Vol.3 No.3 December 2010

ISSN 1883-0978 (Print)
ISSN 1883-2318 (Online)

Synthesiology

English edition

An optimum design method utilizing a strategic system design concept

A methodology for improving reliability of complex systems

National electrical standards supporting international competition of Japanese manufacturing industries

Development of a sensor system for animal watching to keep human health and food safety

Synthesiology editorial board

2010 3

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,

"*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". The views expressed in translated version are exclusively those of the Japanese authors and editors. The Japanese authors are generally consulted regarding the translation of their papers, but are not responsible for the published English version.*

Papers or articles in the "*Synthesiology" originally submitted in English are also reproduced just as they were published in* "*Synthesiology". Some papers or articles in* "*Synthesiology" are not translated due to the authors' or editors' judgement.*

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.3 No.3 (Dec. 2010)

Contents

An optimum design method utilizing a strategic system design concept

— Reduction of CO_2 emissions at a datacenter by reusing emitted heat for agriculture —

Jiro Fukuda[1]* and Taketoshi Hibiya[2]

[Translation from *Synthesiology*, Vol.3, No.3, p.190-196 (2010)]

Datacenters are important infrastructures of information and communication technology (ICT). Reducing electric-power consumption and the CO_2 emissions at the centers are urgent issues from the viewpoint of global environmental concerns. Improvement of efficiency within a single datacenter, however, cannot assure significant reduction of CO_2 emissions. Hence we propose the concept of "strategic system design", which optimizes system design by combining different stake-holders not only from the viewpoint of the "physical system" but also from that of the "value system". As an example, a system in which greenhouse cultivation farms reuse emitted heat at datacenters was considered from both the physical side and the value side. The complex system designed by such a strategic system design idea was found to be effective in reducing CO_2 emissions compared with a single isolated system, and was clarified to be an excellent value system.

Keywords **:** Datacenter, global environment, system design, emitted heat, greenhouse business

1 Introduction

Information and communication technology (ICT) has greatly contributed to the reduction of CO_2 emissions through efficient energy use and conservation by avoiding redundancy in economic activities and by enabling efficient transportation and its alternatives. However, power consumption in offices and homes is increasing due to the wide uptake of ICT, and as a result, it has become one of the main factors that push up CO_2 emissions in Japan. If this increase continues, ICT power consumption in 2025 will be 5.2 times more than 2006, dominating 25 % of the total power generated in Japan[Note 1]. The reduction of power consumption in the ICT field is a major issue.

Particularly, datacenters equipped with multiple servers consume a large amount of electric power, and power consumption increases every year. From the perspective of preventing global warming, energy consumption and reduction of CO_2 emissions are becoming major issues. Therefore, the Japanese datacenter industry is working to introduce efficient servers, air conditioners, and power supply facilities. However, the potential of efforts to increase energy efficiency for a single datacenter alone is limited, and a design approach that looks at the essence of the issue is in demand.

Therefore, as a new design approach, we propose the "strategic system design" in which the systems of multiple companies are combined. As an example of the strategic system design, we shall explain that a composite system, in which low-temperature waste heat from a datacenter is reused in greenhouse farming, is an effective use of energy that is also economically feasible.

2 Limit in achieving efficiency by a single datacenter

The energy flow and energy consumption configuration in a typical datacenter is shown in Fig. 1 and Table 1. The model considered here is a datacenter with maximum capacity of 1,000 racks (actual operation rate 85 %) and maximum power supply at 6 kW/rack (average 4.2 kW/rack). When the power consumption of the entire datacenter is simulated, and the simulated figure is multiplied with an emission coefficient published by electricity companies[Note 2], the CO_2 emissions are as shown in Table 2.

One of the effective methods for improving energy efficiency, when considering power consumption of air conditionings at the datacenter, is to raise the air conditioning efficiency by constructing the datacenter in a cold climate area. For example, comparing Sapporo and Tokyo where there are

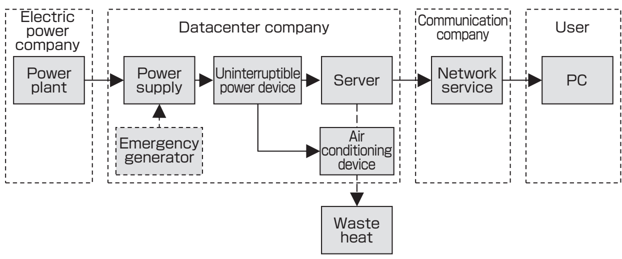


Fig. 1 Energy flow of the datacenter

1. Graduate School of System Design and Management, Keio University / Mitsubishi Research Institute, Inc. 2-3-6 Otemachi, Chiyoda-ku 100-8141, Japan * E-mail : mr-fukuda@mri.co.jp, 2. Graduate School of System Design and Management, Keio University 4-1-1 Hiyoshi, Kohoku-ku, Yokohama 223-8256, Japan

Original manuscript received January 15, 2010, Revisions received May 31, 2010, Accepted June 15, 2010

many datacenters, there is a temperature difference of about 5~10 °C per year[Note 3]. It is projected that the power consumption of air conditioning can be reduced about 8 % by constructing the datacenter in cold climate areas such as Sapporo (Table 2). Conversely, the power consumption of air conditioning increases about 8 % in warm areas such as Naha. However, since the power consumption of air conditioning is about 30 % of the total power consumption of a datacenter, only about 2 % total reduction can be expected between Tokyo and Sapporo (Table 2).

Another method for improving air conditioning efficiency is a method called "capping" where the racks are surrounded by panels to prevent the mixing of waste heat from servers and cold air from air conditioners (Fig. 2)[Note 4]. While this allows reduction of about 20 % of the power consumption of air conditioning, it is projected that the reduction will be about 5 % of the total power consumption of the datacenter (Table 2).

As it can be seen, there are limitations in achieving energy consumption efficiency for a single stand-alone datacenter, and a radical technological innovation or some new design approach is necessary to achieve significant CO_2 reduction.

3 Proposal of the strategic system design

3.1 Physical system and value system

We propose a new design approach through "strategic system design", a concept that transcends the conventional approach to optimizing stand-alone datacenters (a single system).

Figure 3 shows the concept of the strategic system design. In conventional system design, evaluation and optimization were conducted from the perspective mainly of physical performance of a single system. However, a system has a stakeholder who has a vested interest in that system, and therefore, evaluation of a system is based on what is valuable for the stakeholder. The value is dependent on the psychological values of the stakeholder, and while monetary matter is not the only concern, using the monetary scale allows generalization and quantification.

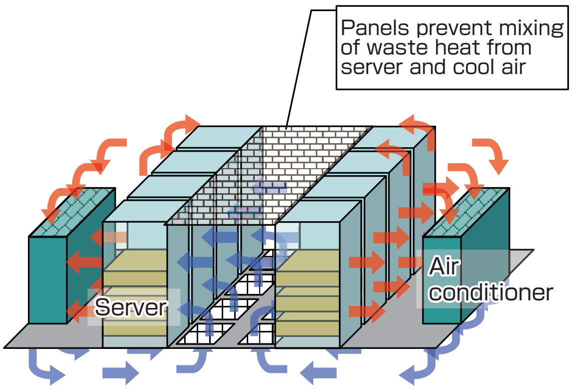


Fig. 2 Example in achieving efficiency of air conditioner by capping

Table 1 Details of energy consumption at the datacenter

Power consumption of server	58 %
Power consumption of air conditioner	27 %
Power supply facility, uninterruptible power supply	13 %
Lighting etc.	2 %

Table 2 Location of the datacenter and CO_2 emission

	Tokyo	Sapporo	Naha	Tokyo Aisle capping	Sapporo Aisle capping
Power consumption of air conditioner (MWh/year)	15,599	14,393	16,810	12,479	11,514
	100.0 %	92.3 %	107.8 %	80.0 %	73.8 %
Power consumption of entire datacenter (MWh/year)	57,817	56,611	59,029	54,697	53,733
	100.0 %	97.9 %	102.1 %	94.6 %	92.9 %
PUE*1	1.72	1.69	1.76	1.63	1.60
Power cost (million yen/year)	694	679	708	656	644
	100.0 %	97.8 %	102.0 %	94.5 %	92.8 %
CO_2 emission coefficient*2 kg-CO_2/kWh	0.339	0.479	0.934	0.339	0.479
CO_2 emission (t/year)	19,600	27,117	55,133	18,542	25,738
	100.0 %	138.4 %	281.3 %	94.6 %	131.3 %

*1 PUE (power use effectiveness) = power consumption of entire datacenter / power consumption of server.
*2 Figures for FY 2006 are according to the source from the Ministry of Environment (figures for Naha are for FY 2007).
Numbers below the dashed line are comparisons when Tokyo is set as 100 %.

The system exists in two spaces: the physical system that exists in the physical space, and the value system that exists in the psychological space of the stakeholder.

The datacenter is composed of the "physical system" including the building, power supply, air conditioner, racks, and others, and the "value system" for the company in the form of sales generated by the physical system.

In this case, the optimization of the physical system and the optimization of the value system do not necessarily coincide. In case of the datacenter, the optimization of the physical system means minimizing the power consumption, while the optimization of the value system means maximizing the profit by minimizing the cost. While the minimization of power consumption and minimization of cost run in the same direction, the two may not match. For example, the introduction of a highly efficient facility will reduce power consumption, but the cost may increase due to the high facility cost. If the value decreases, the company will not introduce the new facility even if it is highly efficient.

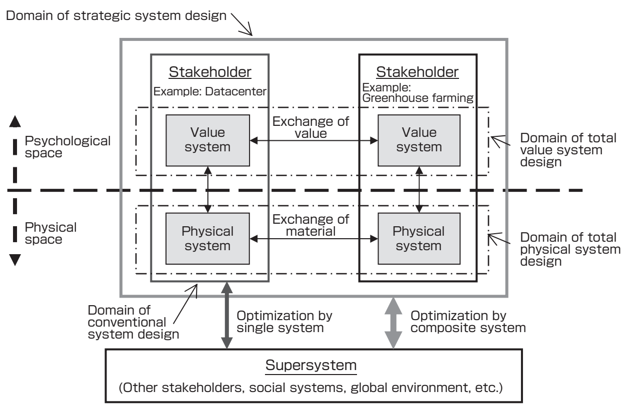


Fig. 3 Concept of strategic system design

No matter how the system is physically excellent, it cannot be realized unless it is also excellent in the value space. To realize a system, one must design the value system, which is a system that generates actual value.

