stylus and the interferometer at all times, even if rotation errors such at pitching and yawing occur in the stylus. When the step gauge with measured length 500 mm was calibrated using this system, uncertainty of 0.30 μm (95 % confidence interval) was achieved.

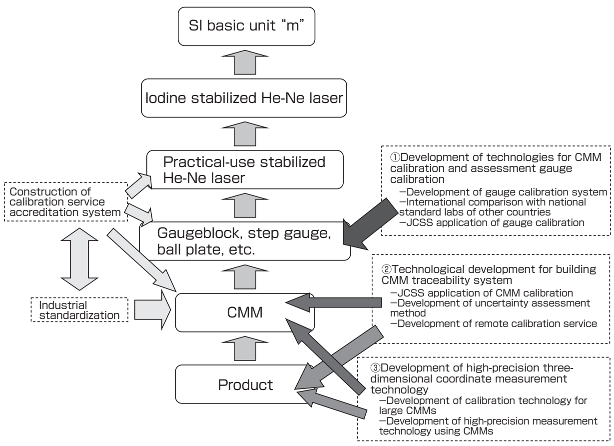


**Fig. 4 Relationship between traceability system and *Full Research*.**

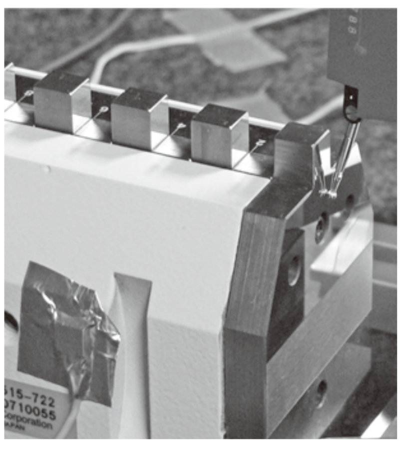

**Fig. 5 Exterior view of step gauge (measurement surface is arranged in comb-tooth form).**

#### *3.2.2 Ball plate*

In Europe, a ball plate and a hole plate (see Fig. 7) that allow two-dimensional assessments are used more often for assessment and calibration of CMM than end measures that are one-dimensional standards. The central coordinates of a sphere or a cylinder placed in the standards are determined, and the CMM assessment is conducted using these coordinates. Compared to end measures, it is possible to obtain more information and know precise errors within the measurement rage. To make the two-dimensional standards available in Japan, AIST constructed a calibration system for two-dimensional standards[5].

Here, the calibration system of a ball plate will be outlined. A ball plate cannot be calibrated using laser distance meters due to its round shape. Therefore, calibration is done using a CMM, but it is impossible to calibrate beyond the accuracy of the CMM when the results of the CMM measurement are used directly. Therefore, central coordinates of each sphere are measured using a method called the inverse method to reduce the geometrical error of the CMM. In measurements using the inverse method, the error of the scale itself (normally, primary tilt factor) remains, and this is corrected using a standard that is traceable to the length standard to calculate the final scale error. Normally, gaugeblocks with differing lengths are used for this correction, but a laser distance meter was used at AIST. Therefore, extremely precise correction data was obtained. By using this system, uncertainty 0.37 µm (95 % confidence interval) was achieved when calibrating the ball plate with measurement length 500 mm. Figure 8 shows the calibration of a ball plate using a laser interferometer. Currently, there are only five laboratories including AIST in the world that use advanced laser interferometer technology for ball plate calibration.

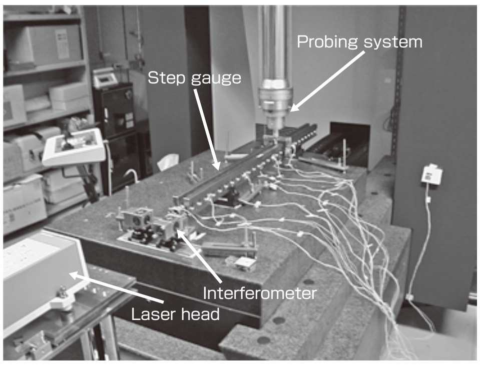


**Fig. 6 Step gauge calibration system.**

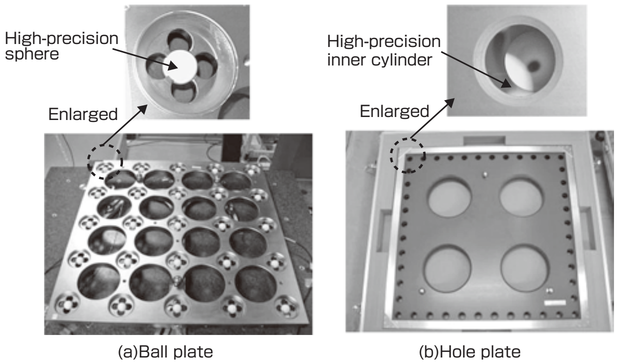


**Fig. 7 Two-dimensional standard.**

AIST also developed a new standard that can be traced to length standards to enable high-precision calibration of a ball plate at laboratories that do not possess an interferometer[6]. This standard is called the ball step gauge, and is in the form of one-dimensionally arranged balls. The sphere which will be measured is positioned at the neutral axis in the cross-sectional secondary moment of the H-shape main plate, and it is designed to keep the changes in relative positions to extremely small levels even when positional changes occur due to distortion by the sphere's own weight or heat distortion in vertical and horizontal directions. The distance between the spheres is calibrated at AIST using the laser distance meter, and then supplied to the user. To check the efficacy of this standard, and as part of the activities of the Council of Promotion of Industrial Technology Collaboration, comparative measurements of a ball plate were conducted by circulating this standard among regional public research laboratories. As a result, almost all labs agreed at a deviation within 0.5 µm against the AIST calibration value. It was confirmed that this standard was effective for comparative measurement, and that the technological level of the regional public laboratories were sufficiently high[5].

### *3.3 International comparison of standards*

#### *3.3.1 International comparison of step gauges*

The international comparison (CCL-K5) for calibration of step gauges was conducted from 1999 to 2002, with the participation of major national metrology institutes. The pilot laboratory prepared a step gauge with excellent stability, this gauge was transported to the metrology institutes of various countries to conduct blind measurements, and the results were reported to the pilot laboratory. The nine national

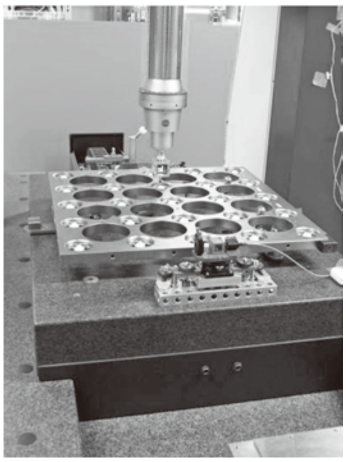

**Fig. 8 Ball plate calibration.**

metrology institues participated with this comparison.

Figure 9 shows the results of the international comparison[7]. In the international comparison, the participating institutes conduct measurements independently based on the national standard of their respective countries, and therefore none of the labs know which of their results are the closest to the true value. The weighted average value considering the uncertainties of measurements of the participating labs is designated as a value that is probably the most certain (reference value), and the deviation of the data of each lab is calculated. However, in this international comparison, it was found that the measurement data of some of the participating labs were greatly deviant. Ultimately, the measurements of four countries, Japan (NMIJ/AIST), U.S.A. (NIST), Switzerland (METAS), and Germany (PTB) were in good agreement, and therefore the average values of these four laboratories were used as a reference value. The graph of Fig. 9 is a plot showing the deviation from the reference value for each lab (the values of AIST run only to 720 mm due to the limitations of the measurement system). From this result, the reliability of the step gauge calibration system developed at AIST was confirmed, and the high level of the calibration technology of AIST was presented to the world.

### *3.3.2 International comparison of ball plates*

The international comparison of ball plate calibration (CCL-K6) was conducted from 2001 to 2004. There were 12 participating institutes. Figure 10 shows the result of this international comparison. The plotted points in this graph show the difference between the AIST result and the reference value, which is the average value of all participating institutes for the distances from 1st sphere to each sphere (2nd to 25th). The number of spheres is shown below the error bar. The error bar shows the uncertainly (66 % confidence interval) for measurement values of AIST, and the blue line shows the uncertainty (66 % confidence interval) against the reference value. It can be seen from this graph that the AIST values and the reference value match within the range of uncertainty. From this result, the reliability of the developed system was confirmed and the high-level calibration technology of AIST was presented to the world.

### *3.4 Calibration service of standards by private companies*

The mission of AIST is to have the technology confirmed in the above international comparison be used widely in industry. Since the number of calibration services that can be undertaken by AIST is limited, private companies with high-level calibration technology can conduct the service and participate as the middle tier of the traceability system, and diffuse the highly reliable three-dimensional shape measurement technology to industry. The Japan Calibration Service System (JCSS) based on the Measurement Act is a mechanism for officially accrediting private companies with proper calibration capacity. The service provider accredited under this system can issue calibration certificates that certify that a standard is traceable to the Japanese national standard. To establish a calibration system for step gauges using this system, a technological committee was established in the National Institute of Technology and Evaluation (NITE), and a draft of Guidelines for Technological Requirements[8] needed for accredited service providers was drafted under the leadership of AIST. Immediately after the establishment of the system, several service providers were accredited, and the traceable step gauges are now employed in several industries.

## 4 Reliability assessment of the CMM

### *4.1 Accreditation of calibration service providers for CMM*

As mentioned in chapter 3, it became possible to calibrate the CMM appropriately since the standard for step gauges was established. In this situation, the service providers that

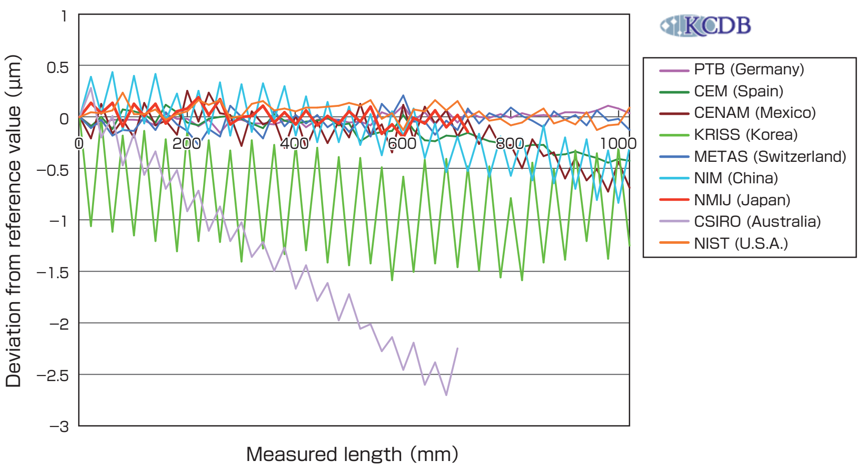


**Fig. 9 Result of international comparison for step gauge (CCL-K5).**

own the CMMs requested official certification for their capability to conduct three-dimensional measurements traceable to the national standard. Therefore, similar to the aforementioned step gauge standards, we established a technological committee for officially accrediting the service providers for three-dimensional measurement in the National Institute of Technology and Evaluation (NITE), and drafted the Guidelines for Technological Requirements[9] for CMM calibration. Currently several companies received the official accreditation for CMMs and are providing calibration services.

Since CMM is a multifunctional device, it is impossible to sufficiently evaluate all of its functions just by a few measurements with step gauges. The challenge is to conduct appropriate assessment with as little procedures as possible. The same problem arises in the performance testing for the buyer and the seller of CMM. In ISO, the testing method at the time of delivery of CMM is standardized. AIST has participated in the ISO meetings as an expert to work on standardization. In determining the Guidelines for Technological Requirements for the calibration of CMM, we decided to use the ISO standards[10]. This means that the metrological standard (metrological traceability system) references the industrial standard (standardization and rules for products and services). On the other hand, this ISO standard rules that a standard traceable to national standard must be used, and in reverse, the industrial standard references the metrological standard. We have been conducting R&D under the thinking that effective application of the system is possible for use in industry through unification of metrological and industrial standards. This time, one of our efforts was rewarded.

### *4.2 Calculation of uncertainty in three-dimensional measurement*

CMM conducts point measurements of each point and gathers the point data. If the measurement is for a circle, least-square fitting is done to calculate the diameter, circularity, and central coordinates. Since there are measurement errors in each measurement point, it is difficult to see at which uncertainty the diameter and circularity were finally calculated. Following items can be listed as factors of uncertainty in three-dimensional measurement (see Fig. 11).

1. Uncertainty of probing
2. Uncertainty arising from geometrical error
3. Uncertainty of data processing (least-square method, etc.)
4. Uncertainty arising from measurement procedure (number of measurement points and their arrangement, etc.)
5. Uncertainty arising from environmental change (temperature, humidity, etc.)
6. Uncertainty arising from positioning of workpiece (holding strength, distortion from own weight, etc.)
7. Uncertainty arising from workpiece itself (surface roughness, shape error, etc.)

Since various factors of uncertainty affect the measurement, it is fairly complicated to assess the final uncertainty. At AIST, with a grant from the International Joint Research Program, New Energy and Industrial Technology Development Organization (the NEDO grant), research on measurement uncertainty in CMM using Monte Carlo simulation was conducted jointly with the Physikalisch-Technische Bundesanstalt (PTB) of Germany, the National Measurement Institute of Australia (NMIA), the University of Tokyo, and others. The method is called virtual CMM[11], and its basic concept was developed by the PTB. Figure 12 shows the outline of the virtual CMM. Virtual CMM is a computer model of CMM including the errors of factors of uncertainly such as geometrical errors. By conducting about 200 measurements on the virtual model on the computer using the measured position information and other data obtained from actual measurements, the standard deviation and the uncertainty of the measured value obtained from virtual measurements are calculated.

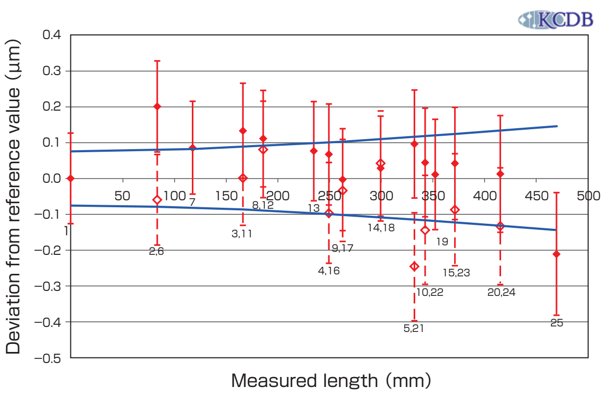


**Fig. 10 Result of international comparison for ball plate (CCL-K6).**
The graph shows the difference between AIST values and reference values for 25 spheres of the ball plate. The error bar shows the uncertainty of AIST value, while the blue line shows the uncertainty of reference value.

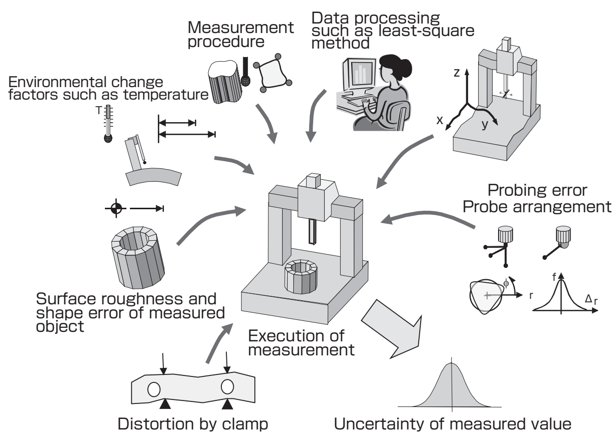


**Fig. 11 Factors of measurement uncertainty for CMM.**

In this study, AIST conducted comparative measurement of a normally workpiece, and assessed the practical usability of the virtual CMM. The diffusion of this virtual CMM technology helped the construction of a traceability system for three-dimensional measurement. The calculation method of uncertainty by simulation was standardized as ISO/TS 15530-4.

### 4.3 Remote calibration of CMM

To calculate the uncertainty using the method mentioned in the previous section, it is necessary to obtain data for geometrical error for the entire measurement space using standards. Since extremely specialized technique is needed to obtain the geometrical error data of measurement space of the CMM, this measurement is preferably done by a specialized calibration service. However, time and money costs are needed when the calibration specialist is dispatched to the site of production. Therefore, AIST developed a system to conduct this work easily using the Internet[12].

Figure 13 shows the outline of remote calibration of CMM using the Internet. The calibration service provider first sends a standard to the CMM user. Changes during transportation such as temperature, humidity, and vibrations are monitored by an accompanying sensor with a recording function. The calibration service determines whether the standard has changed by looking at the recorded information of the sensor. Next, the user's CMM is calibrated using a two-dimensional standard. The standard is set in position by the user, while the setting procedure is monitored by a specialist of the calibration service using the network camera. The user's CMM is controlled by the calibration specialist via the Internet. The environmental temperature during calibration is measured using the thermometer delivered along with the standard. The temperature measurement data are also sent using the Internet and are stored by the calibration service. The parameter setting and the creation of a coordinate system of the probing system are done by talking directly with the user via telephone or Internet camera phone. After completing the measurement, the calibration service uses these measurement data to calculate the geometrical error of the user's CMM. The calculated geometrical error is sent to the user, and used for calculating uncertainty and error corrections. The calibration service specialist does not have to be present at the site of calibration, and we call this remote calibration. This technological development enables traceability of three-dimensional measurement without requiring the user to have knowledge in standards and geometrical error calculation, and can be done at low cost.

AIST has been conducting CMM calibration service using the remote method as a requested test since 2005. This service is conducted by the assessment method based on ISO standards using gaugeblocks and step gauges rather than two-dimensional standards, just as in the CMM calibration in the JCSS.

## 5 Sophistication of three-dimensional shape measurement

### 5.1 Calibration of large CMMs

For shape measurement of automobile body or aircraft fuselage, a large CMM with measurement space such as 5 m × 3 m × 2 m is used. For calibration of such large CMM, large standards may be used, although there are issues of weight and time cost. Therefore, AIST suggested a calibration system using laser tracking laser interferometer (or laser tracker) as one of the methods to calibrate large CMMs without using a standard. The CMM calibration system using the laser tracker was studied at the National Physical Laboratory (NPL) of U.K., the Physikalisch-Technische Bundesanstalt (PTB) of Germany, and AIST. All devices calculate the coordinates by the principle of trilateration from distance measurement of the device. The devices of NPL[13] and PTB[14] use repeated measurements of the target position by transferring one laser tracker to several positions, while the AIST method is to install four laser trackers to measure the positions of the target at once[15]. Since the AIST method allows calculation of coordinates in one shot, it has merit of having shorter measurement time compared to the NPL and PTB methods. Therefore, the external environment effect such as a shift in coordinates of the workpiece due to changes in temperature can be kept to a minimum.

Figure 14 is a photograph of the laser tracker developed at AIST. The characteristic of this system is to reduce

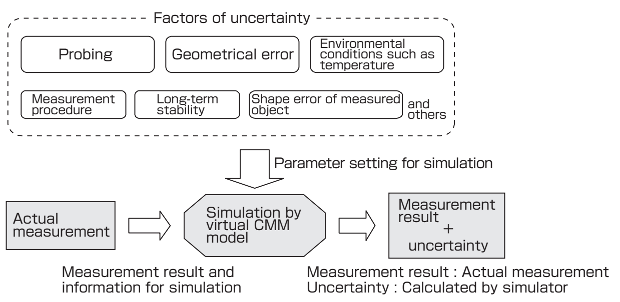


**Fig. 12 Outline of virtual CMM.**

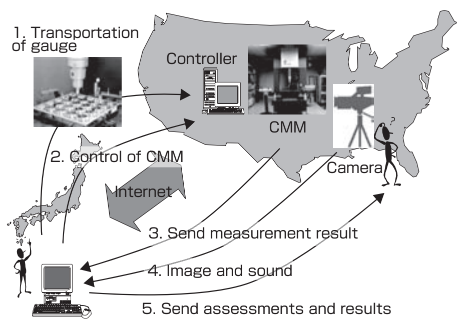


**Fig. 13 Remote calibration technology for CMM.**

mechanical error of the tracking system by using a hemisphere for the mirror to scan the laser. Normally, the two axes for scanning the laser in horizontal and vertical directions must be adjusted accurately, and an advanced skill is required for this adjustment. In our device, three spheres are arranged at 120 ° intervals, and hemispheric mirrors are fixed to the three spheres to create a high-precision laser scanning mechanism using low-cost mechanical elements[16]. Upon comparing this laser tracker with high-precision CMM, it was confirmed that the mechanical precision of the system itself was 0.3 μm or less[17]. The geometrical error of the CMM was calculated and compared using a ball plate and a laser tracker, and the values matched within 2 μm in the measurement space of 300 mm cube[18].

When the user uses the laser tracker, the ease of handling is important. Therefore, we achieved downsizing and weight reduction by using a spherical motor that was developed by the Intelligent Systems Research Institute, AIST[19]. This is a good example of a research result produced by a fusion with other disciplines. With this technological development, high-precision calibrations of large CMM and hand coordinates of industrial robots can be conducted.

Currently, discussions of standardization have been started for the assessment of the laser tracker in ISO meetings, and we plan to contribute to its standardization through our knowledge and experience gained in this technological development.

### 5.2 High-precision measurement by CMM

In industries such as mold making where highly precise manufacturing is done, assessment at higher precision than the innate precision of the measurement machine may be required occasionally. Although normally such assessment is impossible, it is possible to conduct higher precision measurement by special arrangements and procedures that will mutually cancel out the errors of the measuring machine. The inverse method used for calibration of a ball plate is one example. AIST developed such high-precision measurement technology, and we shall present the result for measuring a cylinder as an example.

As shown in Fig. 15, the circularity of a cylinder is measured and assessed by conducting measurement at eight equal-interval points. After the first measurement, the workpiece is rotated 45 degrees for the second measurement. It is again rotated 45 degrees, with measurements for total eight positions. When the average of the eight measurements is calculated, geometrical error, offset error for the two styli, and effects of probe directionalities can be cancelled out. This method is called the multiple measurement method, and can be used for precise measurement of rotationally symmetrical shapes[20]. For calibration of standards, AIST is planning high-precision calibration experiments for such applications. This measurement method can be applied in sites of production, and we plan to disseminate this knowledge widely through regional public laboratories.

## 6 Future of three-dimensional shape measurement

### 6.1 Measurement standards and standardization for digital engineering[21]

As shown in Fig. 1, in digital engineering where the entire process of design, manufacturing, and assessment is done by digital data, it is necessary to compare the CAD design data and the actual measured results. CAD data has planar information, and the volume of information from discrete measurement data of a conventional CMM with a tactile probing system is insufficient. Therefore, noncontact CMM is now being used, since it can obtain measurements for high-density multiple points in one shot. Previously, for noncontact CMM, the manufacturers were conducting precision assessments and providing precision guarantees using their own standards, and there was no system based on common assessment methods. Hence, there was no uniform index when the user was purchasing a CMM, and it was not possible to determine whether the precision of the instrument was as stated in the catalog. Therefore,

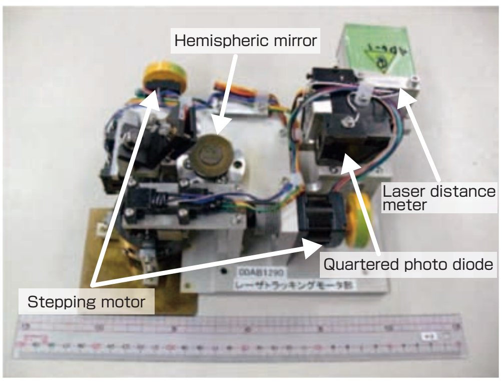


Fig. 14 Laser tracking interferometric distance meter.

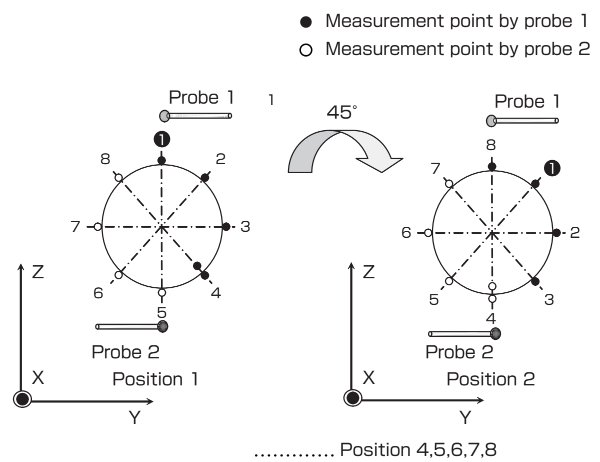


Fig. 15 Multiple measurement method of cylinder.

AIST established a consortium for creating a standard for the precision assessment of noncontact CMM in 2005. The consortium developed standards for use in the assessment of the noncontact CMM (metrological standards) and devised an assessment method using these standards.

Since there are many different types of noncontact CMMs, it is important to create standards that enable assessment of these various measuring machines. In optical measuring machine, error tends to occur in the presence of luster in the measured area of the standard. Therefore, the surface of the standard must have optically diffusing surface. To select an ideal diffusing surface, through cooperation of the consortium members, several spheres were created with slightly different processing methods, conditions, and surface coatings. Figure 16 shows some examples. Processing were done with over 100 different conditions, the spheres were measured using several types of noncontact CMMs, and a sphere for which relatively stable measurements could be obtained in all measuring machines was selected. Next, using the selected sphere, a ball bar, which would be the standard for a precision assessment of the measuring machines, was created (see Fig. 17). A carbon frame was used so it would not be affected by environmental temperature, since many noncontact CMMs were portable and they were unlikely to be used in a room with constant temperature at 20 ºC. Therefore, a standard that was stable against temperature change was needed. Hence, a standard traceable to the national standard was created by the consortium so it could be used for assessment of measuring machines. After conducting comparative measurements, the assessment of noncontact CMM using this standard was standardized as Japan Industrial Standard (JIS). Currently, the drafted JIS is undergoing deliberation at the Japan Industrial Standards Committee as JIS B 7441. It has also been submitted to the ISO committee at the same time. We are collaborating with Digital Human Research Center, AIST, for the standardization of the assessment method of noncontact CMM for the measurement of the human body.

The x-ray CT device that was previously used for the detection of cast pores is now being employed in industry as a CMM that can measure internal structures. Therefore, there are demands from manufacturers and users for the development of a common phantom (standard) to assess the x-ray CT devices, as well as for the standardization of assessment method using the phantom, and AIST is preparing for this study.

**Fig. 16 Spheres manufactured under different conditions.**
Dispersion eutectoid coating (B-MOS) (leftmost)
Sandblast: Cr coating (2nd from left), TiN coating (center)
Chemical etching ($FeCl_2$) (two on right)

### 6.2 Cooperation with regional public research laboratories

Since CMMs are expensive instruments, the financial strain on small to medium businesses is great. Therefore, CMMs are installed in almost all regional public laboratories to provide services, such as requested measurements and the use of the instrument by the local companies. AIST is engaging in activities to improve three-dimensional measurement technology in the Shape Measurement Subcommittee, Intellectual Infrastructure Committee, which is one of the technical committees of the Council of Promotion of Industrial Technology Collaboration. The subcommittee has engaged in comparative measurement of ball plates, demonstration experiment for the calculation of uncertainty in deliberation at the ISO, and assessment experiment of video probe CMM. Also, a project to maintain reliability of CMM measurements is conducted as a local collaborative innovation creation undertaking with public laboratories in the wider Kanto area from FY 2008. Through such activities we are contributing to the improvement of three-dimensional shape measurement technology at the site of production. We hope these technologies will be transferred from public laboratories to local small and medium businesses to vitalize Japanese manufacturing.

### 6.3 Operator training

AIST has engaged in technological developments and diffusion activities for the three-dimensional shape measurement. We feel that the technological development for establishing metrological traceability had been sufficiently organized. In the future, we shall strengthen activities to diffuse daily maintenance methods for CMM to further improve the reliability of the three-dimensional measurement, and train the users. Recent measuring machines including CMMs are digital rather than analog, and the values are shown on the display. Therefore, the operator tends to think that the figures are always correct. However, in measurement, the reliability of the values changes depending

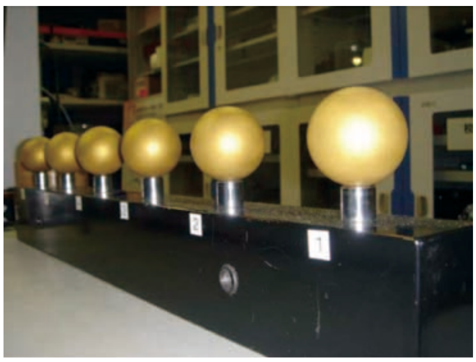

**Fig. 17 Ball bar for noncontact CMM assessment.**

on the conditions and methods of measurement. Great difference may occur in measurement reliability depending on whether the operator understands this point or not. For example, some operators may not know that the sizes written on the plan of an industrial product are sizes at 20 ºC. To improve the reliability of the product, we believe it is very important to educate the people who are using the assessment tool. We think the training system for improving the skill of the measurement operator is the final requirement for constructing the traceability system at the site of production, and as one step for improving the skills, we plan to create an accreditation system for three-dimensional measurement engineers in the near future.

### 7 Conclusion

Japan, after the World War Ⅱ, has developed its manufacturing industry in a wide range of fields including automobiles and electronics. CMM is a measuring machine that developed with the increased performance of computers, and plays a major role at the site of advanced manufacturing. Particularly, it is an essential device in the integrated process from digitized design, manufacturing, and assessment. In this paper, we discussed the technological developments related to CMM in manufacturing.

With the goal for strengthening competitiveness of manufacturing, we created a scenario from the establishment of national standards to the diffusion to the site of production, and executed them starting with important items. To this day, the course for three-dimensional measurement using conventional CMMs has been almost entirely organized, except for the accreditation system of operators, but many issues remain to be solved, such as responses to new three-dimensional measuring instruments and technologies, as well as the creation of a training system. We plan to create a scenario for new devices and technology, to contribute further to the manufacturing industry.

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## Discussion with Reviewers

### 1 Overall evaluation

**Comment (Mitsuru Tanaka, Research Coordinator, AIST)**

This paper can be positioned as a *Full Research* to establish the system for ensuring the reliability of geometrical shape measurement, which is important for promoting Japanese machine parts, for strengthening competitiveness, and for technological transfer. I think it is an excellent research with rich contents.

**Answer (Sonko Osawa)**

Measurement is an important ingredient of manufacturing. It determines whether the product is manufactured in accordance to the design plan, and can improve the product value by reflecting the result in the manufacturing process. It is important to maintain the reliability of measurement to increase the value of Japanese products, and I believe the way to achieve this is the traceability system. Creation of this traceability system is a mission of AIST, and I have been engaging in this research by drafting a scenario.

### 2 Background of the issue

**Question and Comment (Mitsuru Tanaka)**

In the past, there was perhaps one coordinate measuring machine at a large manufacturing company. But now, CMMs are installed in small subcontract factories and in each manufacturing line. How about describing the fact that the demand for reliability at the sites of production is increasing, while on the other hand, there is departure from specialized technology to cut cost of the CMM operator?

As background when discussing the contribution of this *Full Research* to Japanese machine manufacturing businesses, rather than just mentioning "manufacturing," perhaps you should mention the dependency on Europe and US for precision measuring machines, as well as the emerging industrial countries coming up close behind us.

**Answer (Sonko Osawa)**

I added some descriptions in 1 Introduction.

### 3 Explanation of *Synthesiology*

**Question and Comment (Mitsuru Tanaka)**

While carefully explaining the elemental technologies, it is necessary to discuss how they were synthesized to generate the social outcome. For example, in the relationship with public laboratories, why didn't you take the policy of "diffusing the system in Japan by setting traceability through public labs as the only method"? Why didn't you take the policy of "rather than AIST participating, calibration services can take the technical exam of the International Laboratory Accreditation Cooperation (ILAC)"?

What were the considerations for the selection of objects for international comparison, and what is the effect on Japanese industry? Can you explain them in relation to each elemental technology? I think this is synthesis. Also, it is written in the abstract, "We succeeded in linking the national standard of length to the site of production, by powerfully linking the metrological standard and standardization." This seems to be very important in synthesis, but there is no description in the main text about this.

**Answer (Sonko Osawa)**

With the globalization of economy, international Mutual Recognition Agreements in the metrology fields are concluded, and one-stop service is becoming available by presenting the measurement capacity of the national metrology laboratories of the country. In this situation we believe the scenario shown in Fig. 3 provides the three-dimensional coordinate measurement standard to users most effectively.

For the link between standardization and metrological standard, explanations are provided in sections 3.1 and 5.1, and we added the contribution of laser tracker assessment to standardization in section 4.1.

# A secure and reliable next generation mobility

## — An intelligent electric wheelchair with a stereo omni-directional camera system —

**Yutaka Satoh * and Katsuhiko Sakaue**

**[Translation from *Synthesiology*, Vol.2, No.2, p.113-126 (2009)]**

We propose a secure and reliable next generation smart electric wheelchair system that is equipped with a novel 3D stereovision system referred to here as a 'stereo omni-directional camera'. The novel vision system is not only intended for use with a new generation of electric wheelchairs for conventional wheelchair users, but also for use in future advanced personal mobility devices for everyone.

*Keywords* **:** Mobility, active safety, welfare apparatus, computer vision, stereo omni-directional camera system

### 1 Introduction

The development of technology to improve the quality of life (QOL) of the elderly and the physically disabled is a socially important issue, and the utilization of advanced science and technology is expected. Such effort is strongly demanded socially in Japan, which is a rapidly aging country.

The mobility (the ability to move around freely or the means that allow one to do so) is an indispensable element for us. Especially when a person loses the "ability to walk," it becomes very hard to move by one's own will, causing strong limitations of daily activities. This is not the issue only for the elderly and physically disabled, but also for people who can still walk normally now, but has the possibility of losing the ability by an accident or aging. Preparing the sufficient alternative for the walking ability could be the important safety net for all of us.

The electric wheelchair is the major alternative to walking ability. Recently, it has become widely spread, and it has made it easier for people with walking-difficulty to go out freely. On the other hand, as the number of electric wheelchair increases, the accidents have increased, e.g. collision with pedestrians, obstacles and falling, capsizing at level differences and stairs. Thus, the technological developments to ensure safety are of immediate demand. In the area of automobile, the technology for driving safety is actively being developed. For example, monitoring vehicle's forward space with millimeter wave raddear and stereo camera[1] and automatic braking to avoid rear-end collision[2] are technologies that have been put to practical use. Unlike an automobile that runs on the road, an electric wheelchair is used in various situations such as crowded areas and inside a room and it is necessary to deploy next-generation sensing technology for keeping safety. Therefore, we developed an intelligent electric chair equipped with "stereo omni-directional camera" which has the ability to monitor color images and 3D information simultaneously, with no blind areas, in real time. This wheelchair helps the rider to move safely indoors and outdoors and in space shared by pedestrians. It has a basic function of detecting obstacles and level differences in all directions simultaneously, and can decelerate and stop automatically when there is some danger.

In this paper, we present the detailed picture of the process from the beginning. The picture involves the strategy, scenario, and elaborations. In what follows, we shall describe the research scenario in chapter 2. In chapter 3, we describe the selection of elemental technologies necessary for constructing the prototype, and chapter 4 presents the integration and the synthesis. In chapter 5, we describe the experiments and evaluations, and in chapter 6 the summary of this paper.

### 2 The research scenario

This research was conducted as part of the "Development of Assistive Technology for Safety and Convenience of the Physically Disabled People (FY 2004~2006)" Special Coordination Funds for Promoting Science and Technology, Ministry of Education, Culture, Sports, Science and Technology (MEXT) led by AIST and the National Rehabilitation Center for People with Disabilities. The rank and mission of this study within this project was "to propose the potency and necessity of advanced welfare apparatuses supported by future-oriented advanced technology." We were required not to develop a product but to present the potential for improving the welfare apparatus by advanced technology. To execute this mission, we thought it would be particularly

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important to transmit the information to society through papers, the press release[3], and exhibitions as an integrated and synthesized system, rather than to develop individual elemental technologies, and we decided to take the following research strategy (diagram of the model is shown in Fig. 1).

(1) Evaluate and publicize the prototype by creating it as quickly as possible, through the integration and combination of the necessary elemental technologies.
(2) Seek "elemental technologies that must be created or those that must be improved," based on our evaluation results and the external comments obtained by publicizing.
(3) Research developments and the improvements of the elemental technologies.
(4) Return to (1).

In many cases, our researches went along the path from the creation of elemental technology, through the sophisticating stage, reaching a point concerning its applications, which is an upside-down strategy to that mentioned above. This is an attempt to consecutively create the necessary *Type 1 Basic Research* from the starting point of *Type 2 Basic Research* [4] where the elements are integrated and synthesized.

In this research, we decided not to be bound by the framework of a conventional "wheelchair" but decided to engage in R&D for a new personal mobility that can be used by any of us. Development of a device for transporting a person while sharing space with pedestrians, unlike an automobile that runs on a road carrying multiple passengers, is important in allowing all people to travel with minimum energy consumption and low pollution. Also, a large market would be developed in the future by targeting wide user range. The larger market will result in higher performance, lower cost, and better infrastructure designed for the passage of new mobility. As a result, the users of current electric wheelchairs will benefit from such developments.

For the new mobility to run safely while sharing space with pedestrians both indoors and outdoors, it is important to have a technology to sense the surrounding environment quickly and accurately and a technology to accurately detect the risks from the information obtained. In this research, by installing a stereo omni-directional camera and by advanced computer vision technologies mounted on an electric wheelchair, we attempted to realize mobility with functions that prevent collision with pedestrians or obstacles and prevent falling or capsizing from level differences.

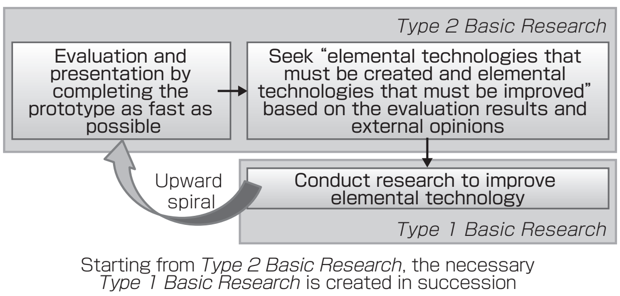



**Fig. 1 Model of the research strategy.**

## 3 Selection of elements

We shall describe the elemental technologies selected to realize the research objectives. This includes the elemental technologies that were added when we found they were necessary after the integration and synthesis of elements which is explained in chapter 4 later.