3.2 System of other stakeholders and the supersystem

The actual system has mutual interaction with the systems of other stakeholders in both the physical and value systems (Fig. 4).

The system is also incorporated into the “supersystem” composed of multiple physical entities and stakeholders. The supersystem is a large physical and value system that influences the existence, performance, and value of the system including, for example, the global environment or the social system. The supersystem influences the individual systems in various ways and sets requirements. A system changes according to the other systems and the supersystem, and must optimize itself accordingly.

In the case of datacenters, the requirement is to minimize CO_2 emissions through the regulations by the social system such as public opinion or environment tax imposed for the purpose of preventing global warming.

In the conventional system design, optimization to meet this requirement was met in accordance with the perspective of a single stakeholder who possessed the system. The system was designed to maximize value for the single stakeholder, and in many cases, value for other stakeholders and the resource allotment were not taken into consideration.

For example, in the case of datacenters, attempts were made to reduce the CO_2 emissions by achieving efficiency of the devices in the datacenter only, such as optimizing air conditioning infrastructure that cools servers.

However, drastic reduction of CO_2 emissions is physically difficult with the improvement of datacenter facilities alone.

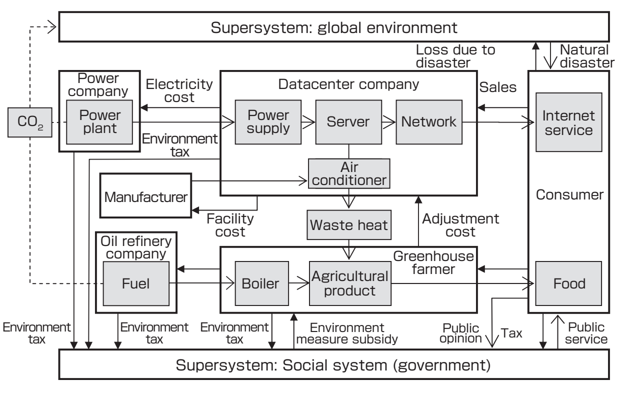


Fig. 4 Systems of other stakeholders surrounding the datacenter and the supersystem

Moreover, in the value space, it is difficult for a single company to increase its value (profit) because expensive facility investment may suppress profit margins and furthermore, environmental taxes may be imposed.

For major issues such as environmental improvement required by the supersystem, there is a limit in the optimization effort that can be handled within the system by a single stakeholder.

3.3 Design optimization using the strategic system design

On the other hand, issues required to be addressed by the supersystem are also placed on other stakeholders. Therefore, design optimization using the “strategic system design” is an attempt to optimize the requirements from the supersystem by combining the systems of multiple stakeholders, and to raise the values of all stakeholders involved.

The physical systems of the individual stakeholders exist in a common physical space. Therefore, they can be optimized as a single system as they are influenced equally by a common physical law and can be combined through physical exchange. This is the “total physical system design” (Fig. 3). Using datacenters as an example, waste heat can be reused for heating greenhouses.

The result of the optimization of a physical system may not necessarily mean optimal value for the stakeholders of different systems. For example, reusing waste heat from the datacenter may be a cost reduction to the farmer, but it will be a cost increase for the datacenter company due to the need for additional facilities. To realize the waste heat reuse system, it is necessary to design a value system that increases the values for the two stakeholders, or both the datacenter company and the farmer. This need is coined as “total value system design” (Fig. 3).

It is necessary to implement some mechanism for adjusting the value, such as a contract whereby the farmer pays the cost (adjustment cost) of using the waste heat to the datacenter company.

The “strategic system design” can be defined as the optimization by designing the “total physical system” and the “total value system” between the systems of different stakeholders.

4 Proposal for a composite datacenter through strategic system design

4.1 Total physical system design for a composite datacenter through strategic system design

To achieve optimization in response to the social requirement for the reduction of CO_2 emissions based on the concept of a strategic system design, a composite datacenter that combines the datacenter and agriculture is designed to review the effectiveness quantitatively.

First, a datacenter seen from the physical aspect is considered. Looking at the energy flow of the datacenter in Fig. 1, most of the energy is emitted from the datacenter as heat. The electricity consumed by the CPU for computation is less than 1 % of the overall energy.

A more efficient system can be proposed by combining the business and system for reusing the waste heat from the datacenter (Fig. 5). The businesses that may reuse waste heat include: cooling/heating and hot water supply in offices, residences, and hospitals; warm water supply for bath, pool, and plants; and heating for greenhouse farming. In heating for greenhouse farming, the required temperature is relatively low, the time change for heat demand is relatively stable, and the waste heat from the datacenter that serves as a low-temperature heat source can be used directly in the form of warm air. Therefore, this system is a likely candidate for adoption by a business that employs waste heat from the datacenter. Also, the farmer can see a direct benefit because the majority of the cost of greenhouse farming during winter is dominated by heating fuel cost (Fig. 6).

An estimate is carried out for the effects of reductions in fuel cost and CO_2 emissions, assuming the greenhouse heating using waste heat from the datacenter in the Utsunomiya area, which is a relatively cold area and is within the supply region of the Tokyo Electric Power Company that is a power company with least CO_2 emission coefficient in Japan.

The assumed model datacenter has a maximum capacity of 1,000 racks (actual operation rate 85 %) with a maximum power supply of 6 kW/rack (average 4.2 kW/rack). It is assumed that the waste heat from the air conditioners of the datacenter will be used for heating a greenhouse, and the necessary amount of heat needed to heat the greenhouse to 15 °C or higher during the winter period from October 1 to May 31 is calculated. As a result of the estimation, the amount of heat generation from the datacenter reaches

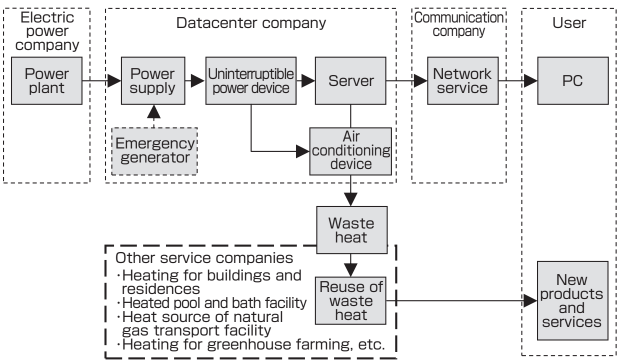


Fig. 5 Energy flow of the composite datacenter

Table 3 Reduction in CO_2 emission by a composite datacenter

Waste heat from entire datacenter (Utsunomiya)	MJ/day	566,308
Surface area of greenhouse	m^2	88,100
Reduction in heating fuel (kerosene)	kL/year	1,709
Cost reduction of heating fuel	1,000 yen	189,734
Reduction in CO_2 emission by reduction of heating fuel	t-CO_2	4,256
CO_2 emission from datacenter	t-CO_2	19,464
Rate of reduction of CO_2 emission seen from datacenter	%	-21.9 %
Rate of reduction of CO_2 emission of datacenter + greenhouse	%	-17.9 %

566,300 MJ/day, and this corresponds to combustion of 12.6 kL/day of kerosene. Even considering the reduction of heating efficiency, this amount is capable of heating a greenhouse of 88,100 m^2 size during the midwinter period (Table 3)[Note 5)].

This will allow a reduction of cost needed for greenhouse heating by about 190 million yen per year, and CO_2 will be reduced by 4,256 t per year. This corresponds to 21.9 % of CO_2 emitted by the datacenter, and the combination of the datacenter and the greenhouse will have a CO_2 reduction effect of 17.9 % (Table 3). Dramatic reduction in CO_2 emissions can be expected by compositing the datacenter and the greenhouse.

4.2 Total value system design for a composite datacenter through strategic system design

Unless the two stakeholders, the datacenter company and the greenhouse farmer, accept the values (stakes), it is not possible to realize optimization by achieving the physical system. Therefore, we shall investigate the value design of the composite system of the datacenter and the greenhouse.

4.2.1 Condition when the datacenter alone invests in environmental measures

The profit of datacenter company is set as P_0, the sales of service is S, and the energy cost is EC. It is assumed that an environment tax (TC) is introduced by the social system that attempts to control the CO_2 emissions of the energy consumption. The company makes an environment measure investment (IC) such as introducing efficient air conditioning to minimize profit reduction, and attempts to reduce the energy cost and environment cost. Here, the condition under which the environment measure investment IC is conducted is when the sum of reduced energy cost ΔEC_2 and the reduced environment tax ΔTC_2 is higher than the investment IC, as

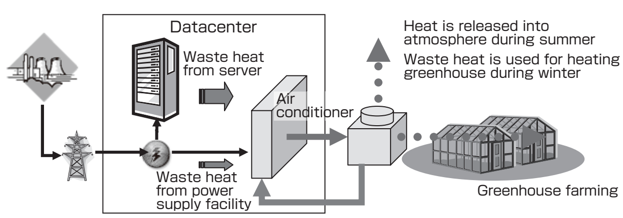


Fig. 6 Use of waste heat from datacenter in farming

shown below (Fig. 7).

$$P_2 \geqq P_1 \quad \Delta EC_2 + \Delta TC_2 \geqq IC \qquad (1)$$

Moreover, when the amount of reduced cost $\Delta EC_2 + \Delta TC_2$ is higher than the sum of environment measure investment IC and environment tax TC, the profit after measure P_2 will be higher than the profit before environment tax P_0, and the company will engage more actively in environment measure investment (Fig. 7).

$$P_2 \geqq P_0 \quad \Delta EC_2 + \Delta TC_2 \geqq TC + IC \qquad (2)$$

However, in practice, it is extremely difficult to fulfill the conditions of (1) and (2) by the effort of the datacenter company alone due to technological limitations.

4.2.2 Two conditions for multiple companies

Next, value design is done for the case where the datacenter company X recovers waste heat energy and the greenhouse farmer Y reuses it.

In this case, the environment measure investment will be conducted to improve the facility, if the total of the cost reduction by both parties $\Delta EC_2x + \Delta TC_2x + \Delta EC_2y + \Delta TC_2y$ surpasses the total environment measure investment ICx + Icy.

$$\Delta EC_2x + \Delta TC_2x + \Delta EC_2y + \Delta TC_2y \geqq ICx + ICy \qquad (3)$$

X and Y are different businesses, and they attain the advantage of significant cost reduction by Y reusing the waste heat from X. To reallocate the advantage between X and Y, it is necessary to conduct some monetary adjustment (AD). Here, the model considered is that in which the greenhouse farmer pays the adjustment cost AD to the datacenter company as the cost of used waste heat.

$$\Delta EC_2x + \Delta TC_2x + AD \geqq ICx$$
$$\Delta EC_2y + \Delta TC_2y - AD \geqq ICy \qquad (4)$$

When condition (4) is fulfilled, X and Y can reduce the profit decrease due to the addition of external measures through investments ICx and ICy, and the two businesses can join hands to take measures (Fig. 8).

Moreover, in the case of condition (5) shown below, the sum of the reduced costs of the two businesses $\Delta EC_2x + \Delta TC_2x + \Delta EC_2y + \Delta TC_2y$ will be greater than the total of the environment tax and environment measure investment TCx + TCy + ICx + ICy, and both businesses can increase profit ability compared to before the imposition of the environment tax (Fig. 8).

$$\Delta EC_2x + \Delta TC_2x + AD \geqq TCx + ICx$$
$$\Delta EC_2y + \Delta TC_2y - AD \geqq TCy + ICy \qquad (5)$$

To realize the composite system in which greenhouse farming uses the waste heat energy from the datacenter, it is necessary to introduce the facility cost ICy that fulfills the conditions of (4) or (5), the facility of ICx, as well as the adjustment cost AD.

4.2.3 Value evaluation of the composite datacenter in case environment tax is imposed

Assuming the case when environmental taxes are introduced by the social system that attempts to control emissions, calculations are done for the single datacenter and the composite datacenter in which the waste heat is used for greenhouse farming, using the model of environment tax rate 2,400 yen/t-CO_2 (electricity 0.25 yen/kWh, kerosene 0.82 yen/L) assumed by the Ministry of Environment in October 2005[Note 6]. Assuming a single datacenter with 1,000 racks and 6 kW/rack located in Tokyo, the annual power consumption is 57,817 MWh. Other than the annual electricity cost EC = 693,807 thousand yen, the annual environment tax TC = 14,454 thousand yen will be required.

When capping, the most effective measure, is done, the annual power consumption will be 54,697 MWh, and this will be a power cost reduction (ΔEC_2) of 37,437 thousand yen per year and an environment tax reduction (ΔTC_2) of 780 thousand yen per year. However, the acceptable upper limit of the facility investment IC for CO_2 reduction must be less than 38,217 thousand yen per year. The investment per rack

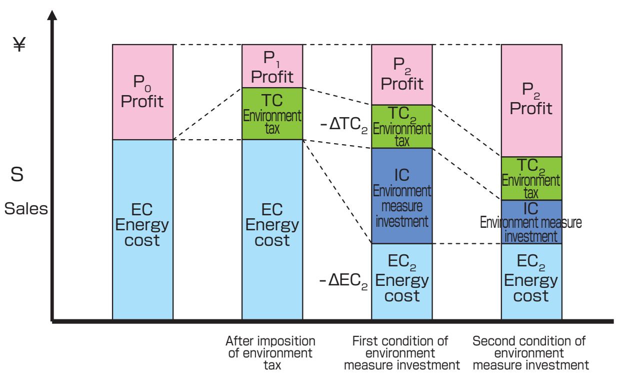


Fig. 7 Earnings from a single datacenter

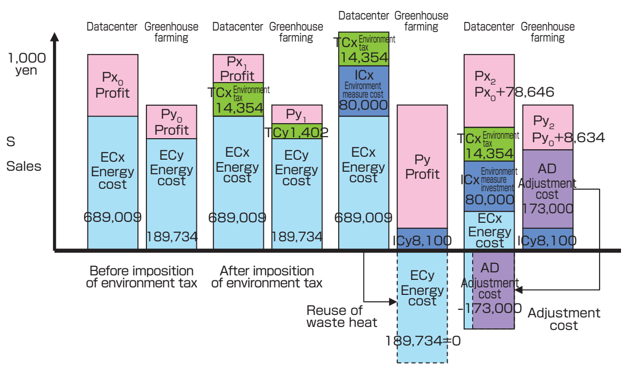


Fig. 8 Earnings from a composite datacenter

is 224 thousand yen (at an amortization period of 5 years) or less. Comparing this to the general cost needed for capping, the figures are unrealistic. If capping could be done at 200 thousand yen per rack, the amount of cost reduction for the datacenter as a whole will be merely 4,217 thousand per year. It is quite impossible to achieve the condition (2) where the profit can be increased more than before tax imposition.

Next, we assume a composite datacenter with the same 1,000 racks and 6 kW/rack located in Utsunomiya, and the greenhouse of 88,100 m^2 size that uses the waste heat.

The annual power consumption of the datacenter is 57,417 MWh, and the annual power cost ECx = 689,006 thousand yen and annual environment tax TCx = 14,354 thousand yen must be paid by the datacenter company. On the other hand, by reusing waste heat, the annual fuel consumption 1,709 kL and the annual fuel cost ECy = 241,390 thousand yen for the greenhouse heating become 0, and the annual CO_2 emissions of 4,256 t and environment tax TCy = 1,402 thousand yen can be reduced. The upper limit of the annual facility investment ICx + ICy appropriate for this reduction effect is less than 191,135 thousand yen (1,124 thousand yen per rack). There is about five times cost difference compared to a single datacenter. Assuming the annual facility investment at 88,100 thousand yen (1,032 thousand yen per rack), compared to before environment tax imposition, the datacenter company will experience a profit increase of 78,646 thousand yen a year, and the greenhouse farmer will see 8,634 thousand yen more profit. With the composite datacenter, it is possible to design a system with high CO_2 reduction in terms of the environment, and the company and the farmer can both enjoy high earnings.

5 Summary

Strategic system design is a comprehensive design of the physical space and the psychological (value) space of the different stakeholders.

As a result of investigating the design of a datacenter for the purpose of CO_2 reduction, the following points became apparent.

(1) In the design optimization of a single datacenter using the conventional design approach, the effect of physical CO_2 emission reduction is limited, the maximum amount that can be invested for environmental improvement in terms of value is small, and facility investment is difficult. Also, it is almost impossible to maintain the same profit as before the imposition of environmental taxes.

(2) In the case of the composite system where the waste heat of a datacenter is used for greenhouse farming by employing the concept of total physical system design, the overall

Table 4 Environment measure investment and improvement of earnings

		iDC capping	iDC+ greenhouse farming
Datacenter location		Tokyo	Utsunomiya
Energy cost of datacenter	1,000 yen/year	656,370	689,009
Environment tax of datacenter	1,000 yen/year	13,674	14,354
Energy cost of greenhouse farming (before use of waste heat)	1,000 yen/year	—	189,734
Environment tax of greenhouse farming (before use of waste heat)	1,000 yen/year	—	1,402
Energy cost reduction by facility investment	1,000 yen/year	37,437	189,734
Environment tax reduction by facility investment	1,000 yen/year	780	1,402
Reduction of CO_2 emission	t-CO_2	1,058	4,256
Effect of reduction of CO_2 emission	%	-5.4 %	-17.9 %
Upper limit of allowable facility investment	1,000 yen/year	38,217	191,135
Per rack	1,000 yen/rack	224	1,124
Upper limit of facility investment for increasing profit	1,000 yen/year	23,763	175,379
Per rack	1,000 yen/rack	140	1,032
Calculation for the model case			
Amount of facility investment by datacenter	1,000 yen/year	34,000	80,000
Amount of facility investment by greenhouse farmer	1,000 yen/year	—	8,100
Cost reduction for datacenter after imposition of environment tax	1,000 yen/year	4,217	93,000
Cost reduction for greenhouse farming after imposition of environment tax	1,000 yen/year	—	10,036
Increase/decrease of profit compared to before tax imposition (datacenter)	1,000 yen/year	-10,237	78,646
Increase/decrease of profit compared to before tax imposition (greenhouse farmer)	1,000 yen/year	—	8,634
Amount of adjustment between datacenter and greenhouse farmer	1,000 yen	—	173,000

CO_2 emission reduction is 17.9 %, and there is potential for achieving greater environmental improvement.

(3) As a value system based on total value system design, by introducing the contract system where the greenhouse farmer pays an adjustment cost for the use of waste heat to the datacenter company, it is possible to maintain sufficient facility investment even after the imposition of the environment tax. This shows the potential of increasing the value by expanding the profit more compared to before the imposition of environmental taxes.

(4) The possibility is shown for designing an efficient system in terms of physical performance and cost-effectiveness through strategic system design for multiple stakeholders, in comparison to the conventional strategic system design that targets single stakeholders.

The basic thinking of the strategic system design of attaining overall optimization by satisfying all stakeholders involved, while maintaining the overall balance of the physical system and values, can be applied to regional cooling and heating reusing the waste heat from plants and power plants, and is not limited to the relationship of datacenters and farming. It can be applied to the realization of new composite systems between the stakeholders with different goals in society, such as the smart grid where the batteries of the electric vehicles parked at home are used as the batteries of the electrical network of the entire society.

In the future, we shall investigate using strategic system design for the optimization of more complex systems such as the composite system with three or more stakeholders, by adding solar power generation to the two-stakeholder system of the datacenter and farming.

Acknowledgments

This research was conducted as a part of the Center for Education and Research of Symbiotic, Safe and Secure System Design, Global COE Program, Keio University. We are thankful to Professor Haruki Sato, Graduate School, Keio University, who provided us with discussions on the use of waste heat.