Figure 2 shows the selected elemental technologies. The function for actively sensing and recognizing the surrounding environment is realized by mounting the following onboard an electric wheelchair: (1) "sensing technology" to obtain information of the surrounding environment, (2) "cognitive technology" to detect danger in the environment from the obtained environmental information, and (3) "interface" that presents the information to the user. The individual elemental technologies are described in the following sections.

### *3.1 Stereo omni-directional camera*

The stereo omni-directional system (SOS)[5]-[7] was developed by Satoh (one of the authors) et al., in the Human and Object Interaction Processing (HOIP) Project, Collaboration of Regional Entities for the Advancement of Technological Excellence in Gifu Prefecture, Japan Science and Technology Agency. It is an innovative camera system with a function to obtain omni-directional color image and 3D information simultaneously and in real time by assembling 36 cameras in a spherical form.

To obtain wide-range images, a camera system using a wide-angle lens and/or a parabolic mirror[8]-[10] was used conventionally. However, since it shot a wide range using just a single lens and imaging device, the optical resolution particularly of the lens was inadequate, and the resolution of the image obtained was insufficient. In contrast, the stereo omni-directional camera shoots in all directions using a large number of cameras, and high resolution can be maintained overall even if low-cost general-use lenses are used. Also, 3D information can be obtained easily by using the parallax between the cameras.


**Fig. 2 Selection of elements.**

Figure 3 shows the exterior view of the stereo omni-directional camera. Table 1 shows its major specifications. The collection of the individual cameras is called the camera-head, and its basic form is a regular dodecahedron. To measure the 3D information, three cameras are installed in each of the plane of the dodecahedron. Since sufficient distance is necessary between the cameras to obtain parallax (called stereo baseline, 50 mm in SOS), increasing size of the camera-head was an issue. To solve this issue, as shown in Fig. 3 right, three cameras are mounted onto a T-shaped arm (this set is called the stereo camera unit). And by arranging them three-dimensionally so each plane of the dodecahedron crosses each other without blocking the views of the cameras, the stereo baseline of 50 mm is maintained, and the camera-head can be downsized to a diameter of 116 mm or the size of a fist. The total number of cameras is 3 cameras × 12 planes = 36 cameras. All cameras are synchronized so they will shoot images at exactly the same time.

The images obtained from the camera-head are transferred to the personal computer (PC) via two optical fiber cables at 1.25 Gbps. On the PC, the 36 images are DMA-transferred to the main memory in the form where images are aligned straight, and the users are notified of the top address with a pointer. The transferred images can be accessed freely using this pointer.

By conducting a preliminary experiment of actually mounting the device on the electric wheelchair, it was found that the vibration transferred to the camera-head was greater than expected, and we strengthened the attachment of the camera-head and changed the imaging device. The initial model employed the CMOS imaging device with a rolling shutter (the shutter is released for each operation line like in a camera tube; although the structure is simple, slight distortion is produced when there is motion because of the time difference at top and bottom of the image), but slight distortion occurred in the image due to severe vibration and affected the accuracy of the 3D measurement. Therefore, we employed a CMOS imaging device with a global shutter (the shutter is released simultaneously for an entire image), since a high-performance device became available.

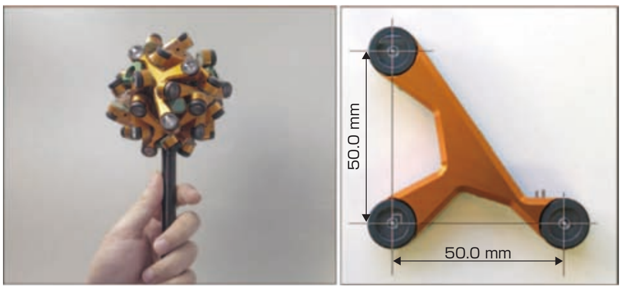



**Fig. 3 Stereo omni-directional system.**
The left photo shows the camerahead (diameter of 116 mm). Right photo is the stereo camera unit. The three cameras are arranged at right angles to each other in a single plane.

### *3.2 Stereo image processing*

The distance can be calculated by the principle of triangulation from the parallax of the image shot by multiple cameras. This is like the human eyes that perceive distance using the parallax between the two eyes. Although simple in principle, there are two points that make the implementation difficult.

(1) Calibration of the stereo camera: To accurately measure the distance, it is necessary to know the actual measurements of camera parameters such as focal length, lens center, and distortion, as well as the actual measurements of positional arrangements of the multiple cameras.
(2) Search for corresponding points: Correspondence is found between points of high similarity among images shot by multiple cameras (that is, point assumed to be the same in the real world), and the distance between the corresponding points is the parallax. Objects that are near the camera have greater parallax while objects far away have smaller parallax. Since it is necessary to find correspondence for all pixels in an image, the processing cost is extremely high.

For (1), in the stereo omni-directional camera, all parameters are obtained accurately during manufacturing using the general calibration method. The camera-head has a sturdy structure so no readjustments will be necessary after manufacturing. In fact, the camera-head has been mounted on the electric wheelchair for over three years, and it has not required readjustment to the present. For (2), we considered building hardware since the processing cost was extremely high. However, considering the rapid advancement in high-speed PC, we chose implementation by software. In fact, in about three years since the commencement of the project, the computation speed of stereo image processing increased about five times purely on account of improved PC performance. Since more speed was needed with the software for it to be implemented on a small wheelchair-mountable PC, about twofold acceleration was achieved by employing parallel computation and by thoroughly removing overlapping computations.

**Table 1 Major specifications of the stereo omni-directional system.**

| | |
|---|---|
| Basic form | Regular dodecahedron |
| Imaging device | 1/4' CMOS (global shutter) |
| Device resolution | 640 (H)×480 (V) pixels |
| Focal length of each camera | 1.9 mm |
| Angle of view of each camera | 101° (H)×76° (V) |
| Stereo baseline length | 50.0 mm |
| Frame rate | 15 fps (30 fps when color image only) |
| Camerahead diameter | 116 mm (diameter of circumscribed circle) |
| Weight | About 480 g (camerahead and support) |
| Power consumption | About 9 W (12 V, 750 mA) |

Stereo image processing can be achieved by a minimum of two cameras (binocular stereo) without any other measures such as mirrors. Yet, accuracy can be improved by using more cameras that will allow multiple results for the reliability assessment of the measurements. In the stereo omni-directional camera, trinocular stereo was used in consideration of the balance of accuracy and camera-head size.

### *3.3 Image integration*

Figure 4 shows an example of image integration. The stereo omni-directional camera is composed of multiple cameras, and an omni-directional image is obtained by integrating the images of individual cameras using software. In our intelligent electric wheelchair, one of the functions considered for future addition is remote transmission of the omni-directional video using a cell phone line to provide remote support. Therefore, it is necessary to integrate the images in good quality, while risk detection of the surrounding environment must be done frequently, and the computation cost must be minimized as much as possible.

In general, a camera lens has greater distortion and light fall-off at the edge of the image (Fig. 5). This is not a major issue when viewing one image as in an ordinary digital camera, but gaps and differences in lightness occur at the boundaries when integrating multiple images. To solve this problem, it is necessary to: (1) correct the barrel-shaped distortion of the lens, (2) correct the peripheral light fall-off of the lens, (3) conduct geometric conversion from the coordinate system of individual cameras to the integrated coordinate system, (4) correct the color variation between the cameras, and (5) conduct the blending process for smooth connection of the boundaries between the images. Due to the limitation of space in the paper, we leave the specific computation equations to a referenced paper[11]. Since they are nonlinear conversions containing several trigonometric functions, they require over ten seconds (when 3.2 GHz CPU was used) for a single image composition. In order to improve the performance, we determined all the parameters that are dependent on the properties of the camera-head and camera unit, and performed above calculations in advance to make a transformation look-up table. With the look-up table, one finely corrected omni-directional image can be obtained from twelve raw color images with no correction at all. The time required to process an omni-directional image of 512 × 256 pixels is only 10 ms or less.

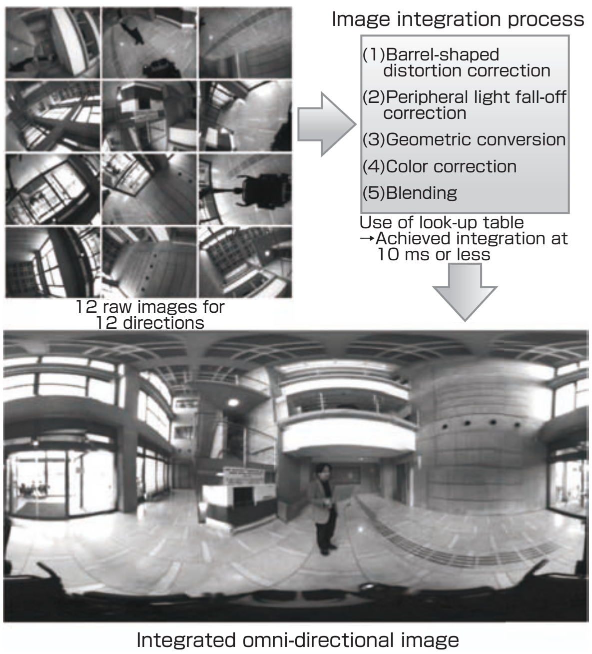



**Fig. 4 High quality and high speed image integration.**
The omni-directional image is produced in high quality and in high speed from 12 raw images that include lens distortion and peripheral light fall-off. Although it is difficult to present the omni-directional image in 2D, we present the image in Mercator projection, as in a world map.

### *3.4 Estimation of camera-head position*

To obtain accurate information on the surrounding environment of the electric wheelchair, it is necessary to know accurately at what position the camera-head of the stereo omni-directional camera is attached to the electric wheelchair. In the initial design, the pose of the camera-head was obtained by detecting the direction of the gravity using an acceleration sensor fixed to the support bar of the camera-head when the wheelchair was stationary. However, two issues emerged when testing the prototype: (1) the movement of the camera-head due to unevenness and bumps during the test run was greater than expected, and it became necessary to estimate and correct the camera-head pose parameters in real time, and (2) it was discovered that a lifter (a device to hoist up the user and move him/her to the seat of the electric wheelchair) may be needed for the rider to mount and dismount the electric wheelchair. Therefore, we employed a swinging attachment arm to prevent interference of the camera-head with the lifter, but this caused slight changes of the attachment position after every swing and fix. Therefore, a method to estimate the camera-head pose parameters in real time became necessary.

**Fig. 5 Lens distortion correction.**
The person in the photo is holding a ruler in his hand. In the left photo, the ruler is arched since this is the image before correction. On the right is the corrected image. The distortions of the line of the ceiling and other parts are also corrected.

To estimate the camera-head pose parameters, the standard method is to use an acceleration sensor and gyroscope, but this is a relative position estimate and cumulative error is a problem. Therefore, we developed and implemented a method that allows absolute estimate of the pose of the camera-head from an omni-directional image in high speed [11]. Specifically, all edges (segments with highest brightness gradient) are extracted from the omni-directional image. Next, the directions of edges are plotted onto the voting space, and two large peaks can be obtained. This is because there are many vertical and horizontal edges in our daily environment. For example, tabletops and boundaries between the ceiling and wall have horizontal edges, while the pillars and support of the bookshelves have vertical edges. The position at which these peaks appear in the voting space presents the relative pose of the camera-head. Of course, estimation will go wrong if there is a forest of trees that grow diagonally, but the error can be detected by also using a gyroscope and an acceleration sensor.

For this method, by using look-up tables as much as possible, correction of the coordinate system and estimation of position can be accomplished in about 10 ms. Figure 6 shows an example of an image correction by actually estimating the pose of the camera-head. The upper image is an image before correction, and since the camera-head is mounted on the electric chair at a tilted position, the image seems to be distorted. The lower image is an image after conducting geometric conversion using estimated camera-head pose parameters against the same data as the one in the upper image.

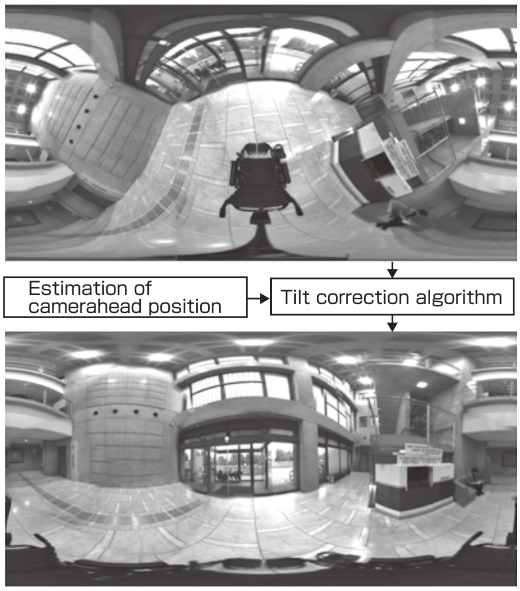



**Fig. 6 Estimation of camerahead position and tilt correction.**
The position of the camerahead is estimated from the vertical and horizontal edges of the omni-directional image. The upper image is the one before correction. Since it is omni-directional, the effect of the tilt appears in sine curve form. The black object in the middle is the electric wheelchair. The lower image is the image corrected according to estimated parameters. It is corrected so the sideway direction corresponds to the horizontal, and up-down direction corresponds to the vertical.

### *3.5 Risk detection*

Figure 7 shows an example where the omni-directional distance information obtained by the stereo omni-directional camera has been visualized. The coordinate conversion is done for the distance information obtained from each stereo camera unit arranged on the regular dodecahedron, and the information is mapped onto an integrated coordinate system with the center of the camera-head as the origin. Figure 7 is an observation of the same data shot in one shot from three virtual viewpoints. Using the stereo omni-directional camera, such omni-directional distance information can be obtained 15 frames/sec (angle resolution of 360/512 degrees = approx. 0.7 degrees; about 300,000 points are shot at once). The risk detection in the environment for electric wheelchairs is conducted by directly using this omni-directional distance information. The detailed algorithm for risk detection is described in the referenced paper[11]. Basically, when the height of the floor is set at 0, all obstacles that are within the range of -0.5 m (lower than the floor) and 1.6 m high are detected. Whether the detected obstacle will be barrier to the wheelchair depends on the direction in which the electric wheelchair is moving. By setting the decision area that is switched according to the direction of the joystick, as shown in Fig. 8, when the obstacle enters the deceleration/stop area, the chair automatically decelerates or stops. In the experiment for this paper, the diameters of the decision area were 1.2 m (for deceleration) and 0.4 m (for stop). In forward straight ($F_0$), the decision area is rectangular to allow passage through narrow corridors. In $F_{+1}$~$F_{+2}$ where the wheelchair turns while moving forward, it is expected that the amount of turn will change continuously according to the user's joystick maneuver, so a fan-shaped decision area is set to handle probabilistic spread. In the case of $F_{+2}$ where the amount of turn becomes greater, collision at an inner radius of the direction of the turn and collision at an outer side of the turn must be considered in addition to the obstacles in the forward front direction. Therefore, the decision area is widened in the inner side of the turn, and a stop area is set in the outer side of the turn which is the opposite of

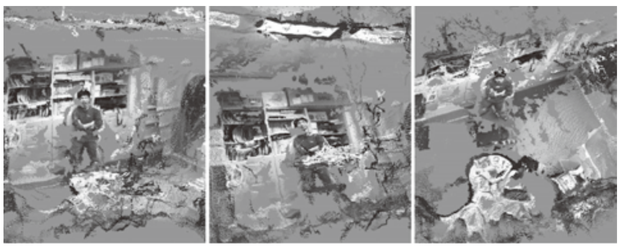


**Fig. 7 Omni-directional distance information.**
Same data is seen from three virtual viewpoints. There are about 300,000 observation points. Three-dimensional data for all directions can be obtained 15 times in 1 second.

the traveling direction. The observation and detection of obstacles are done in all directions at all times regardless of these decision areas, and the risk decision can be done without delay, even if the decision area is switched suddenly by sudden joystick maneuver. Moreover, since the area lower than the floor is detected, level differences and descending stairs can be detected, and the wheelchair can automatically decelerate or stop if it is judged that the situation is beyond the performance of the wheelchair. Since a bump may have rounded corners to allow passage of automobiles or carts, passage may be possible even if there is a level difference. However, if it is judged that there is a level difference of more than 5 cm, the chair is stopped unconditionally. This is because the error of distance measurement by stereo image processing may occur in the order of 2~3 cm depending on the environment condition and a decision with sufficient margin of safety is not currently possible. To solve this problem and to realize more advanced and finer risk detection, we are working separately on the development of a stereo imaging processing system using near-infrared pattern projection, and have succeeded in observing level differences of a few mm order [12]. The application of this technology to the stereo omni-directional camera will be considered in the future.

### 3.6 Gesture detection

We implemented the function of capturing the changes in posture and gesture of the wheelchair rider in 3D, and controlling the electric wheelchair. Specifically, (1) the function to detect abnormality of the rider's posture, and (2) the function to detect arm gesture were implemented. The space near the rider is divided into small cube regions (voxels), and recognition is conducted based on the pattern of the presence of objects within each voxels[11]. Seating position and gesturing are registered for each rider. The gesture and posture detection is done based on the comparison of the registered pattern and the observed pattern. Specific performance of the function will be described in detail in section 5.1. Although this function was not implemented at the beginning of the R&D, it was considered for implementation by request from the users after completion of the prototype.

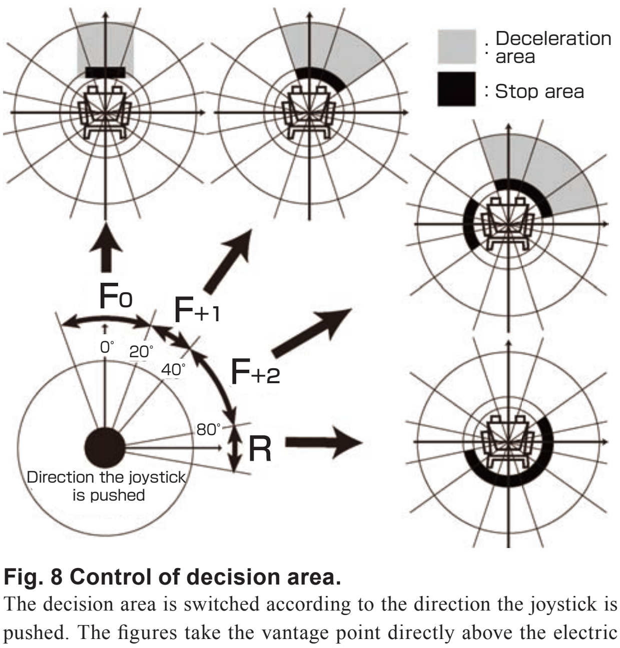



**Fig. 8 Control of decision area.**
The decision area is switched according to the direction the joystick is pushed. The figures take the vantage point directly above the electric wheelchair and the joystick. Top is the forward direction, and bottom is backward. Due to the limitation in space, only the forward straight ($F_0$) ~ right turn on spot (R) are shown, but other directions are defined in a similar manner.

### 3.7 Information display user interface

In an experiment using the prototype, when the electric wheelchair entered the deceleration or stop mode, the rider felt very uncomfortable when he/she could not understand the reason for the movement. Therefore, we devised a user interface to notify the state of risk detection to the rider. First, we installed a small mobile information terminal in the rider's hand region, and then considered how to display the information. In the initial stage, we thought it was better to communicate as much information as possible, and created a graphical display showing the direction and height of danger. However, it was difficult to see and understand the information that was displayed all at once when the wheelchair was moving. Therefore we devised a display that could be understood intuitively. Figure 9 left shows the display that was finally employed. The risks such as collision or fall are expressed by easy-to-understand pictograms displayed in the direction of the risk. By displaying "STOP" or "Slowdown" in large letters and in high contrast, the rider can intuitively understand "where the risk is and what kind of control is taking place."

This terminal also has a function of displaying the omni-directional image obtained by the stereo omni-directional camera. For example, it can be used to check the back view when backing up or to check the surrounding area in a bird's eye view (Fig. 9 right). The screen is a touch panel, and the desired view can be displayed by touching the screen with a finger.

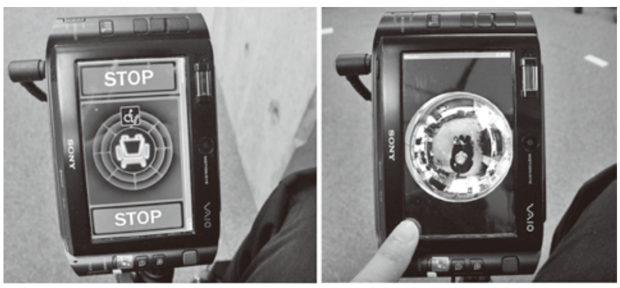



**Fig. 9 Information display user interface.**
The left photo shows the control status of the electric wheelchair. The type and direction of the existing risks are shown as pictograms. The right photo is the omni-directional spherical image from the vantage point of looking directly down at the rider. The sphere can be rotated freely on the touch panel.

## 4 Integration and synthesis of the elements

### *4.1 Specific process of the research*

We shall describe the overall picture of the research process. Figure 10 shows the specific processes of the research based on the research strategy model diagram shown in Fig. 1. The flow is as follows. (1) As elemental technologies to realize “the sensing function” and “the danger recognition function” that are the core technologies, we initially selected the stereo omni-directional camera, stereo image processing techniques, image integration processing techniques, and risk detection techniques from conventional research ideas. (2) The integration and synthesis of the elemental technologies were conducted at the shortest time possible, the research and technology were visualized by completing the prototype, and the information was transmitted actively (through a press release and exhibitions as well as papers) to the users and to society. The exterior design of the prototype was important to increase the accuracy and efficiency of the information transmission. (3) In the evaluation phase, effort was spent on obtaining external evaluations, demands, and findings, as well as on experiments and discussions, to evaluate the current status. By doing so, the elemental technologies that must be improved or must be newly created were discerned. (4) Research for creation and improvement of the elemental technologies was conducted. This corresponds to *Type 1 Basic Research*. Since the issues that had to be solved and the evaluation standards were clear, the research could be carried out efficiently. (5) The updated or added elemental technologies were reintegrated and re-synthesized, and the cycle was repeated.

The above can be called a structure in which *Type 2 Basic Research* serves as an engine to produce *Type 1 Basic Research*, and by returning to *Type 2 Basic Research*, the research results evolve continuously in an upward spiral. Initially we expected the feedback from the user or society in the evaluation phase would be abstract and indirect (in a manner that will simply have the content or direction of the research be adjusted). However, in actual practice, the users’ evaluation became the power to directly generate the elemental technology. In the conventional research approach that originated from *Type 1 Basic Research*, users and service providers were not given much attention, but in our structure, they became the engine of *Type 2 Basic Research*, and the elemental technology generated directly became the power to propel *Type 1 Basic Research*. We feel this structure may be a new case study of “*Full Research*” [4].

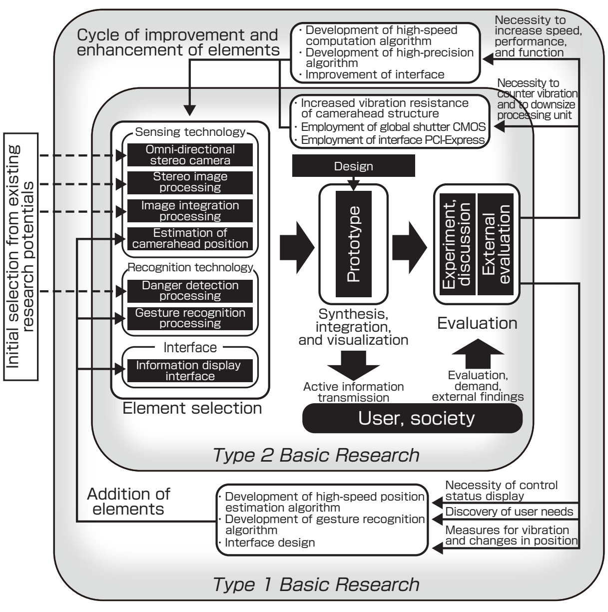



**Fig. 10 Overall picture of the research**

### *4.2 Outline of the prototype*

The exterior of the prototype in which all elemental technologies described in chapter 3 are integrated and synthesized is shown in Fig. 11. This prototype has basic functions as follows: (1) the function to simultaneously detect in all directions surrounding pedestrians, obstacles, and level differences, and to automatically decelerate or stop if it determines that there is danger, and (2) the function to recognize the gesture and the posture of the rider and provide assistance.

The stereo omni-directional camera is positioned above and anterior to the rider’s head with a support arm. This position corresponds to the height of human eyes when walking, and is practical for detecting risk in the environment. Also, the position that is lower than the top height of the head is unlikely to interfere with obstacles when moving through our daily living spaces. The arm and the camera-head are kept outside the trajectory of the mounting/dismounting action of the rider. Even when lifters are used and the camera-head may be in the way, the bending part of the arm can swing away and the camera-head can be pushed to the rear.

In the initial stages of experiments with prototypes, a large


**Fig. 11 Photograph of the prototype.**
The stereo omni-directional system is installed in the forward position above the user’s head. All devices such as PC and power source are mounted onboard the wheelchair. It does not require external cables, and is capable of running continuously for four hours.

PC was installed outside the wheelchair and connected by cable along with an exterior power source. To mount all these devices on the chair, it was necessary to implement all functions that required large amounts of computation on just one small PC for stereo image processing, image integration, camera pose estimation and correction, risk detection, and gesture detection. To realize this, we developed and implemented various high-speed computation algorithms as described in chapter 3, and supplemented the decreased processing capacity due to downsizing the PC from the software side. We conducted thorough review of the implementations such as eliminating overlapping computation, using look-up tables as much as possible, along with introduction of parallel processing. In hardware, to deal with a small motherboard, we changed the interface of the stereo omni-directional camera from PCI-X to PCI-Express standard. Although the PCI-X standard has wide bandwidth for data transfer, it is limited for use in a server motherboard. PCI-Express standard is recently being used widely and can be used in almost all motherboards, and can maintain sufficient bandwidth for data transfer of the stereo omni-directional camera.

Figure 12 shows the exterior view of the PC mounted on a wheelchair. The PC fits compactly in the cover behind the seat. The interface unit for the electric wheelchair and PC, the joystick interface unit, and the wireless LAN device are all fitted under the seat. Lead battery (12 V, 52 Ah × 2) for driving the motor is used as the power supply for other devices as well. This requires no exterior cables, and about four hour continuous operation is possible.

**Fig. 12 Mounted PC.**
Right photo shows the device exposed without the cover. The PC is mounted behind the seat.

### *4.3 Exterior design*

To create something that will "present the potential and necessity of advanced welfare device through future-oriented advanced technology" according to the research scenario, the product must draw people's interest and convey the concept and future potential. It is necessary to be concerned about the exterior design, and our team repeated discussions and created prototypes. Figure 13 left shows a scene during prototype creation. The right photo is a design for Prototype 1, and a press release[3], exhibitions, and demonstration on the TV news were done using this design (currently, the devices mounted on the wheelchair are downsized further; Prototype 2 shown in Fig. 11 is also in operation).

The points of the design are as follows. (1) The mechanics and cables should be covered as much as possible. To show them exposed will express that the product is "still at the level of laboratory experiment" and that will not be appropriate for the mission. (2) The cover should not be forcedly made small with no consideration for the design theory. If the cover is made small to appeal that the mounted devices are small, the overall balance will be lost and the covered part will stand out as an "extra area." For example

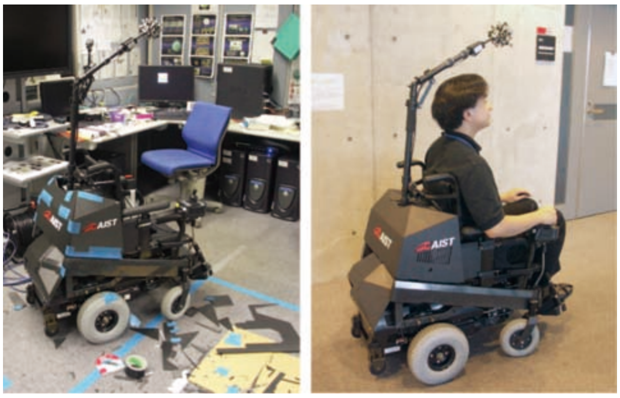
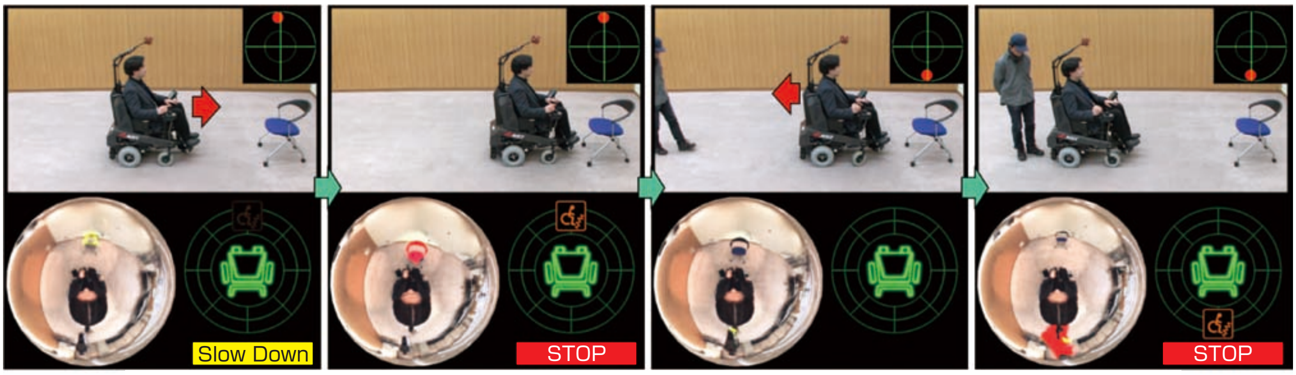


**Fig. 13 Consideration of the exterior design.**
Left photo shows the process of designing. The design was determined after repeated trials. The right photo is the design for Prototype 1. This model was used for the press release.




(1) (2) (3) (4)

**Fig. 14 Detection of obstacles.**

in Fig. 13 right, the volume filled by the mounted device is about one-third of the volume of the cover. However, it does not stand out since there is an overall good balance. We even received a question, "Where is the computer?" (3) To show that this project is an AIST effort, the AIST logo is included in the design.

## 5 Evaluations

### *5.1 Experiments using the prototype*

Figure 14 shows the basic obstacle detection experiment. (1)~(4) show four scenes in chronological order. For each scene, the direction of the joystick operated by the rider is shown in the right-top (top direction is the forward direction), the omni-directional image shot by the stereo omni-directional camera in the left-bottom (expressed as a sphere; the rider is in the center), and the screen of information display interface described in section 3.7 is shown in the right-bottom. In (1), the wheelchair approaches the obstacle (chair) in front and goes automatically into deceleration mode. Since the rider continues to push the joystick forward, the wheelchair stops automatically (2) right before collision with the obstacle. In (3), the rider pulls the joystick to start backing, but a pedestrian approaches from behind out of the view of the rider, and the wheelchair stops automatically at (4) due to danger of collision.

Figure 15 is an example of an automatic stop after detecting a staircase. Since the wheelchair detects level differences and descending stairs as well as obstacles on the street, it can prevent falls in advance.

Figure 16 and 17 show examples of gesture and posture detection function. In Fig. 16, the wheelchair stops in emergency since it detects that the posture of the rider differs greatly from the preliminary registered posture. When this situation lasts longer than preset time, it is possible for the system to automatically call for assistance by the cell phone. Figure 17 is an example where gesture detection and risk detection functions are used at the same time. When grabbing something or approaching something such as in order to press the elevator button from the electric wheelchair, if the rider cannot reach the target, the gesture of extending the arm can be used as a trigger to advance the wheelchair automatically toward the target while checking the safety. Specifically, in (1), the rider extends his arm for 3 sec. or more to grab a PET bottle, assistance begins in (2), and the electric wheelchair advances slowly. It stops automatically when the arm is retracted or before colliding with an obstacle (table in this example), and in (3) the rider succeeds in grabbing the PET bottle.

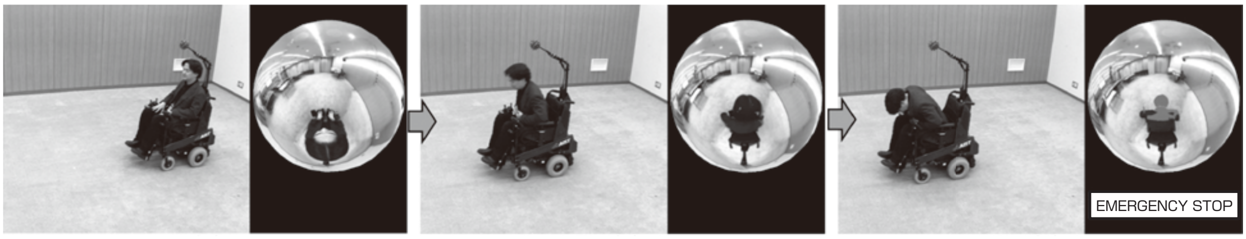

**Fig. 15 Detection of descending stairs.**
The descending stairs and bumps/dips are detected. The wheelchair automatically decelerates or stops if it is determined that the situation is dangerous.

This gesture recognition function determines the posture and gesture by simple comparison of the preliminary registered pattern with the 3D shape pattern roughly quantized by voxels as explained in section 3.6. This can be used only in detection of relatively large movements as in the example of Figs. 16 and 17. Some users who have disability of the arms have requested, "Can slight movement of the shoulder be recognized as a gesture?" In the future, we shall consider accurate recognition of fine movements by introducing machine learning approach.

The function shown in Fig. 17 was requested by an actual wheelchair user, and was investigated for realization. Much experience is required to fine-position the electric wheelchair using the joystick. Particularly, approaching a table to grab something or approaching a wall to press the elevator button carry large risks because of the possibility of collision with the table or wall. To avoid such problems, human assistance may be sought when fine positioning is necessary. However, such assistance is required dozens or several hundred times a day, and this makes the rider of the electric wheelchair reserved and may prevent him/her from going outdoors. Can machines support seemingly minor but high-frequency assistance? That was the users' request and we conducted investigations.

These are the basic functions of the prototype, and we implemented several functions as their extensions. In Fig. 18, the wheelchair recognizes the nearest person, and automatically tracks the person face to face at 1 m distance. Since all directions are constantly monitored, it does not lose track even if the person makes sudden movements. In the future, we are considering a function that automatically tracks a certain person (such as an assistant) by using facial recognition technology. Figure 19 is an experiment of automatic route selection in a crowd. In Fig. 19(2), the wheelchair is surrounded by several people, but since it is observing all directions at once, it instantly decides the direction that it can take and escapes automatically in (4). In a crowd, the environment changes dynamically and constantly, and the situation may change if time is taken to gather information. Since the stereo omni-directional camera gathers information simultaneously in all directions, control is possible using the latest information at all times for all directions even in crowd situations. Here, these functions are introduced since they readily demonstrate the sensing capability of the prototype, and unlike other functions that “assist the user,” the electric wheelchair itself moves automatically. Therefore, solid safety is essential and the hurdle to practical use is high. However, the demand for such automation technology is high, and we are engaging in research for functions that must be developed for the future.

Figure 20 shows the test runs in varying environments. Test runs were conducted in various environments such as indoor space with complexly arranged furniture and outdoor space hit directly by sunlight, and stability was evaluated. The balance of “safe” and “free” became major issues in the course of the experiment. In an extreme case, the stop mode (that is, the wheelchair does not move) regardless of the user’s operation of the joystick is the “safest.” In contrast, reduced intervention by the safety system will allow “freer” movement although danger may increase. Appropriate setting differs according to the skill and physical condition of the user, as well as to simple preferences. To continue discussion of this matter in the future, we believe it is necessary to build a framework to evaluate safety in a quantitative manner, including the issue of automation mentioned before. It is also necessary to thoroughly discuss the issue of liability in case accidents do occur. The same issue exists in driving assistance for automobiles, an automatic parking function, and assistant robots. It is necessary to build social consensus




(1) (2) (3)

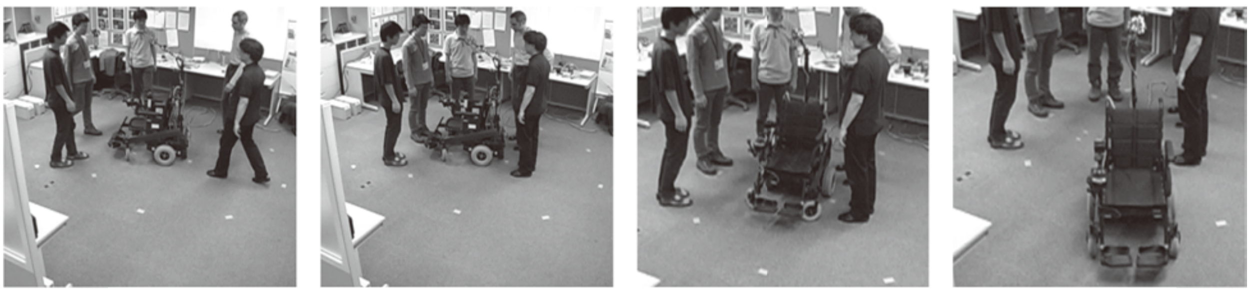
**Fig. 16 Emergency stop when an abnormality in the rider’s seating position is detected.**


(1) (2) (3)

**Fig. 17 Automatic assistance is provided to the position that allows the hand to reach the bottle, by recognizing the rider’s gesture.**

(1) (2) (3) (4)

**Fig. 18 Automatic tracking experiment.**



(1) (2) (3) (4)

**Fig. 19 Automatic route selection in crowd.**

by working on the framework of safety and liability while collaborating with other fields.

### *5.2 User response*

In this research scenario, gathering the opinions of the users and incorporating them to the research was important for the upward spiral. Therefore, we exhibited in several exhibitions such as the International Home Care and Rehabilitation Exhibition (total visitors of about 100,000 people in 3 days) to hear comments of the current wheelchair users. Initially, we were concerned that "this was a rather future-oriented proposal and may not capture the interest of the current wheelchair users." Actually, we obtained comments such as: "I have been waiting for this, I'd like one right now," or "Please continue this kind of research." Even when an exhibition was held in Tokyo, there were wheelchair users who came all the way from Osaka. There was a strong demand for a support system using advanced technology. Comments were provided by the visitors, and new research topics were born. As explained earlier, the automatic assistance function in Fig. 17 was produced through this process.