Notes

Note 1) 25 % of total national power generation: Projection of energy consumption by IT devices, *IT Policy Roadmap*, 31P, 2008.6.11 (Strategic Headquarters for the Promotion of an Advanced Information and Telecommunications Network Society)

Note 2) Emission coefficient of the power companies: On the publication of the emission coefficients by power companies for FY 2006, 2008.9.27 (Ministry of Environment)

Note 3) Temperature difference between Tokyo and Sapporo: Climate statistics information 2008 (Japan Meteorological Agency)

Note 4) Capping: Rack air conditioning system, Patent Publication 2009-257730, 2009.11.5 (NTT Facilities, Inc.)

Note 5) Heating for greenhouse: Fuel consumption estimate tool for greenhouse heating (prototype Ver.0.90), 2008.2.25 (Advanced Greenhouse Production Research Team, National Institute of Vegetable and Tea Science, National Agriculture and Food Research Organization)

Note 6) Environment tax rate: Specific plan for environment tax, 2005.10.25 (Ministry of Environment)

Authors

Jiro Fukuda

Senior researcher, Strategic Consulting Room, Mitsubishi Research Institute, Inc. Completed the masters program for mechanical engineering at the Faculty of Science and Engineering, Waseda University. Currently enrolled in the doctorate program at the Graduate School of System Design and Management, Keio University. After joining the Mitsubishi Research Institute in 1989, worked as a consultant for Government and agencies on social systems such as tax system, technological development plan, traffic system, and medical information system. Recently, engaged in consulting for Internet business and Internet datacenter, and supports the activities of the Japan Datacenter Council. In this paper, proposed the strategic system design and conducted simulation estimates.

Taketoshi Hibiya

After working as a senior researcher of Fundamental Research Labs, NEC Corporation, visiting professor of Tokyo Institute of Technology, and professor of Tokyo Metropolitan University, currently working as the professor of the Graduate School of System Design Management, Keio University. Doctor of Engineering. Worked on the development of electronics material, heat property measurements of high-temperature melt, and material process research in zero gravity using rockets and aircrafts. In this paper, considered the composition of datacenter and greenhouse farming from the perspective of system design management.

Discussions with Reviewers

1 Hierarchy of the system

Question (Koh Naito, Center for Service Research, AIST)

The terminologies such as “single system”, “supersystem”, “social system”, and “stakeholders” are used. Please explain how each system is related to one another.

Answer (Jiro Fukuda)

The systems have various levels such as personal, organizational, social, and global levels. They have a hierarchical, stratified structure and influence each other. This paper intends to point out the existence of various stakeholders outside the single system. The effect on the system and the optimal solution under a certain environment on the scale, attribute, and structure of the stakeholders shall be the subjects for future research. In this paper, we explain the optimization in the simplest combination involving two stakeholders and the external environment of environment tax imposition.

2 Case of the datacenter

Question (Akira Yabe, AIST)

I think the proposal of the concept of strategic system design and the discussion of the combination of multiple systems from the perspective of physical and value systems is a unique way of thinking. For example, I can think of many applications of this concept such as the combination for using biomass and waste disposal, as in the use of the waste material from the manufacture of distilled spirits as fertilizer. However, it is said to be unrealistic to apply this concept to the reuse of waste heat from datacenters. This is because the efficient use of low-temperature waste heat has been discussed for a long time as an issue of efficient use of waste heat from power plants, and there have been many discussions assuming various physical and value systems, and we have not yet been able to propose any economically feasible applications. Yet, I think you are proposing a very unique and useful concept. I think it will be convincing if you present this thinking as an analysis of the case that has been realized. What do you think about this point?

Answer (Jiro Fukuda)

In the latest datacenters, there are places that use outdoor air-cooling, where the outside air is directly taken in to cool the server and the heat is released outside of the building, alongside cooling using the heat pump. I think it is possible to maintain the temperature necessary for greenhouse farming using waste heat from the datacenter. There are cases of successful greenhouse farming using waste heat in the Japanese datacenters as a physical system (IDC Frontier: Press release – The effect of outdoor air conditioning was confirmed in the demonstration experiment of Asian Frontier of the IDC Frontier; the reduction in power consumption of air conditioning was maximum 40 %; efficacy of use of waste heat in agriculture was also confirmed, 2010.3.29). Also, the calculations are done assuming that the waste heat during summer is unused, but the result shows that the reuse of energy in winter alone is sufficiently economically feasible. Even considering the environment tax that is expected to be imposed in the near future, I think it is one of the factors that lead to the increased value of waste heat use.

In this paper, our goal is to establish both the physical and value (economic) feasibility that cannot be optimized by a single stakeholder, by taking the strategic viewpoints including those of different stakeholders such as the datacenter company and farmer, other than looking at the dual system of physical and value systems. From this perspective, we used the datacenter as a subject rather than the case of energy reuse within a plant by a company.

Comment (Koh Naito)

You propose a model for optimization from the mutual relationship of the system using the datacenter as a case study. I think it is better to clarify that the use of waste heat from a datacenter is a case study, and to emphasize the universal applicability of the idea proposed in this paper.

Answer (Jiro Fukuda)

The basic view of “strategic system design” can be expanded to other models of energy management by stakeholders with different objectives such as the smart grid, not just reuse of waste heat. We made the revisions to reflect this thought.

A methodology for improving reliability of complex systems

— Synthesis of architectural design method and model checking —

Atsushi Katoh *, **Masataka Urago and Yoshiaki Ohkami**

[Translation from *Synthesiology*, Vol.3, No.3, p.197-212 (2010)]

This paper describes a methodology for decomposing a system specification into component specifications and interface specifications whose cooperative behavior is consistent with each component. The methodology is constructed by a bridge method of combining architectural design method in systems engineering standards and model checking, which have already been confirmed to be effective in developing systems. As a trial, the methodology was applied to develop an industrial robot system. The result demonstrates that the proposed methodology is effective for complex industrial systems.

Keywords : Developing methodology, systems engineering, architectural design method, model checking, bridge method, complex systems, reliability

1 Introduction

System is a combination of interacting elements organized to achieve one or more stated purposes[Term 1][1]. Through advances in technology, technological systems (or systems) such as electronic equipment systems[Term 2] or information systems[Term3] have become deeply ingrained in society. On the other hand, the systems are getting more and more complex with the sophistication of required functions and the advent of system of systems[Term 4] where a new system is formed by multiple systems with different purposes. Recently, there are many system failures due to their complexity. As seen in the accident cases of irradiation device[2], explosion of Ariane 5[3], or disruption in air traffic control system[4], the failures of complex systems have drastic influences on society. Improving the reliability of complex systems is an important issue in realizing a safe and secure society.

In the complex system, components of the system are connected and cooperate with each other. For example, in the case of the irregular-rigid-body-transport robot system which is described in chapter 5, the integrated control subsystem understands the surrounding situation based on the results of measurement by the measurement subsystem, and the robot subsystem operates accordingly. This is called cooperative behavior[Term 5] by components in this paper. In detail, processings of the system component cooperate with processings of the other system components through the interface between components in order to achieve the system function. In the complex system, it is important that the cooperative behavior by the components occurs consistently (consistency[Term 6]) according to the system specification. However, due to its complexity, errors may creep into the specifications for the cooperative behavior by the components, and the behavior may not occur consistently (inconsistency) according to the system specification. The cooperative behavior by the system components is generally tested in a system test conducted in the final phase of system development where actual products of the components are combined. In a case where inconsistency of the cooperative behavior is detected in the system test, it is necessary to return to the upstream of the system development and redesign the cooperative behavior by the components. Large amount of cost is required to correct such inconsistency. When redesigning of the cooperative behavior occurs in the final phase of system development, the reliability of the system may be compromised. Although it is necessary to design and verify the cooperative behavior by the system components surely in the upstream of system development, no method has been proposed for this purpose. The first reason is that there has been no attention paid to the cooperative behavior by the system components from the perspective of the reliability of the system. The second reason is that incorporating the quality of the system at the upstream of system development is a relatively new concept. Therefore, we study a methodology for decomposing a system specification into component specifications and interface specifications, and verifying consistency of their cooperative behavior in the system design phase[5][6]. By developing the components based on the specifications where the cooperative behavior is consistent, it is expected to improve the reliability of the complex system. This methodoloy is constructed by synthesizing architectural design method[Term 8] in systems engineering[1] [Term 7] and model checking[7] [Term 9].

Systems engineering is technological methodologies for achieving systems which satisfy the required quality within a given budget and time period. The research of

Graduate School of System Design and Management, Keio University 4-1-1 Hiyoshi, Kohoku-ku, Yokohama 223-8526, Japan
* E-mail : katoh.atsushi@z7.keio.jp

Original manuscript received January 19, 2010, Revisions received June 4, 2010, Accepted June 7, 2010

systems engineering were started mainly in the military and aerospace fields, and systems engineering evolved through the accumulating and reflecting of “best practices” of the system development. The systems engineering process is standardized as know-hows and rules independent of technological fields[8]-[10]. Architectural design method is defined as a part of the systems engineering process. Architectural designing is a method to allocate the functions and performances required of a system to the system components, and to define the specifications of the components and the interface among the components. By architectural designing according to the standardized process, the complex system can be decomposed into its components smoothly and surely. In this paper, standardized architectural design method is simply called “architectural design method”.

Model checking is a method to verify whether a given property is valid or invalid in all possible state transitions which can be achieved by the models which represent the state transitions of the system, using a computer exhaustively. Model checking is one of the formal methods[11] Term 10. Model checking is already established as a verification method, and nowadays is popular in software development. According to the functional safety standard IEC 61508[12] Term 11, applying the formal method is recommended for the system development, and it is gaining attention as a method for achieving the high reliability of the system. Whether the properties which must be satisfied by the cooperative behavior is valid or not is thoroughly verified by applying model checking to the specifications for the cooperative behavior between components. As a result, it is possible to detect inconsistency of the cooperative behavior which may occur in the complex states.

Architectural design method is systematic knowledge which is formed by collecting best practices in the system design fields based on systems engineering. Model checking is a research result which improves the reliability in the system verification field, based on mathematical logic and computer science. In this research, we aim to achieve the high reliability in the complex systems, synthesizing architectural design method and model checking, and develop a methodology which utilizes the characteristic of both methods. Our research corresponds to *Type 2 Basic Research* which widely selects the knowledge of different technological fields and synthesizes them to satisfy social and economic needs.

This paper describes a methodology for decomposing a system specification into component specifications and interface specifications among components whose cooperative behavior is consistent with each component. It also describes the research process of this methodology. It is structured as follows. Chapter 2 describes the research goal and the research scenario. Chapter 3 describes architectural design method and model checking. Chapter 4 describes the synthesis process of architectural design method and model checking. Chapter 5 describes the application of an industrial use. Chapter 6 discusses the effectiveness and issues of this methodology. Chapter 7 summarizes this paper and describes the future work.

2 Research objective and research scenario

The objective of this research is to establish a methodology for decomposing a system specification into component specifications and interface specifications among components whose cooperating behavior is consistent with each component, which is not specific to particular technological systems. Figure 1 shows the research scenario. For the research scenario to achieve the research objective, the methods whose effectiveness has been fully verified are selected among the technological fields related to the system development. The reason for this is that a high-quality methodology can be established efficiently by employing methods which are already recognized as being effective for the system development. The methodology is established by synthesizing the selected methods to maximize their characteristics. The reason for this is that there is a possibility to produce a new research or technological field through developing a new technology by the synthesis of methods from different researches or technological fields. Also, the effectiveness of methodology is evaluated by applying this methodology to an actual case in industry. There are two reasons for selecting the industrial case as the application. The first reason is that in order to evaluate the practical applicability of this methodology in industry, it is necessary to take a functionally complex case as the application to consider safety, rather than a mere sample. The second reason is that by propagating the effectiveness of this methodology to industry, it may be possible to bridge the gap between the research activities and the social contributions of the research results, or the so-called valley of death.

3 Selection of methods

In establishing the methodology in this research, the functions which must be satisfied by the methodology are

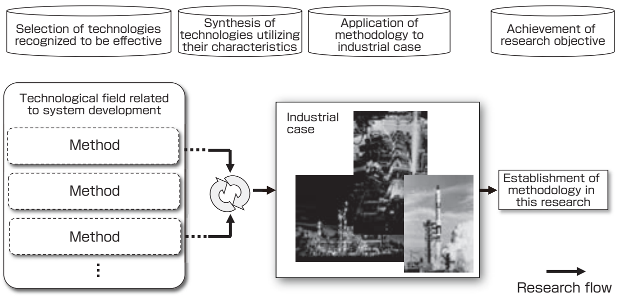


Fig. 1 Research scenario

divided as follows:

a. The function for decomposing a system specification into component specifications and interface specifications among components;
b. The function for verifying whether the cooperative behavior of the component specifications and interface specifications among components are consistent.

The system design mehod which satisfies the function “a” is selected among the system developing methods. In general, system designing is a work for defining a system specification by analyzing the user’s needs, and defining specifications for functions of the components which compose the system, realization means of the components, and relationship among the components, based on the system specification. The representative method of system designing other than architectural design method includes structured analysis and structured design (SA/SD) method[13] Term 12. SA/SD method is a design method where a system is decomposed into components by focusing on data flows of the system. In SA/SD method, the system is designed by focusing on the data such as business information rather than the functions and processings, because the data is stable against changes in requirements or a technological evolution. This allows to construct systems with maintainability and expandability. However, since SA/SD method is developed primarily for technological systems such as information systems, it does not deal with control flows or processing timing[14]. Therefore, it is inappropriate for designing anything other than information systems such as embedded systems. On the other hand, architectural design method requires more efforts compared to the specific design method such as focusing on the data as in the aforementioned example, because the procedures and tasks specific to a certain designing are not defined. However, architectural design method is a general design method which is not dependent on some specific technological systems where the process for defining functions and realization means of the system are defined. Therefore, taking into account the research objective of achieving a methodology which is not specific to particular technological systems, we select the architectural design method as the system design method which satisfies function “a”. Also, the representative systems engineering standards which defines architectural design method include ISO 15288[9] Term 13, ANSI/EIA 632[10] Term 14, and IEEE 1220[11] Term 15. While ISO 15288 can be applied to the entire system lifecycle process from the conceptualizing phase to the dismantling phase, the tasks and procedures of architectural designing are not finely defined. While ANSI/EIA 632 can be applied widely to the system lifecycle process from the conceptualizing phase to the transition to operation phase, the tasks and procedures for architectural designing are not finely defined. On the other hand, although IEEE 1220 limits the range of application from the system requirement analysis phase to the system test phase, the tasks and procedures for architectural designing are finely defined. Therefore, we select architectural design method defined by IEEE 1220 for our methodology.

The system verification method which satisfies function “b”. is selected among the system development methods. In general, system verification is a work for verifying whether a developed system satisfies the system specification or not. The representative system verification methods other than model checking include test method[Term 16] and simulation method[15] Term 17. Test method is a verification method for verifying behavior of actual products against the test cases. While it can verify the actual behavior of actual products, it is difficult to extract all of the cases which may occur and to verify the behavior in all possible cases. Simulation method is a verification method where a target to be verified and peripheral environment of the target is simulated as models on a computer, and behavior of the models is verified against the test cases. While it can verify the behavior of the target in the early phase of system development when actual products and peripheral environment do not exist, it is difficult to extract all of the cases which may occur and to verify the behavior in all possible cases, as in the test method. On the other hand, although model checking can only verify state transitions of a verification target, it can verify whether the properties to be satisfied are valid or not for all state transitions exhaustively. If there is a deadlock[Term 18] in state transitions of a system, fatal accidents may occur during the system operation. Therefore, we select model checking for our methodology.

Next, architectural design method defined in IEEE 1220 and model checking are described in detail.

3.1 Architectural design method in IEEE 1220

Figure 2 shows the architectural design process. Architectural designing is composed of functional designing[Term 19] and physical designing[Term 20]. Functional designing is a work where functions defined as a system specification are decomposed and refined, and performances defined as the system specification are allocated to the decomposed and refined functions. Physical designing is a work where system components are specified, and the functions and performances decomposed and refined in functional designing are allocated to the components. The outputs of architectural designing are component specifications and interface specifications among components.

Figure 3 shows the process of functional designing defined in IEEE 1220. The process of functional designing is defined in IEEE 1220 chapter 6 section 3 Functional analysis[Term 21]. Figure 4 shows the process of physical designing defined in IEEE 1220. The process of physical designing is defined in IEEE 1220 chapter 6 section 5 Synthesis[Term 22]. By conducting the tasks according to the numbers in Figs. 3 and 4, it is possible to decompose a complex system into its components smoothly and surely. Architectural design method in IEEE 1220 has been used in various industrial fields, and has produced results. Therefore, a certain level of effectiveness is guaranteed[16].

3.2 Model checking

Figure 5 shows the process of model checking. The process of model checking can be categorized into four works: developing models, developing fomulae, conducting model checking, and analizing the model checking results. First, state transitions of a target to be verified are modeled based on the target specification according to the expression form of a model checking tool to be applied. Next, properties which must be satisfied by the verification target are considered. Formulae which express the properties are developed according to the expression form of the model checking tool. Then, the models and the formulae are input to the model checking tool on a computer, and model checking is conducted. Model checking verifies whether the models satisfy the properties expressed by formulae or not in all state transitions achievable by the models exhaustively. Finally, results of whether the models satisfy the properties expressed by formulae or not are analyzed based on outputs from the model checking tool. If the models satisfy the formulae, it means that the specification based on the models satisfy the properties. If the models do not satisfy the formulae, the state transitions of the models up to the state where the property is not valid are output as the counterexamples, If no errors are found in the models

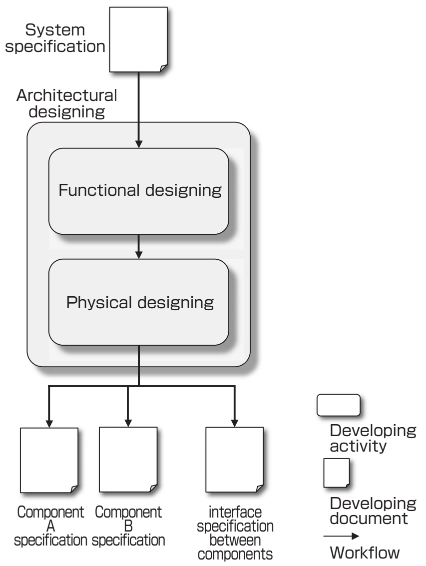


Fig. 2 Process of architectural designing

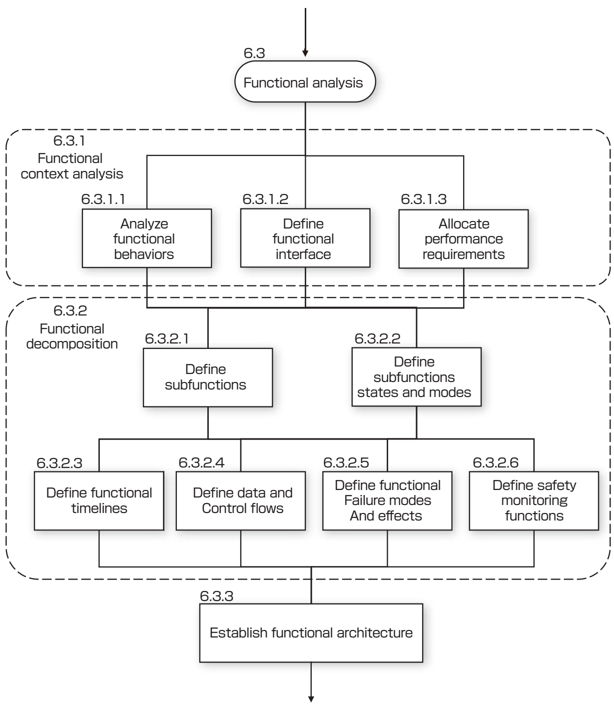


Fig. 3 Process of functional designing in IEEE 1220[11]