Since the user of welfare apparatuses is limited and customization is frequently required according to the user's condition, it is difficult to establish as business compared to mass-produced apparatuses. Therefore, advanced technology has not been introduced despite pressing demands. However, IT and robot technologies should be actively used to meet this kind of demand, and it is necessary to consider some kind of scheme to improve the current situation. In this sense, we received lots of support and expectations from current wheelchair users for the concept of developing a new mobility rather than limiting it to conventional wheelchairs. Also, parts of the elemental technology developed in this study can be applied to safety technology in automobile industry that has a large market, and when high performance and low cost are achieved by diffusion in such a market, they can be returned and used in electric wheelchairs.

**Fig. 20 Test runs in varying environments.**
Test runs were conducted in varying environments, both indoors and outdoors. The left photo shows passage through a narrow corridor. Since there is almost no extra room for the width of the wheelchair, the chair stops automatically frequently when the level of safety is set high. The balance of "safety" and "freedom" is difficult. The right photo shows a test run under direct sunlight. Stability evaluations were done for various environmental changes.

## 6 Summary and future prospects

We described the development of an intelligent electric wheelchair with stereo omni-directional camera. As mentioned in the beginning, research and technology were visualized by integrating and synthesizing the initially selected elemental technologies based on conventional research potentials, and then by completing a "moving" prototype as quickly as possible. From the results of the evaluation and presentation of the prototype, "elemental technologies that must be created or improved" were discerned, elemental technology research was conducted, and the result was reintegrated and re-synthesized, to practice research strategy with an upward spiral structure. Necessary elemental technologies were produced consecutively. Since they were all immediately necessary and the evaluation standard of performance was clear (whether it could solve the immediately occurring problems), we were able to engage in research efficiently and with good balance.

In this research, technology for accurately and quickly sensing the surrounding environment, and the technology to accurately detect risks from the obtained information were developed to realize mobility that allows safe movement and sharing of space with pedestrians. The technologies were implemented in an electric wheelchair, and demonstration experiments were conducted. For further developments as a new mobility for all people in the future, we shall continue our investigations on many issues such as infrastructure and laws and regulations.

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## Discussion with Reviewers

### 1 Goal setting and scenario leading up to the goal

**Question and Comment (Motoyuki Akamatsu, Institute for Human Science and Biomedical Engineering, AIST)**

It is written in chapter 2 that this R&D is not limited to electric wheelchairs, but the goal is to develop new personal mobility, as you mentioned in the title. However, the scenario and technologies described after chapter 3 talk only from the perspective of application to wheelchairs. Of the functions obtained by integrating elements, please state clearly which were the functions you sought to achieve for this new personal mobility.

**Question and Comment (Koh Naito, Center for Service Research, AIST)**

The technologies described in the paper can be applied to things other than electric wheelchairs, and this point has been expressed in chapter 2 as well as in the title. On the other hand, the paper describes the development of various elemental technologies, their integration process, and evaluation results as *Type 1 Basic Research*, centering on the development of the prototype electric wheelchair. Please add your ideas of personal mobility society that may be constructed as this research result diffuse further, the scenario leading up to such achievements, and the technological issues that must be overcome.

**Answer (Yutaka Satoh)**

As you mentioned, it was unclear which of the functions among those obtained by integration of the elements were aimed at a new personal mobility. Therefore, we added in chapters 1 and 2 that the relevant points are: we are assuming the level of mobility for electric wheelchair running amidst pedestrians in indoor and outdoor spaces; and to achieve such a mobility, the “functions to quickly and accurately sense the surrounding environment and to appropriately detect the risk from the information obtained” are necessary to prevent collision with pedestrians or obstacles or to prevent fall at level differences and stairs.

Since the research was basically conducted to increase the performance of an electric wheelchair, “improvement of QOL for the elderly and the physically disabled” was an important theme from which we could not stray, and the flow of the paper emphasizes this theme. On the other hand, viewed in simple technical terms, “an electric wheelchair is a chair attached to a motor-driven cart that can be ridden by a person,” we can reset the concept of a conventional electric wheelchair, and consider it as a form of new personal mobility (therefore, the exterior was designed to look different from traditional wheelchairs). We hope this may result in attracting a wider range of users, and may solve the problem of the market for electric wheelchairs. Perhaps there was a problem in mixing the QOL element and the new personal mobility element in the same text flow.

This idea has received support from the wheelchair users and the researchers at the National Rehabilitation Center for People with Disabilities, who are the counterparts of this research, and we added some comments in section 5.2. On the other hand, for the realization of new mobility, it is insufficient simply to introduce safety technology to vehicles such as electric wheelchairs, and there are mountains of issues that must be solved such as infrastructure and rules and regulations. This point was added to chapter 6.

### 2 Diagram on research topic setting

**Question and Comment (Motoyuki Akamatsu)**

You take the approach of *Type 2 Basic Research*, where you take the upward spiral research strategy, and engage in the process of prototype creation and evaluation as you set and integrate the elemental technologies. Although the specific contents are well described in the text, please show the process of setting the research topics in a diagram, so readers can understand your research process. For example, which elemental technologies did you think were necessary in the initial phase, and what problems could be solved by these elemental technologies? Also, what were the technological issues clarified through the processes of manufacturing and evaluating the prototype, and what were the perspectives of those issues (for example, durability, lack of accuracy, newly found user demand, actual use in real environment, etc.)? Please consider using something such as a block diagram to show this. Also, in the summary, please add a discussion (good points and points that must be improved) for taking the upward spiral method.

**Question and Comment (Koh Naito)**

The research style is described as a continuous evolution of research results by making the results visible through prototype development and efficient introduction of external knowledge. You demonstrated yourself that the various basic scientific researches (*Type 1 Basic Research*) were driven from the researches for application (*Type 2 Basic Research*). This is an important find in terms of research management, and in chapter 3, you can clarify the flow by structuring the description of each elemental technology to show what kind of *Type 1 Basic Research* was driven based on what findings. Please reconstruct the descriptions and organize them as a table at the end of chapter 3.

**Answer (Yutaka Satoh)**

We added Fig. 10 that summarizes the specific processes of the research. Also, we added the explanation of this diagram in section 4.1. While the specific explanations are as in section 4.1, "the cycle to enhance values" is realized when *Type 2 Basic Research* becomes an engine to actively produce *Type 1 Basic Research*, and *Type 1 Basic Research* creates or increases the performance or value of the elemental technology, and higher level *Type 2 Basic Research* is conducted using the newly created or enhanced elemental technologies. Moreover, the elemental technologies studied in *Type 1 Basic Research* are immediately needed and the result desired is clear, and therefore the evaluation standard of performance (whether it can solve the immediate problem) is clear. I think the balance and efficiency of the research was very good. We added a description on this point in chapter 6.

Initially, we thought the feedback from the evaluation phase would be indirect and abstract, and the content and direction of the research will only be slightly adjusted. Actually, the users' evaluations directly generated the elemental technologies. This was a new finding for us, and we described that process in Fig. 10. The engine for *Type 2 Basic Research* included the users and services that were ordinarily ignored in the research approach starting from *Type 1 Basic Research*. We believe that the structure in which the power to directly generate elemental technologies that will then propagate *Type 1 Basic Research* may be one form of *Full Research*.

### 3 Realized functions

**Question and Comment (Motoyuki Akamatsu)**

You introduced five main realized functions: obstacle detection, downhill slope detection, abnormal position detection, gesture detection, and automatic tracking and automatic route selection. However, you didn't provide a clear description about the situation when these functions could be useful. I think you should provide an explanation of goal setting for R&D. Are you assuming that the user may not be paying attention to his/her course of travel, are these functions set to match the level of the handicap, or are they based on the analysis of wheelchair accidents?

**Answer (Yutaka Satoh)**

As you indicated, the objectives and reasons for selecting each function were not clear, so we added descriptions in chapters 1, 2, beginning of 3, Fig. 2, and section 4.2. The assumed users are all people including non-physically disabled people. In considering safe runs in an environment shared with pedestrians, we thought "accurate and quick sensing of the surrounding environment and accurate detection of the risk from information obtained" were mandatory, and implemented obstacle and level difference detection as a priority item.

When we gathered information from the elderly and the physically disabled, we found there was a demand for gesture recognition, and implemented this function in the process of an upward spiral cycle (this is described in section 3.6). The functions of automatic tracking and automatic route selection were studied as additional efforts for future mobility. They were described in the paper since they demonstrated the sensing capacity of the prototype in a readily understandable manner. Yet their positioning was unclear, so we added an explanation in section 5.1.

### 4 Relationship to other automation technologies

**Question and Comment (Motoyuki Akamatsu)**

At the end of section 5.1, there is a discussion on safety and freedom. About 10 years ago in the field of automobile ITS, much were discussed about test runs on actual roads for automatic driving. In case of automobiles, the potential for damage was high, and the point of discussion was who would be responsible in case an accident occurred. After all, if an accident occurred under complete automatic drive, the manufacturer would likely be held liable, so the direction shifted to driving support technology where the driver will be in control. The strategy is to maintain a situation where the driver is always involved, and the technology will be introduced to society as an assistance technology for actions initiated by the driver. In the process of diffusion of assistance technology, the reliability of the system and the performance may increase, and society may become more willing to accept the automation system. As a driving support system centering on sensing technology, the collision warning system is starting to diffuse into the market. Here, we are discussing the design of user interface (how to communicate the detected situation to the user accurately and quickly) and the overconfidence in a warning system (such as distraction because the user depends on the warning system). In the ITS field, the problem of safety and freedom are discussed in terms of role division of the system and the user for control, and overconfidence and user interface design for sensing.

This R&D is based on sensing technology, and I think the point of introduction to society is how to balance the control by user him/herself and the control by the system, as mentioned above. Please include your comment on this point.

**Answer (Yutaka Satoh)**

This is a complicated issue, but I think the case of ITS which you described presents the situation accurately. We shall aim for a society where automation is accepted, by increasing the reliability and performance of the system. Although we do not have a specific plan yet, we believe it is necessary to actively build a framework for evaluating safety in collaboration with the fields of automobiles and home support robots that have similar issues. We added an explanation in the latter half of section 5.1.

### 5 Technology for accurately detecting risk

**Question and Comment (Motoyuki Akamatsu)**

You mention risk detection as an important technological issue, but risk decision that matches the user's risk recognition is extremely difficult as mentioned in section 5.1, and future R&D is essential. Therefore, the "risk detection" in section 3.5 is an explanation of the technology for obstacle detection (including dips). I think you need a description on the decision for the degree of risk and the decision to decelerate or stop.

**Answer (Yutaka Satoh)**

As you indicated, the technology for accurately detecting risks was insufficient, so we added the description in section 3.5 and newly added Fig. 8. For the analysis of level differences, we described that the detailed analysis of bumps and dips is difficult due to precision issues in the current system, and that we are separately working on a stereo image processing system using near-infrared pattern projection to solve this problem, and added a reference for this research.

## 6 Gesture detection

**Question and Comment (Motoyuki Akamatsu)**

The description about gesture detection is rather simple, and the range of application is not clear. Please provide a more detailed explanation for sensing and judgement on gestures and seating positions.

**Answer (Yutaka Satoh)**

As you mentioned, the description of gestures was insufficient so we added descriptions in section 3.6 and section 5.1. Specifically, we added the points: currently implemented are (1) the function to detect the abnormality of the seating position and (2) the function to detect the gestures of the arm; and we presupposed large motions since currently the gestures are determined by simple matching of quantized three-dimensional patterns. However, in actual fact, there is high expectation for gesture recognition from people who can move only parts of the body due to handicaps. Specifically, there is a request for recognizing the gesture of slightly moving the shoulder and we are working on it, but unlike the assumption of relatively large motion in the current technology, normal action and gesture motion cannot be separated and recognized at this point. Simple matching is insufficient, and we are considering a learning pattern-matching method. We added a description on this.

# Energy savings in transportation systems by weight reduction of their components

## — Research and development of non-combustible magnesium alloys —

**Michiru Sakamoto[1]* and Hidetoshi Ueno[2]**

**[Translation from *Synthesiology*, Vol.2, No.2, p.127-136 (2009)]**

Technological innovation bringing direct energy savings and reductions in carbon-dioxide emissions has been cited as an urgent issue in the field of transportation machinery. To cope with this issue, demand has been growing for structural materials that are lightweight yet offer high functionality because weight reduction of machinery can be immediately beneficial. A new non-combustible magnesium alloy with drastically improved areas of application is sought in which flammability is suppressed –– the worst weakness of magnesium alloys. Developing this new alloy as a basic component for reducing environmental load will contribute greatly to technological innovation for weight reduction in transportation machinery. This paper examines one methodology for industrialization of a new material through the resolution of the various technical issues related to practical application of non-combustible magnesium alloys.

*Keywords* : Non-combustible magnesium alloy, $SF_6$ gas-free process, basic material, lightweight structural materials, research network

## 1 Research objective and outcome

Energy saving in the transportation field, which consumes a large part of our energy and is expected to grow dramatically in the future, is an urgent issue that must be solved globally. One of the most direct and effective measures is to reduce the weight of the transportation machinery. The current transportation machineries are made of core materials including steel, iron, and aluminum, but a lighter weight material is desired as a new core material. Magnesium is one of the candidates that fulfill this objective, and it is recently receiving attention due to the social demand and concern for environment-friendly recycling technology. It is a remarkably abundant resource, is available throughout the world, can be easily recovered as metal material, is safe without environmental toxicity, and therefore has high potential to become a recyclable core material like iron, steel, and aluminum. However, it never became a core material due to various technological issues. If we are able to quantify the properties of magnesium from an industrial viewpoint and nurture it as a core material, it can certainly contribute to a truly sustainable society in terms of optimization of resource and energy use.

Specifically, practical application of magnesium will allow weight reduction in almost all moving things. High efficiency can be realized through weight reduction of transportation machineries such as automobiles, railroad vehicles, and aircrafts, as well as machine components and robots. The initial goal will be to save energy by using magnesium in railroad vehicle components, since railroad is a mass transportation system with excellent energy efficiency. Through future developments in mass production technology this will be followed by wider application to machine structural materials such as in automobiles. This will help establish magnesium as a core material that is in itself environmentally sustainable, and will contribute in saving energy of transportation machineries.

## 2 Greatest problem with magnesium

The greatest and most serious problem with magnesium is that it burns in the atmosphere. Despite the fact that magnesium was already put to practical use as a structural material for aircrafts before the World War, this combustible property was a major psychological barrier for civilian use. In terms of manufacturing technology, melting and casting processes of magnesium are special due to its ignition and combustion properties, and it was difficult to apply the general metal material techniques that have been developed so far. The research for noncombustible magnesium concentrated on establishing a low-cost process acceptable to industry, and centered mainly on the development of a process that can be used in ordinary atmosphere by making the magnesium less combustible. Particularly, the process that does not use sulfur hexafluoride ($SF_6$) gas, which is necessary as fireproof gas in the melting process, is an important technology that will determine the future direction of this industry, since $SF_6$ is a global greenhouse gas that places a burden on the environment. With these possible developments, the manufacturing technology for magnesium can be converted from a special technology into a common one . We aim to

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establish a highly efficient mass production process that is also safe and environment-friendly, by turning something considered to be a special material into a core material that can be used readily by everyone.

The manufacturing technology for noncombustible magnesium is not only a blessing for the manufacturer in terms of safety at the plant and decreased cost of production (special facilities are not needed), but also satisfies the user's demand for safety. In addition to psychological fear for magnesium ignition, the issue of safety in accidents and fires was an important point that was often ignored.

### 2.1 Discovery of noncombustibility by addition of calcium and the mechanism of noncombustibility

The discovery of noncombustibility was like finding a bargain. In the development of lightweight metal matrix composites in which various ceramic fine particles are dispersed in aluminum, to directly mix and disperse the ceramic fine particles into the molten aluminum, it is important to improve the wettability of the molten metal and the particle surface and to optimally control the viscosity of molten aluminum. In the process of investigating the effect of adding various elements to the property of molten metal, it was found that calcium was effective in controlling the viscosity of the molten metal, and the low-cost manufacturing process for fine particle dispersed aluminum alloy composite was developed. The study of noncombustible magnesium alloys started from the accidental discovery of noncombustibility in the atmosphere, or the dramatic change in the property after adding calcium to the molten magnesium in the process of applying this technology to molten magnesium for further weight reduction. Figure 1 shows the ignition temperature in the atmosphere of a major noncombustible magnesium alloy AZX912 (A=Al, Z=Zn, X=Ca, number is wt%). As apparent in this figure, addition of calcium increases the ignition temperature by over 200 ºC. Melting in the atmosphere becomes possible when the ignition temperature rises to this level.

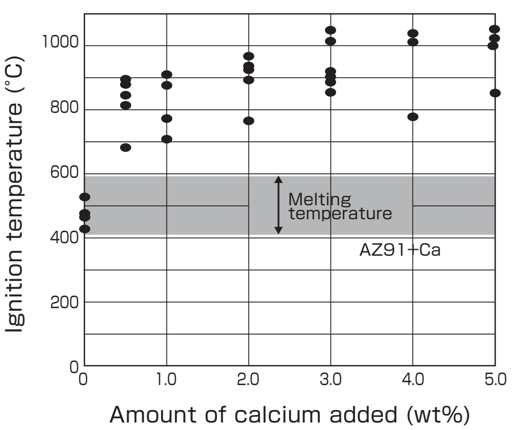


**Fig. 1 Ignition temperature of noncombustible magnesium alloy (AZX912).**

On the other hand, just as in ignition property, the state of oxides formed on the surface of molten magnesium differs significantly according to whether it contains calcium or not. In case of pure magnesium, the surface oxide of the sample, which was molten in inert atmosphere, immediately exposed to the atmosphere, and cooled rapidly before it ignited, had grown extremely thick even when the time exposed to the atmosphere in the molten condition was only a few seconds. The structure was porous composed of fine particles, and it could be inferred that the oxide did not provide a protective film for the surface. This is shown in the SEM photograph of the oxide surface in Fig. 2. In the figure, (a) is the overall structure at low magnification, and (b) is the enlarged structure at high magnification. The structure of the oxide can be seen from how it is formed. At melting point temperature, with pure magnesium the volume ratio of the produced oxide (Pilling-Bedworth ratio) is much smaller than 1, and the produced oxide will not function as a protective film that completely covers the surface of the molten metal. This is thought to be the reason why the oxidized film formed on the alloy that does not contain calcium has a porous structure.

In contrast, the surface of the oxide of calcium-containing alloys is shown in the SEM photograph in Fig. 3. In this figure, (a) is the overall structure at low magnification, and (b) is the enlarged structure at high magnification. In the calcium-containing alloy, the film formed does not grow thick even if the surface is sufficiently oxidized by exposing to the atmosphere for 1 hr, and the surface structure is extremely dense. The oxidized film formed on the magnesium containing calcium presents a completely different state compared to the magnesium not containing calcium. This shows that when the alloy with calcium is in a molten state, a dense oxidized film forms on the surface, and this functions as an extremely effective protective film against oxidation.

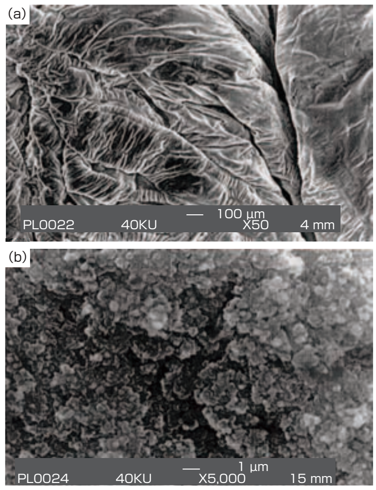


**Fig. 2 Surface structure of oxide film in pure magnesium.**

The significant difference between the surface structures of pure magnesium and magnesium-calcium alloys shows that there are differences in the constituent phase and formation mechanism of the oxidized film. Studying the oxidized film carefully, it was clarified that the outermost layer of the surface oxides of calcium-containing alloys was mainly composed of oxidized calcium[1]. Since this oxide has a dense structure, it acts as an effective barrier against oxygen supply from the atmosphere and against evaporation of magnesium from the molten surface, and the ignition temperature is thought to increase due to this protective action.

Although why such a dense oxide film forms only on calcium-containing alloys is a very important and interesting issue, not much is known about the formation mechanism. Calcium is more active than magnesium, and a dense surface oxide film is not formed in calcium alone, as in magnesium alone (or a magnesium alloy without calcium). What is clear is that the coexistence of magnesium and calcium is significant. When oxidation occurs when calcium and magnesium are coexisting, various interactions occur. Since calcium is one of the few elements that can be expected to reduce magnesium oxides at temperature range near the melting point, the formation of the outermost oxidized film layer composed of calcium oxide is probably a complex process that involves the reduction of magnesium oxide by calcium and production of calcium oxide, in addition to the preferential oxidation of calcium over magnesium.

After the discovery of the effect of calcium, the search for a similar effect among various elements was futile, and no additive element that showed dramatic ignition suppression like calcium was discovered. To the present, we found no element that enhanced noncombustibility as much as calcium. It is thought that this is an appropriate conclusion, since, considering the above mechanism, the only element with lower free energy to form oxide than magnesium is calcium.

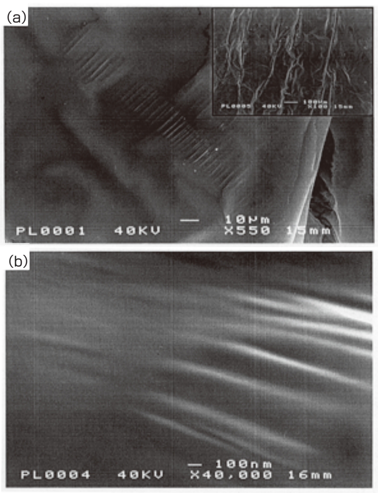


**Fig. 3 Surface structure of oxide film in Mg-5Ca binary alloy.**

## 3 Solution of individual elemental technology issues

For practical application, it is necessary to appropriately set the individual elemental technology issues and solve them one at a time. However, this is easier said than done. If issues are dealt with as they arise, a long time will be required to reach the goal. A clear scenario is necessary to send out a new material to the world. In the development of noncombustible magnesium, (1) following the discovery of a new raw material described above, (2) the development of refining technology to raise the raw material to material, (3) the technology for fabricating members (forming and processing technology), (4) the reliability assessment, and (5) a technological breakthrough in the product realization phase were necessary.

Through the mechanism described in the previous section, calcium-containing alloys can be melted and cast in the atmosphere safely, and the manufacturing process can be done safely and simply using the magnesium-based alloy. To be simple is important from the industrial perspective. The most important point here is to be conscious that the original motivation for employing magnesium as a core material is to realize a low environment load society that may become possible if magnesium is used. Therefore, this development will be meaningless unless all elemental technologies follow the guiding principle. The outline is described as follows.

### *3.1 Clean molten metal refining technology*

In noncombustible alloys, active metal calcium is added to active magnesium, and, inclusions such as oxides that are produced in the smelting process[Term 1] mix into the molten metal in larger amounts compared to other alloys, and this may affect strength and corrosion resistance. Since the specific gravity of the inclusions is close to that of the molten metal, it is difficult to separate them by precipitation or floating, and therefore, complete separation and removal are difficult. Normally, they are removed using flux such as chlorides or fluorides of magnesium or calcium. However, the corrosive resistance is compromised if the flux remains even in small quantity, and the material yield may be decreased if attempt is made to avoid this problem. Also, there is the problem of industrial waste composed of chlorides and fluorides. Even if an atmospheric melting process that does not use fireproof gas or flux is developed, the value of this technology is greatly diminished if flux or other materials are used in the refining process. Our condition for survival was to develop an environmentally clean, simple, and yet effective method.

We focused on the fact that in addition to the prevention of oxidation by the dense oxide film formed on the surface of the molten noncombustible alloy, the high vapor pressure of the molten magnesium appeared to be held extremely low. This, in other words, was the development of a refining technology by a reduced pressure method, and it was a breakthrough for converting the noncombustible magnesium alloy into a practical material. This method is characterized by being extremely simple so it can be executed easily, and therefore can be implemented in large-scale production facilities.

The reduced pressure method is a simple method for removing the inclusions by floating and separating them on the surface of the molten alloy, by maintaining the molten state under decompression. Since various gases are dissolved in the molten metal, the inclusion floats to the surface of the molten metal by attaching to the gas bubbles generated by reduced pressure. In ordinary magnesium alloys, since the vapor pressure is high, the pressure cannot be reduced. In noncombustible magnesium alloys, the metal vapor pressure becomes extremely low in appearance due to the oxide film formed over the molten metal surface, and therefore, reduced pressure refining can be applied as in aluminum, iron and steel. The target pressure can be reached sufficiently by the evacuation capacity of an ordinary mechanical pump, and the retention time is several seconds to several minutes depending on the quantity of the molten metal. Therefore, it can be applied readily to a large melting furnace. Figure 4 shows the melting furnace with 100 kg capacity for noncombustible magnesium alloys at AIST. It is equipped with the reduced pressure refining mechanism. In the conventional flux method, the working environment deteriorates due to steam originating from flux, but in this method, the working environment remains safe and clean, and the integrity of the material will not be lost since no flux will remain in the molten metal. This technology, at present, has been transferred to four companies and the development of a mass production process is in progress. This series of smelting process is mainly atmospheric melting. It is basically an atmospheric process where in the final step, refining is done by placing a lid and reducing pressure to remove the inclusions. It leads directly to cost reduction of the casting process, and has been put to actual practice. However in reality, many know-hows are required to cast noncombustible alloys, as will be described later.

### 3.2 Plastic forming process

The second issue pertains to the plastic forming process. Compared to aluminum, iron and steel, the formability of magnesium in the cold process[Term 2] is poor, and there is a great risk when a user introduces this process for the first time. This raises the manufacturing cost of magnesium and becomes a realistic barrier in industry. While alloys of iron, steel, and aluminum have cubic crystal structure with small anisotropy, magnesium is a hexagonal crystal structure with large anisotropy, and therefore does not show rich formability in the cold process, and also has a basic problem in the plastic forming process. The problem is more serious in noncombustible alloys. Since magnesium alloys must contain aluminum to increase its strength and corrosion resistance, high melting point aluminum-calcium intermetallic compound is formed due to the calcium added for noncombustibility, and this becomes a primary crystal that crystallizes as a network into the grain boundary, decreases the flow of the molten metal, and negatively affects the mechanical properties, particularly the ductibility. This is shown in Fig. 5a. Since the aluminum-calcium intermetallic compound has extremely small solid solubility into the metal matrix, it is not easy to control such solidification structure by heat treatment.

On the other hand, the situation is different when plastic forming is considered. Even with a noncombustible alloy of poor plastic formability, good formability can be achieved by applying the extrusion process that is a hydrostatic

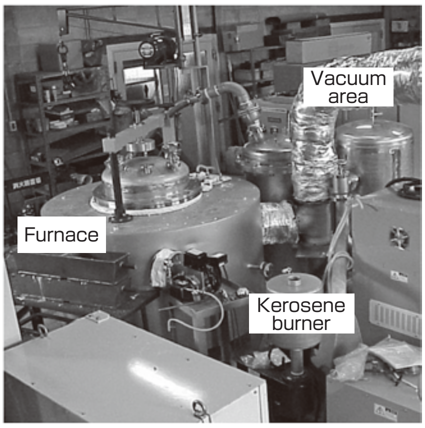


**Fig. 4 Smelting furnace for noncombustible magnesium alloy equipped with reduced pressure refinement mechanism (capacity100 kg).**

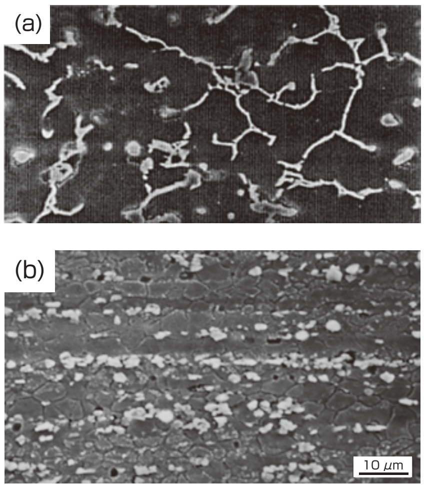


**Fig. 5 Structure of noncombustible magnesium alloy (AMX602).**
a: Solidified structure, b: Structure after extrusion.

processing method during the hot process[Term 2]. The network-form aluminum-calcium intermetallic compound in the grain boundary is crushed finely in the direction of extrusion. The crystal grain of the metal matrix becomes smaller by the recrystallization effect, and the overall structure becomes extremely fine (Fig. 5b). The strength and elongation properties increase significantly. Figure 6 shows the mechanical property of the AMX602 alloy. In case of the extruded materials, the room temperature elongation improved to the level of over 20 % in materials that underwent T4 treatment[Term3] after hot extrusion. This shows that a material with good balance of strength and elongation can be obtained if the plastic forming of noncombustible alloys is done optimally.

Important plastic forming technology includes forging and rolling. Along with product development by hot extrusion, it is necessary to develop a manufacturing technology for forging and rolling using the extruded material as a starting material. Also, the research is in progress for direct casting technique from low cost continuously casted material where the solidification structure is finely controlled. For plate material, composition and structure with excellent cold forming property is being discovered as a result of basic research, and it is entering the development phase for low-cost mass-production technology. Also, further basic research is necessary to compensate for the lack of alloy types for magnesium alloys, particularly for high strength and heat resistant materials.

To realize this alloy as a structural material, reliability assessment is important. Figure 7 is an example of the endurance strength assessment by rotary bending of extruded noncombustible alloy AMX602. The characteristic of this material is its clear endurance limit. It is also known to have a lower notch sensitivity compared to aluminum alloys[2]-[4], and can be used readily as a structural material. However, all fractures start at the inclusion initiation point[Term 4], and a clean manufacturing technology of high quality material is extremely important[2].

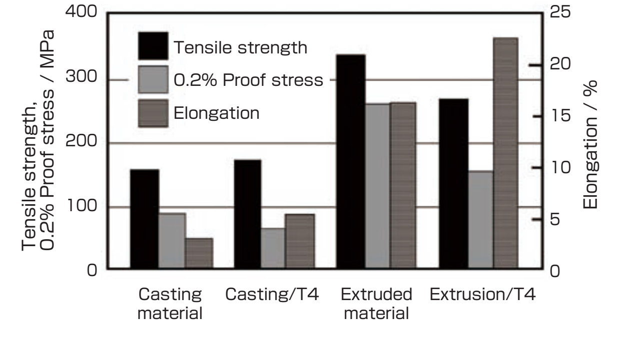


**Fig. 6 Mechanical property of noncombustible magnesium alloy (AMX602).**

### *3.3 Recycling technology*

As a guideline of material selection for the user, high recyclability is recently becoming important. Recyclability is an important property linked directly to manufacturing cost. As part of recycling research, an in-house recycling technology during smelting is being developed by the foundries, and the current refining level is recycled material use of 50 % or more. An example of mechanical pulverization in the atmosphere is shown in Fig. 8, as a case investigating the safety when used as an automobile component to be shredder treated later and the usability of the material after shredder treatment. The photograph shows the particle of sieve gauge of under 38 μm, and this indicates that mechanical pulverization can be accomplished safely. To study the use of such pulverized particles, the adsorption property of arsenic, boron, zinc, and chromium in wastewater were investigated, and magnesium hydroxides were demonstrated to be powerful adsorbents[5]-[7].

## 4 Industry-academia-government collaboration scheme for product realization

To send out a new material into the world, a clear vision and a scenario for its realization are necessary, after carefully looking at the overall picture of the technology the new material may promote. The noncombustible magnesium alloy is not flammable, so it can be developed in the same manner as ordinary metal materials. However, since it is similar but different from the existing aluminum alloys, it is necessary to prepare the comprehensive technological data and processing systems as in other metal materials.

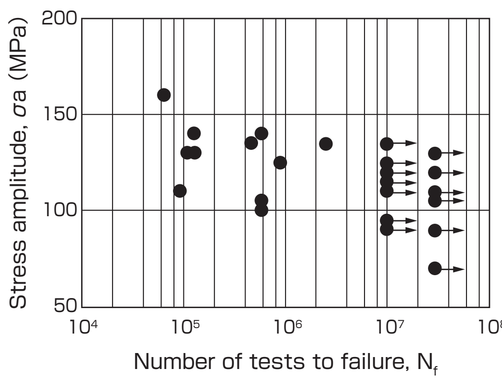


**Fig. 7 Endurance strength assessment of noncombustible magnesium alloy (AMX602).**

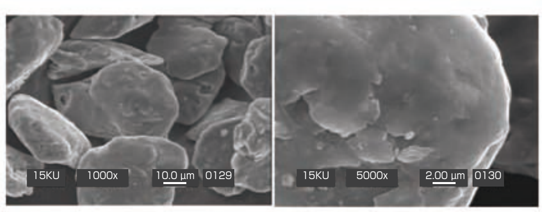


**Fig. 8 Crushed particles of noncombustible magnesium alloy (AMX602) (sieve gauge 38 μm).**

Therefore, it was necessary to write the scenario from the perspective of what would be the individual technologies adapted to magnesium. Fortunately, we were able to establish a collaborative organization with a common objective, with several companies in different businesses that were interested in noncombustible magnesium and saw its unique potential. We were able to write and share the scenario of R&D through this collaboration and were able to engage in development efficiently.

A material is a material only when it is used, and wide-ranging accumulation of technologies and experiences is necessary, just as it was with the conventional materials. If it is to be employed as a core material, further accumulation of integrated technology is needed, and normally, extremely long time is required if this process is left to a natural course of development. To accelerate the practical use of noncombustible magnesium, we made conscious effort to engage in R&D under one scenario, which is the realization of the material, while sharing an integrated and total vision with the members to develop individual elemental technologies. Through the activities in which the elemental technologies mutually influenced each other, we rapidly shifted the image of a novel material to an industrial material, and nurtured it as a core material. To accomplish this, we found that R&D through wide-ranging collaborative network of institutions with varying characters, including companies, universities, and public research institutions was effective.

We engaged in R&D with shared objective of application through the integration of technology, or the construction of an environment-friendly material system. For efficient research, a planar R&D system was created through collaboration of research activities that differ in character, using industry as a vertical line and core technology as a horizontal line. For industry, the technical issues became clear by taking a vertical collaborative system with mutual feedback, from upstream to downstream, or from material to product as shown in Fig. 9. Since we recognized that the research itself would not be possible unless the materials and components were not available at the industrial level, the companies in the figure had minimum commercial mass production systems. On the other hand, for core technology, a support system was constructed by a close network of universities and public research institutions to enable thorough and careful technical assistance for potential technologies and technical issues in various aspects as shown in Fig. 10. In this scheme, rather than each business engaging in technological development independently, they were encouraged to be part of integrated technological development that progressed in a planar manner. In the network of core technology, the significance and positioning of the individual technological issues were not left to become isolated, but were made clearly visible, so elemental technology could be developed while maintaining direct relationship with industry. As a secondary result in the core technology network (perhaps this is an ultimate outcome for a public institution), we were able to possess a successful experience of the R&D method where one scenario was shared and the direction was determined, and a collaborative research platform was created for integrated technological development. Not limited to noncombustible magnesium, this platform is expected to become the center of growth of various innovations.

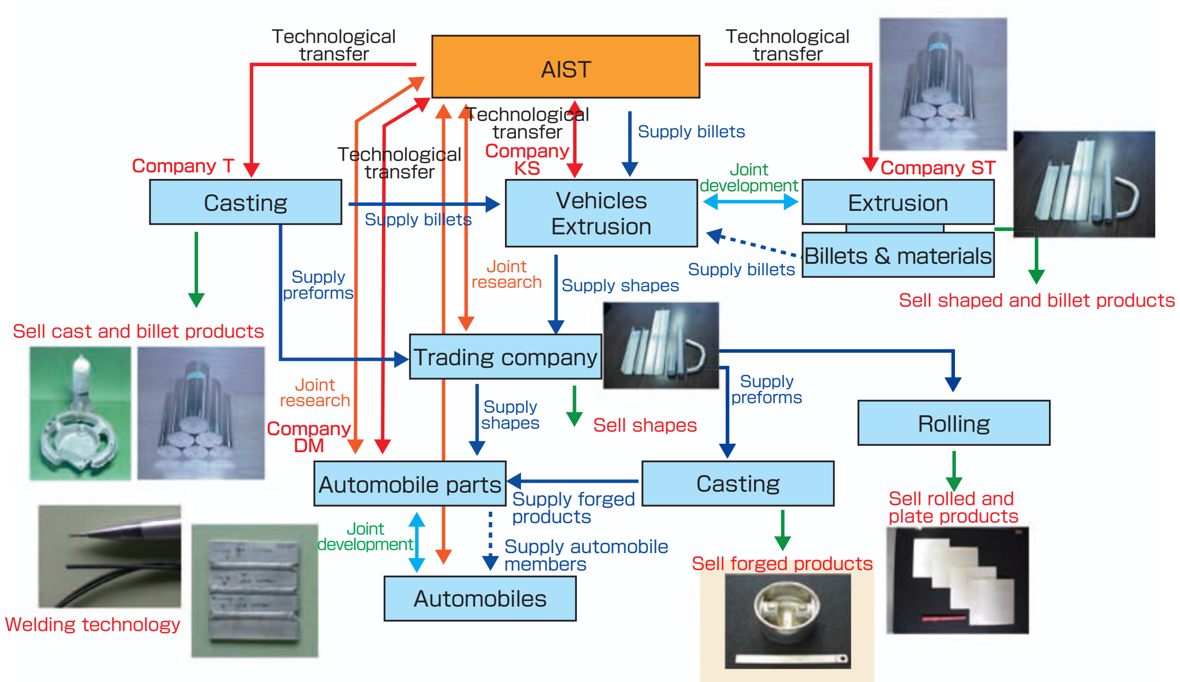


**Fig. 9 Mass production system for noncombustible magnesium alloy.**

## 5 Current state of practical use and R&D

*• Casting material and billet for plastic forming*

The materials for plastic forming must be highly clean and have the highest quality possible, and the quality of the material in the most upstream position greatly affects the quality and cost of the plastic formed products. We transferred the molten metal refining technology by reduced pressure method to three material supplier companies, and is engaging in usage development and mass production of high-quality, low-cost billet materials. We selected multiple companies as material manufacturers to ensure stable supply of the material. One company was capable of an integrated mass production system from billet manufacturing to extrusion, while another company was a casting company capable of multi-type low-volume production, and we aimed for a flexible production system considering the future demand for machinery structure components. The photographs on top right and left center in Fig. 9 show the plastic forming billet in rod form.