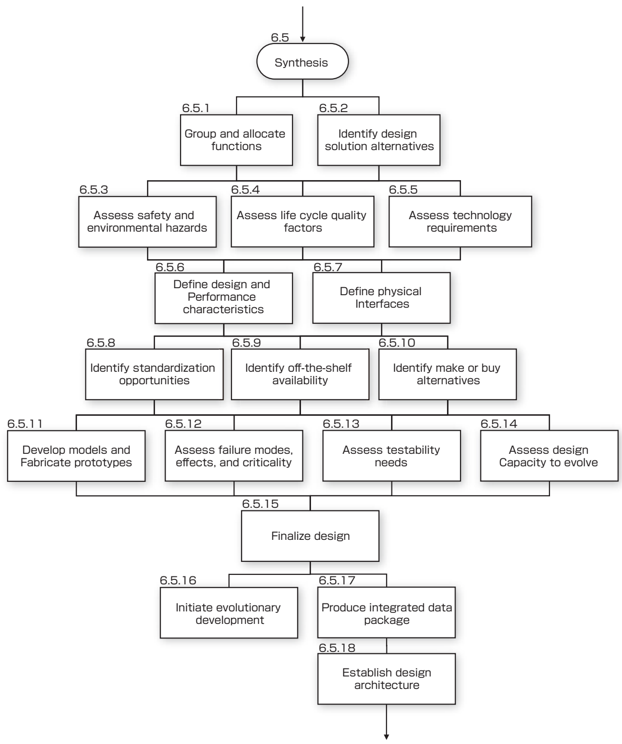


Fig. 4 Process of physical designing in IEEE 1220[11]

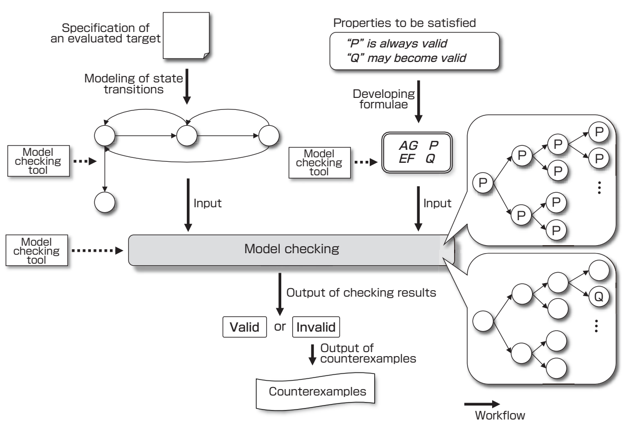


Fig. 5 Process of Model checking

when the counterexamples are analyzed, it means that the specification of the target based on the models has flaws.

The following two effects can be expected by applying model checking. First, it may be possible to reduce the cost of detecting flaws in the specification by using the counterexamples. If results of test method and simulation method come out incorrect, it is necessary to analyze the cause by hypothesizing the many causes which may lead to incorrectness. Much effort may be necessary to identify the real cause. By applying model checking, it is possible to trace the occurrence of incorrectness using the counterexamples which are output from the model checking tool automatically. Therefore, it is possible to identify the cause of incorrectness efficiently. Second, there is a possibility for detecting flaws in the specification to be verified through modeling, or the formalization of specification, when model checking is conducted.

4 Synthesis of methods

Architectural design method and model checking are synthesized while taking advantage of the characteristics of each method, to construct the methodology for this research. In this chapter, the process of synthesizing architectural design method and model checking is shown by describing workflows in this methodology.

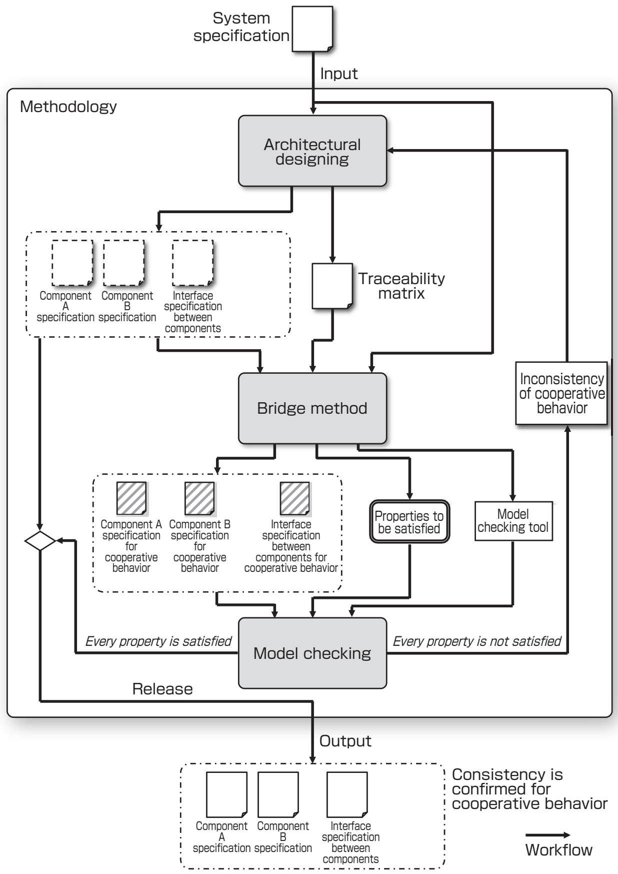


Fig. 6 Methodology in this research

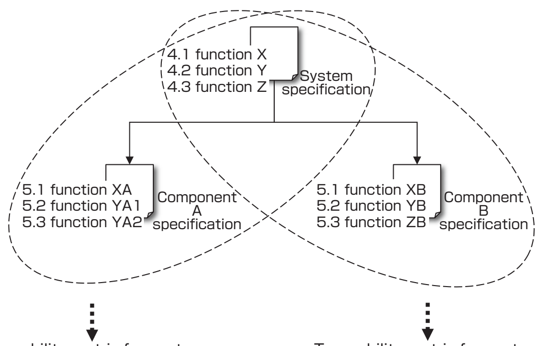
4.1 Proposed methodology

Figure 6 shows the methodology proposed for this research, whereby architectural design method and model checking are synthesized. This methodology is composed of architectural design method, model checking, and bridge method[Term23] which connects two methods.

First, a system specification is input to this methodology. Based on the system specification, architectural designing including functional and physical designing are done according to IEEE 1220. By architectural designing, the system specification is decomposed into component specifications and interface specifications among the components (dashed-line specifications in upper left in Fig. 6). A traceability matrix[Term 24] defined in IEEE 1220 is developed in the process of architectural designing. Figure 7 shows the traceability matrix. An identification number is assigned to each specification for the system specification and the component specifications. The traceability matrix summarizes the correspondence between the system specification and component specifications which are broken down from the system specification.

Next, bridge method developed in this research is applied to the component specifications, the interface specifications among components, the traceability matrix, and the system specification. By applying the bridge method, specifications related to the cooperative behavior are extracted from the component specifications and interface specifications among components (striped specifications in lower left of Fig. 6). Properties which must be satisfied by the cooperative behavior are derived. A model checking tool which is applied in the methodology is selected. Outputs of the bridge method are necessary inputs for conducting model checking.

Specifications related to the cooperative behavior extracted from the component specifications and interface specifications



Traceability matrix for system specification and component A specification

System specification	Component A specification
4.1 function X	5.1 function XA
4.2 function Y	5.2 function YA1
	5.3 function YA2
4.3 function Z	N/A

Traceability matrix for system specification and component B specification

System specification	Component B specification
4.1 function X	5.1 function XB
4.2 function Y	5.2 function YB
4.3 function Z	5.3 function ZB

Fig. 7 Traceability matrix

among components are modeled according to the expression form of the model checking tool to be applied. Also, formulae are developed from the properties which must be satisfied by the cooperative behavior, based on the expression form of the model checking tool. The developed models and the formulae are input to the model checking tool. If counterexamples are output from the model checking tool, the counterexamples are analyzed and the inconsistency of the cooperative behavior is fed back to architectural designing. Based on the inconsistency of the cooperative behavior which is fed back, architectural designing is done according to the workflows of this methodology. If no counterexamples are output from the model checking tool, the component specifications and the interface specifications among components whose cooperative behavior is consistent are released, and they are output as results of this methodology.

4.2 Bridge method

In the methodology of this research, system verification is conducted for the cooperative behavior by components in the system design phase. It is necessary to connect the outputs of architectural designing to the inputs of model checking seamlessly. We develop the method to derive the specifications related to the cooperative behavior, the properties which must be satisfied by the cooperative behavior, and the model checking tool to be applied, based on the component specifications, the interface specifications among components, the traceability matrix, and the system specification. This is called bridge method because it serves as the bridge between architectural design method and model checking. Bridge method is novel since it focuses on the cooperative behavior to present a specific means for synthesizing the systems engineering standard such as IEEE 1220 and model checking. Figure 8 shows the bridge method for architectural design method and model checking. Figure 8 corresponds to the details of the bridge method shown in the central part of Fig. 6. The inputs of the bridge method include the component specifications, the interface specifications among components, the traceability matrix, and the system specification.