*• Casting material*

Since the noncombustible alloy does not burn readily in the atmosphere, casting is possible at low cost in the casting process where metal is melted and then solidified in a mold. Therefore, we are working on R&D for casting technology for various machinery components with the aforementioned casting companies. Casting itself can be done in a similar manner as aluminum, and it should be specifically mentioned that green sand casting in the atmosphere is possible in the case of AZ91-based noncombustible alloy. However, since the noncombustible alloy has poor flow property compared to ordinary alloys due to its special solidification structure, and also since solidification occurs rapidly due to its low heat capacity compared to aluminum and casting iron, the problems in casting methods and their conditions are not entirely solved. In actual practice, technology, experience, and know-hows must be accumulated. However, it has definite cost advantage, and application to various machine parts are expected in the future. Figure 11 is an example of the shelf support that was selected for use in the state-of-the-art Shinkansen car. It is made of die-cast noncombustible alloy AZX912, and this is the first time in the world for a magnesium component to be used in a railroad vehicle.

*• Hot extruded shape materials*

Long products with complex but uniform cross section like the aluminum window frame can be mass-produced efficiently, by applying pressure to the metal and pushing it through a perforated die. The extruded materials that are easily formed into shapes with complex cross sections or hollow interiors are basic industrial materials. Since the noncombustible magnesium alloy can be fabricated easily into shapes by the hot extrusion process, usage development is being conducted by the aforementioned billet company and the aluminum extrusion specialist company. Currently, as the first practical application of noncombustible magnesium shape, the specialist company created a product in the form of a square pipe to be used as gate bars for the ETC (Electronic Toll Collection) system at the expressway toll gates. There was a demand for weight reduction, as there were many cases where the shaft of the conventional aluminum bar broke due to the increased frequency of opening and closing of the gate bar. Initially, CFRP was used, but from the perspectives of product price and recycling after exchanging with a new bar, it was changed to the noncombustible magnesium alloy product. It was not merely a replacement of aluminum for further weight reduction, but this was an interesting and illustrative example of a material alternative where high specific strength and recyclability were the key considerations.

*• Hot forged material*

Forging is done by beating a simple-shaped metal material to improve strength and reliability. By forging using a mold, parts with uniform quality can be mass-produced, and it is an important processing technology in industry. Forging of noncombustible magnesium alloys is more difficult compared to other alloys, because cracks occur readily unless the temperature and speed of the process are finely controlled. However, in forged materials with fine recrystallized structure by preliminary hot extrusion processing, the forgeability improves dramatically and high speed forming using a hammer forger is possible. Therefore, even if the addition of preliminary extrusion increases the number of steps, there may be advantage in terms of total cost for

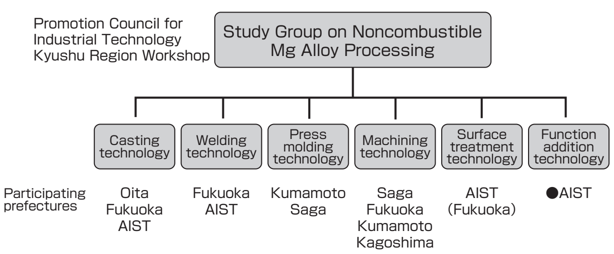


**Fig. 10 Core research system for processing technology of noncombustible magnesium alloy by public research institution collaboration.**


**Fig. 11 Luggage shelf support made of noncombustible magnesium alloy (AZX912).**

some products, and joint development is in progress with automobile parts manufacturers. However, the manufacturing cost is a barrier at present, and basic research must be conducted by returning to the basic principles as soon as possible to overcome this issue, as mentioned in section 3.2.

• *Plate material*
Metal plates can be easily formed into various shapes, and therefore they are basic industrial materials. Normally, they are formed by rolling the metal at room or high temperature between two rollers to make thin plates. Although magnesium alloy plates are highly in demand, rolling is difficult since the material tends to crack. Therefore, it requires more rolling processes compared to aluminum and other metals, and that increases the price. Although there are limitations on size and precision, the plates can be manufactured satisfactorily by hot extrusion. The aforementioned two extrusion companies have easily manufactured plates with thickness of 1 mm or less. It is also confirmed that good properties are shown when the extruded material is rolled afterwards. Here, one advantage of noncombustible alloys is that thin sheets can be manufactured since there are no worries of ignition or oxidation at temperature required for hot rolling, and the rolling company has succeeded in manufacturing products with thickness of 0.1 mm. However, the manufacture process of plates requires several steps and therefore, the cost is a more serious problem than forging. For mass supply of low cost plate materials, more technological developments including development of material with good formability are necessary.

• *Welded structures using extruded materials*
The structures fabricated by joining plastic formed materials such as forged, plate, or extruded materials are core technologies for various applications to automobiles, railroad vehicles, aircrafts, and other machine structures. Figure 12 is an example of such an application – passenger seats for railroad vehicles. This product cleared the current standard for seats for train cars and is expected to play a role in weight reduction. We presented the product to the Japan Railway Company, and it is under consideration. Even

**Fig. 12 Railroad vehicle seat made of noncombustible magnesium alloy (AMX602).**

for just one item such as this seat, integrated technology is important since it involves cast, extruded, and plate materials, as well as bending and pressing processes. Joining requires guarantee of reliability through basic joining and fatigue tests. In this example, TIG welding[Term 5] was used, and fabrication of a welding rod for this process was necessary. Also, in some parts, new surface treatment appropriate for noncombustible alloys was done. This shows that a wide range of technological integration is necessary in actual product development, and feedbacks from universities and public research institutes in the aforementioned R&D network were very important for the investigation of all elemental technologies.

## 6 Remaining issues

To nurture one material as a core material, extremely wide-ranging technological development from upstream to downstream and the accumulation of technologies are necessary. In that sense, rather than asking what are the remaining issues, we must say we just arrived at the starting line of development. However, we must develop the technology to utilize magnesium as an environment-friendly material for the future. To accomplish this, a wide scope of technological development for the material must be considered from the perspective of life cycle assessment, starting with ore mining, as well as the refining, processing, and recycling technologies, and the social system of cascade recycling. Particularly, the current refining process consumes high quantity of energy as exemplified by titanium and aluminum, and the effort for true energy saving has just begun. Although the potential in Japan for refining technology has advanced remarkably, innovative breakthrough is strongly desired. On the other hand, there are still mountains of issues such as quality assessment technology for molten metal and ingot, low-cost surface treatment technology, highly reliable joining technology, as well as standards for various materials and standardization of the assessment technologies. We hope to solve the above issues, and achieve commercialization of the core materials by employing low environmental load and low cost processes.

## Terminology

Term 1. Smelting: The process of working metal in its molten stage. This includes casting where the molten metal is poured into a mold and then hardened, as well as manufacturing of metal blanks for plastic forming. In contrast to smelting, there are methods where metal powder is hardened and formed, as well as plastic forming where metal is deformed into shapes.

Term 2. Cold process and hot process: Differentiation is made according to the temperature range when plastic forming metals. When metal crystal is plastic formed at low temperature such as room temperature, hardness and strength can be increased (work hardening), but the formability decreases due to cracks. When plastic forming is done at high temperature, the formability increases dramatically although strength cannot be improved. In general, the former is called cold processing and the latter is called hot processing. By heating the processed material to a certain temperature, the crystals undergo a phenomenon of recrystallization where new crystal grains are formed without distortion. Strictly speaking, processing at low temperature without recrystallization is cold processing, and processing at high temperature with recrystallization is called hot processing.

Term 3 T4 treatment: One of the heat treatment processes to control the mechanical properties of metals. When an alloy element added to a base metal is maintained at high temperature, dispersed evenly, and then cooled rapidly, the alloy metal that usually precipitates at low temperature can be solidified in a state where it remains dissolved in the base metal, and this is called solution. When the solution material is maintained at an appropriate temperature for some time, the dissolved alloy elements precipitate into the base material as fine crystals, and the properties such as strength, hardness, and ductility change. This series of heat treatment is called aging. Aging done at room temperature from the solution state is called natural aging, and aging forced at high temperature is called artificial aging. Among various heat treatment methods, these two are used frequently in the field of light metals. The former is known as T4 treatment while the latter is T6 treatment.

Term 4 Inclusion initiation point: The reduction in strength due to fatigue is caused by microscopic cracks in an object, and these cracks become gradually larger by repeated applied force. The first microscopic crack occurs in a place where stress is concentrated in the object. Stress concentration occurs in various places, but most often occurs around heterogeneous solid impurities (in metal, nonmetallic inclusions such as oxides). When the bond between the interface of such an inclusion and the base metal is weak, the presence of an inclusion becomes a defect of the base metal, and functions similarly to microscopic cracks. The failure is then initiated around the inclusion.

Term 5 TIG welding: Tungsten inert gas welding. One of the welding methods where the metal is melted and joined using arc discharge. This is a method of joining by melting the base metal by producing an arc from a tungsten rod by applying high voltage between the base metal and the tungsten rod with high melting point. Basically, this is done by hand so it can be applied to complex shapes, and it is widely used for welding non-iron metals.

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Graduated from the School of Sciences, University of Tsukuba in 1980, and completed the doctorate at the Institute of Geosciences, University of Tsukuba in 1985. Doctor (Geology). Joined the Machinery and Metal Section, Kyushu National Industrial Research Institute, Agency of Industrial Science and Technology in April 1985, and worked on R&D of metal matrix composites. Appointed to the Materials Research Institute for Sustainable Development, AIST in August 2007, and transferred to AIST Chubu in November 2007. In this paper, clarified the non-combustion mechanism of the noncombustible magnesium alloy, and built and managed the collaborative network.

**Hidetoshi Ueno**
Graduated from the Fukuoka Prefectural Ukiha Industrial High School in 1965. Joined the Machinery and Metal Section, Kyushu National Industrial Research Institute, Agency of Industrial Science and Technology in April 1965, and worked on the R&D of metal matrix composites. Became leader of the Environment Adaptable Alloy Development Group, Materials Research Institute for Sustainable Development, AIST in 2001. Worked steadily on lightweight metal materials, and developed a practical processing technology for metal matrix composites and succeeded in the realization of foamed aluminum. In this study, mainly worked on plastic forming process of noncombustible magnesium alloys.

## Discussion with Reviewers

### 1 Positioning of magnesium alloys

**Comment & question (Toshimi Shimizu, Coordinator AIST)**

The social value of this study is energy saving through weight reduction and improved efficiency of transportation machinery and machine components. However, it is unclear why magnesium is the target of research instead of the current core materials of iron, steel, aluminum, and CFRP that are mentioned in the text. In chapter 1, I think you need to clarify the positioning of magnesium as background for introducing the scenario.

**Answer (Michiru Sakamoto)**

The goal is to achieve weight reduction of transportation machineries at a different level than with the existing core materials such as iron, steel, and aluminum, by making magnesium noncombustible and establishing its position as a core material. There aren't many materials that have the potential as core materials, and we consider magnesium as one of the few candidates.

Considering the volume of transportation machineries that are the foundation of society, the material for their weight reduction must be a core material that can be supplied readily like iron, steel, and aluminum. Therefore, we selected magnesium from the perspective of a material having such a qualification as an industrial material. Qualitatively, there are many materials that can be considered lightweight. Also, I don't think the existing transportation machinery system will be used in the future, and it is certain that a new system will emerge and the component materials may be totally different from the existing materials. However, considering the use as structural material, stability of supply equivalent to the existing iron, steel, and aluminum is necessary, and an assurance in terms of environmental load is also necessary.

### 2 Creation of scenario with product realization in mind

**Comment & question (Norimitsu Murayama, Advanced Manufacturing Research Institute, AIST)**

The point that is interesting from the viewpoint of synthesis is, when the noncombustible property of magnesium by addition of calcium was discovered, which elemental technologies you set for development and how you designed and planned your research toward product realization. Also, I am very interested in research after the refining technology. Did you select the reduced pressure method assuming the effect of the oxide film formed on the molten metal surface? Did you have refining of structure by extrusion, and the subsequent forging and rolling in mind when you initially wrote the scenario? I imagine there were many trials and errors. Isn't the coexistence of trial and error and inevitability a characteristic of a scenario for material development?

**Answer (Michiru Sakamoto)**

Researchers like us are not very good at scenarios with product realization in mind, while it is routine for companies, and it is important to set up a scenario that leads to product realization most efficiently and at a shortest route possible. However, even if it is the shortest route, it won't work if the route is "off the wall," and a solid technological backing is important. I think that role can be filled by the collaborative organization of university and public research institutions. Here, for the collaborative organization to share a common scenario is important, and without a scenario, the researches will be scattered and they will be points without linkages.

### 3 Energy saving effect by weight reduction of components

**Comment & question (Toshimi Shimizu)**

The research progressed under the mission to achieve weight reduction of most moving things, and the main result is the cast material using noncombustible magnesium alloys that was employed as a shelf support in the state-of-the-art Shinkansen. Although I sort of understand the initial idea of weight reduction, I think the readers' understanding will be bettered if you add some quantitative figures showing how much weight reduction or energy saving was accomplished by employing this shelf support.

**Answer (Michiru Sakamoto)**

Your indication that the contribution of weight reduction to energy saving will become clearer if we present actual figures is very true, and we are keenly aware of this point. However, showing the energy saving effect is not so easy. For example, in our joint research with a certain automobile manufacturer, clear difference was measured between a magnesium piston and an ordinary aluminum piston in an engine bench test for a piston of the reciprocating engine. However, this is only a test, and the realization of the piston is still in a development stage. The weight of a Shinkansen is about 50 tons per compartment. The weight of the noncombustible magnesium shelf support is 15 kg. Direct comparison is difficult since this is not a direct replacement of aluminum parts to magnesium and there was a change in design, yet the weight reduction is about 7.5 kg in total. In the state-of-the-art Shinkansen car project, the primary goal was weight reduction of 500 kg per compartment. Although it is only 7.5 kg, there was some contribution, and the vehicle manufacturer was very grateful. It is difficult to see the effect of this weight reduction now, but I think it will eventually become a common material that will be used normally in various components in the future.

### 4 Industry-academia-government collaboration scheme

**Comment & question (Norimitsu Murayama)**

I think the key to success of this research is that you were able to create a collaborative organization with a common objective by several companies in different businesses that took interest in the discovery of noncombustible magnesium. Please tell us the points you found difficult or the issues you worked around in creating a collaborative organization, such as in handling intellectual property, making adjustments among companies, and in connecting companies, universities, and public institutions.

**Answer (Michiru Sakamoto)**

What was important in creating a collaborative organization was first and foremost the matching of philosophy. This means that the members of the collaborative organization are companies that share consciousness that environment friendliness is most important for society and the realization of noncombustible magnesium alloys must be conducted in this framework. Many people, including the authors, tend to think the companies are only interested in technological development and the profit they can make from it, but actually they routinely make decisions taking into consideration the social issues that lie at the base of the technological development. The members of this organization finally boiled down to companies with such consciousness. Here, it was significant that the university played the role of supporting the philosophical background of environmental friendliness. In addition, to maintain the motivation of the collaborative companies, it was important for the public research institution to take the stance that the main player was the company. Thinking on greater terms, I think the effort to maintain a common goal as a collaborative organization is important.

However, in reality, various issues such as division of labor and intellectual property arise one after the other as business sets in. To deal with this, I think we have to share as much information as possible, and patiently deal with issues one at a time by discussing them carefully among the members. It was important to set up a place of opinion exchange for all members of the collaborative organization using every opportunity possible, and to repeatedly check our understanding of the direction and scenario.

# A strategy to reduce energy usage in ceramic fabrication

## — Novel binders and related processing technology —

Koji Watari[1] *, Takaaki Nagaoka[2], Kimiyasu Sato[2] and Yuji Hotta[2]

[Translation from *Synthesiology*, Vol.2, No.2, p.137-146 (2009)]

Because of serious global environmental problems, the ceramic industry has been concentrating on the reduction of energy usage during manufacturing. In this project, we have investigated low-energy processing techniques for ceramic components. Our research and development approach was carried out with the goal of realizing new ceramics that can be manufactured using conventional manufacturing processes and equipment at low-cost without significant degradation in material properties. After a careful investigation of possible technologies, we concluded that a decrease in the amount of organic binder is the most effective technique to promote low-energy processing, and have successfully developed a novel binder technology. Our technology and knowledge have contributed to greatly reduce the amount of energy required for ceramic fabrication through a collaborative research project with a private company.

*Keywords* : Ceramics, manufacturing, energy saving, binder, process, water

## 1 Introduction

Ceramics are used in the field of industrial machines, and have spread to various other fields including semiconductors and electronic parts, electronic devices, automobiles, processing, environment, energy, and biotechnology. They are recognized as important materials for supporting industry, together with metals and polymers.

Looking at the ceramic manufacturing process from the perspective of environmental load reduction, there are many issues. In Japan, industries including the ceramics industry produce about 40 % of the greenhouse gas generated by energy consumption. Comparing the changes of energy consumption unit index per industrial production index by industries, the index for ceramics related industries is about 1.5 times higher than those of iron and steel, chemical, and paper and pulp industries[1]. Particularly, resource saving, energy saving, or environmental load have not been sufficiently considered in the ceramic manufacturing process, and there are many issues in practicing highly efficient manufacturing. Therefore, the development of a process technology to promote energy saving in current ceramic manufacturing as well as the development of an innovative high-efficiency manufacturing process is in immediate demand.

With this social background, our research group has been engaging in R&D to develop a low environmental load manufacturing process including the development of energy-saving process for ceramics. In this paper, we shall present the results of our research and describe how we arrived at the development of the energy-saving process for the existing ceramic manufacturing.

## 2 State of existing manufacturing process

Although ceramic manufacturing is a high-variety low-production activity compared to other materials such as metals and polymers, it requires many steps including mixing and dispersion, drying, forming, debinding, and sintering. Figure 1 shows the steps for ceramic manufacturing. First step is the preparation of raw material, where the binder and the solvent are added to the starting material such as raw powder and auxiliary agents, and mixing and dispersing the mixture. Auxiliary agent is an additive that promotes densification and expression of function. Binder is an organic additive used to add shape to the green body and to maintain strength. In general, polymer materials are used since they can be broken down and removed by heating. Ceramic products is obtained after following several steps including drying where the solvent is evaporated, forming where the powder is molded into certain shape, debinding where the added binder is removed, and sintering where the body is heated to high temperatures. In addition to these steps, exhaust gas decomposition is added to the manufacturing line, because the gas produced from the binder during debinding contains harmful substances.

Since ceramic manufacturing consists of multiple steps, the development of a manufacturing process involves not just the technological development of a single step, but must involve the steps before and after as well as the preliminary steps. For example, in a case where the formability of the powder is extremely low, it is necessary to investigate the material factors such as raw powder, binder, and solvent, as well as

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the process control factors of mixing, dispersing, and drying. Only after several experiments, production, and assessment of prototypes, an optimal process condition can be reached. Therefore, ceramic manufacturing requires broad knowledge and experience from material preparation to sintering, in addition to high technological capability in each step. Japanese manufacturing gained high technological capability by repeating the process of extracting issues and then solving them. As a result, the Japanese ceramic products have been leading industrial competitiveness in the world. However, this technological capability may have become a black box of know-how, and no engineering investigations have been conducted. This has prevented technological development of the existing manufacturing process, and increased the distance between the site of production and academic research institutes studying production technology.

## 3 "Valley of death" in energy-saving process technology

It is thought that there are two "valleys of death" that must be overcome in introducing the energy-saving process technology to the site of production. For realization, there exist the "economic valley of death" concerning costs in comparison to existing technology and the "technological valley of death" concerning the introduction of the technology to the existing manufacturing line.

### *3.1 Economic Valley of Death*

The "economic valley of death" is the increased cost in introducing the new technology. The companies are constantly pressured to reduce cost and are wary about any investment in new equipment. Even if the investment is for a technology that is expected to surpass the conventional yield, the companies are reluctant if it departs from the existing process. Therefore, the new technology must be developed under assumptions that it can be incorporated into the existing process and that the existing equipments can be used. Also, since many of the manufacturing lines are in operation 24 hours, results must be obtainable with little change as possible.

### *3.2 Technological Valley of Death*

Various elemental technologies are suggested for energy saving in the manufacturing process. However, many such technologies have issues of complicating the steps, difficulty of incorporation in the successive process, reduction in workability, and of production of waste and hazardous materials. Also, the effort to achieve energy saving may require substantial changes in raw materials and in the existing manufacturing line. As a result, many developed technologies are not put into practical use at the site of ceramic production.

## 4 Scenario for achieving the objective

For the developed technologies to be incorporated effectively at the site of production, it is necessary to overcome the aforementioned two "valleys of death." To overcome the "valley of death," it is important to consider the incorporation of developed technology into the existing manufacturing line. In an effort to achieve energy savings of the entire production system, the steps may become complicated and the manufacturing cost tends to rise greatly when several factors are changed. Therefore, we focused on the step that consumes high amount of energy, and clarified the relationship between the process factor and the energy consumed. Based on that result, we investigated elemental technologies that could be incorporated into the existing manufacturing line.

### *4.1 Consumption energy needed in ceramic manufacturing*

Figure 1 shows the steps of the ceramic manufacturing and the flow of the input and output of the materials. Figure 2 shows the percentage of energy consumed in each step. From the result of Fig. 2, it can be seen that the steps that consume large quantities of energy are debinding, exhaust gas decomposition, and sintering. This is because heat energy is necessary for the removal of the organic binder in the green body, the conversion of exhaust gas to vapor or carbon dioxide, and for the ceramic firing. Moreover, energy efficiency is extremely low. Therefore, to reduce the amount of energy consumed by heat energy, it is necessary to: (1)

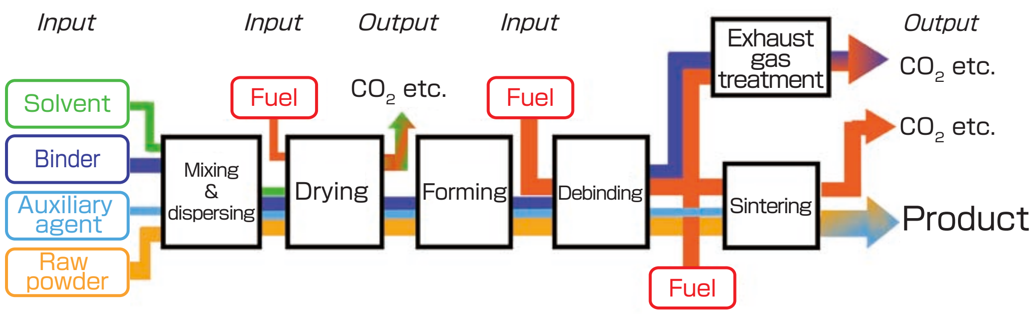


**Fig. 1 Steps of ceramic manufacturing and the flow of resource materials.**

use highly efficient firing furnace, (2) reduce heat energy by lowering the sintering temperature, and (3) reduce heat energy generated from debinding and exhaust gas decomposition.

### 4.2 Approach from equipment development

For (1), taking for example the gas firing furnace, the energy needed to sinter the ceramic body at 1300 °C is about 2 % of the total energy consumed. The remainder is about 25 % to heat the furnace wall, about 17 % is heat loss from the furnace wall, and the loss from exhaust gas is over 50 %. Therefore, swift measures such as the development of a firing system for high-efficiency sintering are necessary. Recently, a microwave furnace and a regeneration furnace that recovers high temperature exhaust gas have been developed[2]. The development of a high-efficiency sintering furnace is extremely necessary for energy saving in the ceramic manufacturing line. However, this issue was removed from the scenario to achieve the objective, because the main issue here concerns the development of equipment.

### 4.3 Approach from sintering technology

For (2), one of the ways is to reduce the total amount of energy needed for heating by using the existing sintering equipment by developing a low-temperature sintering technology. To promote low-temperature sintering of ceramics, it is necessary to mobilize nanoparticle handling technology[3][4], low melting point sintering additive technology[5], dispersion technology[6], surface coating technology (for auxiliary agents that may accelerate the sintering reaction of auxiliaries and particles), high-density forming technology, and others. All technologies work effectively for low-temperature sintering, and enables production of dense sintered body at firing temperature 100~300 °C lower than conventional sintering. However, there are problems such as shrinkage after firing due to addition of nanoparticles, difficulty in controlling the shrinkage, changes of material property due to addition of low melting point auxiliary agent and pollution of material surface, and reduced workability by using high-density forming technology. Therefore, we withdrew from the approach based on sintering technology.

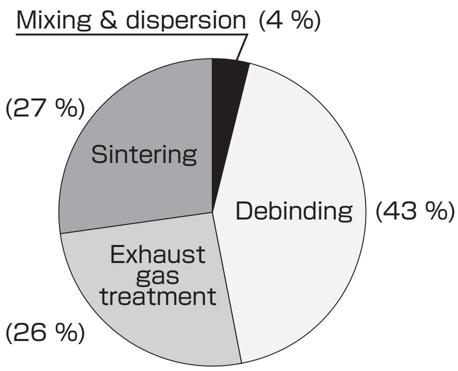


**Fig. 2 Percentage of consumption energy in each process (all are laboratory level; energy required for powder production is not included).**

Consumption energy required to sinter 1 kg alumina. Organic binder additive: 10 mass%. Degreasing step: maintain 600 °C 1 hr (12 °C/h). Exhaust gas treatment step: maintain 900 °C. Sintering step: maintain 1400 °C 4 hrs (600 °C/h). For degreasing and sintering steps, 6 KW electric furnace was used. For exhaust gas treatment step, 1.4 KW electric furnace was used.

### 4.4 Approach from binder technology

The method of (3) is the reduction or elimination of the currently used organic binder. Addition of organic binder enables formation of complex shapes and improves the strength of the green body. However, since an organic binder has low affinity for ceramic raw particle, it causes partial binder aggregation and also weakens the bonding strength between particles. Therefore, for good formability and shape maintenance after forming, a large amount of the organic binder must be added. Although the amount of binders differs according to size, thickness, shape, and processing of the green body, in general, it is 5 wt% or less in the case of dry mold product, 10 wt% or more for sheet mold product, and 20 wt% or more for complex shape product. Since the binder is unneeded after forming, it is removed from the body by heat decomposition or evaporation in the debinding step. The organic material used as a binder normally gasifies when heated at around 600 °C. Since sintering quality decreases when any binder remains on the powder surface as ash or carbon, precise process control is necessary in the debinding step. At the same time, the gas produced may cause structural defects such as pores, flaking, and warping in the green body and sheet, so the temperature must be increased gradually[7]. If the temperature at which the binder is completely eliminated is 600 °C, 60 hours of heating is necessary at a heating rate of 10 °C/h to reach the temperature, and 20 hours at 30 °C/h. Moreover, considering the heating and cooling times, the amount of energy required for debinding is extremely high.

It is known that the gas generated by heat decomposition of binders contains organic material, and therefore, it is decomposed into harmless substances such as carbon dioxide and water, normally using the afterburner in the exhaust gas decomposition step. The heat decomposition temperature of many organic gases is 600 °C or above, and if the temperature of the afterburner is set above the heat decomposition temperature, the energy required for the treatment of exhaust gas becomes fairly considerable[8]. As shown in Fig. 1 and Fig. 2, the energy consumption related to binders is extremely high. If the amount of the organic binder used can be reduced by some sort of technological development, the amounts of heat energy required for debinding and exhaust gas decomposition can be reduced. Therefore, to promote energy savings of the existing ceramic manufacturing process, we decided to make our approach from the binder technology.

If the developed binder technology necessitates major changes in the existing manufacturing line, the initial objective will be defeated. Therefore, it is important for the developed binder to have almost the same function as the conventional binder. Therefore, we considered a binder technology using a material with high binder function but which can be used at fewer amounts.

## 5 Development technology and research result

### *5.1 Extraction of key technology*

Figure 3 summarizes the functions of the binder. The functions can be roughly categorized into two types. First is to firmly bond the particles and to stably maintain the shape (shape retention). The ceramic green body must have a certain level of strength. One of the important functions of the binder is to maintain the given shape against the weight of the green body itself as well as against the strain of handling at the site of production. The binder with such function is used in the fabrication of ceramic films, sheets, and large products. Second is for the binder to give both fluidity and shape retention to the particles assembly (plasticity). That is, when the raw powder and the binder are mixed, the particles are bonded together weakly through the binder and retain shape (shape retention). Moreover, the shape is changed by simply applying certain amount of force (fluidity), and the shape must be maintained when the force is removed (shape retention). Plasticity is a function required in the production of complexly shaped products such as in extrusion and injection molding.

We investigated the materials with high binding functions such as shape retention and plasticity, while aiming to reduce the amount of organic material. Moreover, other than the binder function, we considered properties that are sought in binders in general, such as: (1) low cost, (2) no reaction to raw powder, (3) being soluble in water and solvent, (4) ashes not remaining after decomposition and evaporation, and (4) decomposition gas not being harmful or corrosive.

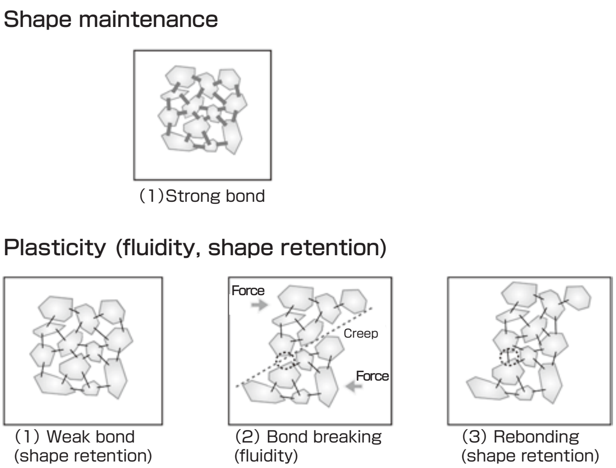


**Fig. 3 Functions of binder.**

### *5.2 Reactive binder technology*

We selected the method of reducing the amount of organic binder by adding the same function as the existing organic binder used in the manufacturing line to very small amounts of organic substances. First, we developed a new binder technology where the "shape retention" function (Fig. 3) is expressed with minimum amount of organic material. Highly reactive organic molecules that would be binders were anchored onto the surface of the ceramic raw particle in a form of a film. The whole partilcle assemblies were formed into desired shapes, the reaction trigger (external stimulus) that excites chemical reaction was applied, and the molecules of the organic film layer were chemically bonded, to create the ceramic green body in which the particles were bonded together firmly. Figure 4 shows the concept of the technology to reduce the amount of organic binders. Unlike in the conventional forming method, the shape of the green body could be maintained efficiently with only a small amount of binders, because of the structure in which the binder molecules linked the ceramic particles with strong chemical bond. Also, partial aggregation of the binder could be prevented since the binder molecules were fixed on the particle surface in film form, and therefore the amount of the organic binder could be reduced.

In this forming method, it was not desirable for the particles to bond before the particle assembly formed the desired shape. Therefore, the chemical bond was introduced at an arbitrary moment by using external stimulus as a reaction trigger. Irradiation of electromagnetic waves (ultraviolet rays[9], microwave[10]) and heating at 100 °C[11] were used as reaction triggers. When ultraviolet rays were used as reaction triggers, we succeeded in fabricating a solid body, as strong interparticle bond occurred by coating the ceramic particles with amino groups and phenyl azide groups[9]. For organic materials that react with microwave, we conducted experiments by referring to past reports, but were unable to reproduce them. Therefore, we looked at water, a high dielectric loss substance that absorbs microwave, and used water-soluble carbodiimide with water as a microwave reactive binder. The oxyethylene (-$C_2H_4O$-) that composes the water-soluble carbodiimide becomes the hydrophilic segment,

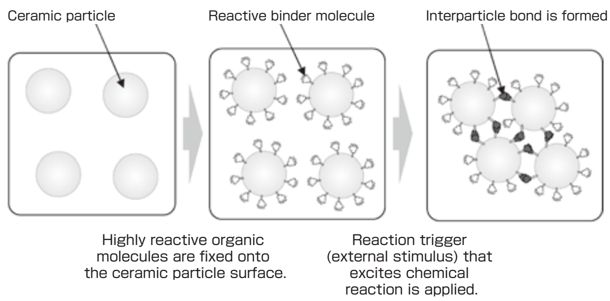


**Fig. 4 Fixing of organic molecule and application of reaction trigger to reduce the amount of organic binder.**

absorbs microwave, and generates heat. On the other hand, the carbodiimide (-N=C=N-) of the reactive segment firmly bonds the segments present on other particle surfaces[10].

While the UV reactive binder was effective for forming ceramic sheets, ultraviolet rays did not readily reach the interior in large samples since they have short wavelengths. Because microwave possesses longer wavelengths compared to UV, the microwave reactive binder was effective for the fabrication of a large green body. The ceramic green body fabricated using these binders contained only 0.5 wt% of organic substance, and the shape could be maintained with significantly lower amount of organic substance compared to the conventional method. This is an application of surface coating and reactive trigger technologies that we nurtured as elemental technologies to realize the energy-saving process.

### 5.3 Inorganic binder technology

Next, we investigated the inorganic binder technology using inorganic substances, for the total elimination of organic binders that express a "plasticity" function (Fig. 3). First we focused our attention to the fact that clay minerals possess plasticity. Although the expression mechanism of plasticity in clay minerals has not been clarified, it is thought to be related to: (1) effect of water film formed on the particle surface, and (2) slippage caused by the intercalation compound of clay. We focused on (1) and studied the inorganic materials that can retain water. Assuming that the mechanism whereby a new inorganic binder provides shape retention and fluidity is the same as in clay minerals where it is "the effect of water film formed on the particle surface" that does so, we looked for materials in which there was interaction between the particle surface and water, and which could retain sufficient amount of water. Hydrates chemically contain large quantities of water, and take multiple forms in accordance to the chemical bonds of the component elements. Therefore, we thought hydrates could be applied widely to various ceramics. Also, the advantages of hydrates were that most of them were of low cost and had high purity compared to clay minerals. Hence, our research started with the technology for hydration material with fluidity and shape retention properties.

There is a saying that "one who controls binders controls ceramics," and the importance of binder technology is extremely high in the ceramic manufacturing process. Therefore, the guideline for binder development is almost never publicized. Also, since the binder function involves complex factors, it is difficult to express it in physical quantities. Therefore, at the sites of research and production, for example, in investigation of extrusion technology, it is "ultimately determined by actually extruding the product on the machine." In the first phase of the research, the definitions of binder functions (shape retention and fluidity) were set originally, and these were evaluated from the behavior of the samples formed by the extruder. Since this method was based on the observation of the extruded sample and on the relative assessment of shape retention and fluidity, it was far from an absolute assessment of physical quantities. However, it was extremely useful in narrowing down the material and seeking optimal conditions since assessment could be done easily with a small amount of material[12].

For the development of inorganic binder technology, we decided to look for inorganic material that showed the same plasticity behavior as the existing organic binders and clay minerals based on the assessment of binder functions. As a result, for the expression of plasticity of alumina ceramics, we found that the addition of hydraulic alumina (ρ-alumina) was useful. Hydraulic alumina separated out onto the surface of alumina particle as hydrate particles by hydration. It was found that the particles contained large amounts of water and had high binder functions. As a result, we succeeded in the extrusion of alumina ceramic tubes without using organic binders depending on the added amount, as shown in Fig. 5[13]. Moreover, a similar effect was seen in other hydrates, and we confirmed an expression of plasticity in various ceramics.

### 5.4 Assessment of inorganic binder particle surface

The development of the inorganic binder mentioned in the previous section succeeded by hypothesizing that the shape retention and fluidity properties were due to the water film existing on the binder surface. We considered the mechanism of plasticity expression in inorganic binders as follows. Shape is retained since the ceramic particles obtain mild bonding force through the surface tension of water that accompanies the inorganic binder. On the other hand, fluidity is gained because the water film works like a bearing and lubricity occurs between the surfaces of the inorganic binder. While the effect of surface tension could be understood readily, experimental demonstration was necessary for the expression of lubricity. Therefore, our group established the measurement technology for surface-surface interactive force using the atomic force microscope (AFM) to make actual measurements of the interactive force that act between the

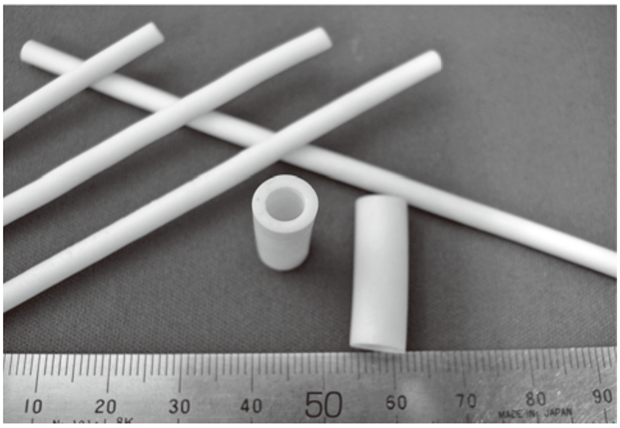


**Fig. 5 Alumina ceramics fabricated using inorganic binder technology.**

surfaces of the ceramic particle and the inorganic binder.

AFM detects the interactive force generated between the sample and the probe as the displacement of cantilever (a plate spring for force detection). Conventionally, it is used as a "microscope" to obtain morphological information of the sample surface, but it can be used to actually measure the interactive force between the particle sample and planar sample by attaching the desired particle onto the tip of the cantilever to be used as a probe (colloid probe method) (Fig. 6). The force in vertical direction (attraction and repulsion) against the planar sample can be estimated from the deflection of the cantilever, and the force in parallel direction (lateral direction) against the planar sample can be estimated from the torsion of the cantilever. We attached the hydraulic alumina particle to the tip of the cantilever, and measured the interactive force with the alumina single crystal substrate set as a model substance of ceramic particle. This was the first attempt to assess the interactive force that the inorganic binder may exert on the ceramic surface.

As a result of measurements, a repulsion that could not be explained by general electrostatic interaction or van der Waals force was detected between the inorganic binder particle and the alumina substrate. It was concluded that this was an interactive force called the hydration repulsion. When a substance with high hydrophilic property is placed in water, a thin layer (hydration layer) where the water molecules are bound and structured by hydrogen bonds is formed on the surface. The repulsion force generated when a foreign surface approaches is hydration repulsion. Also, from the measurement of interactive force in the lateral direction, it was found that a more "slippery" condition occurred when hydration repulsion was observed between the surfaces compared to when there was no hydration repulsion (no hydration layer)[14].

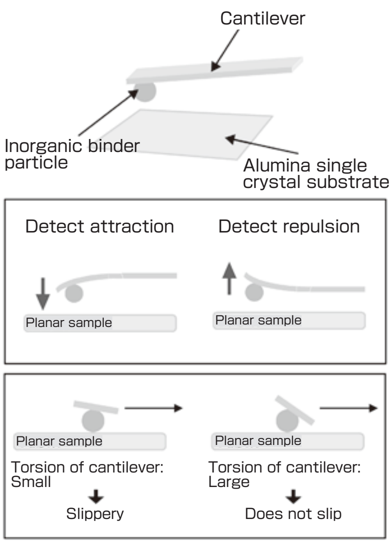


**Fig. 6 Measurement of inter-surface interactive force.**

The existence of the water film that was hypothesized in the development of the inorganic binder was confirmed as a hydration layer that caused hydration repulsion. Also it was indicated that the fluidity was expressed since the hydration layer increased the lubricity between the inorganic binder and the ceramic particle.

## 6 Discussion

The flow of our research is summarized in Fig. 7. Many researchers including us worked on the elemental technologies to realize the energy-saving process, and arrived at various findings. This corresponds to *Type 1 Basic Research*, and some elemental technologies are shown on the left of Fig. 7. However, many of the elemental technologies developed fell into the "valley of death" due to poor compatibility with the existing manufacturing process or increased costs. In this research, we first narrowed down the conditions assuming that the result will be used at the site of production. As a result, the technological and economic issues that may lead to the "valley of death" were clarified. The R&D to solve these issues corresponds to *Type 2 Basic Research*.

The development of low-temperature sintering technology is an attractive area in material process research. There are diverse approaches to low-temperature sintering, and an effective energy-saving process seems to be possible by combining various methods. However, all of the elemental technologies for low-temperature sintering accompany great material transfer for ceramics, and greatly alter the conditions of the existing manufacturing process. On the other hand, the newly developed binder technology has the characteristics of: (1) not greatly changing the property of the raw powder, and (2) not enforcing great material transfer for ceramics. Since we thought we should construct an energy-saving process without requiring great changes to the existing manufacturing process, the research topic became clear. Considering the positioning of this research, it corresponds to the definition of the research theme. However, this definition is "to find simplicity in complexity," and is based on the knowledge and experience gained over the years.

Since binder function changes significantly due to the type and amount of the raw powder, solvent, and binder, there is an extremely small number of systematic research publication. Also, since several binders are combined to obtain an optimal forming function, the roles of each binder are intricately intertwined. Therefore, although positioned as an extremely important element of ceramics R&D, there was hardly any scientific investigation of binders. Therefore, we decided to aim for reduction or elimination of the organic binder while maintaining the same function as the existing organic binder. We worked on the organic and inorganic binder technologies under these conditions. This is an extraction of technologies to develop a novel binder technology.

Various conditions became clear as the research progressed and the elemental technologies were refined. By conducting R&D for the expression of plasticity in inorganic binders and R&D of the particle surface analysis technology using AFM colloid prove method, the relationship between the particle surface and water was investigated from macro and micro levels. As a result, the importance of water in the plasticity of ceramics, as well as the ways of selection of inorganic binders to increase the water content were demonstrated quantitatively, and we were able to approach the technologies for reduction and elimination of organic binders based on scientific evidence. These researches correspond to the core and basic researches of the *Type 2 Basic Research*.

The flow of inorganic binder research for the reduction and elimination of the organic binder with plasticity shifted from: (1) development of binder assessment technology, (2) process research of inorganic binders, (3) research of water-particle interface, and (4) clarification of process factors that control the inorganic binder technology. As a result, it was shown that inorganic material with high water content could be used as an inorganic binder expressing plasticity. This is the outcome of the *Type 2 Basic Research*.

Discussions within the group of the importance of water in clay minerals and inorganic binders led to the organic binder with hydrophilic properties or those that contain water as candidates of organic binders that reacted to microwave, and this led to the development of a microwave reactive binder. Although the roles of water in inorganic binders and microwave reactive binders are different, in the greater concept of binders, "water" was an important keyword.

Based on the results and findings obtained, a product was realized by a major material company through joint research. These researches correspond to *Product Realization Research*, and the efficacy of the developed technology was tested in the manufacturing lines.

The advantages of the developed binder include its technological excellence as well as the low cost of incorporating this technology. Since the reactive and inorganic binders can be placed in solvent along with the raw materials and auxiliaries and then mixed and dispersed, no new step is added. Moreover, the binder is used in large amounts for other purposes, and the cost of material is low.

## 7 Evaluation of result and future developments

As a result of engaging in research to fulfill the demand of society and industry such as adaptation to the existing process, use of existing equipment, and low cost, we believe we were able to develop a technology that can be put to actual practice, as the boundary conditions of the technology as well as the elemental technologies became clarified. Extraction of core technology is to find "simplicity in complexity" of the manufacturing process that seems to be complexly intertwined. If the boundary conditions of the research and the core of the technology to be developed are known in the early phase of R&D, resources can be introduced efficiently

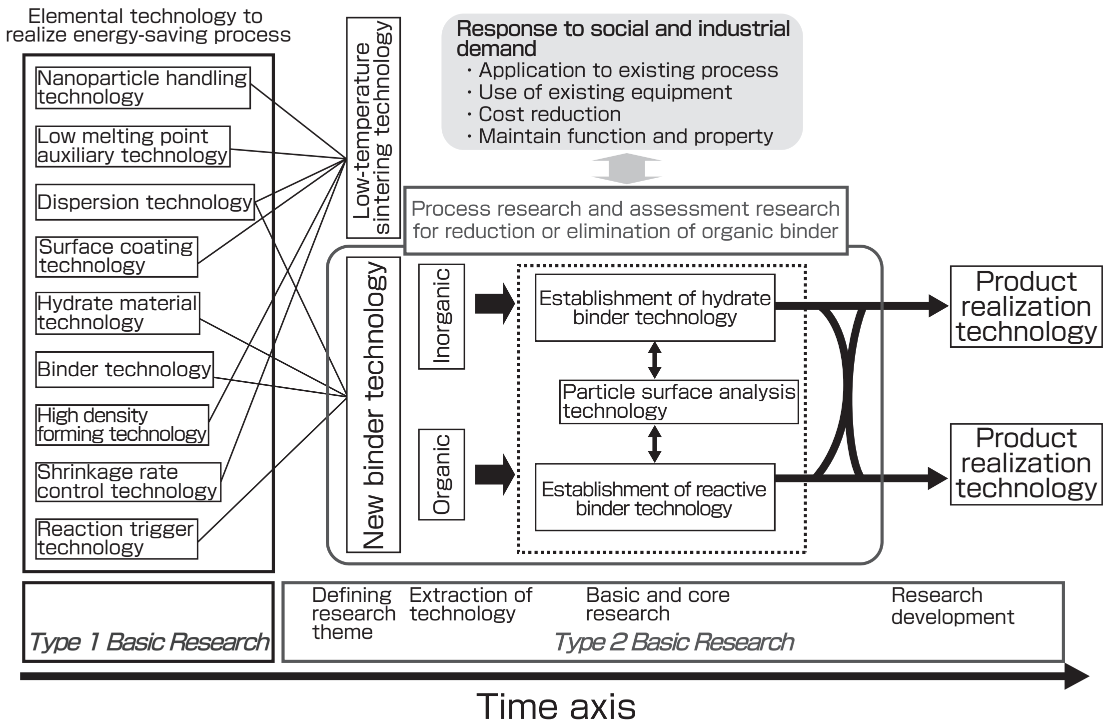


**Fig. 7 Building of low-environment load process and mutual relationship in existing ceramic manufacturing steps.**

and the speed of R&D can be accelerated considerably. However, since the manufacturing process is composed of the accumulation of elemental technologies and linkage between the technologies, more time than expected is required for the extraction of core technology. To solve this problem, it is necessary to systematize the elemental technologies and extract the issues and core technology to maintain the succession of the process. This is to create a research scenario for industry. By doing this, we believe various issues in technological realization can be understood, plans to solve the issues can be created, and the speed of research can be further increased.

However, information on the materials and the processes that we can learn from private companies are limited. Therefore, to engage in R&D while writing the scenario for industry, it is important to obtain human resources that have long years of experience and wide-ranging knowledge in the field, and to thoroughly understand the theme and its background.

Also, we believe the public research institute of industrial technology is expected to have a “universal thinking” that does not weather over the years. This is one of the outcomes of the *Type 2 Basic Research* conducted by AIST. In our research, we set the objectives to reduction and elimination of the organic binder, and we obtained a general solution that water on the surface of the raw particle greatly affects the formation of ceramics. When working on research topics that arise from the site of production in joint research, most are technological contributions and one-shot service to a company, but the outcome of *Type 2 Basic Research* may become extremely meaningful by also considering the construction of concepts with scientific universality.

The final target of this research is the complete elimination of organic binders. We succeeded in simple extruding using an inorganic binder. By achieving this technology, ceramic manufacturing without debinding and exhaust gas treatment became possible, and as a result the reduction in $CO_2$ emission was about 70 % (see Fig. 2). Also, since the amount of the reactive binder was one to two digits less compared to the amount of binders in the ordinary process, the debinding and exhaust gas treatment steps can be eliminated in the future. The estimated reduction in $CO_2$ will have an impact on the ceramics industry. However, in reality, the demands of industry cannot be met without conventional organic binders in members of certain size or complex shape. Therefore, the current practice is to add small amounts of organic binders to the newly developed inorganic binder.

Since the developed technology can be used in the current ceramic production process, we are working actively to spread the technology. We have engaged in R&D based on materials and processes, and wish to continue the R&D while looking at the development of manufacturing equipment to improve the energy-saving property based on the findings from this research project. Particularly, we shall fuse the R&D of materials and process with the R&D of manufacturing equipment, bring about a synergy effect, and contribute further to the development of the energy-saving ceramic process.

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## Discussion with Reviewers

### 1 Energy saving and reduction of $CO_2$ emission by the developed binder

**Comment and question (Nobumitsu Murayama, Advanced Manufacturing Research Institute, AIST)**

What were the degrees of reduction in energy and $CO_2$ emission, or how much is expected by using the inorganic binder or by reducing the organic binder?

**Answer (Koji Watari)**

By using the inorganic binder, so far we have succeeded in simple extrusion forming of alumina and silicon nitride ceramics, and the reduction in $CO_2$ emission for manufacturing was about 70 % (see Fig. 2). In the actual production line, the amounts of reactive and inorganic binders added are different depending on the forming process, as well as the type, size, and shape complexity of the members. Also, conventional binders must be added in some cases. I have heard that the $CO_2$ emissions were greatly reduced at the companies to which the technology was transferred, but I shall decline disclosure of specific figures and details of the reduction due to the limitation of joint research.

In the future, we would like to estimate the necessary amount of binders according to the member specs (material, size, shape, etc.) at actual equipment level, and quantitatively assess the $CO_2$ emission and the relationship of reductions based on the estimate.

### 2 Cost increase or decrease in introducing the developed binder

**Comment and question (Toshimi Shimizu, Research Coordinator, AIST)**

It is described that the cost factor of the newly developed technology is important from the perspective of “economic valley of death” in the energy-saving attempts for manufacturing process. What are the costs of introducing reactive and inorganic binders?

**Answer (Koji Watari)**

One of the advantages of the binder we developed is the low cost of introduction, in addition to its technological excellence. The reactive and inorganic binders are simply mixed and dispersed in the solvent along with the raw materials and auxiliaries, and no new step is added. Also, the binder we used is abundantly available, and the cost of material can be kept low.

### 3 Relationship between the elimination of organic binders and the introduction of inorganic binders

**Comment and question (Toshimi Shimizu)**

You stated that the objective for the realization of energy-saving process is reduction or elimination of organic binders. Does this mean "elimination = introduction of inorganic binders"?

**Answer (Koji Watari)**

It is as you have indicated. The introduction of inorganic binders is the elimination of organic binders, and this leads to significant reduction of $CO_2$ emission in the ceramic manufacturing process.

### 4 Relationship between material production and assessment technology

**Comment and question (Nobumitsu Murayama)**

In the development of the inorganic binder, first the binder assessment technology was developed, then followed the development of the inorganic binder. This research progression is very interesting. In ordinary material process research, first, the material is developed and then assessed. However, in the research for a new function, it is necessary to establish the assessment technology of that new function. Please comment on the relationship between material production and assessment.

**Answer (Takaaki Nagaoka)**

In the R&D of material and process through search of materials and their optimization, it is necessary to conduct tests for assessments. In this research, however, there were two limitations. One was that there was a lack of assessment method for binder functions. As a result, "ultimately it was determined by actually extruding the product on the machine." Second was that high quantity (several hundred grams) of samples was needed per assessment on an actual machine. Although that amount may be small at the site of production, it was difficult at AIST when considering the time and labor needed. This was more pronounced when several assessments had to be done. Therefore, we set the definition of binder functions (shape retention and fluidity) for extruding, and developed a method for assessing the functions with minimum amount of samples. As a result, we could easily and quickly narrow down the prospect samples using small amounts of samples.

When searching for new material functions, if there is no function assessment technology at the laboratory level, then the researchers themselves must establish the assessment technology. Although this seems to be taking the long way around, by simultaneously developing the assessment technology, the researcher can think deeply about the meaning of the expressed function, and can work on material production from the same perspective as the person doing the assessment. Moreover, by accumulating the assessment technology, the developed technology and material together become a bundle of highly original, advanced knowledge.

### 5 Significance of scientifically investigating the know-how technology

**Comment and question (Nobumitsu Murayama)**

It can be said that this research is a scientific investigation of the know-how technology for binders. While this will certainly promote the advancement of manufacturing process, disclosure of the companies' know-hows, which is the primary practice in the ceramics industry, may lower the competitiveness of these companies. Please comment on the significance of scientific investigation of a technology that was dependent on experience in the material process field.

**Answer (Koji Watari)**

As the reviewer indicated, the basic and core research of binder technology is a scientific consideration of a technology that relied on corporate experience, and in the future, this may lower the competitive edge of the Japanese ceramics companies. Therefore, as a research leader, I considered the contents of patent and paper that will be publicized, explained carefully to the companies engaging in joint research, and disclosed some of the research results with their approval.

Scientific investigation of a technology that relied on experience, i.e. understanding the scientific basis of a technology, systematization of a technology, and extraction of the major factors, are extremely important outcomes of a public research institution like AIST, which is a collection of research professionals. Also, one of the roles of AIST is to find how to overcome the "valley of death" in a scientific perspective, and I think we can provide appropriate elemental and alternative technologies by scientific investigation of a technology that was dependent on experience.

Many of the companies that engaged in joint research with us set the ultimate objective as "development of high value-added product and improvement of production efficiency through basic and core research." They became aware of the importance of basic and core research and demanded better research results. I think this is an indication that the companies want to make better products and improve production efficiency by scientifically investigating their know-hows that were dependent on experience. On the other hand, technological know-hows are important assets for the companies, and must be handled with care.

### 6 Technological transfer of innovative material process that requires total change in the manufacturing line

**Comment and question (Nobumitsu Murayama)**

To overcome the economic valley of death that you mentioned, I am certain that it is more efficient if "the technology developed is technology that can be incorporated into the existing process, and the existing manufacturing equipment can be used." However, there is always a possibility of technological transfer of innovative material process that requires total change in the manufacturing line. In case of the latter, one of the ways may be for a public research institute like AIST to have a prototype manufacturing line. Can you comment on this.

**Answer (Koji Watari)**

Many private companies are reluctant to invest newly in their manufacturing line. Considering the importance of the technology and its dissemination, it may be greatly significant for a public research institute like AIST to create a prototype manufacturing equipment for trial manufacturing. However, investment is large. Therefore, before making the new investment, it is necessary to set up a business model including the possibility of alternative technology, procurement of user and cost of maintenance, extraction of key application, and understanding of market trend.

# Development of high-sensitivity molecular adsorption detection sensors

## — Biomolecular detection for highly-developed diagnosis, medication, and medical treatments —

**Makoto Fujimaki** * **and Koichi Awazu**

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High sensitivity sensors for detection of molecules are aspired in various fields of application, particularly in medical technology, pharmacy and environmental sciences. In the present research, we have developed a high-performance molecular detection sensor for diagnosis, medication, and medical treatments that utilizes waveguide modes as basic technology. We successfully obtained sensors with high sensitivity and stability by applying nano-perforation technology, optical simulation and experiments, and an originally developed sensing-plate fabrication process. In this report, the scenario of the present research, elemental technologies and their synthesis for achieving the scenario and the properties of the realized sensors are described. In addition, a rapid progress in sensing performance obtained by a breakthrough is reported.

*Keywords* **:** Biosensor, waveguide modes, optical waveguide, evanescent field, molecular adsorption

## 1 Introduction

One of the important functions expected of medical sensors is the early detection of diseases. With the recent advances in medicine, many substances associated with various diseases have been identified, and the presence and progress of the disease can be determined by detecting these substances. The possibility of curing a disease increases dramatically by early discovery. To find a disease in its early stage, it is necessary to detect these substances even at low concentration. This means that there is a demand for higher sensitivity of the sensor.

Other functions of the sensor include the identification of the cause of the disease and observation of the patient's progress. For example, in case of a cold or food poisoning, it is necessary to immediately identify the virus or bacterium that is causing the symptoms. When the patient is admitted to a hospital and administered some drug, it is important to conduct an on-spot observation to see whether the drug is taking effect. In such situations, the sensors are expected to quickly detect the target substance. In addition to sensitivity, the sensor must also be compact so it can be portable, and be capable of performing without being influenced by the environment in which the measurements are made.

If a high-performance sensor allows early discovery of diseases, early identification, and accurate progress observation with minimal stress, the patient can be expected to recover early. This will reduce physical strain on the patient, as well as reduce the time and cost of medical care. Of course, there are many methods for detecting minute substances, but considering use in a medical care situation, it must be of low cost and the device must not require extensive training to operate. For certain diseases and conditions, sensors that fulfill such requirements have been designed and put to actual use. They include the influenza diagnosis using the immunochromatography method (Tamitest Influenza AB of Roche Diagnostics K.K., QuickVue Rabid SP Influ of DS Pharma Biomedical Co., Ltd.) and pregnancy test using gold colloid chormato-immunosorbent assay (Dotest of Rhoto Pharmaceutical Co., Ltd., Check One Fast of Arax Co., Ltd.).

However, in many cases, effective sensors that can surmount the issues of very low concentration of target substance produced by the disease or difficulty in separation from other substances have not been developed. Much is expected in future developments. With these demands and with objectives of establishing a biosensing technology that enables quick discovery of a disease at its early stage, even at small hospitals, we developed a biological substance sensor that is highly sensitive to certain minute substances, compact so it is portable, and that enables stable measurements not dependent on the measurement environment. Also, one of the major issues was the mixing of various substances that may interfere with the target substances when using human samples such as blood, urine, or saliva. Therefore, we developed a method to prevent the interference caused by these foreign substances.

## 2 Development of molecular adsorption detection sensor

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Figure 1 shows the issues that must be solved in sensor development, performance that can be expected by solving the issues, and merit that can be gained through the performance gained. The sensor must detect the presence of a certain substance (sample) at high sensitivity, stably, and with low noise. For the development of this sensor, we applied the technology of detecting the change in dielectric environment resulting from specific adsorption of an analyte through the change in waveguide mode[Term 1 [1][2]]. The characteristics of this technology and the scenario for achieving higher performance through this development are explained below.

### *2.1 Principles of the EFC-WM sensor and expected performance*

The surface plasmon[Term 2] resonance (SPR) sensor is known as a biosensor that is available on the market mainly for R&D and has extremely similar mechanism to the evanescent-field[Term 3] -coupled waveguide-mode (EFC-WM) sensor that we developed[1]. To help understand the mechanism of the EFC-WM sensor, we shall briefly explain the measurement principle of the SPR sensor that is already available for practical application.

In general, in the SPR sensor, a metal film is deposited onto the glass substrate surface with high refractive index, and a prism made from the same glass is placed on the opposite side of the metal film surface. Usually, Au and Ag are used for the metal film since surface plasmon resonance can be excited in them with visible light. Figure 2(a) shows the optical system frequently used in the SPR sensor. This optical configuration is called the Kretschmann configuration[3]. In the Kretschmann configuration, when the light is incoming from the prism under total reflection condition, the surface plasmon is excited on the metal film surface at a specific incidence angle. This angle of incidence is called the ‘resonance angle’. When the light is incoming at the resonance angle, the incident light combines with the surface plasmon and the intensity of reflected light decreases significantly. Since the surface plasmon is sensitive to the change of permittivity at the metal surface, this resonance angle changes when biomolecules are adsorbed on the surface and the intensity of reflected light changes greatly. The adsorption of biomolecules can be detected by detecting the change of the intensity of the reflected light. To detect only specific molecules, the metal surface is modified with a substance that specifically adsorbs the target molecule.

The sensing plate used in the EFC-WM sensor has a reflective film and a transparent dielectric waveguide on the substrate glass[4][5]. Same optical system as the SPR sensor can be used for measurement. Figure 2(b) shows the optical configuration of the EFC-WM sensor using the Kretschmann configuration. When light is incoming via the prism as in the SPR sensor, coupling occurs with waveguide mode that propagates the waveguide and the incident light through the evanescent field generated at the reflected film at a certain angle of incidence (resonance angle). When light is incoming around this specific angle, the intensity of reflected light decreases significantly. Since the waveguide mode is sensitive to the surface condition as in the SPR mode, when biomolecules adsorb onto the waveguide surface, the aforementioned resonance angle changes and the intensity of reflected light changes. The EFC-WM sensor uses this intensity change of reflected light to detect the molecule adsorption.

SPR sensor is a label-free detection method where the sample is not tagged with a labeling substance, and its greatest characteristic is having high sensitivity that enables sample detection without labeling. Therefore, the complex procedure of labeling is unnecessary, and detection can be carried out easily. Also, since the sample is not labeled, the properties and features of the original sample are not lost. Therefore, the behavior of the target molecule, for example, in what condition the specific molecules are adsorbed can be observed accurately. However, in terms of sensitivity, it is said to be double to triple-digit inferior to the highly sensitive detection method using labeling substance, such as the enzyme-linked immunosorbent assay (ELISA)[6] (however, direct comparison is difficult since sensitively is greatly influenced by various factors such as the type and size of the target molecule, capture method of the target molecule, measurement environment such as whether it is in blood or in buffer solution, or presence of foreign substance). The EFC-WM sensor is a label-free detection method as in the SPR sensor. Until now, the EFC-WM sensor fell behind the SPR sensor as a molecule adsorption sensor even with

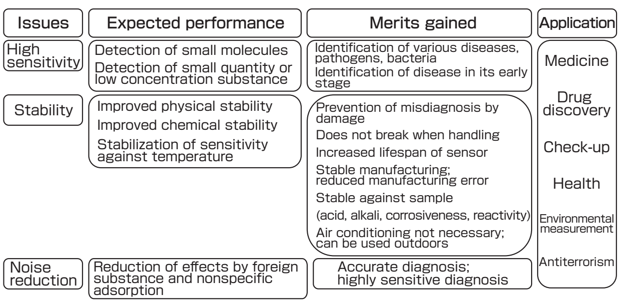


**Fig. 1 Issues, expected performances, merits gained, and fields of application of the sensor.**

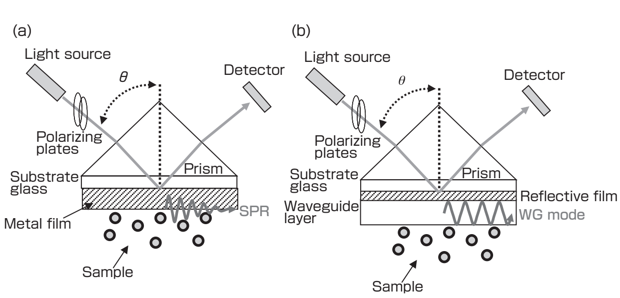


**Fig. 2 (a) Optical configuration used in the SPR sensor. (b) Optical configuration used in the EFC-WM sensor.**

its advantages of having no limitations to the reflective substance and of being able to use both s and p waves. The greatest reason is because the absolute value of change of resonance angle at the time of molecule adsorption is small compared to the SPR sensor. However, the EFC-WM sensor has a sharp band of resonance angle, and therefore can sense large changes in reflectance property at a small angle change. Also, compared to the SPR sensor, the preparation of the EFC-WM sensor is complex since the waveguide layer must be created. However, we thought the key to increasing sensitivity was devising this waveguide layer. If the sensitivity of the EFC-WM sensor can be raised double to triple digits by using these features, it will have sufficient sensitivity as a molecule adsorption sensor.

Other than sensitivity, stability in the environment in which the sensor is used, particularly in room temperature, is required. Highly sensitive detection method is affected readily by the environment because of its high sensitivity. In general, biomolecules are dissolved in water in some form such as in blood, urine, or buffer solution. Since the permittivity of water changes according to temperature, the sensor that detects the change in permittivity as in the SPR or EFC-WM sensor is extremely unstable against temperature. In developing a highly sensitive sensor, solving the problem of temperature stability is a major issue.

When developing the EFC-WM sensor as an effective sensing method usable in the medical field, there are various requirements in its performance. However, unlike the SPR sensor which can be used only with material that produces SPR, the EFC-WM sensor has higher degree of freedom where any material, as long as it reflects light, can be used as the reflective film, and any material can be used as the waveguide layer, as long as it is a transparent film. There are several areas that can be devised to increase sensitivity and performance. Therefore, we drew the following scenario to increase the sensor performance.

### 2.2 Scenario to increase the performance of the EFC-WM sensor

First we looked at the structure of the waveguide. Figure 3 shows the simulation result of the electric field profile in the waveguide when a waveguide mode is excited therein. Here the incident light was s-polarized light with wavelength of 632.8 nm, the refractive index of substrate glass was 1.769, the reflective film was Au with thickness of 40 nm, and the waveguide layer was silica glass with thickness of 500 nm. The wavelength surface was immersed in water. The incident light was incoming from the left side of the figure. As shown in the figure, the electric field was strong inside the waveguide, while it became weak at the surface. If the molecules could be guided to the area with a strong electric field, they could be detected sensitively. Therefore, we considered forming pores in the waveguide layer and guiding the sample into the waveguide[7][8]. Pore formation will increase the surface area of the waveguide and will increase the number of adsorbed samples. This is also expected to contribute to higher sensitivity. The size of the pore should be sufficiently smaller than the wavelength of the incident light to prevent scattering. Therefore, when visible light is used, the diameter of the pore should be several tens to 100 nm. Since greater increase in surface area can be obtained by deepening the pores, the pores should be deep so they penetrate the waveguide layer. As a method for forming nanopores with such small diameters and high aspect ratio, we used selective etching by hydrofluoric acid (HF) vapor of latent tracks formed by irradiation with swift heavy ions[9]. Using this technology, it was possible to form nanopores with diameters of several 10 nm and aspect ratio of 40 or more[8].

Next we reviewed the materials for the sensing plate, particularly the reflective film[5]. In the conventional EFC-WM sensor, there are many reports of using noble metals such as Au and Ag for the reflective film[10][11]. High sensitivity has been obtained by using such materials. However, these metals have extremely poor adhesion with the glass substrate and plastic substrate used in the EFC-WM sensor or the dielectric layer used as waveguide layer, and have problems of easily peeling away. Therefore, it is necessary to introduce an adhesive layer to maintain high reliability for practical use, but addition of an adhesive layer produces problems of reduced sensor sensitivity, increased cost, and increased manufacturing error. Using optical simulation, we investigated what kind of optical properties a material should have for the EFC-WM sensor, and conducted a comparison of sensor performance by fabricating various sensing plates.

Based on the results obtained by the above-mentioned development, we found the silica glass created by thermal oxidation of Si was appropriate as waveguide for nanopore formation, and Si was appropriate as a reflective film. Based

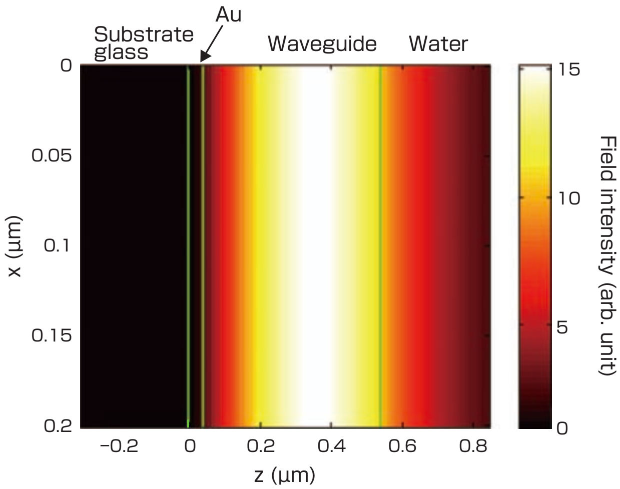


**Fig. 3 Simulation result of the electric field profile in a waveguide in which a waveguide mode is excited.**

on these results, we used a substrate called silicon-on-quarts (SOQ) which comprises of single-crystalline Si layer on silica glass substrate[12] to fabricate the sensing plate, and devised a method for fabricating the waveguide by oxidizing the single-crystalline Si layer[13]. We called the plate fabricated with this method monolithic sensing plate. In addition, we were able to achieve dramatic high sensitivity using the property in which the monolithic sensing plate sensitively detects the optical absorption of an adsorbent substance. This will be explained in chapter 4. Figure 4 shows the series of R&D.

## 3 Results of the development

The results obtained in this research are presented as follows.

### *3.1 Achievement of high sensitivity through nanopore formation technology*

As mentioned above, we used the selective etching by HF vapor of latent tracks formed by irradiation with swift heavy ions for formation of nanopores in the waveguide. For ion irradiation, the 12 UD Pelletron tandem accelerator at the University of Tsukuba was used. The ion irradiation method is shown in Fig. 5. The Au ions accelerated at 150 MeV were irradiated onto a Al foil with thickness of 0.8 µm. The ions were scattered by the foil, and a uniform ion beam with low current density was formed. The current density of the ion beam was set to be 100 pA/cm$^2$ on the sensing plate. The reason for using low current density was to accurately control ion fluence, since the ion fluence was extremely low at the order of $10^9$ to $10^{10}$ per 1 cm$^2$. For the vapor etching, a 20 % HF solution was used. An irradiated sensing plate was placed in a container of HF solution so it would not become immersed in HF solution, yet the sample would be exposed to HF vapor.

Figure 6 shows the SEM photographs of the surface and cross section of a thermally grown $SiO_2$ film with thickness of 2.0 µm which was irradiated with Au ion and etched by HF vapor for 60 min. The temperature of HF solution during etching was 21.5 ºC. The figure shows that the formed pores penetrate the $SiO_2$ film. The thickness of the $SiO_2$ film after etching was 1.9 µm. That is, the aspect ratio of the pore was 42. Using this method, nanopores with diameters in several 10 nm order could be formed accurately.

Sensitivity improvement was attempted using this method, by forming nanopores in the waveguide layer of the sensing plate with silica glass waveguide. A glass (OHARA, S-LAH66, refractive index of 1.76924 at 632.8 nm) was used as a substrate. The glass was cut and polished into a 20 mm × 20 mm piece with thickness of 1 mm. Au was used as the reflective film. Cr layers were used as adhesive layers between the Au film and the glass substrate and between the Au film and the waveguide layer. These films were formed by the vacuum deposition method. The thickness of the Au film was 53 nm, and that of the Cr layer was 0.8 nm. The waveguide layer was formed by RF magnetron sputtering using a silica glass plate as a sputtering target. The thickness of the waveguide was 550 nm. After the sputtering, a thermal annealing at 600 °C for 24 hrs was applied to the substrate in order to densify the formed waveguide layer. The nanopores were formed on the waveguide surface using the aforementioned method. The Au ion fluence was 5.0 × $10^9$ cm$^{-2}$, and HF vapor etching was done for 30 min. The temperature of HF solution was 19.0 ºC. Figure 7 shows the SEM photographs of the surface and cross section of the plate after etching. As shown in the figure, nanopores of diameters of about 30 nm can be observed. It can also be seen that the pores penetrated to the Au layer. The thickness of the waveguide layer after the etching was 400 nm.

A right triangle prism made of S-LAH66 was optically attached to the fabricated plate using matching oil, and the measurement of incident angle dependence of reflectance was conducted using the Kretschmann configuration. The light source was s-polarized He-Ne laser (632.8 nm). A cuvette was placed on the waveguide to support liquid samples. The detection sensitivity was assessed by modifying the waveguide surface with biotynil group and by observing the change in reflectance by specific adsorption of streptavidin[Term 4] on biotin[Term 5]. Streptavidin was dissolved

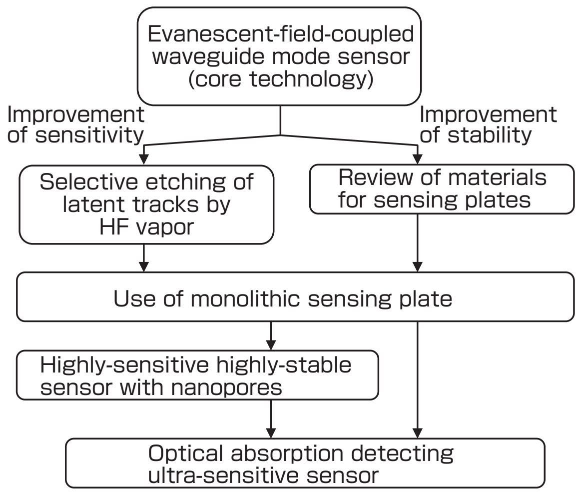


**Fig. 4 Synthesis of R&D.**

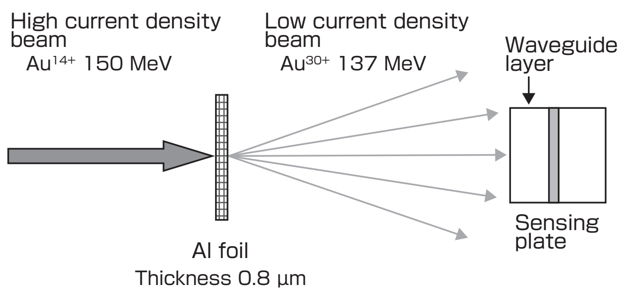


**Fig. 5 Ion irradiation method used in nanopore formation.**

in PBS buffer, and the concentration was set to 100 nM. Figure 8 shows the measurement results. Figures 8(a) and 8(b) show the results of measurement using the sensing plates with nanopores and without nanopores, respectively. White dots show the reflectance property measured with filling the cuvette with PBS buffer without streptavidin, and black dots show the reflectance property after the adsorption of streptavidin on biotin when the cuvette was filled with PBS buffer containing streptavidin. In both cases, the dip caused by excitation of waveguide mode was observed, and it could be seen that the peak position shifted by adsorption of streptavidin. The amount of shift of the peak by the adsorption of streptavidin in the substrate with nanopores was 0.38°. On the other hand, the peak shift was 0.06° in the substrate without pores. It was shown that dramatic improvement in sensitivity could be obtained by forming pores. However, as shown in Fig. 8(a), the width of the peak widened and the depth decreased by the formation of nanopores. This is thought to be due to the roughening of the waveguide surface by the etching. In fact, as shown in Fig. 7, particle-like roughness could be observed on the waveguide surface after the etching. This problem was greatly improved by the development of monolithic sensing plate as explained in section 3.3.

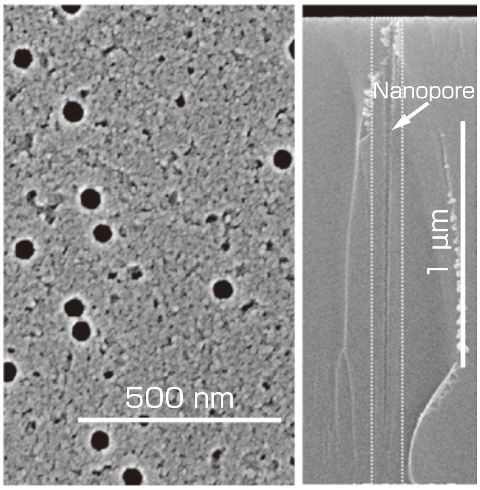


**Fig. 6 SEM photographs of the surface (left) and cross section (right) of nanopores formed on a thermally-grown $SiO_2$ film.**

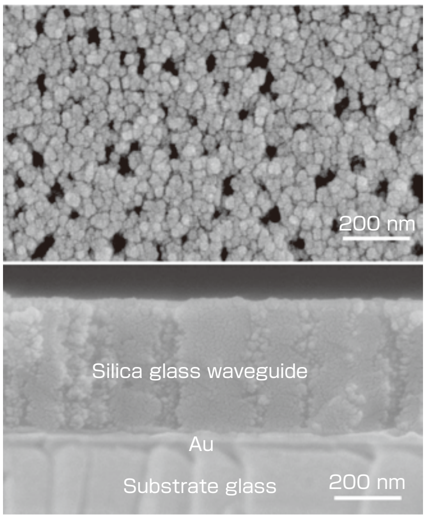


**Fig. 7 SEM photographs of the surface (top) and cross section (bottom) of the sensing plate with nanopores.**

### *3.2 Material of the reflective film*

The sensitivity of EFC-WM sensor is greatly dependent on the optical property of the reflective film. Therefore, we conducted simulations to project sensor sensitivity for various reflective film materials, and also actually fabricated several types of sensors for demonstration.

Figures 9(a), 9(b), and 9(c) show the results of the calculation of reflectance property when Au, W, and Si are used as reflective films, respectively. The refractive index of the substrate used for calculation was 1.769; the thickness of the reflective films were 40, 20, and 30 nm, respectively; and the refractive index and thickness of the waveguide layer were 1.485 and 500 nm. The incident light was s-polarized monochromatic light with wavelength of 632.8 nm. The waveguide surface was assumed to be immersed in water. Although the shape of the reflectance property differs by reflective film materials, peaks are observed in the reflectance properties in all cases. The shape of the reflectance property, that is, whether the waveform peaks upwards or downwards, is determined by the intensity of the background reflected light and the condition of resonance. The positions of these peaks shift due to substance adsorption to the waveguide surface.