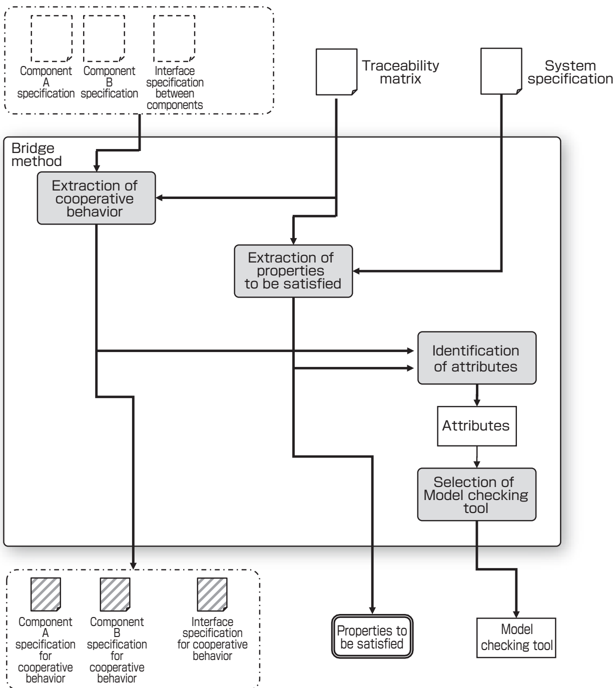


Fig. 8 Bridge method for architectural design method and Model checking

First, specifications related to the cooperative behavior are extracted from the component specifications and interface specifications among components. Figure 9 shows specifications related to the cooperative behavior in the component specifications and interface specifications among components. The traceability matrix is used when specifications related to the cooperative behavior by the component specifications are extracted. If the system specification corresponds to multiple component specifications in the traceability matrix, a function of the system is achieved when these components cooperate. In the case of Fig. 7, the 5.1 function XA of the component A specification and the 5.1 function XB of the component B specification cooperate to achieve the 4.1 function X of the system specification. In Fig. 9, this corresponds to the striped part of the component A specification and the component B specification. The specifications related to the cooperative behavior in interface specifications among components are extracted based on interface information within the component specification related to the cooperative behavior. In Fig. 9, this corresponds to the part of the message in the center.

Next, the properties which must be satisfied by the cooperative behavior of the components are extracted from the system specification based on the traceability matrix. The reason is that it is necessary for the cooperative behavior by the components extracted by the traceability matrix to satisfy the system specification achieved by the cooperative behavior. In case of Fig. 7, the cooperative behavior of the 5.1 function XA of the component A specification and the 5.1 function XB of the component B specification must satisfy the properties of the 4.1 function X of the system specification.

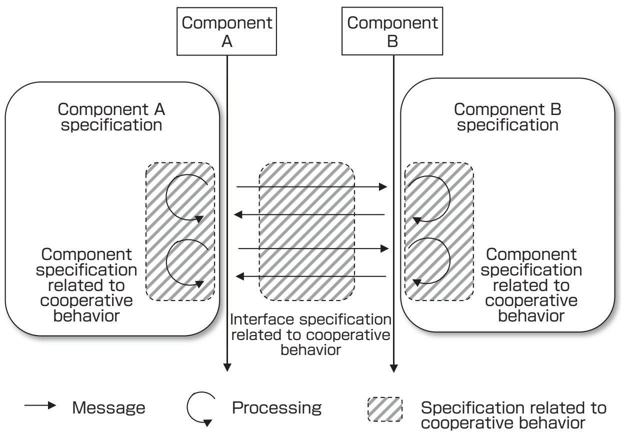


Fig. 9 Specifications related to cooperative behavior

The attributes of the cooperative behavior are determined based on the specifications related to the cooperative behavior and the properties which must be satisfied by the cooperative behavior. The attributes of the cooperative behavior can be categorized as follows:

(1) There must be no lacks and variances in messages which are sent or recieved among components and processings related to the messages;
(2) The timing of messages which are sent or recieved among components and processings related to the messages are correct.

The model checking tool to be applied is selected according to the identified attributes. The representative types of model checking tools are finite automaton[17] Term 25 and timed automaton[18] Term 26 which is extended based on finite automaton. When verifying point (1), the model checking tool which corresponds to finite automaton is selected. SPIN[19] Term 27 is one of the representative model checking tools for finite automaton. When temporal limitations such as the timing are verified as in point (2), the model checking tool which corresponds to timed automaton is selected. Timed automaton is an extension of finite automaton. The model checking tool based on timed automaton can also verifiy point (1). UPPAAL[20] Term 28 is one of the representative model checking tools for timed automaton. Also, each component in the system behaves in parallel. Therefore, it is necessary to select the model checking tool which can model parallel systems. SPIN and UPPAAL can model the parallel systems.

5 Application to industrial case

There is recently a rapid advancement in functions of industrial robots[21] Term 29. Many industrial robots have a strong mechanical output due to the nature of their works; therefore safety of operators must be considered. The industrial robot is one of the systems which are appropriate for the application of this methodology. As of writing this paper, we are developing an industrial robot system for transporting irregularly shaped rigid-bodies, jointly with a manufacturer of industrial robots. We select the irregular-rigid-body-transport robot system as an industrial case study, and apply our methodology.

Followings are descriptions of the irregular-rigid-body-transport robot system and results of applying this methodology.

5.1 Irregular-rigid-body-transport robot system

The irregular-rigid-body-transport robot system is an industrial robot system which engages in grasping, transporting, and placing of heavy rigid-bodies with irregular shapes and sizes. The characteristic of requirements for the irregular-rigid-body-transport robot system is that the system must have a strong autonomy in grasping and placing the irregular rigid-body. Although the area of grasping the irregular rigid-body is limited, the shape and size of the rigid-body, the position where the irregular rigid-body is grasped, and the direction of the irregular rigid-body are indefinite. The system must accurately determine the shape, size, and direction of the irregular rigid-body. Also, while the area in which the irregular rigid-body is placed is limited, the location in which the irregular rigid-body is placed within that area is indefinite. The system must accurately determine the location where other irregular rigid-bodies are not present, or the location with the lowest height in that area which is laid with other irregular rigid-bodies.

In developing the irregular-rigid-body-transport robot system, system requirement analysis is conducted based on the system needs. The system specification is defined through system requirement analysis. This methodology is applied with the defined system specification as an input.

5.2 Application of this methodology

In this section, the specific applications of this methodology are described for architectural design method, bridge method, and model checking mentioned in chapter 4.

5.2.1 Architectural design method

Architectural designing is done using the system specification of the irregular-rigid-body-transport robot system as an input. By architectural designing, the specification of the irregular-rigid-body-transport robot system is decomposed into the specifications of the measurement subsystem, the robot subsystem, and the integrated control subsystem, as well as the interface specifications among the subsystems Term 30. Figure 10 shows the results of architectural designing for the irregular-rigid-body-transport robot system. In architectural designing, each subsystem is designed by assuming the subsystem components Term 31 which compose the subsystem to make the most of COTS (commercial off the shelf) Term 32 products and existing technologies.

The measurement subsystem is composed of a laser scanner to measure a three-dimensional shape, a vertical motion mechanism for the laser scanner, and a measurement control computer which controls them. The measurement subsystem measures the shape, size, position, and direction of the irregular rigid-body when grasping it. It also measures the unevenness of the area where the rigid-body is placed.

The robot subsystem is composed of a robot arm, a robot hand, and controllers which control each subsystem component. It also has a teaching pendant Term 33 for programming actions and emergency stop of the robot arm. The robot subsystem grasps, transports, places irregular rigid-bodies.

The integrated control subsystem is composed of an integrated control computer which controls the measurement and robot subsystems and a console[Term 34] to input work instructions and to check system status. The integrated control subsystem controls the robot subsystem based on the results of measurements by the measurement subsystem.

Also, the traceability matrixes for the measurement, robot, and integrated control subsystems are developed for architectural designing.

5.2.2 Bridge method

Bridge method is applied to the subsystem specifications, the interface specifications among the subsystems, the traceability matrix, and the system specification for the irregular-rigid-body-transport robot system. Here, we discuss the measurement and integrated control subsystems to describe the specific application of the bridge method.

First, the specifications related to the cooperative behavior are extracted from the subsystem specifications and the interface specification between subsystems based on the traceability matrix. The specific extraction of the specifications related to the cooperative behavior follows the means described in subchapter 4.2. For the measurement subsystem specification, six items are extracted from 39 specification items, and for the integrated control subsystem, six items are extracted from 78 specification items. For the interface specification between the measurement and integrated control subsystems, 22 items are extracted from 26 specification items.

Next, the properties which must be satisfied by the cooperative behavior of the subsystems are extracted based on the traceability matrix and the system specification of the irregular-rigid-body-transport robot system. The specific extraction of the properties which must be satisfied by the cooperative behavior follows the means described in subchapter 4.2. For the measurement and integrated control subsystems, 23 items are extracted as the properties which must be satisfied by the cooperative behavior. Table 1 shows two items from the 23 properties extracted.

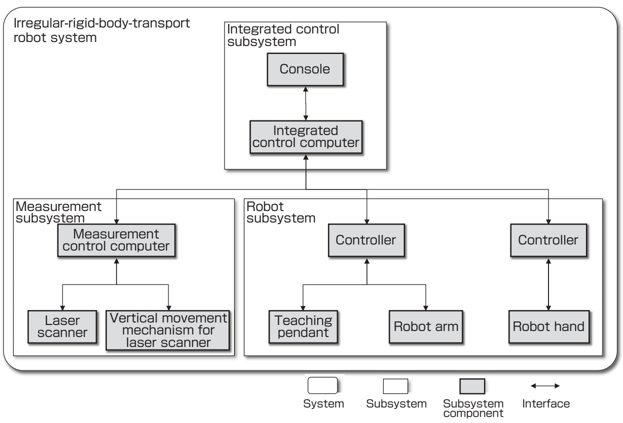


Fig. 10 Results of architectural designing for the irregular rigid-body transport robot system

Table 1 Properties to be satisfied for the cooperative behavior by the measurement and integrated control subsystems (2 out of 23 items)

No.	Property
1-5	The integrated control subsystem must receive the result of rigid-body measurement or the failure response of rigid-body measurement from the measurement subsystem, when the rigid-body measurement request is sent to the measurement subsystem.
3-3	The measurement subsystem must stop the measurement processing within 100 ms after the measurement stop request is transmitted by the integrated control subsystem.

The attributes of the cooperative behavior are determined based on the extracted specifications related to the cooperative behavior and the properties which must be satisfied by the cooperative behavior. In the cooperative behavior of the measurement and integrated control subsystems, the lacks and variances of the messages which are sent or received between subsystems and processings related to the messages are suspected. There are specifications for the timing of the messages which are sent or received between subsystems and processings related to the messages as well as the temporal limitation within 100 ms. Therefore, the two attributes, (1) and (2), as shown in subchapter 4.2, are determined.