To learn what kind of optical property a material should have

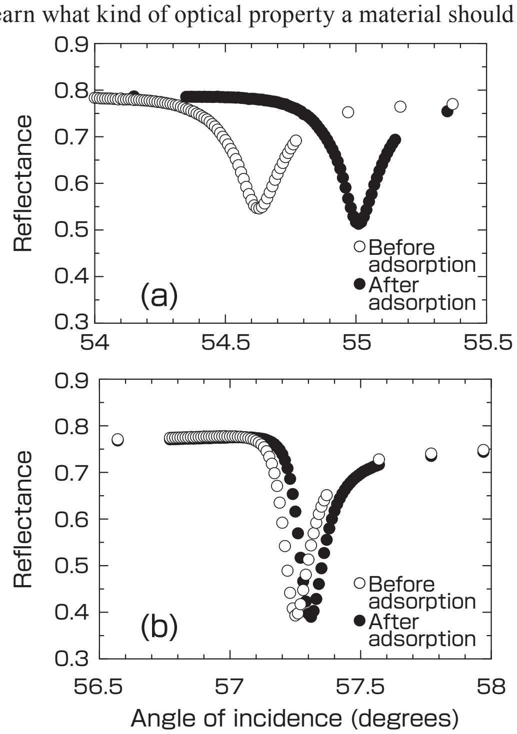


**Fig. 8 Reflectance property before and after adsorption of streptavidin on biotin observed using the sensing plate with nanopores (a) and without nanopores (b).**

as a reflective film, we calculated the relationship between the complex refractive index $n + ki$ of the reflective film material and the detection sensitivity. The calculation results are shown in Fig. 10. The figure shows the relationships between the maximum change in reflectance obtained when substance with thickness of 5 nm and refractive index of 1.45 was adsorbed to the waveguide surface, and the $n$ and $k$ of the reflective film. Here, the wavelength of incident light was 632.8 nm, and the refractive index of the substrate glass and prism was 1.769. Also, the thickness and refractive index of the waveguide was 350 nm and 1.485 respectively. The optimal values for incident angle of light, direction of polarization, and thickness of the reflective film were calculated by simulation. The material with a complex refractive index with a large change in reflectance can be the considered material suitable as the reflective film material. In the figure, the complex refractive indices of some materials are shown as black dots. From the calculation result, Au, Ag, and Cu, which are materials that have been conventionally used, showed high sensitivity. It could also be seen that Si and Ge, which are materials with large $n$ and small $k$, also showed good sensitivity.

Sensing plates were fabricated using some of the materials listed in Fig. 10, and observation was done using biotin-streptavidin adsorption as in the previous experiment. Streptavidin had a diameter of about 5 nm and a refractive index of 1.45, so similar results could be expected as previous calculations. Table 1 shows the reflective film materials used in the experiment, the maximum reflectance change $|\Delta R_{ex}|$ due to the streptavidin adsorption for each reflective film material, and the maximum reflectance change $|\Delta R_{cal}|$ obtained by the above calculation. When Au was used as the reflective film, the Au layer peeled off after forming the sensing plate without the adhesive layer, and no experimental values could be obtained. The highest value of $|\Delta R_{ex}|$ obtained in the experiment was 0.505 when Cu was used. However, Cu, although not as bad as Au, had poor adhesiveness, and some peeling occurred. When using a Au reflective film with Cr adhesive layers with a thickness of 0.8 nm, $|\Delta R_{ex}|$ was 0.263. This was a relatively high value among the experimental values obtained, but the sensitivity was way lower than the calculated value $|\Delta R_{cal}| = 0.719$ when Au only was used as the reflective film. The next highest value

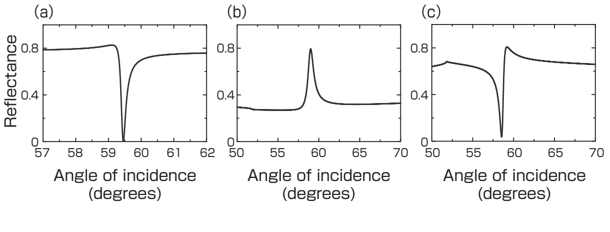


**Fig. 9 Calculation results of incident angle dependency of reflectance when Au (a), W (b), and Si (c) are used as reflective films. The thicknesses of reflective films are 40, 20, and 30 nm, respectively.**

**Table 1 Relationship among the reflective materials used for the sensing plate fabrication, the values of $|\Delta R_{ex}|$, and the values of $|\Delta R_{cal}|$.**

| Reflective film material | $\|\Delta R_{ex}\|$ | $\|\Delta R_{cal}\|$ |
|---|---|---|
| Au | NA | 0.719 |
| Cr/Au/Cr | 0.263 | 0.380 |
| Cu | 0.505 | 0.683 |
| Cr | 0.064 | 0.101 |
| W | 0.070 | 0.098 |
| a-Si | 0.234 | 0.271 |
| Ge | 0.139 | 0.405 |

was 0.234 when a-Si was used. Large reflectance change was expected in the calculation for Ge, but the actual sensitivity was about one-third of the calculated value. This is thought to be because the calculated value was obtained using the complex permittivity of single-crystalline Ge, while in the experiment, Ge layer was deposited using the sputtering method and the formed Ge layer was amorphous.

In this research, it was found that high sensitivity could be obtained in conventionally used materials such as Au, Ag, and Cu, but there was a problem in their stability. Although stability issue could be solved to some degree by introducing the adhesive layers, the sensitivity with the adhesive layers was the same as when Si was used as the reflective film. Also since Si has extremely high adhesiveness with glass materials, Si was suitable as the reflective film material for securing both stability and sensitivity.

### *3.3 Monolithic sensing plate*

From the above approach, it was found that our nanopore formation technology was effective in increasing sensitivity, and the Si reflective film was effective in both sensitivity and durability. However, as shown in the SEM photographs of Fig. 7, the surface of the waveguide layer formed by the sputtering method became roughened by the nanopore formation and the reflectance property deteriorated, and as a result, sufficient improvement of sensitivity could not be

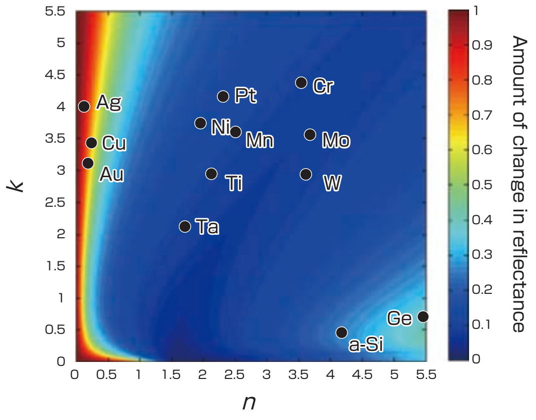


**Fig.10 Calculation result of relationship between the complex refractive index of the reflective film material and detection sensitivity. The black dots in the graph show the complex refractive index of some materials that may be used as the reflective film.**

obtained. Since almost no surface roughening occurred in the thermally grown $SiO_2$ film as shown in Fig. 6, we considered the thermal oxidation process of Si in the waveguide layer formation. When Si is used as the reflective film, and if the Si layer is formed thick and the waveguide is formed by thermal oxidation of the surface, we can fabricate a sensing plate with a thermally grown $SiO_2$ film as a waveguide. In this case, it is necessary to use a glass substrate that can endure high-temperature treatment.

To realize this idea, we considered using the SOQ substrate for sensing plate formation. Since thick oxidized layer was necessary for waveguide formation, we incorporated the water vapor oxidation method[14] where the speed of oxidizing the Si layer of the SOQ substrate was fast, and we fabricated a plate having a single-crystalline Si reflective layer and a $SiO_2$ waveguide layer on a silica glass substrate. The fabrication process of the sensing plate is shown in Fig. 11. The thickness of the single-crystalline Si layer before the thermal oxidation was 440 nm. When this layer was oxidized for 1 hr in oxygen atmosphere containing water vapor at 1000 ºC, the Si layer surface was oxidized and a waveguide layer with thickness of 482 nm was formed. The remaining Si layer of a thickness of 220 nm would function as the reflective film. We named this sensing plate 'monolithic sensing plate'.

The fabricated sensing plate was set in the optical setup as shown in Fig. 12 to conduct molecule detection tests. Figures 13(a) and 13(b) show the changes in reflectance properties

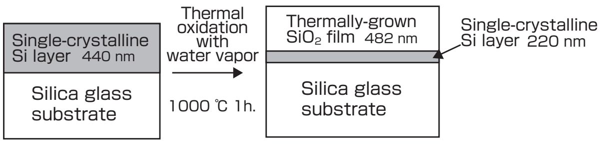


**Fig.11 Explanation of the process for fabricating the sensing plate by thermal oxidization of the single-crystalline Si layer of the SOQ substrate.**

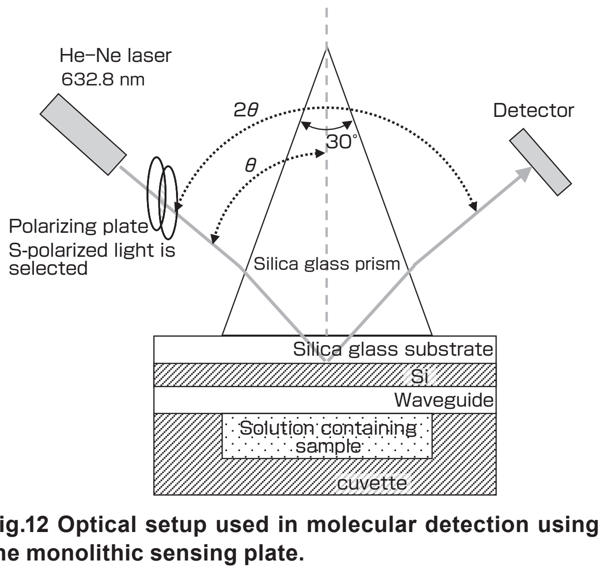


**Fig.12 Optical setup used in molecular detection using the monolithic sensing plate.**

when biotin-streptavidin adsorption was detected using the monolithic sensing plates with nanopores and without nanopores, respectively. The incident light was s-polarized light of He-Ne laser (632.8 nm wavelength). The diameter of the nanopores was about 50 nm, and there were $5 \times 10^9$ pores/cm$^2$. The white dots in the figures show the incident angle dependency of the reflected light intensity before adsorption, while the black dots show the intensity after adsorption. It can be seen that the amount of shift of peak position increased about 10 times by the nanopore formation. By the nanopore formation, the width of the dip increased slightly while the depth hardly changed. This is due to the reduction of damage during etching.

To ensure the improvement of sensitivity by nanopore formation theoretically, we conducted a simulation using the Fresnel equation. Figures 14(a), 14(b), and 14(c) are conceptual diagrams used in the simulation. Figure 14(a) shows a conventional SPR sensor, 14(b) shows an EFC-WM sensor using a monolithic plate without nanopores, and 14(c) shows an EFC-WM sensor using monolithic plate with nanopores. The prism of the SPR sensor was a right triangle prism with a refractive index of 1.769 and the sensing plate was assumed to have a gold film with a thickness of 51 nm formed on a substrate with a refractive index of 1.769. The prism of the EFC-WM was an isosceles triangle prism having a vertex angle of 30° with refractive index of 1.456. The substrate of the sensing plate was silica glass (n = 1.456), the thickness of the Si reflective layer was 220 nm, and the thickness of the waveguide layer was 450 nm. As in the experiment condition, the diameter and the number of nanopores were set to be 50 nm and $5 \times 10^9$ pores/cm$^2$, respectively. As an imitation of the adsorption of streptavidin,

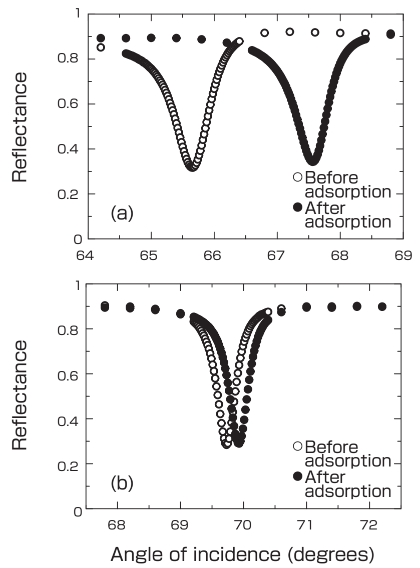


**Fig.13 Reflectance property before and after adsorption of streptavidin on biotin observed using the monolithic sensing plate with nanopores (a) and without nanopores (b). The concentration of streptavidin was 1.5 μM.**

it was assumed that a layer (light pink layers in Fig. 14) with a thickness of 5 nm and a refractive index of 1.45 was formed on the detection surface. Figures 14(d), 14(e), and 14(f) show the calculation results of the reflectance property before and after the molecule adsorption shown in Figs. 14(a), 14(b), and 14(c), respectively. In these sensors, the sensitivity is higher if the full-width at half maximum (W) of the dip is small and the shift of the peak position (S) is large. Namely, the sensitivity is higher if S/W values is higher. Table 2 shows the values of change in reflectance ($\Delta R$), S, W, and S/W caused by the molecule adsorption in the experiment and in the simulation. In case of the EFC-WM sensor without nanopores, almost all the values obtained in the experiment agree well with the values obtained in the simulation. In case of the EFC-WM sensor with nanopores, the S values were greater in the experiment value. To obtain the shift of S = 1.91 obtained in the experiment for calculation, the diameter and the number of the nanopores had to be set at 65 nm and 6 × $10^9$ pores/$cm^2$, respectively. This means that the diameter and the number of the nanopores formed in the experiment were slightly larger than those in the fabrication setting. As shown in Table 2, the value of S/W obtained in the experiment was 2.98 with nanopores, and 0.514 without nanopores. These values were both larger than the theoretical S/W value of the SPR sensor, and it was about 4 times greater without nanopores and about 25 times greater with nanopores.

Monolithic sensing plate is excellent in stability. The monolithic plate is physically stable because the substrate, the reflective film, and the waveguide layer are atomically bonded to each other. Also, since it is composed only of Si and $SiO_2$, it is chemically stable.

**Table 2 Comparison of sensitivity of SPR and EFC-WM sensors. Sim. is calculated values, and Ex. is experimental values.**

| | $\Delta R$ | S | W | S/W |
|---|---|---|---|---|
| SPR sensor Sim. | 0.15 | 1.00° | 8.4° | 0.12 |
| EFC-WM sensor without nanopores Ex. | 0.38 | 0.19° | 0.37° | 0.51 |
| EFC-WM sensor without nanopores Sim. | 0.40 | 0.17° | 0.34° | 0.49 |
| EFC-WM sensor with nanopores Ex. | 0.60 | 1.91° | 0.64° | 2.98 |
| EFC-WM sensor with nanopores Sim. | 0.63 | 0.72° | 0.34° | 2.12 |

## 4 Breakthrough

To apply this sensor to the actual detection of substance originating from various diseases, we conducted a hospital survey to see which substances should be targeted. In this survey, we realized that many sensors used at hospitals for similar purposes detect disease substance using color density. The monolithic sensing plate is sensitive to changes in refractive index as mentioned above, and it is even more sensitive to changes in optical absorption, or density of "color." Therefore, we redesigned the sensor so it can detect changes in "color" more sensitively. The dip seen in the reflectance property of the EFC-WM sensor changes in the angle direction or along the horizontal axis direction against the change in refractive index, while for the change in optical absorption, it changes in reflectance intensity or vertical axis direction. Therefore, we changed the structure of the

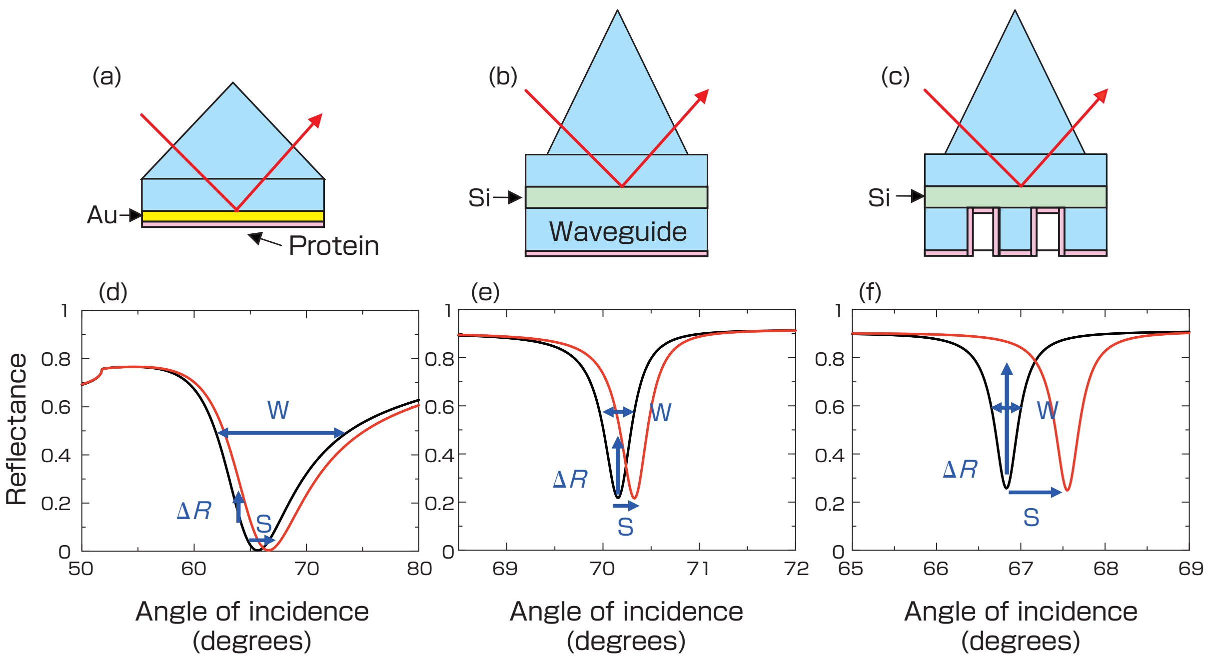


**Fig.14 Conceptual diagram of molecule adsorption in the SPR sensor (a), the EFC-WM sensor without nanopores (b), and the EFC-WM sensor with nanopores (c). (d), (e), and (f) show the calculation results of reflectance property before and after the molecule adsorption in (a), (b), and (c), respectively.**

sensing plate so the change in vertical direction would appear more clearly. Specifically, we reduced the thickness of the Si reflective layer.

The fabricated sensing plate had a single-crystalline Si layer of a thickness of about 35 nm and a thermally grown $SiO_2$ waveguide layer of a thickness of about 520 nm on a silica glass substrate. After modifying the waveguide surface with biotin, this plate was set in the optical setup shown in Fig. 12 to conduct the detection test using immunogold conjugate as a sample. The immunogold conjugate consists of 4 to 5 streptoavidins attached to a Au nanoparticle with diameters of 20 nm. The Au nanoparticle absorbs the incident light. We used Tris-buffered saline containing 10 pM of this sample. Figure 15 shows the reflectance property before and after the introduction of the sample. White dots show the reflectance property before introduction and black dots show the reflectance property 20 hrs after introduction. Reduction in reflectance of 0.046 was observed, indicating that the sensor successfully detected the sample at such low concentration.

Next, to examine improvement in sensitivity by using dyes, we detected the capture of streptavidin by biotin after dying the streptavidin with a blue dye, Coomassie Brilliant Blue G-250. This dye has an optical absorption band at around 600 nm. The sensing plate and the optical setup used were the same as the previous experiment. The detection test was done using a PBS buffer containing 100 pM of the dyed streptavidin. Figure 16 shows the reflectance property before and after introduction of the sample. White dots show the reflectance property before introduction, and black dots show the reflectance 1 hr after introduction. In this case also, sufficiently large change in reflectance was observed. This detection sensitivity was about three orders of magnitude higher than the sensitivity of a conventional EFC-WM sensor.

In the above two examples, change in the dip position accompanying the change in refractive index was thought to have occurred by the adsorption of the samples, but the amount of molecule adsorption was small in both cases, and the change in dip position could not be confirmed clearly. In this type of sensor, further improvement of sensitivity could be expected by nanopore formation. This shall be our future subject of study.

In this method, when settings are done to measure only the change in depth of the dip, the detection sensitivity will not be affected by temperature change. This is because the change in refractive index of water by temperature difference causes a change only in the position of the dip, and does not accompany any change in the depth of the dip. Also, since detection is achieved by capturing the optical absorption of substances, there is almost no effect on reflectance property even if a substance without optical absorption is adsorbed. That is, even when some foreign substance adheres to the detection surface, as long as the substance does not absorb the incident light, it will not be detected. Therefore, this method is scarcely affected by adhesion of foreign substances. As described, the present method has several advantages over the conventional method.

## 5 Composition of the research

The flow of the development is summarized in Fig. 17. In the research for increasing the performance of the sensor, we used a synthesis method called strategic selection[15]. First, to increase the sensitivity of the EFC-WM sensor, which is the core technology, based on simulation, we selected nanoprocessing to the waveguide layer. While we were able to improve the sensitivity by conducting the nanoprocessing, new problems arose in the physical stability of the sensor and the evenness of the processed surface. To solve these problems, we returned to material selection, and selected reflective film materials from a different perspective, that is, we set adhesiveness and processing capabilities as well as sensitivity as new standards of selection. We found that

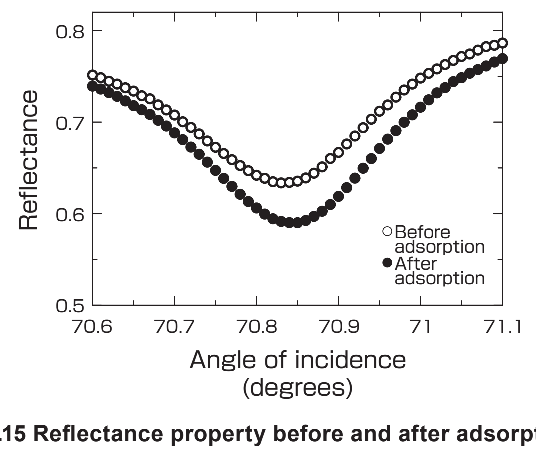


**Fig.15 Reflectance property before and after adsorption of streptavidin with gold nanoparticles (immunogold conjugate, concentration 10 pM) on biotin, observed using optical absorption detecting monolithic sensing plate.**

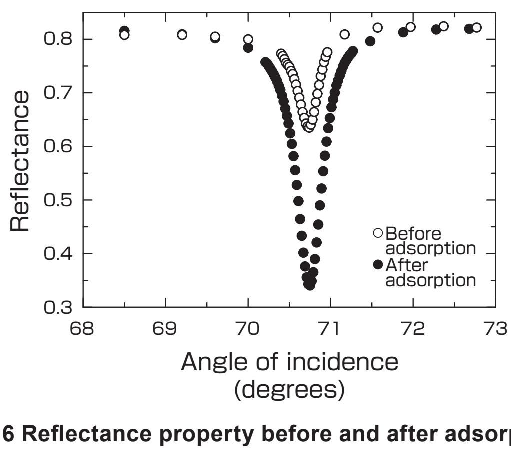


**Fig.16 Reflectance property before and after adsorption of streptavidin dyed with Coomassie Brilliant Blue G-250 (concentration 100 pM) on biotin, observed using optical absorption detecting monolithic sensing plate.**

Si was suitable as a reflective film, and devised a method for forming the waveguide layer by thermal oxidation. Single-crystalline Si is suitable to obtain a uniform thermally grown $SiO_2$ layer, which is scarcely damaged by the nanoprocessing. Therefore, we decided to use the SOQ substrate with a single-crystalline Si layer on a silica glass substrate. By forming the waveguide by thermal oxidation of the Si layer, we were able to develop a high-performance sensor as described above. By strategically combining several elemental technologies, we were able to obtain an integrated technology in the form of a high-performance sensor.

## 6 Future issues

There are two major issues in realizing the sensor. One is to demonstrate its function by detecting a target substance in actual measurement environment, that is, using samples of human origin such as blood and saliva that contain various foreign substances. Here, "selectivity" is important. The primary issue is to obtain high selectivity where other substances are separated from the target substance accurately. Therefore, to realize the actual outcome, it is important to develop a substance that can specifically capture a target substance originating from a particular disease. Also, we would like to aim for high selectivity by using the detection method using color based on what we learned through this study and by developing dyes that can specifically colorize target samples. The second issue is production costs. Since it is for medical use, it is desirable to keep the cost of the sensing plate to about 100 yen at most. We hope this can be achieved by incorporating the integration technology and mass-producing the product.

## 7 Conclusion

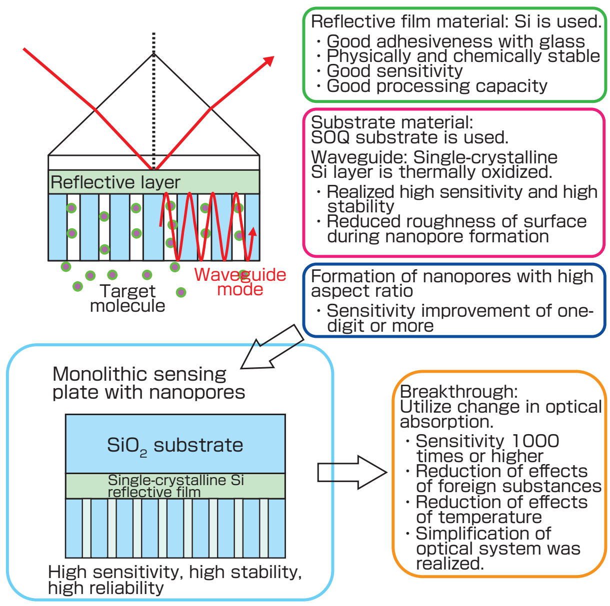


**Fig.17 Flow of the R&D.**

Through this sensor development, we were able to obtain detection sensitivity that can sufficiently meet the demand of practical use. We were also able to show the possibility of reducing the effects of foreign substances and temperature change that were major issues in the conventional sensors. The developed sensing plate has high physical and chemical stability. Moreover, though it was not mentioned in the paper, by using the $SiO_2$ waveguide, it is possible to use silane coupling for surface modification in molecule detection. Silane coupling is a very strong, simple, and low-cost surface modification method. Also, our device is suitable for downsizing. Currently, we are working on a desktop device about the size of a college dictionary. We obtained good results for the factors assumed at the start of the development. In the future, we would like to cooperate with the researchers of fields that require such sensors, and promote collaboration with medical institutions and researchers of different fields such as chemistry and biosciences. We would also like to continue our research to realize a sensor that can serve the medical field.

## Acknowledgement

We express our gratitude to Nobuko Fukuda, researcher of Biophotonics Group, Photonics Research Institute, Professor Yoshimichi Ohki and the students of the Ohki Lab, Faculty of Science and Engineering, Waseda University, who helped us with the waveguide mode measurement experiment; Dr. Tetsuro Komatsubara of the University of Tsukuba Tandem Accelerator Complex, who helped us with the ion irradiation experiment; Xiaomin Wang of Center for Applied Near-Field Optics Research and Dr. Carsten Rockstuhl of Friedrich Schiller University Jena, who helped us with the simulation; and all the people involved. The authors would also like to thank the Advanced Functional Materials Research Center of Shin-Etsu Chemical Co., Ltd. for supplying the SOQ substrate.

## Terminology

Term 1. Waveguide mode: When light is transmitted by total reflection within a limited medium, the angles of reflection are limited and become intermittent. The distribution of light intensity within the medium forms "nodes" where the light intensity is mutually strengthened and weakened by resonance. The state where the light is propagating while maintaining such light intensity distribution is called the waveguide mode. One example is the propagation mode in an optical fiber.

Term 2. Surface plasmon: Plasmon is a phenomenon in which the free electrons in metal vibrate as a group. In general, light does not couple with plasmon, but an evanescent wave can couple with surface plasmon. That means the surface plasmon can be excited by the evanescent field.

Term 3. Evanescent field: When light is reflected, it penetrates into the medium that is reflecting the light. The electromagnetic field that penetrates the medium is called the evanescent field. Under total reflection condition, light penetrates into the medium with low refractive index to about one wavelength.

Term 4. Streptavidin: A glycoprotein with molecular weight of about 60,000. It has extremely high affinity to biotin, and the biotin-streptavidin adsorption reaction is used to bind various biomolecules and nanoparticles.

Term 5. Biotin: Molecular weight 244.31, molecular equation $C_{10}H_{16}N_2O_3S$. It is also called vitamin B7 or vitamin H.

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## Author


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Completed the doctoral course at Waseda University in 1998. Doctor (Engineering). Engaged in research of optical communication devices at Waseda University and Montreal University in the Research Fellowships of the Japan Society for the Promotion of Science for Young Scientist. Engaged in development of power electronics devises and optical communication elements at the Electrotechnical Laboratory as Domestic Research Fellow, Japan Science and Technology Corpration. After serving as an associate professor of Waseda University, joined AIST in 2004. Works on the development of biosensing technology using near-field optics. Appointed director of AIST Technology Transfer Venture, and works to commercialize the technology developed at AIST. In this paper, mainly worked on the optical design and integrated the overall concept.

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Completed the doctoral course at the Tokyo Institute of Technology in 1991. Doctor (Engineering). Joined the Electrotechnical Laboratory in 1991, and engaged in research of accelerator application engineering. Visiting researcher at the Montreal University from 1996 to 1998. Chief researcher at the New Energy and Industrial Technology Development Organization from 2001 to 2002. Visiting professor at the Institute for Molecular Science from 2002 to 2004. Team leader of the Center for Applied Near-Field Optics Research from 2003. Visiting professor at the Faculty of Engineering, The University of Tokyo from 2005. Engages in research of nanophotonics, as well as in fused discipline of medicine and beam application. In this paper, investigated nanopore formation technology and waveguide formation technology.


## Discussion with Reviewers

### 1 R&D scenario

**Question (Naoto Kobayashi, AIST Special Advisor)**

It is clear that we need the development of ultra-sensitive molecule sensors. What effects that were unseen before can we expect when the results are achieved in this R&D? Is it merely that we get higher sensitivity, more stability, and easier to use sensors compared to conventional ones? If those are the results, what differences do increased sensitivity and stability make? Please explain those points and also describe the R&D scenario leading up to this.

**Answer (Makoto Fujimaki)**

In sensor development, improvement of sensitivity and stability is number one. Also, other important points include accurate identification of the sample or low-noise detection.

Figure 1 is a summary by functions, “high sensitivity,” “high stability,” and “low noise.” Specific issues, merits obtained by solving each issue, and final target of application are summarized. This figure was inserted at the beginning of chapter 2. Also, the research scenario was shown as a diagram in Fig. 4, and added to the end of section 2.2.

## 2 Summary of elemental technologies

**Question (Naoto Kobayashi)**

I understood that the main focus of the development of this paper was to improve sensitivity of the “evanescent-field-coupled waveguide-mode (EFC-WM) sensor” that has been already developed by forming pores with high aspect ratio in the waveguide so the number of molecules adsorbed to the waveguide surface would be increased and by measuring the change in reflectance due to the change in the waveguide mode by the adsorption, to improve the stability by the development of the monolithic sensing plate, and to further improve the sensitivity by detecting optical absorption of samples.

Even though an EFC-WM sensor has more advantages than a SPR sensor in that there is no limitation on reflective substance and that both s and p waves can be used, why wasn’t it put to practical use?

**Answer (Makoto Fujimaki)**

The principle of the EFC-WM sensor has been known for a long time. The greatest reason it fell behind the SPR sensor for measuring molecular adsorption is because the absolute value of changes in resonance angle caused by molecular adsorption is smaller compared to the SPR sensor. Also, it has the disadvantage of requiring complex maneuvers to form the waveguide layer. I added these points in the latter half of section 2.1.

**Question (Naoto Kobayashi)**

I understood that one of the major contributions of the authors is to improve the sensitivity by making nano-sized pores with high aspect ratio. In this paper, it is described that the sensitivity is improved because the nanopores with high aspect ratio greatly increases the surface area to which the sample substance can be adsorbed, and because the sample substance is distributed within the waveguide in which the electric field is strongly confined. However, theoretical discussion using calculation and simulation is lacking. I recommend you include some quantitative explanation including the data for dependence of sensitivity on the density of pores.

**Answer (Makoto Fujimaki)**

To theoretically check the improvement of sensitivity by the nanopore formation, we conducted simulation using the Fresnel equation, and compared the results against the experimental values. In this sensor, sensitivity is higher when the full width at half maximum (W) of the dip is small and amount of shift (S) of the peak position is large. Namely, the sensitivity is higher when the S/W value is large. In the case of an EFC-WM sensor using a monolithic plate with nanopores, the increase in the S/W value by the nanopore formation was very large, about 4 times in the simulation and 6 times in the experimental value. We added this point in section 3.3 as a result showing the improvement of sensitivity.

**Question (Naoto Kobayashi)**

In the Breakthrough chapter, you mentioned that you realized an ultra–sensitive sensor (about 1000 times) using the reflectance change by optical absorption. In this case, what effects are there by the change of dielectric environment such as the change in refractive index and the change of resonance angle? Or, is there very little effect on the angle change due to extremely small amounts of adsorption? Even if that is so, do you think there is sufficient effect of the nanopores? If so, please explain. Also in this case, is the Kretschmann configuration optimal?

**Answer (Makoto Fujimaki)**

Angle change does occur in this case, but the adsorption is very small and hardly any angle change occurs. I added this in chapter 4. Although we haven’t conducted experiments yet, nanopores do have effect, and sensitivity will increase with pores. I added this also to chapter 4. For configuration, regardless of having or not having nanopores, it does not have to be always a Kretschmann configuration. However, this configuration is easy to use because it can be built readily and the optical system is simple.

## 3 Synthetical approach

**Question (Naoto Kobayashi)**

In this study, I think the build up of synthesiology is still insufficient. In the paper, the content, significance, and effects of the individual elemental technologies are well described. However, I recommend you describe in detail the uniqueness and originality of synthesis in which the technologies were combined to create an ultra-sensitive, stable sensor.

**Answer (Makoto Fujimaki)**

In our research to increase the performance of the sensor, we used a synthesis method called strategic selection. First, to increase the sensitivity of EFC-WM sensor, which is our core technology, we selected nanoprocessing of the waveguide layer based on the simulation. To solve the problems of physical stability and evenness of the processed surface of the sensor, we returned to material selection, and selected the reflective film material suitable for the sensor. We found that Si was suitable as a reflective film, and decided to use the SOQ substrate consisting of a single-crystalline Si layer on a silica glass substrate. By strategically combining several elemental technologies, we were able to obtain an integrated technology in the form of a high-performance sensor. We added this description in chapter 5, and provided detailed explanation of Fig. 17.

## 4 Future developments

**Question (Naoto Kobayashi)**

I think this research produced great results in ultra-sensitivity and stability of molecule adsorption sensor, but I think there are still many issues to be considered before it can be put to practical use in the medical scene. I hope you add the prospect for realization and the issues that must be solved.

**Answer (Makoto Fujimaki)**

In chapter 6, I added the prospect for realization and issues, which are mainly the reduction of noise or removal of foreign substance, the reduction of non-specific adsorption, and more accurate identification of samples to be detected. I also added comments about the cost. If these issues are solved, we expect this technology will be realized.

## 5 Measures against pandemic influenza

**Question (Naoto Kobayashi)**

Will this technology help in the early detection of the new pandemic influenza virus that is currently spreading globally?

**Answer (Makoto Fujimaki)**

One of the themes on which our group is currently focusing our efforts is “ultra-sensitive detection and quick identification of new pandemic influenza virus.” We have so far succeeded in detecting the virus fragment (called the HA). Using the high-sensitive molecule detecting technology that we developed, in the near future, we wish to develop a device that can be used to prevent the spread of influenza pandemic.

# Study on the PAN carbon-fiber-innovation for modeling a successful R&D management

## — An excited-oscillation management model —

**Osamu Nakamura[1]*, Tsuguyori Ohana[2], Masato Tazawa[3], Shinji Yokota[4], Wataru Shinoda[5], Osamu Nakamura[6] and Junji Itoh[7]**

**[Translation from *Synthesiology*, Vol.2, No.2, p.159-169 (2009)]**

We have investigated the processes of invention of PAN (Polyacrylonitrile) carbon fiber and its technology transfer to private companies. From this investigation and analysis, we have found a new R&D management model, named “excited-oscillation model”. This model suggests that both the top-down management and the personal motivation should be in phase and synergetic with each other. In this paper, the results and concept of the above model are described in detail.

*Keywords* **:** PAN-based carbon fiber, innovation model, technology transfer, management

## 1 Introduction

“Research” varies by age and by field. Therefore, the results born from the researches may be “results whose relationship with society can be seen in short-term, those that require long-term, and those that are both.” Therefore, if they are categorized under one phrase “research useful to society,” one may lose sight of the essence. Moreover, there is often a gap between the “useful” perceived by the researcher and the “useful” construed by society.

If this is true, the most useful approach in considering the innovation model (methodology for producing innovation) is to investigate the process of innovation for a case study where the research was actually found to be useful in society, after some time has elapsed. At least, if there are guidelines for actions that can be applied to the present for some technology transfer process, we believe it is useful to study such process to learn the way the research was conducted and how the information was transmitted. Of course, the social background and other conditions may differ, and some elements may not be helpful even if they are reproduced accurately. However, we believe it is possible to extract the essential mechanism of how the research results were transmitted to society and the system in which this transmission occurred effectively, including how the research was conducted, its focal point, and awareness of the supervisor and peers (including companies).

In this paper, we shall focus on the PAN (polyacrylonitrile) carbon fiber, which is an example where the research result of a public institution was recognized widely by society and revolutionized industry. We shall investigate the process of this significant innovation by comparing the activities mainly of the researchers at the Goernment Industrial Research Institute, Osaka (GIRIO) that was part of the Agency of Industrial Science and Technology (AIST), Ministry of International Trade and Industry, and the actual course of events of the PAN carbon fiber research in the following perspectives:

(1) Researchers’ mind
(2) Mind of researchers and research management involved in setting the research theme
(3) Transmission and reception of the research results
(4) Human and information network for utilizing the research results

Also, we attempted to derive an innovation model by organizing the process.

Here, we shall not discuss the processes of technological transfer of the manufacturing and assessment methods of PAN carbon fiber to corporation and the following evolution into essential material through the corporate efforts in creating composite material[1]-[3].

Starting from the conclusion, the innovation of PAN carbon fiber occurred because the organic collaboration of the research elements took place in the manner of “excited

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oscillation." Excited oscillation means "'cooperation' where synchronization of the research management and the autonomy was achieved in setting a new research theme that might be useful in society, in the progress of R&D spurred by the researcher's interest," and also includes manifest and latent exchanges and "collaborations" with the companies toward industrial use.

We present the innovation model based on the process of handing over the PAN carbon fiber to industry as the "exited oscillation model," and suggest strengthening the management for future innovation production.

## 2 Course of technological invention

### *2.1 Situation of carbon fiber development*

(1) Summary of invented carbon fiber

In the 1950s, products made from carbon or graphite (highly crystallized carbon) was used only in molded products that took advantage of the heat resistance and conductivity properties, such as electric equipment brush, electrolysis electrode, graphite for nuclear reactors, or in powder products such as carbon black, activated carbon, and colloid graphite. No carbon material in fiber form was known, and graphite fibers were thought to be extremely difficult to manufacture.

Since graphite does not melt until it is heated to nearly 4000 ºC under high pressure, carbon could not be melted and spun like glass fiber. Like the manufacture of carbon materials in general, fiber could be obtained only by carbonizing organic material, and investigations were done using various fibrous materials such as cellulose and polyvinylidene chloride fibers. As a result, it was found that acrylonitrile fibers, if carbonized under suitable heating conditions, could be made into graphite by releasing the nitrogen and hydrogen in the molecule mainly as ammonia and hydrocyanic acid, providing carbon that maintained the form of the fiber, and by graphitizing this fibrous carbon by high-temperature treatment. The obtained product had metallic luster, and was observed by x-ray measurement to be profoundly graphitized[4]. The PAN carbon fiber was developed in this manner.

(2) Course of development

Originally, carbon fiber was developed in the United States in 1956, using rayon as the raw material (Fig. 1)[1]. In the United States, Union Carbide Corporation (UCC) had some success with the rayon carbon fibers.

In Japan, Dr. Akio Shindo of GIRIO became aware of the events in the United States, and started studying the carbonization of polyacrylonitrile fiber instead of rayon. In September 1959, a patent was filed[5] for the PAN carbon fiber, and a research entitled "Study of graphite fiber (1st report) – Growth of crystallites in heat treatment" was presented at the Annual Meeting of Chemistry-Related Societies held in October 1959[6]. In November 1959, this research result was also published in the *GIRIO News*[7] that was circulated widely among the people of companies in the Kansai region. The details of the research are summarized in the *GIRIO Report* No. 317[8].

Through these activities, it could be imagined that the result of PAN carbon fiber research was strategically announced under the judgment that it was highly innovative and had excellent prospects.

An advice from a U.S. military personnel in 1965 provided a major turning point for Dr. Shindo's R&D[2]. Until then, attempts were made to utilize the PAN carbon fiber as a material characterized for its "flexibility" along with its main properties, heat resistance and conductivity. However, the military specialist mentioned that its superiority was "mechanical strength" and "tensile modulus." The direction of research turned to use as structural material. Since this turning point, the corporate participation in carbon fiber research increased, and the companies' effort toward industrial use accelerated. For these companies, GIRIO was essential because it was producing outstanding results in the PAN carbon fiber research.

In addition to the "collaboration" with industry in research and technical assistance, the research on "standardization," which is mandatory for the development of new materials, started in 1975. The Japan Industrial Standard (JIS) for carbon fibers was established in 1980. These efforts contributed greatly to the increased competitiveness of the Japanese companies in carbon fiber. It was initially used in leisure products for their light weight and strength. Its use expanded to industrial structural materials for architecture and aircrafts that required reliability, and now the world share of carbon fibers by Japanese companies is about 80 %.

### *2.2 Research environment (research management at GIRIO)*

At the time carbon fiber development started, GIRIO declared "promotion of industrial technology through research," and organized the infrastructure and raised people's enthusiasm.

In about 10 years after the World War II, there were several products that were put to industrial use from the researches done at GIRIO. The following description is from the *GIRIO Annual Report* for 1959[9]. "Part 1 is the research of inorganic chemical engineering. Research on carbon is one of the traditional researches at GIRIO. In addition to the basic research conducted from the past, research of increasing the density of carbon products, electrode for air cell, carbon material for nuclear reactors, and deboronization of caking additive were conducted, but the greatest achievement for this year was 'the successful manufacturing of graphite fiber and graphite woven fabric with considerable mechanical strength,' and this is expected to become new industrial material in the future." At this point, focus of carbon material shifted to fiber graphite in addition to conventional graphite materials for nuclear reactors, and we could see that this was an organizational effort.

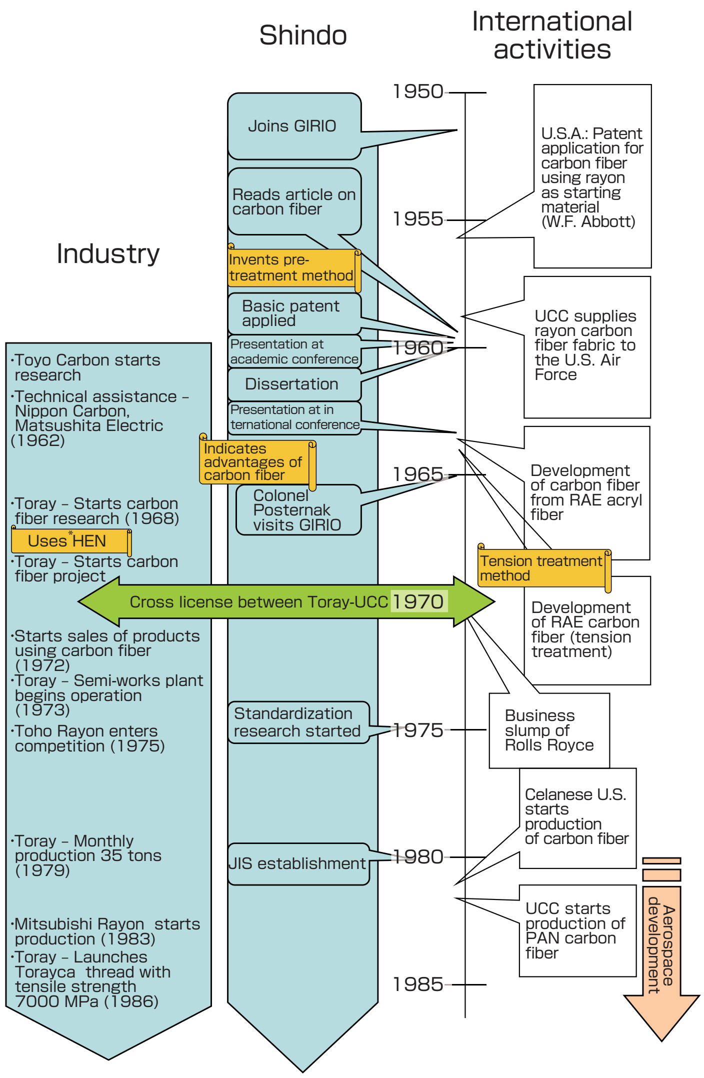
When Tadashi Sengoku became the director general on August 1958, many results were produced at GIRIO and the number of publications and patent applications increased sharply. As will be mentioned later, this was the time when the economic growth was taking off in Japan, and many companies established research laboratories to capture the wave of technological innovations. The companies dispatched their personnel to GIRIO to seek technical assistance. There were several people who left GIRIO at the invitation from the private sectors. The exchange of human resource with industry was promoted.

In 1961, which was two years after filing the basic patent for carbon fiber, the "Technological Consultation Office" was established to process the work of technical assistance and consultation to transfer the research results, many of which were valuable research that remained unused at GIRIO, to the appropriate private companies. The management at that time was highly aware of the collaborations with industry.

### *2.3 Motivation that lead to the invention*

Dr. Shindo, the inventor, joined GIRIO in 1952, and was assigned to work on carbon at the laboratory, yet he did not think that the result would necessarily be put to industrial use. Dr. Shindo sought a novel theme for his engineering technology research with a basic stance of "wanting to be useful to society."

With this mindset, he found an article in a newspaper that he read as part of daily information gathering, that fibrous graphite was manufactured in the United States (Fig. 2)[10].




* HEN: Abbreviation of hydroxyethyl acrylonitrile. By copolymerization, firing time was reduced and great improvement in mechanical property was achieved.

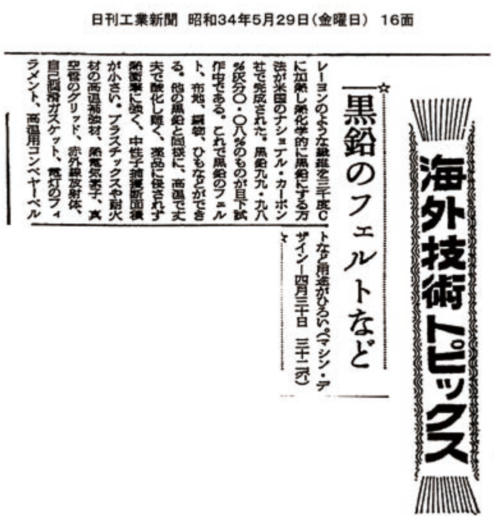
**Fig. 1 Flow of carbon fiber development.**

Inspired by this article, he started research on the new carbon fiber (one-dimensional carbon material).

In engaging in this research, Dr. Shindo asked himself, “What kind of new uses does the fibrous graphite promise in the future?” and self-answered as follows[7]:

(1) Since it has excellent chemical resistance, it is suitable as filter material for acid and alkali
(2) Since it has very good heat resistance, it can be used for filtering non-oxidized high-temperature gas
(3) Since it has good electric conductivity in addition to heat resistance, it can be used as infrared radiator or vacuum tube filament (Author’s note: although transistors were known at this time, vacuum tubes still dominated).
(4) It can be used as filler for synthetic resin
(5) Although there is a problem of black color, it can be useful for preventing static electricity in synthetic resin
(6) String or fabric form product can be used as ribbons for electric devices
(7) It can also be used as fireproofing material.

Since the direction of industrial application of PAN carbon fiber was set on mechanical strength, none of the above was put to practice. What is important here is the idea and basic stance of clarifying the objective of research as something useful in society. Although the research theme was set according to Dr. Shindo’s personal interest and enthusiasm, it should be noted that he carefully considered in advance “where in society his own research would be useful.”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海外技術トピックス

黒鉛のフェルトなど

レーヨンのような繊維を三千度Cに加熱し熱化学的に黒鉛にする方法が米国のナショナル・カーボン社で完成された。黒鉛九九・九八％灰分〇・〇八％のものが目下試作中である。これで黒鉛のフェルト、布地、織物、ひもなどができる。他の黒鉛と同様に、高温で丈夫で酸化し難く、薬品に侵されず熱衝撃に強く、中性子捕獲断面積が小さい。プラスチックスや耐火材の高温補強材、熱電気素子、真空管のグリッド、赤外線放射体、自己潤滑ガスケット、電灯のフィラメント、高温用コンベヤーベルトなど用途がひろい。(マシン・デザイン―四月三十日 三十二頁)

**Fig. 2 Newspaper article that provided inspiration for PAN carbon fiber development (used with permission of *Nikkan Kogyo Shimbun*).**

Overseas Technology Topics: Graphite Felts, etc.

A method of creating graphite by heat-treating fibers like rayon to 3000 ºC was developed by the National Carbon Company of the United States. The current prototype has 99.98 % graphite and 0.08 % ash. This product can be made into graphite felt, fabrics, textiles, and strings. Like other graphites, it is resistant to high temperature, does not become oxidized, is not corroded by chemicals, resistant to thermal shock, and the thermal neutron capture cross section is small. It can be used widely as high-temperature stiffener of plastic and refractory materials, heat electric element, grid of vacuum tube, infrared radiator, self-lubricating gasket, lighting filament, and for high-temperature conveyor belt.
(Machine Design – April 30, p.32)

### *2.4 Background of technological transfer and researchers’ actions*

(1) Background

The basic patent for PAN carbon fiber was filed in 1959. This was the year of abolition of the Japanese measuring system (employment of the metric system), start of construction of Tokaido Shinkansen, and start of commercial television stations. In the following 1960s, the primary energy shifted from coal to oil, industrial complexes sprung up along the Pacific coast, and Japan entered the period of rapid economic growth.

The “three holy appliances (black-and-white television, washing machine, and refrigerator)” were becoming common in the households, and people were trying to reach the American and European living standards. However, the industrial products of this age were already realized in the U.S. and Europe, and therefore, if the product had function and price suitable for use in Japan, it could be readily sold in Japan. By the latter half of the 1960s, with the opening of free trade, the necessity of strengthening Japan’s industrial technology was felt strongly, and the expectation and interest of industry in the public research institutes rose higher than it was before the World War[11].

In this historical turning point, GIRIO underwent a structural change to promote technological transfer to contribute further to the R&D of industrial technology. In April 1967, the management underwent an organizational change along with five other research institutes under the Agency of Industrial Science and Technology, and the general affairs division and the research planning management were established.

Toray Industries, Inc., which is currently highly successful in the commercialization of PAN carbon fiber, started production of carbon fiber in full force around 1968. This matches the time when GIRIO started technological transfer for carbon fiber to various industries after gaining momentum through this organizational change.

(2) Action of the researchers

While the role of the national research institutes became clear as supporter of development of industry in response to social demand, the researchers started to place importance on actions to carry out their mission, and followed the research management policy of GIRIO. However, their actions were not severely regulated, and Dr. Shindo’s research theme was based on the researcher’s curiosity and sense of mission (what was expected of the national research institutes) with approval of the supervisor. Unlike the present situation where there is a flood of information, back then it was possible to think thoroughly about one's research while conducting experiments.

On the other hand, the research results were handled appropriately by the research management, by prioritizing patent application rather than the researchers taking initiative to present them at academic conferences. The initial research period of PAN carbon fiber was not only driven by the researchers' interest, but was a result of good judgment and decisions of the research colleagues and managers as well as the industrial policy of the Agency of Industrial Science and Technology.

### *2.5 Action of industry*

(1) GIRIO and local industry

Ever since its inception, GIRIO valued the relationship with local companies. In Osaka, trade developed in modern age, and new businesses were started up using the wealth gained in the trade. In fact, many businesses in pharmaceuticals and home appliances were started in Osaka by individuals, as well as by zaibatsu conglomerates. Because of this environment, people were constantly seeking ideas for business and information about latest developments. GIRIO was a place to obtain information, but GIRIO was not really aware of the underground information exchange outside of its activities as a public organization.

In fair-sized companies that engaged in R&D, the supervisors ordered, "If your research gets stuck in a rut, go seek guidance at GIRIO." One of the authors has heard that when a corporate researcher obtained certain results after solving a problem or produced new proposals after getting help by technological information obtained from daily conversations at GIRIO, the researcher went on to company presentation without mentioning that the idea was picked up at GIRIO. Therefore, there are very few official data such as of joint research and patent licensing that show the relationship between GIRIO and a company.

However, there were several cases where technological transfer to companies was done through official technical assistance or joint research, and some companies have expressed gratitude to GIRIO in the "company history." Examples of articles pertaining to PAN carbon fibers include the following:

(1) *Fifty Years History of Nippon Carbon* (Nippon Carbon Co. Ltd., published August 31, 1967)

(2) *Fifty Years History of Toray* (Toray Industries, Inc., published June 1, 1977)

(3) *Progress through Effort: Fifty Years History of SEC Corporation (formerly Showa Electrode Corporation)* (SEC Corporation Ltd., published October 23, 1984)

All mention that joint research and patent licensing from GIRIO for carbon fiber development helped their businesses.

(2) Action of industry in carbon fiber development (Fig. 3)

At the time, there were two groups that engaged in carbon fiber development, the primary group and the second group, and the two groups took different actions. The former worked on the commercialization of carbon composite material CFRP, and conducted high profile R&D. The latter

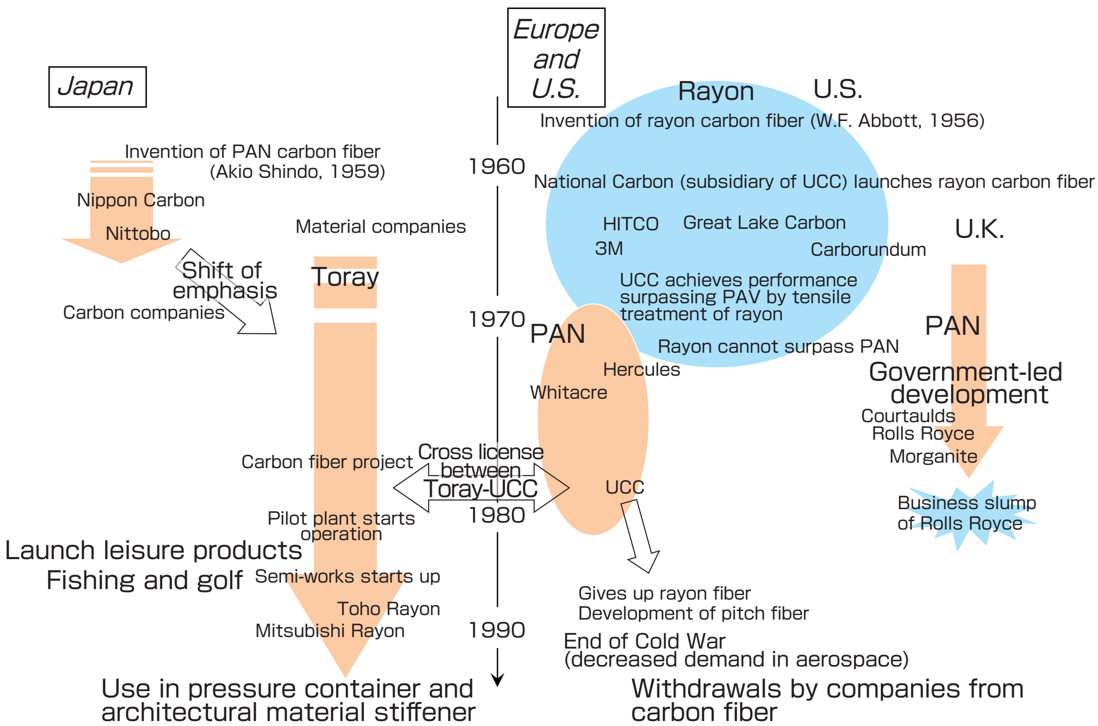


**Fig. 3 Efforts by Japanese and overseas industries on carbon fiber**

concentrated on lower-cost material as alternative to PAN products and studied cost-reduction manufacturing process, and were not publicized overtly and became "underground" activity. That is, they aimed to obtain actual results through daily but unofficial "conversations" with Dr. Shindo's research group.

Although no product that surpassed the performance of PAN was discovered, GIRIO was able to systematize the effective materials with awareness that the sample and information that the corporate researchers brought to them were to be kept "secret." With the companies' intentions to obtain technological hints and the fine-tuned information compilation of GIRIO, the material development in this area progressed and the international competitiveness increased. The interest of industry ("awareness" and "utilization") and the daily research activities at GIRIO were later proven to be essential for the innovation in a form that did not receive the spotlight.

## 3 Analysis of the innovation model

### *3.1 Individual interest and motivation of organizational research (Fig. 4)*

(1) Individual interest

In working on carbon fiber, Dr. Shindo started by imagining the social effect of his research and thought, "Perhaps this and that could be accomplished." If one has a specific goal, the goal itself will provide prospect and guidance even when the researcher hits a wall. Also, by changing the goal or by raising or lowering the goal value, an unexpected hint for solving the problem may appear.

The autonomous action driven by personal interest increases the possibility of serendipity. Such serendipity means ability or gift to find something valuable although it may be different from the item one was looking for initially, and is not the "phenomenon" of finding something. As it is an "ability," it can be polished. It is possible to polish such ability by interest and observation, filing (recording), increasing the range of behavior, and by association. It is important to maintain a degree of freedom so personal interest can be nurtured. However, it should not be wild freedom, and it is necessary to instill the mindset of desiring what is wanted by society.

(2) Motivation of organizational research

GIRIO's policy was management that strongly pushed the industrial use of research results[11]. The ways in which the results were presented to society (patent, papers, reporting sessions, and others) were always planned according to the progress of the research and contact with industry. To propel the results, the scale of the research funding was controlled carefully according to growth. When basic research shifted to Ordinary Research[Term] and many companies participated and the demand for technological development from industry increased, it was shifted to Special Research[Term] where large-scale research funding was granted. The motivation of organizational research starts by capturing the trend of industry. It is necessary to give out a message that if a good result is produced and can be sent out to society, the research driven by the researcher's interest can be supported powerfully.

### *3.2 Research management*

When the research management is investigated carefully, some characteristics can be listed.

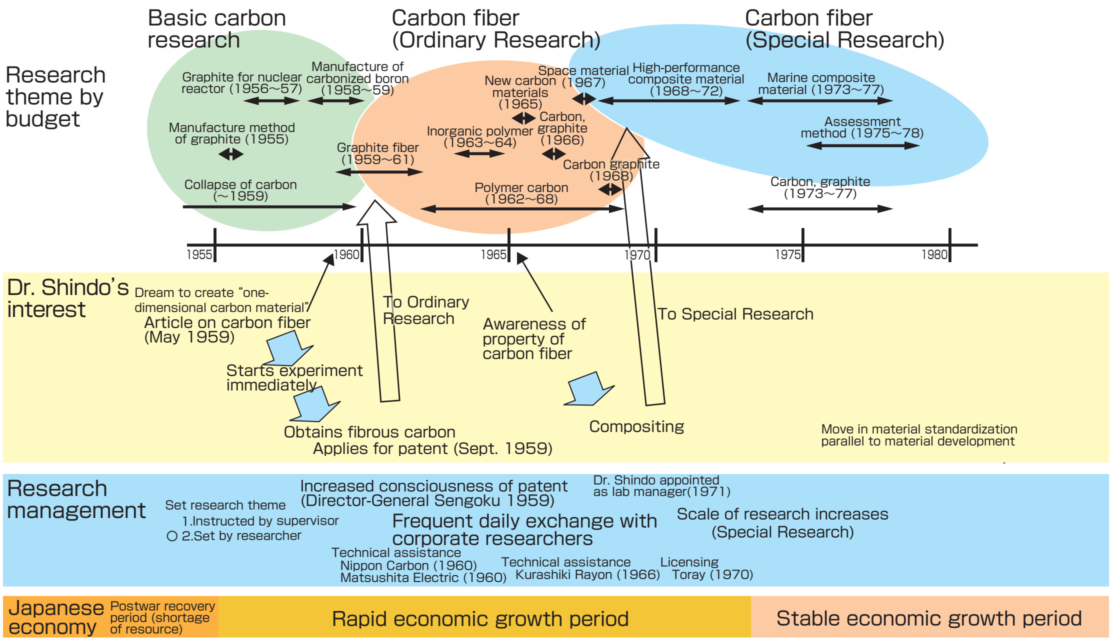


**Fig. 4 Personal interest and direction of research theme.**

(1) Clear goal
At GIRIO, various efforts for "promoting industrial technology" were conducted. Researches were organized along these policies. Although the research may be driven by personal interest, the researchers are encouraged to consider practical application because the policy of the organization states so. Externally, particularly to the companies, this instilled confidence that the researches would be conducted for application.

(2) Daily exchange with companies
GIRIO became a "reliable place" for local Kansai companies. There was a system where the companies could seek advice casually, and information was exchanged without official procedures. Visits by corporate researchers were frequent, and there were many transfers of human resource from GIRIO to companies, and the ground for "technological transfer through human resource exchange" was laid. Exchange of knowledge would make companies reconfirm their research status and direction of the companies, and this confirmation also induced awareness of the companies. Later in the course, demand for "technological standardization" by the companies was raised, and the standardization research that would be the foundation of industrial use was started.

(3) Research fund allotment in synch with growth of research theme
Since its invention, carbon fiber headed steadily toward industrial use. Until attention was brought to its mechanical properties, corporate participations were mostly done by carbon manufacturers, and there were only little participation by material manufacturers like Toray, which would become greatly successful later. This research was therefore positioned as Ordinary Research, but when the corporate participation increased rapidly and new developments in industrial use were perceived, it became Special Research and large-scale Project Research, and this accelerated the research further.

### *3.3 Actual state of technological transfer*

Through the presentation of Dr. Shindo at the Carbon Conference in the United States in 1963, the British carbon researchers realized the advantage of using PAN fiber and started research of PAN carbon fibers. Also, it was an American military personnel that recognized the value of the invention by Japan that was still a developing nation at the time[2]. This surprised the inventor, Dr. Shindo, himself. "Mechanical strength" was a totally different requirement for a product originally developed for heat resistance, conductivity, and one-dimensional form. The researcher narrowed down the focus, and the focus of research shifted to search something with higher function or whether such product could be synthesized.

At this point, the Japanese carbon product companies and chemical fiber companies started to join. However, they could not reproduce the product with the same strength even when they referred to the publicized patent. What was the condition that determined the property? They sought technical assistance "unofficially" from the inventor group on what should be the center of assessment. The companies that were not fiber manufacturers were eyeing the opportunity to enter this field. This accumulated various data in the inventor group. Since the rule of never disclosing the competitors' information was strictly observed, the world's top data and analysis results were concentrated in the hands of the inventor group.

Such spiral can occur even today. In the R&D under market principle, systemization and efficiency cannot be manipulated in this area. Of course, after successfully commercialization through the incessant effort of the primary group, technical assistance to the secondary group may be done systematically without revealing the name of any specific company. In such a case, it is important for both the researchers of the public institution and the companies to be aware that the secondary group does not merely develop the same product as the primary group, but it engages in development to add their own original idea.

This originality is the power that allows the product to grow into something that surpasses the primary product. Various steps exist in the technological revolution including the power to find something that does not exist in the world (inventor group), power to capture the budding research result (primary group), and the power to conduct improvements to enhance the performance of the product that starts to take shape (secondary group). Although the achievement of the inventor group is often praised, it should not be forgotten that the technological innovation through the combination of technologies also strengthens industrial competitiveness.

In the development of PAN carbon fiber, some companies such as manufacturers of carbon products, chemical fiber, and electric appliances became interested and attempted learning the technology, and technological transfers were done 10 years prior to the actual marketing of the product. Since carbon fiber and CFRP that combined resin and carbon fiber were totally new materials, there was a long period of trial and error without evaluation standards to judge whether a product was of the best performance in the R&D phase. Confusion arose in the late-starting companies, and many brought their products to the Shindo lab and asked everything from, "Is this really what you call carbon product?" to "Which property should we set as R&D target?" and "What is the key point in making the same product?" Of course, it would have been lucky if something surpassed the PAN carbon fiber developed at the Shindo lab. However, no such product appeared.

Needless to say, there is no argument against the continued research to improve performance (or check that there is no material that surpasses the current material) by the original researchers and joint researchers. The corporate researcher tries to accumulate peripheral data in R&D considering corporate profit. However, in this case, not all data are publicized. Patent filing for intellectual property is done actively. However, there is a mixture of patents of "the main product" and "everything else." It is necessary to be aware that this is part of the corporate activity. The "everything else" products serve as a smoke screen against competitors, and they may also become barter items when buying and selling the technology.

What is important here is that "technological transfer" is not singular or uniform, but is done by absorbing the background situation. In some cases, the later generations may focus only on the success stories, and the readers must be careful when reading them. What we wish to point out here is the fact that only the best product (in this case PAN) survives with the support of a great quantity of latent research results because there are many competitors and people involved. Researchers of national institutions may be deeply involved in this development.

Lester and Piore propose the "sheltered space" model, because for producing innovation, "if the researchers are given a place where they can engage freely in interpretive effort, the autonomy of the researchers will bring about new development"[12]. On the other hand, the "space" at GIRIO was a gathering of industrial researchers with clear technical demand, but it was of private interactions with the Shindo group rather than a place of exchange among the researchers. However, the space for interaction for improving the international industrial competitiveness around the Shindo group including the Ministry of International Trade and Industry, the Agency for Industrial Science and Technology, and the Japan Carbon Manufacturers Association were open. The authors think that, rather than a "sheltered space" which is a static space, the complex of the interactive space and the Shindo group at GIRIO functioned as a "dynamic space" where the R&D and management mutually interacted in synch.

## 4 Conclusion

We investigated the process of innovation in detail taking PAN carbon fiber as an example. The development from invention to product realization, though staged in a background that is vastly different from now, is thought provoking for today's researchers.

From the information on carbon fiber development coincidentally learned from the daily information gathering, the researcher considered its industrial use from the beginning, selected themes with clear objectives, searched for the experiment method, and engaged in research. The procedures for timely patent obtainment went smoothly and patent application was accepted. The dramatic progress that followed started with the information that the demand of industry for carbon fiber material was mainly for mechanical strength. The direction of research was shifted, and collaborative and cooperative research was done with industry to optimize the material property, study compositing with plastic, and achieve practical application as CFRP composite material. Even more important was the effort on standardization of measurement of mechanical strength to guarantee the reliability of the product, and this contributed greatly to solidify the foundation of industrial use of carbon fiber. Also, the steady accumulation of research results that might never see the light conducted in the incubation period before the product set out into society including daily information exchange with GIRIO induced new awareness, and this led to joint research. This brought about industrial

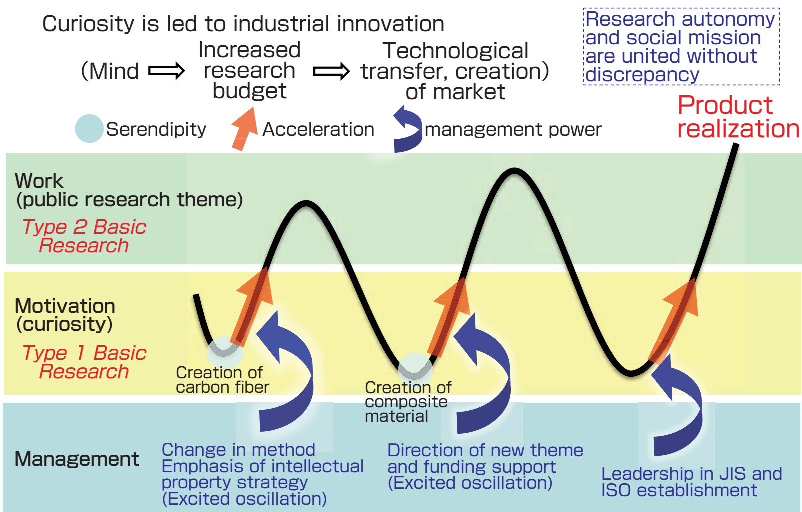


**Fig. 5 "Excited oscillation model" of innovation.**

change far beyond the original expectation of the inventor.

It was reaffirmed that the following points were important as components of this process:

(1) Serendipity based on clear issue consciousness of the researcher

(2) Matched phase between the researcher's motivation and management

(3) The industry's aggressive desire to develop new business

Today's industrial change would not have resulted or would have remained small, if any of the process was absent.

Moreover, timely cooperation effect of each element is important. This will develop into "excited oscillation" where mutual actions are strengthened, and the progress to industrial use accelerates from a certain point in time. The "excited oscillation model" can be presented as an innovation model to unify the research autonomy and mission in society without discrepancy (Fig. 5).

Again, reconsidering the innovation process of the PAN carbon fiber to check this excited oscillation model, the series of research on PAN carbon fiber was born as a serendipity driven by a researcher's interest in the manufacture method of carbon fiber through graphitization, and the management led it to practical use by encouraging patenting. Also, the unforeseen meeting with a third party offered a chance to shift the focus to mechanical strength, and the R&D for material development and creating composite material (CFRP) was conducted due to this change in policy, the management accelerated the process through funding support by raising its status to a Project, and dramatic progress followed. In addition, research on the standardization of carbon fiber material contributed to guaranteeing the reliability, and pushed the spread of industrial use. All these processes were accomplished under close cooperation of the researcher-management and research-industry.

Positioning the findings obtained through the model and analysis as proposals for the efforts for future creation of innovations, the following will be the key scenario:

(1) Clarification of "mindset" that is the basis of researcher's "autonomy"

(2) Establishment of "management" that synchs the researcher's mind to society

It can be concluded that it is important that the research organization (executer of R&D) and government organization (planner of R&D policy) to understand and to operate appropriately.

Based on this model, the management is required to "motivate the researchers when they are setting the research theme," "review the research theme and system when it is matched against the social values according to the progress of the research," and to "engage in technological transfer and related committee activities to improve or create social values." Organic collaboration, particularly resetting of research theme by the researcher and synchronization by the management as the research progresses, are strongly desired.

This model seems to have similarities with the chain model of Stephan J. Kline[13]. While the Kline model is a phenomenological model, the excited oscillation is a management model for producing innovation. This is a point that we emphasize in this paper, and to produce innovations in the future, the role of management is the most important over everything else, and we believe this model is effective as a model to create a guideline.

## Acknowledgement

In preparing this paper, we made full use of an interview with Dr. Akio Shindo, the father of PAN carbon fiber, as an information source for course of events that do not show up in papers and patents. We obtained detailed information about the people's awareness and actual practice in research through interviews with Dr. Yoichiro Nakanishi and Yoshihiro Sawada, who were joint researchers of Dr. Shindo. We learned of the views on Dr. Shindo's interest and curiosity through an interview with Dr. Rokuro Fujii who was a joint researcher in the early stages of carbon fiber research. We learned about the research environment at that time and the daily activities of researchers through interviews with Dr. Kanji Matsuo and Isao Ogino, former senior researchers. This paper was prepared by compiling the information from Dr. Kazuo Ohtani and current AIST employees who were involved.

## Terminology

Ordinary Research and Special Research: The researches conducted at the former Agency of Industrial Science and Technology could be roughly grouped into basic "Ordinary Research" and "Special Research" that includes large-scale projects or researches directed by the MITI. Based on the Outline for Research Management of the Agency of Industrial Science and Technology, the theme selection, planning, fund allotment, and management of the results were left to the deliberations of the director general.

## Resource Material

Dr. Shindo *et al.* discovered the basic principle of the PAN carbon fiber and its manufacture method, and obtained the patent. Toray received licensing and engaged in long-term R&D as a government-industry collaboration. Many major companies around the world joined the challenge, but the Japanese companies (Toray Industries Ltd., Toho Tenax Co., Ltd., and Mitsubishi Rayon Co., Ltd.) hold 80 % of the world share in the high-performance carbon fiber market. The reasons the Japanese companies conquered the world in this area were:

(1) The American and European companies dropped out in the technological innovation competition

(2) The Japanese companies continued long-term investment in R&D, and

(3) The Japanese government continued to support the R&D.

(Cited from Minoru Yoshinaga (Japan Carbon Manufacturers Association): Innovative materials of the 21st century lead by Japan – carbon fibers that contribute to low-carbon society," Material 4-1 (April 21, 2009) distributed at the 80th Council for Science and Technology Policy.)

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## Authors


**Osamu Nakamura**

Withdrew from the doctorate course at the Graduate School of Science, Osaka University in 1973. After some time at the Institute of Scientific and Industrial Research, Osaka University, joined GIRIO in 1974. After 1998, appointed director of Ehime Institute of Industrial Technology, acting director of AIST Kansai, and council member of Evaluation Division. Studied the contribution of research results to society from the aspects of management and evaluation of research organization. In this paper, based on his own experiences at GIRIO and Osaka National Research Institute, and from the interviews to people involved, built the framework of the paper and selected the points of emphasis.

**Tsuguyori Ohana**

Completed the master's course in Applied Chemistry, Graduate School of Engineering, Osaka City University. Joined the National Chemical Laboratory for Industry, which became the National Institute of Materials and Chemical Research, which now is AIST. Planning officer of the Research and Innovation Promotion Office from May 2007 to August 2008. Currently, appointed to the Advanced Manufacturing Research Institute. Doctor (Engineering). In this paper, in charge of collecting and analyzing resource materials. Studied the background through interviews with Dr. Shindo.

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Completed the master's course in Applied Physics, Graduate School of Engineering, Nagoya University, and joined the National Industrial Research Institute, Nagoya (GIRIN, currently AIST Chubu). Doctor of Science. General planning officer of the Research and Innovation Promotion Office from April 2007 to April 2008. In this paper, interviewed people involved and compiled the information.

**Shinji Yokota**

After working at the Institute of Future Technology, appointed senior researcher at the National Institute of Science and Technology Policy, MEXT from 2001 to 2006. Joined AIST in 2006. After working at the Technological Information Department, appointed general officer of the Research and Innovation Promotion Office. Visiting researcher at the National Institute of Science and Technology Policy from 2006, and surveyed science and technology policies (technology foresight, evaluation of effect of science and technology, etc.). Currently, engaged in development of a calculation method estimating science-based innovation impact at AIST, as well as research on innovation system of public research. In this paper, in charge of overall editing, mainly on interpretation of facts and composition of the model.

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Completed the doctorate course at the Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology in 1998. Doctor of Science. After working at the Mitsubishi Chemical Corporation, joined the National Institute of Materials and Chemical Research, which became AIST after reorganization. Planning officer at the Research and Innovation Promotion Office from June 2008 to May 2009. In this paper, in charge of collecting and compiling

materials.

**Osamu Nakamura (Note: different person with same name and surname)**

Completed the master course at the Graduate School of Agriculture, Kyushu University in 1979. Engaged in education and research as an assistant professor of Oral Biochemistry, Kagoshima University Dental School. Received Doctor of Dentistry (Osaka University) in 1987. Visiting research associate, Case Western Reserve University, Cleveland, Ohio, U.S.A.; Senior researcher, Kyushu National Industrial Research Institute; Deputy director and Manager of Biological Chemistry Division, Biotechnology and Food Research Institute, Fukuoka Industrial Technology Center; Senior researcher, Evaluation Department, AIST; and Director for Technology Evaluation, Technology Evaluation and Research Division, METI. Appointed Deputy Director of Evaluation Department, AIST in 2007. Evaluated R&D management, and has built up a network of personal connections involved in evaluation both in Japan and abroad. Currently, Director general of the Science and Technology Promotion Bureau, Nagasaki Prefectural Government. In this paper built the framework of the paper and selected points of emphasis.

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Completed the doctorate course at the Graduate School of Engineering, Tokyo Institute of Technology. Doctor of Science. Joined the Electrotechnical Laboratory in 1984, which became AIST by reorganization. Worked as head of the Nanoelectronic Research Institute, vice-president of Planning Headquarter, and as Industrial Technology Architect. Vice president of AIST from 2007. In this paper, in charge of basic model design and overall direction.

## Discussion with Reviewers

### 1 R&D scenario

**Question and comment (Naoto Kobayashi, AIST Advisor)**

The “excited oscillation model” proposed in this paper is new and interesting. I recommend you clarify the scenario for “what should be done to excite innovations in the Japanese industry in the future” (that is, scenario for utilizing the research result). I think the value of this paper will be enhanced by doing so, and therefore I expect you to add descriptions.

**Answer (Osamu Nakamura)**

As you indicated, the “excited oscillation model” was derived from the analysis of case studies that brought about significant socioeconomic impact among the R&D efforts of AIST. Using the findings gained from this model and the process of analysis as proposals for efforts toward future innovation, the following two points should be particularly emphasized:

- clarification of “mindset” that will be the basis of the researcher’s “autonomy,” and
- establishment of “management” that synchs the researcher’s mind with the society.

We added descriptions that point out that it is important for the research organization (execution of R&D) and government organization (planning of R&D policy) to consider the above points.

### 2 Components

**Question and comment (Naoto Kobayashi)**

The pillar of this paper is the statement that the effective correlations and linkages of various components functioned in how the PAN carbon fiber developed by Dr. Shindo was put to practical use. Using the words of the paper, (1) the researcher’s serendipity (product of the researcher’s autonomy), (2) research environment in synch with the researcher’s interest (combination of autonomy and management), and (3) the awareness of the industry (starting point of market creation). You should clarify whether these components are sufficient or that they are merely requirements for building a universal model containing these components. Also, I think you should select words so (1)~(3) will become more universal expressions (they should be understandable when they are cited as “excited oscillation model” in the future). For example, how about (1) free conception and social consciousness of the researcher, (2) appropriate time-space support by the research management, and (3) awareness of the industry and straightforward exchange of opinion, and others. (Also, does the suggestion from the American military personnel belong to (3)?)

Pertaining to (3), do you suggest that the “sheltered space (http://www.arengufond.ee/upload/Editor/industryengines/files/foorum/lester%20slides%20021208.pdf),” as described by Professor R.K. Lester of MIT, existed at GIRIO 40 years ago?

**Answer (Osamu Nakamura)**

As you indicated, this paper explains the excited oscillation model using the three components. The process leading to innovation was analyzed and summarized into three essential components, and we think they are sufficient as components of this model. However, we shall change the expressions as follows to clarify and to add universal character to the function of each component:

(1) Serendipity based on clear issue consciousness of the researcher
(2) Matched phase between the researcher’s motivation and management
(3) The industry’s aggressive desire to develop new business

For (3), the sheltered space as proposed by Professor Lester did not exist at GIRIO back then. For sheltered space, Professor Lester states, “If the researchers are given a place where they can engage freely in interpretive effort, the autonomy of the researchers will bring about new development.” However, simple provision of a place gives the impression that the model is static. In the “excited oscillation model,” the mutual interaction between the researcher and the management lies at the base, and it is “a dynamic model where the management excavates and exposes the intentions that the researchers themselves may not be aware, and provides action in synch with the phase toward production of innovation.” We analyze that there was a dynamic model at GIRIO from its inception, and in that sense it was different from the sheltered space concept.

In this paper, we explained Professor Lester’s sheltered space and stated the difference from excited oscillation model.

### 3 Effect of the model

**Question and comment (Naoto Kobayashi)**

While the proposed “excited oscillation model” is extremely interesting, why have there been just a few results that lead to major innovations in the later Agency of Industrial Technology and Science?

**Answer (Osamu Nakamura)**

I think there were several cases where results led to major innovations during the time of Agency of Industrial Technology and Science. After reorganization to AIST, there have been more opportunities and efforts than before to send research out into society and to promote innovation, through the “*Full Research*” method. In this paper, we looked at the carbon fiber at GIRIO, but in the future we shall select both old and new cases, study their processes, and help build up the innovation model.

# Energy-saving policy and standard research for solid-state lighting in the United States

**[Translation from *Synthesiology*, Vol.2, No.2, p.170-175 (2009)]**

When Dr. Yoshi Ohno, who engages in the research of photometry standards at the National Institute of Standards and Technology (NIST) of the United States, visited AIST in December, 2008, Ono and Tanaka, editors of the *Synthesiology* Editorial Board, took this opportunity to interview him. We were able to hear the ambitious plans of the United States Government to execute its energy-saving policy in the field of illumination, as well as the great enthusiasm among the standards researchers in meeting the requirements. It was also interesting to see several common points between Dr. Ohno's research at NIST and the *Full Research* conducted at AIST.

***Synthesiology* Editorial Board**
**Yoshi Ohno: Leader of Optical Sensor Group, Optical Technology Division, National Institute of Standards and Technology**
**Akira Ono: Senior Editor, *Synthesiology*; Vice President, AIST**
**Mitsuru Tanaka: Editor, *Synthesiology*; Research Coordinator, AIST**

## *Full Research* and *Synthesiology*

**(Ono)**
AIST has been publishing an academic journal entitled *Synthesiology* since 2008. Considering the relationship between scientific research and society, when a scientifically significant discovery or invention is made, it draws the attention of society, and large amounts of research funds may be allotted to its research. Yet in general, it is rare that the discovery or invention makes it into society as a so-called "product." There is a period where steady effort and patience are required, when the researcher must realize his goals one step at a time, even after popular initial interests dies down. This is the "nightmare period" for the researcher, when popular interest fades and the research funding becomes thinner. I believe the mission of a public research institution like AIST is to meet these types of challenges during the nightmare period to ensure the utilization of the research results by society.

Today, the value of basic research and, at the same time, the importance of applied research are increasing. We are becoming aware that the issues of global environment, energy, health, food, and other social issues cannot be solved only by engaging in our narrow fields of basic research. Unless we boost what we call "applied research," science will not become part of our social values.

The conventional way of writing a research thesis is to describe the facts, and to draw conclusions from the facts to confirm the logical consistency. One can say, "that's all", although there is actually more to it than that. Yet, we have been writing papers because we believe that there is value in accumulating new facts in our respective fields and polishing logical completeness, without considering what if any linkage there is with social values. Daily research, however, is much more vivid and is affected strongly by social demands and government policies, but we cannot write about such things.

**(Ohno)**
That's right. Perhaps we see only a few lines of such backgrounds of research in the introduction part of papers.

**(Ono)**
Yes, indeed. The introduction of a paper is interesting to read, but it does not determine the quality of the paper. Even if the authors have the passion and desire to meet the demands of society, if they put that down in writing, they will be met with the comment: "That's not an academic thesis." Through *Synthesiology*, we wish to present a combination of the researchers' intelligence and intentions.

**(Tanaka)**
Dr. Ono described for us the objectives of *Synthesiology* and our intentions. I think it is important to maintain the perspective of applied research even if one is engaging in basic research. Is this way of thinking prevalent in the United States?

**(Ohno)**
In case of NIST where I work, some basic research is done, but I think the majority is applied research. At various opportunities, we are required to explain, “Why I am doing this research.” For example, in our Division, we have a project review once in several years, where each project leader presents what is being done in his/her project, what kind of contacts we have with industry, how it will be useful, and then we discuss the project. Since our funding is always limited, it is difficult to do research for which we cannot provide a decent explanation on its benefits to the industry.

## Photometry standard research at NIST

**(Tanaka)**
In the United States, both the Bush and Obama Administrations clearly stated the policy of disseminating solid-state lighting (SSL) for energy savings. Dr. Ohno has been working on photometry standard research at NIST and has made great contributions. This effort can be called a social technology that links the photometric standards research at NIST and the American SSL policy. It probably falls into the general category of the “standardization, policy, and regulation of a technology and product.” Can you tell us how you have been working on the photometry standards research?

**(Ohno)**
The energy currently used for lighting such as incandescent and fluorescent lamps amounts to an enormous quantity. The U.S. Department of Energy (DOE) has set a goal to reduce the current electricity consumption from lighting to half over the next 20 years by gradually introducing SSL to the market.

In 2005, the U.S. Congress decided to promote SSL as a national policy, and DOE was directed to head the promotion. It is expected that using SSL will bring twice as high energy efficiency in lighting. This has gathered a lot of attention since creating light sources twice as efficient will enable considerable energy savings and will also be helpful in halting global warming.

However, since this is a next-generation light source, problems are expected because it is dissimilar to the conventional light sources in many aspects and requires new challenges. In its policy to promote SSL, the DOE is looking at the big picture from the development of core technology (the basic research for semiconductors), to the development of light-emitting diode (LED) and lighting products, and to their introduction to the market as the final step. As Dr. Ono mentioned, in this realm, basic research is linked all the way to market. In this picture, standards play an extremely important role. If a standard is poor, inferior products will become rampant. When a consumer purchases a bad product with poor performance, he/she may be disappointed with the performance of LEDs and may decide not to buy it any more. The initial stage of market introduction is very important for the success of the new technology, and the DOE is working hard to support such commercialization process.

NIST supports standardization in various ways, and is helping Energy Star issued by the DOE. Energy Star is a government program that endorses energy-efficient products including many of electric appliances. The Energy Star label is allowed to be attached to the products that meet the requirements. DOE selects products not only for their energy efficiency but also the quality of the product. The Energy Star program for SSL products has just started.

**(Ono)**
You mean that NIST is setting the standards for giving out the Energy Star?

**(Ohno)**
Yes, applications for Energy Star program for SSL are officially accepted since October 2008. We started developing the standard two years in advance. NIST participated

**Dr. Yoshi Ohno**

**Dr. Akira Ono**

actively, and took the leading role in some parts.

## No standard, no recommendation

**(Ono)**
So NIST is cooperating in the creation of not only metrology standards, but also industrial standards?

**(Ohno)**
Yes. I talked about quality earlier. For example, talking about the chromaticity of a lighting source, people dislike lighting when the overall appearance gives a yellowish or greenish hue and this is a cause for products to be returned. Since this was a very important issue, a task group to create a standard for chromaticity for SSL light sources was set up in the American National Standards Institute (ANSI). I became the leader to develop the standard.

**(Ono)**
As a matter of perception, I don't want to be in a yellow room, and a green room is unsettling. A red or blue room would be more acceptable.

**(Ohno)**
Yes. We wanted to define that, and establish it as an industrial standard, and ensure good color quality of products through Energy Star.

For measurement, the Illuminating Engineering Society of North America (IESNA) published a document (LM-79), which is a standard for the testing method used as a reference by the Energy Star. I also led this standardization project. For example, it sets standards for how to measure the luminous flux using the unit lumen, how to arrange the integrating sphere, and what kind of detector should be used. There are two types of integrating spheres: one using a photometer and the other using a spectroradiometer. The accuracy for industrial use is much higher when the spectroradiometer is used. But, in order to use a spectroradiometer, a metrology standard for the spectral radiant flux will be needed. NIST has been working on this standard for several years and has made it available, which is one of the key points in this standard.

If you want to recommend this method, you must have a metrology standard required in the method. Unless you have that standard available, you cannot just put that method down in a document and say, "Please use this method."

**(Ono)**
The importance of spectral radiant flux measurement has been also recognized at AIST, and we just started working in that direction.

## Do we get high quality product by raising the assessment values?

**(Ohno)**
There's another point concerning the quality of a LED light source. When assessing the color rendering of a lighting source, there is an index called the CRI (color rendering index). This index has a full scale value of 100. 80 points or higher is recommended for interior lighting. This index was created about 40 years ago for fluorescent lamps. However, using my simulation program, it was found that there were many problems when this index was applied to LED light sources.

When the spectrum of the output light is focused to the center of the visible range, the efficiency of the luminous flux value (lumen/watt) will increase, while, in general, color rendering decreases. Companies are competing with each other over the value of lumen/watt. However, it was found by my simulations that if they seek for a spectrum with the highest lumen/watt, for example, at a CRI of 80, the appearance of the light will have an unacceptable poor red color. A LED light source can become unusable for interior lighting even if it has a CRI number of 80 (Fig. 1).

Also, it is possible to raise the color contrast by manipulating the spectrum to some degree. For example, a neodymium lamp, which absorbs the yellow spectrum, is sold on the

Dr. Mitsuru Tanaka

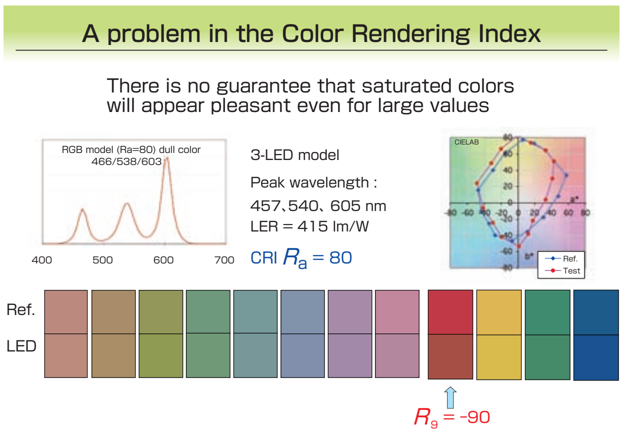


**Fig. 1 A problem in the Color Rendering Index.**

market. This lamp makes things look brilliant. However, the assessment index of this light bulb is rather low. Yet, I think this is a very good light source to be used in actual practice. In industry, since R&D is conducted to raise the index value of manufacturing products, the development may head in the wrong direction if the index is wrong.

**(Ono)**
Here, you mean that the industrial standard itself that specifies the quality index is not good?

**(Ohno)**
Exactly. I thought there will be major problems if such poor LED products with a CRI of 80 are sold on the market.

We've been doing this research for several years, and entered into the "Innovation Measurement Science," which is a competition for a research budget hosted by the Director of NIST. Our proposal was selected for preliminary document screening, and I did a final presentation in front of the Laboratory Directors of NIST, and it passed.

**(Ono)**
Congratulations.

**(Ohno)**
First, we were doing simple experiments in a small inspection booth. We found that when objects were placed inside the booth and the RGB (red, green, and blue) spectra were slightly changed, the color rendering changed greatly. At a CRI of 82, which is a good value, the red sample appeared brown. This verified that my simulation was correct (Fig. 2).

**(Tanaka)**
Yes, I see. Comparing 82 and 71, 71 looks more vivid.

**(Ohno)**
71 appears very vivid, and your hand looks good when you put it in there. But in Energy Star, it has to be 75. If a CRI of 82 was selected for Energy Star, and not 71, there will be problems. The DOE told us "hurry up and make a new industrial standard."

**(Ono)**
The values do not reflect the actual performance.

## Integrated progression of research and standardization

**(Ohno)**
This has been published as a paper, but we created a new index that will solve all such problems. We are proposing a new Color Quality Scale (CQS). In this index, the light with CRI=82 in Fig. 2 will have CQS=74, and the vivid light with CRI=71 will have CQS=83, and the numbers are reversed (Fig. 3). A new assessment method is meaningless unless it becomes an industrial standard, and people won't use it unless it becomes an industrial standard. Color rendering is historically an international standard. Therefore, we made a proposal to the International Commission on Illumination (CIE) to set up a committee, where we presented our method, and we are continuing discussions.

This research will come to fruition only after it becomes an international standard and is actually used by the industry.

**(Ono)**
Yes, indeed. We call this "an integrated progression of research and standardization." Rather than starting to work on standardization after research is complete, we pick up the demand for standardization and this demand is reflected in the research. Then, the result is fed back to standardization. AIST claims that both must run together, and this is a good example.

**(Ohno)**
I certainly think so. Particularly, DOE's Energy Star is already up and running, and the CRI is currently used because the new standard was not in time.  Not just Energy Star, but also the entire SSL industry is advancing rapidly,

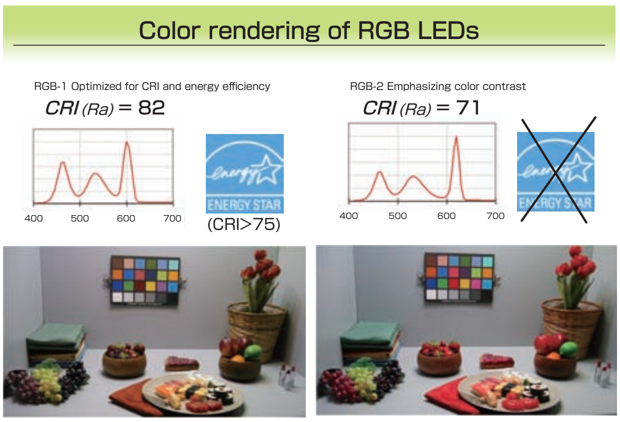


**Fig. 2 Color rendering of RGB LEDs.**

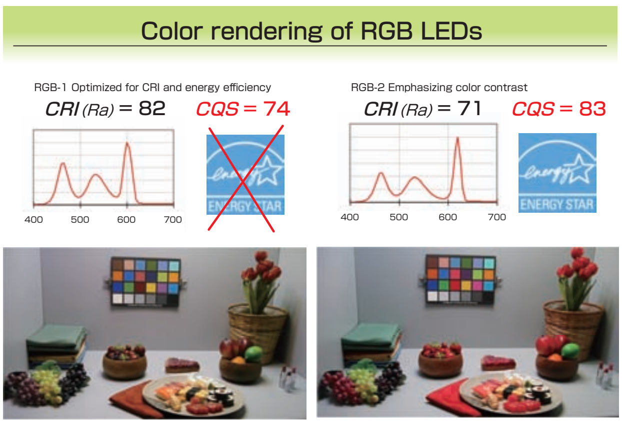


**Fig. 3 Color rendering of RGB LEDs.**

so if the standard cannot catch up, there is a danger that development may go in the wrong direction producing inefficient products.

Currently, the mainstream for white LED is the method in which blue emission and phosphor are combined. Some people say that RGB method is high cost and has very poor color rendering (CRI). Yet the color rendering to the eye is not that bad. The companies that are working on RGB support us with great enthusiasm.

**(Ono)**
RGB is composed of three wavelengths with a relatively narrow spectral width. So you will use the CQS rather than the CRI. By the way, what would the Japanese terminology for CQS be?

**(Ohno)**
I never thought about the Japanese for color quality scale. I'd better think of something.

**(Ono)**
How about *shikishitsudo*?

**(Ohno)**
Yes, *shikishitsudo* sounds good. For this research project, we received about half million US dollars as budget for the facilities in addition to cost of labor, so we are creating a new experimental facility where the entire room can be illuminated while freely changing the spectra, the first of its kind in the world (Fig. 4).

**(Ono)**
I see. You are going from a booth to a room.

**(Ohno)**
In a room, there is great advantage in that you can actually work in it, talk in it, and see the colors of people's faces. We can't do a final check of the new metric unless we go that far. Currently in this room, we have a temporarily installed system with only three RGB colors. In February 2009, we will have a system that can control peak wavelengths for 25 separate colors. We can study color perception under various lighting conditions, and I believe this will contribute greatly to the research on SSL.

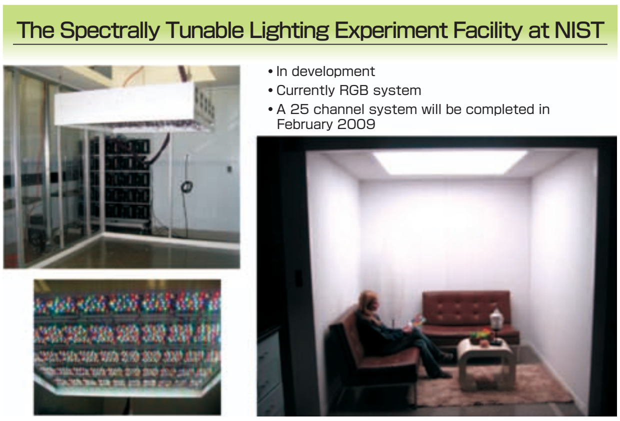


**Fig. 4 The Spectrally Tunable Lighting Experiment Facility at NIST**

### *Full Research* at NIST

**(Tanaka)**
You are getting good results of *Full Research* for the DOE policy on SSL.

**(Ohno)**
Yes. As I mentioned earlier, I think the industrial standard for the chromaticity specification and another standard for the test method called LM-79 are our major outcomes. Chromaticity is the color of light, but even when the color of light is at a good setting, this does not necessarily mean that the color rendering is good. Both are related, but we first need to set the color of light as an industrial standard. Next will be the standard for color rendering.

Although I wasn't in charge, there are additional standards published, for example, the industrial standard of life testing of LEDs. The lifetime of LEDs is very long like 30,000 to 50,000 hours or even longer. Therefore, the current practice in the industry is to test LEDs only for 6,000 hours and extrapolate the degradation curve to 30,000 to 50,000 hours. This method involves very large uncertainties for projected lifetime and it was not agreed upon. Since we had a deadline for the Energy Star, this standard was published without inclusion of the projection method. How far we can go in standardizing such lifetime prediction will be our next challenge.

**(Ono)**
Newly created technology will progress in a good direction if there is an accumulation of data. In creating such industrial standards, what are the contributions of Japanese companies and researchers?

**(Ohno)**
Since ANSI and IESNA are American standard organizations, there is basically no participation from Japan. However, Japanese corporations that have companies in the United States can participate. For international standardization such as CIE, there are participants from around the world, but there is not yet very active participation by Japanese companies in LED lighting.

### Carrying out research while staying in touch with the demand of industry

**(Ono)**
Photometry is basic research oriented while at the same

time it is an energy-saving measure that the whole world is interested in. I feel you are doing very important work that links between the two. You are practicing "engaging in research while standardizing." Since Dr. Ohno is a Group Leader at NIST, you must consider the career of young researchers. What kind of advice do you give to people whom you want to become established as researchers and also want to make contributions to society? It will be helpful to hear from you since we face the same problem.

**(Ohno)**
It is my experience that, when I attend committee meetings or workshops, I hear about many problems in the subject and I find what new researches will be needed. I always learn a lot from various questions asked and requests made at standards committee meetings. I try to take young researchers or let them go to these meetings and conferences as much as possible.

Of course, we let them do research freely in part, but I think it is useful to have them conduct research while staying in touch with the demands of industry.

## Important for non-experts to understand

**(Ono)**
When publishing the results of standardization, I think it is important in which form they are presented. NIST publishes the results in various forms such as monographs and technical notes that are different from research theses. Do you think they are highly valuable?

**(Ohno)**
Definitely. Scientific papers are important and they must be published, but on the other hand, we also write articles for magazines for lay people. Recently we wrote for *LED Review* and *LEDs Magazine*, which are published on the Internet. I write about color rendering and measurements, and I receive good responses from people in the industry.

In addition to these efforts, NIST publishes press-release articles to the media. They are typically about two pages long. I wrote such articles recently when we completed two standards for SSL and when we developed the measurement method for high power LEDs. These are written for people who are not experts, and perhaps they may be somewhat like AIST's *Synthesiology*. These are highly recognized by management.

**(Ono)**
As you say, *Synthesiology* covers physics, engineering, agriculture, and pharmacology, and contains everything from life sciences to electronics and metrology standards. We have such editorial policies, and present papers in forms that can be read by people from other fields.

**(Ohno)**
Yes. I've read it, and felt that I can read the articles of the fields that are outside my expertise.

**(Ono)**
Thank you. That is one of the issues we were concerned about when we published this journal. I was a reviewer for the paper in the fields of the environment and geology, and I understood the content. I was surprised that I understood them. I was even more surprised that I was writing comments on them.

**(Ohno)**
You had discussions with the authors. That must have been fun.

## Research community works on various issues

**(Ono)**
There are many important issues such as global environmental problems in which the role of science and technology is huge. However, I felt that the scientists and researchers could not exchange their thoughts, and although they are connected with society through their respective channels, they could not issue a comment as a community. I think it is great that researchers got together for the Intergovernmental Panel on Climate Change (IPCC) to collaborate and publish reports for the process of standardization. The engineers and researchers attending exchanged their thoughts to create something together. I think this is wonderful.

**(Ohno)**
Standards are taken for granted, and it is a low-profile field. In fact, it's difficult for this field to be visible. Therefore, the issue of SSL standardization was an opportunity for carrying out a major change. SSL is once-in-a-hundred-years event in the history of light sources. I think demand is very high, so if we capture the opportunity well, we can make many contributions as a national institute. There's measurement technology, and in some parts we are moving into the research area of vision science. That is leading to a big dream led by DOE, and I hope to contribute to it.

**(Tanaka)**
Japan has similar demands and issues, but perhaps we need a clear message in terms of policy.

**(Ono)**
Thank you very much for talking with us today. I felt there were many common points with *Synthesiology* that came to light.

**(Ohno)**
It was informative for me, too. Thank you very much.

**Profile of Yoshi (Yoshihiro) Ohno**

Currently, group leader of the Optical Sensor Group, Optical Technology Division, National Institute of Standards and Technology (NIST) in Maryland, U.S.A. Graduated from the School of Science and Technology, Kyoto Institute of Technology in 1977. Joined the Lighting Research Laboratory, Matsushita Electric Industrial Co. Ltd. (currently Panasonic Corporation) in 1977, and worked on photometry and colorimetry. Studied at NIST (formerly National Bureau of Standards) of the U.S.A. for two years from 1984, and engaged in research of absolute measurement integrating sphere. Received Ph.D. in engineering from Kyoto University in 1993. Immigrated to the United States in 1992, joined NIST, and was appointed Photometry Project Leader. Group leader from 2003. Currently Director of International Commission on Illumination (CIE) Division 2. Also active in American National Standards Institute (ANSI), Illuminating Engineering Society of North America IESNA, and International Committee of Weights and Measures (CIPM) - Consultative Committee of Photometry and Radiometry (CCPR).

# Editorial Policy

*Synthesiology* Editorial Board

## Objective of the journal

The objective of *Synthesiology* is to publish papers that address the integration of scientific knowledge or how to combine individual elemental technologies and scientific findings to enable the utilization in society of research and development efforts. The authors of the papers are researchers and engineers, and the papers are documents that describe, using "scientific words", the process and the product of research which tries to introduce the results of research to society. In conventional academic journals, papers describe scientific findings and technological results as facts (i.e. factual knowledge), but in *Synthesiology*, papers are the description of "the knowledge of what ought to be done" to make use of the findings and results for society. Our aim is to establish methodology for utilizing scientific research result and to seek general principles for this activity by accumulating this knowledge in a journal form. Also, we hope that the readers of *Synthesiology* will obtain ways and directions to transfer their research results to society.

## Content of paper

The content of the research paper should be the description of the result and the process of research and development aimed to be delivered to society. The paper should state the goal of research, and what values the goal will create for society (Items 1 and 2, described in the Table). Then, the process (the scenario) of how to select the elemental technologies, necessary to achieve the goal, how to integrate them, should be described. There should also be a description of what new elemental technologies are required to solve a certain social issue, and how these technologies are selected and integrated (Item 3). We expect that the contents will reveal specific knowledge only available to researchers actually involved in the research. That is, rather than describing the combination of elemental technologies as consequences, the description should include the reasons why the elemental technologies are selected, and the reasons why new methods are introduced (Item 4). For example, the reasons may be: because the manufacturing method in the laboratory was insufficient for industrial application; applicability was not broad enough to stimulate sufficient user demand rather than improved accuracy; or because there are limits due to current regulations. The academic details of the individual elemental technology should be provided by citing published papers, and only the important points can be described. There should be description of how these elemental technologies are related to each other, what are the problems that must be resolved in the integration process, and how they are solved (Item 5). Finally, there should be descriptions of how closely the goals are achieved by the products and the results obtained in research and development, and what subjects are left to be accomplished in the future (Item 6).

## Subject of research and development

Since the journal aims to seek methodology for utilizing the products of research and development, there are no limitations on the field of research and development. Rather, the aim is to discover general principles regardless of field, by gathering papers on wide-ranging fields of science and technology. Therefore, it is necessary for authors to offer description that can be understood by researchers who are not specialists, but the content should be of sufficient quality that is acceptable to fellow researchers.

Research and development are not limited to those areas for which the products have already been introduced into society, but research and development conducted for the purpose of future delivery to society should also be included.

For innovations that have been introduced to society, commercial success is not a requirement. Notwithstanding there should be descriptions of the process of how the technologies are integrated taking into account the introduction to society, rather than describing merely the practical realization process.

## Peer review

There shall be a peer review process for *Synthesiology*, as in other conventional academic journals. However, peer review process of *Synthesiology* is different from other journals. While conventional academic journals emphasize evidential matters such as correctness of proof or the reproducibility of results, this journal emphasizes the rationality of integration of elemental technologies, the clarity of criteria for selecting elemental technologies, and overall efficacy and adequacy (peer review criteria is described in the Table).

In general, the quality of papers published in academic journals is determined by a peer review process. The peer review of this journal evaluates whether the process and rationale necessary for introducing the product of research and development to society are described sufficiently well.

In other words, the role of the peer reviewers is to see whether the facts necessary to be known to understand the process of introducing the research finding to society are written out; peer reviewers will judge the adequacy of the description of what readers want to know as reader representatives.

In ordinary academic journals, peer reviewers are anonymous for reasons of fairness and the process is kept secret. That is because fairness is considered important in maintaining the quality in established academic journals that describe factual knowledge. On the other hand, the format, content, manner of text, and criteria have not been established for papers that describe the knowledge of "what ought to be done." Therefore, the peer review process for this journal will not be kept secret but will be open. Important discussions pertaining to the content of a paper, may arise in the process of exchanges with the peer reviewers and they will also be published. Moreover, the vision or desires of the author that cannot be included in the main text will be presented in the exchanges. The quality of the journal will be guaranteed by making the peer review process transparent and by disclosing the review process that leads to publication.

Disclosure of the peer review process is expected to indicate what points authors should focus upon when they contribute to this journal. The names of peer reviewers will be published since the papers are completed by the joint effort of the authors and reviewers in the establishment of the new paper format for *Synthesiology*.

## References

As mentioned before, the description of individual elemental technology should be presented as citation of papers published in other academic journals. Also, for elemental technologies that are comprehensively combined, papers that describe advantages and disadvantages of each elemental technology can be used as references. After many papers are accumulated through this journal, authors are recommended to cite papers published in this journal that present similar procedure about the selection of elemental technologies and the introduction to society. This will contribute in establishing a general principle of methodology.

## Types of articles published

*Synthesiology* should be composed of general overviews such as opening statements, research papers, and editorials. The Editorial Board, in principle, should commission overviews. Research papers are description of content and the process of research and development conducted by the researchers themselves, and will be published after the peer review process is complete. Editorials are expository articles for science and technology that aim to increase utilization by society, and can be any content that will be useful to readers of *Synthesiology*. Overviews and editorials will be examined by the Editorial Board as to whether their content is suitable for the journal. Entries of research papers and editorials are accepted from Japan and overseas. Manuscripts may be written in Japanese or English.

## Required items and peer review criteria (January 2008)

| | Item | Requirement | Peer Review Criteria |
|---|---|---|---|
| 1 | Research goal | Describe research goal ("product" or researcher's vision). | Research goal is described clearly. |
| 2 | Relationship of research goal and the society | Describe relationship of research goal and the society, or its value for the society. | Relationship of research goal and the society is rationally described. |
| 3 | Scenario | Describe the scenario or hypothesis to achieve research goal with "scientific words" . | Scenario or hypothesis is rationally described. |
| 4 | Selection of elemental technology(ies) | Describe the elemental technology(ies) selected to achieve the research goal. Also describe why the particular elemental technology(ies) was/were selected. | Elemental technology(ies) is/are clearly described. Reason for selecting the elemental technology(ies) is rationally described. |
| 5 | Relationship and integration of elemental technologies | Describe how the selected elemental technologies are related to each other, and how the research goal was achieved by composing and integrating the elements, with "scientific words" . | Mutual relationship and integration of elemental technologies are rationally described with "scientific words" . |
| 6 | Evaluation of result and future development | Provide self-evaluation on the degree of achievement of research goal. Indicate future research development based on the presented research. | Degree of achievement of research goal and future research direction are objectively and rationally described. |
| 7 | Originality | Do not describe the same content published previously in other research papers. | There is no description of the same content published in other research papers. |

# Instructions for Authors

*Synthesiology* Editorial Board
Established December 26, 2007
Revised June 18, 2008
Revised October 24, 2008
Revised March 23, 2009

## 1 Types of contributions

Research papers or editorials and manuscripts to the "Readers' Forum" should be submitted to the Editorial Board.

## 2 Qualification of contributors

There are no limitations regarding author affiliation or discipline as long as the content of the submitted article meets the editorial policy of *Synthesiology*, except authorship should be clearly stated. (It should be clearly stated that all authors have made essential contributions to the paper.)

## 3 Manuscripts

### 3.1 General

3.1.1 Articles may be submitted in Japanese or English.
Accepted articles will be published in *Synthesiology* (ISSN 1882-6229) in the language they were submitted. All articles will also be published in *Synthesiology - English edition* (ISSN 1883-0978). The English edition will be distributed throughout the world approximately four months after the original *Synthesiology* issue is published. Articles written in English will be published in English in both the original *Synthesiology* as well as the English edition. Authors who write articles for *Synthesiology* in Japanese will be asked to provide English translations for the English edition of the journal within 2 months after the original edition is published.
3.1.2 Research papers should comply with the structure and format stated below, and editorials should also comply with the same structure and format except subtitles and abstracts are unnecessary. Manuscripts for "Readers' Forum" shall be comments on or impressions of articles in *Synthesiology*, or beneficial information for the readers, and should be written in a free style of no more than 1,200 words. Editorials and manuscripts for "Readers' Forum" will be reviewed by the Editorial Board prior to being approved for publication.
3.1.3 Research papers should only be original papers (new literary work).
3.1.4 Research papers should comply with various guidelines of research ethics.

### 3.2 Structure

3.2.1 The manuscript should include a title (including subtitle), abstract, the name(s) of author(s), institution/contact, main text, and keywords (about 5 words).
3.2.2 Title, abstract, name of author(s), and institution/contact shall be provided in Japanese and English.
3.2.3 The manuscript shall be prepared using word processors or similar devices, and printed on A4-size portrait (vertical) sheets of paper. The length of the manuscript shall be, about 6 printed pages including figures, tables, and photographs.
3.2.4 Research papers and editorials shall have front covers and the category of the articles (research paper or editorial) shall be stated clearly on the cover sheets.
3.2.5 The title should be about 10-20 Japanese characters (5-10 English words), and readily understandable for a diverse readership background. Research papers shall have subtitles of about 15-25 Japanese characters (7-15 English words) to help recognition by specialists.
3.2.6 The abstract should include the thoughts behind the integration of technological elements and the reason for their selection as well as the scenario for utilizing the research results in society.
3.2.7 The abstract should be 300 Japanese characters or less (125 English words). The Japanese abstract may be omitted in the English edition.
3.2.8 The main text should be about 9,000 Japanese characters (3,400 English words).
3.2.9 The article submitted should be accompanied by profiles of all authors, of about 200 Japanese characters (75 English words) for each author. The essential contribution of each author to the paper should also be included. Confirm that all persons who have made essential contributions to the paper are included.
3.2.10 Discussion with reviewers regarding the research paper content shall be done openly with names of reviewers disclosed, and the Editorial Board will edit the highlights of the review process to about 3,000 Japanese characters (1,200 English words) or a maximum of 2 pages. The edited discussion will be attached to the main body of the paper as part of the article.
3.2.11 If there are reprinted figures, graphs or citations from other papers, permission for citation, if needed, should be clearly stated and the sources should be listed in the reference list. All verbatim quotations should be placed in quotation marks or marked clearly within the paper.

### *3.3 Format*

3.3.1 The headings for chapters should be 1, 2, 3…, for subchapters, 1.1, 1.2, 1.3…, for sections, 1.1.1, 1.1.2, 1.1.3.
3.3.2 The text should be in formal style. The chapters, subchapters, and sections should be enumerated. There should be one line space before each paragraph.
3.3.3 Figures, tables, and photographs should be enumerated. They should each have a title and an explanation (about 20-40 Japanese characters or 10-20 English words), and their positions in the text should be clearly indicated.
3.3.4 For figures, clear originals that can be used for printing or image files (resolution 350 dpi or higher) should be submitted. In principle, the final print will be 15 cm × 15 cm or smaller, in black and white.
3.3.5 For photographs, clear prints (color accepted) or image files should be submitted. Image files should specify file types: tiff, jpeg, pdf, etc. explicitly (resolution 350 dpi or higher) . In principle, the final print will be 7.2 cm × 7.2 cm or smaller, in black and white.
3.3.6 References should be listed in order of citation in the main text.

Journal – [No.] Author(s): Title of article, *Title of journal*, Volume(Issue), Starting page-Ending page (Year of publication).

Book – [No.] Author(s): *Title of book*, Starting page-Ending page, Publisher, Place of Publication (Year of publication).

## 4 Submission

One printed copy or electronic file of manuscript with a checklist attached should be submitted to the following address:

*Synthesiology* Editorial Board
c/o Publication Office, Public Relations Department, National Institute of Advanced Industrial Science and Technology(AIST)
Tsukuba Central 2, Umezono 1-1-1, Tsukuba 305-8568
E-mail: synthesiology@m.aist.go.jp

The submitted article will not be returned.

## 5 Proofreading

Proofreading by author(s) of articles after typesetting is complete will be done once. In principle, only correction of printing errors are allowed in the proofreading stage.

## 6 Responsibility

The author(s) will be solely responsible for the content of the contributed article.

## 7 Copyright

The copyright of the articles published in “*Synthesiology*” and “*Synthesiology English edition*” shall belong to the National Institute of Advanced Industrial Science and Technology(AIST).

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# Letter from the editor

I am glad we were able to publish *Synthesiology* Volume 2, Issue 2, although slightly behind schedule. In this issue, there are six original papers of diverse contents including topics in materials, sensors, measurement standards, geology, manufacturing technology, systems, and research management. I was reminded of the fact that the synthetic approach in researches that incorporate various factors are now being conducted in various scenes and at various scales, and they are forming somewhat of a fractal structure. Dr. Nakamura's paper describes the activities of researchers and research organizations spanning a period of 30 years. Dr. Sangawa's paper introduces archaeology to address a subject in the time frame of one thousand years. By obtaining knowledge that could not be gained by conventional methods, earthquake prediction, a synthetic approach, can be more precise. They are papers of grand scale from the perspectives of organizational management as well as of a life work of a researcher. One of the points common to these synthetic approaches is the stance that any means will be taken to achieve the end.

Using the opportunity of the visit by Dr. Ohno of the National Institute of Standards and Technology, USA, we held a three-cornered talk involving editors Ono and Tanaka. Dr. Ohno has his roots in a Japanese electric company, and is a researcher who is well versed in the process from basic research to product realization. To promote synthetic approach, it is necessary to have the sponsors understand the impact the research will ultimately have on society. Dr. Ohno uses the lighting demonstration very nicely. In the three-cornered talk, there is a story about poor presentation of red color, and he shows how the red looks bad by using slices of tuna of sushi. Japanese food probably contributed in promoting synthetic approach in research in the United States.

As educational training at AIST, we established the Innovation School for post-doctorates. At this School, we used *Synthesiology* as an important text in presentations with free discussions. In these sessions, the students presented the content of the paper and what they learned as *Synthesiology*, and then all participants joined in the discussion. The students of the School all are engaging in research in their respective fields, but some people selected papers that were outside of their fields. In the discussions, the students understood the main points of the papers even though the subjects were not within their specialty, and some made astute comments on the papers. I felt one of the good points of *Synthesiology* papers is people can comment on researches of non-specialty areas. I also strongly felt that it is very important to see through the eyes of different fields to advance synthetic approach. Although this was our first School attempt, it was worth the while to learn that *Synthesiology* could serve as an excellent textbook for people engaged in a wide range of R&D, as well as for management of technology studies. I hope some of the readers will consider using *Synthesiology* as educational material.

We started out by asking the AIST researchers to submit their original papers, but now we have voluntary submissions as well as submissions from outside AIST. I believe there are many people who have their own thoughts and comments about synthetic approach in research. I hope there will be further active submissions from various places that will allow us to accumulate the knowledge of *Synthesiology*.

Executive Editor
Motoyuki Akamatsu

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## Messages from the editorial board



*"Synthesiology-English edition" is a translated version of "Synthesiology" which is published quarterly, ISSN 1882-6229, by AIST. Papers or articles published in "Synthesiology-English edition" appear approximately four months after the publication of the original "Synthesiology".*

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