Also the model checking tool to be applied is selected based on the identified attributes. For the cooperative behavior by the measurement and integrated control subsystems, it is necessary to verify the temporal limitation and the timing of messages which are sent or received between subsystems and processing related to the messages. Since the measurement and integrated control subsystems behave in parallel, it is necessary to select the model checking tool which can deal with the parallel systems. Therefore, UPPAAL is selected as the model checking tool which satisfies these requirements.

5.2.3 Model checking

As in the previous section, the measurement and integrated control subsystems are discussed in this section to describe the specific application of model checking.

First, the specifications related to the cooperative behavior extracted by the bridge method are modeled according to the expression form of the model checking tool. Figures 11 to 13 show the results of modeling the specifications for the cooperative behavior by the measurement and integrated control subsystems using UPPAAL. The developed model is composed of three models for the specifications related to cooperative behavior: the model corresponding to the measurement subsystem (Fig. 11); the model corresponding to the integrated control subsystem (Fig. 12); and the model corresponding to the interface between the measurement and integrated control subsystems (Fig. 13).

Next, the formulae for model checking are developed based

Table 2 Formulae of the cooperative behavior for the measurement and integrated control subsystems (2 out of 23 cases)

No.	Formula
1-5	A[] (bing_syscont_sendreq == bing_req_rod) imply (bing_syscont_req == bing_req_rod)
3-3	A[] P_BING_SCAN.BING_SCAN_REQ_STOP imply (bing_stopreq_time <= 10)

on the properties which must be satisfied by the cooperative behavior. For the measurement and integrated control subsystems, the formulae for 23 cases are developed based on the properties which must be satisfied by the cooperative behavior according to UPPAAL expression form. Table 2 shows the formulae corresponding to the two items shown in Table 1.

Model checking is conducted based on the developed models and the formulae. For the measurement and integrated control subsystems, model checking using UPPAAL is conducted based on the cooperative behavior models shown in Figs. 11 to 13 and the formulae for the 23 cases including the two cases shown in Table 2. The results of model checking are analyzed. For the measurement and integrated control subsystems, the results show that the models do not satisfy some formulae. When the counterexamples output by UPPAAL are analyzed, six cases of inconsistency of the cooperative behavior are detected including the results of the formulae shown in Table 2. Table 3 shows the results of model checking corresponding to the two cases in Table 2.

Inconsistency of the cooperative behavior is fed back to architectural designing. For the measurement and integrated control subsystems, architectural designing is done again, based on the six cases of inconsistent cooperative behavior

Table 3 Model checking results of the cooperative behavior for the measurement and integrated control subsystems (2 out of 6 cases)

No.	Model checking result
1-5	Depending on the messages which are sent or recieved between subsystems, or the timing of processings related to the messages, the response for rigid-body measurement request/the measurement request for placement area/the measurement stop request issued before n-th time may be returned to the rigid-body measurement request issued on the n-th time.
3-3	The measurement processing may not stop within 100 ms from receiving the measurement stop request. Also, the measurement subsystem itself may stop by receiving the measurement stop request.

including the results of Table 3. As a result of re-architectural designing, the measurement subsystem specification, the integrated control subsystem specification, and the interface specification between the measurement and integrated control subsystems whose inconsistency of the cooperative behavior is corrected, are developed.

5.3 Application results

The methodology in this research is applied to the system specification of the irregular-rigid-body-transport robot system. As a result, the measurement subsystem specification, the integrated control subsystem specification, the robot subsystem specification and the interface specifications among the subsystems are derived from the system specification of the irregular-rigid-body-transport robot system. It is also possible to detect inconsistency of the cooperative behavior, as shown in Table 3, from the measurement and integrated control subsystems before fixing these specifications. Later, it is possible to develop the subsystem specifications and interface specifications between subsystems whose cooperative behavior is consistent. We are able to apply this methodology to the

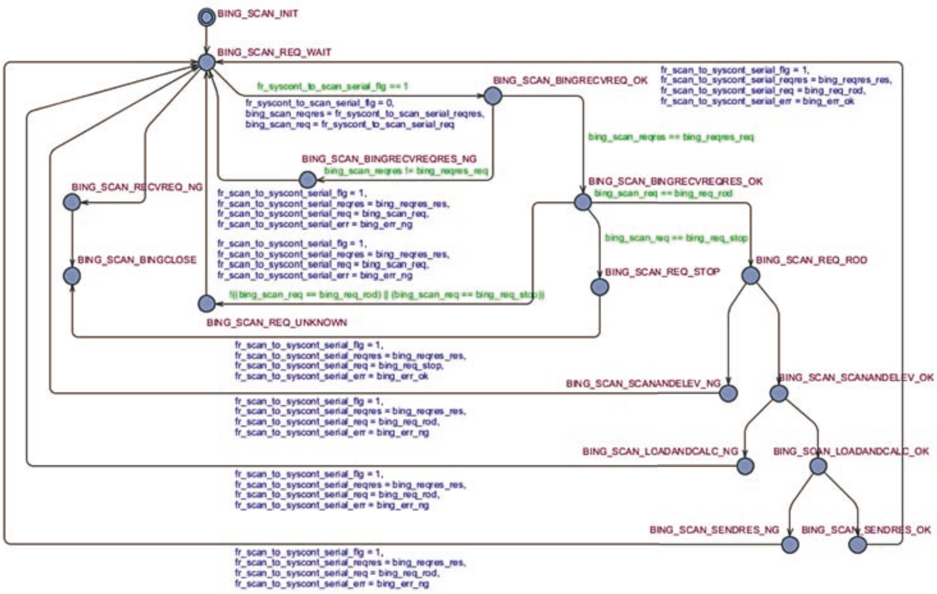


Fig. 11 Cooperative behavior model for the measurement subsystem

actual product development of this industrial robot, and contribute in increasing the reliability of it. It is reconfirmed that this research corresponds to *Type 2 Basic Research*. As of writing this paper, the irregular-rigid-body-transport robot system is being developed based on the specifications whose cooperative behavior is consistent to meet the needs of industry.

6 Discussion

In this chapter, the effectiveness of this methodology is demonstrated. Issues of this methodology are also described.

6.1 Effectiveness of this methodology

The effectiveness of the methodology in this research is discussed based on the application results to the industrial case shown in chapter 5. In demonstrating the effectiveness, we focus on the QCD (quality, cost and delivery)[Term 35] of the case study.

First, this methodology is considered from the perspective of the quality of a development target. The methodology is applied to the functionally complex industrial case of the irregular-rigid-body-transport robot system. As a result, it is possible to develop the measurement and integrated control subsystems specifications whose cooperative behavior is consistent by feeding back inconsistency of the cooperative behavior by the measurement and integrated control subsystems to architectural designing in one cycle. Particularly, inconsistencies of the cooperative behavior shown in Table 3 are flaws which are difficult to detect by human beings only, but it is possible to detect them because of model checking where the validity of the properties to be satisfied is verified exhaustively. The fact that such flaws are detected in the early phase of system development demonstrates the effectiveness of this methodology.

Table 4 Man-hours required to apply the methodology to industrial case

Work	Man-hour
Architectural designing	189
Bridge method	5※
Model checking	12※

※Values in the measurement and integrated control subsystems

Next, this methodology is considered from the perspective of the development cost and delivery time. Table 4 shows the man-hours for applying this methodology to the industrial case. For bridge method and model checking, the values for the measurement and integrated control subsystems described in chapter 5 are shown. For architectural designing, 189 man-hours are required. For system development, there are many previous researches on the effectiveness of applying systems engineering method including architectural designing[22]-[25]. In the previous researches, it was shown that it was possible to shorten the cost and delivery time

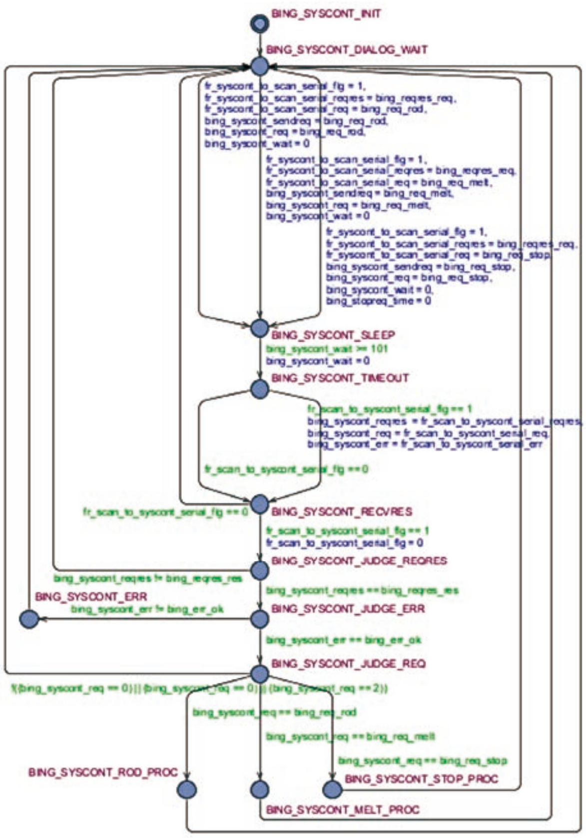


Fig. 12 Cooperative behavior model for the integrated control subsystem

of the system development by appropriately applying the systems engineering methods. In this paper, it is not possible to present the degree of reducing the cost and delivery time by the application of architectural design method in the industrial case. However, considering the fact that certain results are obtained for architectural designing, there is a high possibility that the cost and delivery time can be reduced for the system development. For bridge method and model checking, as shown in Table 4, 5 man-hours and 12 man-hours are required for the measurement subsystem and the integrated control subsystem, respectively. Here, we discuss inconsistency of the cooperative behavior detected by conducting model checking through the bridge method. Inconsistency of the cooperative behavior between subsystems can generally be detected in the system test where the subsystems are combined, conducted at the final phase of system development. If inconsistency of the cooperative behavior among subsystems is detected in the system test, large amount of cost and time are required for correcting. Boehm, in Reference[26], analyzed that if the cost of detecting and correcting the requirement flaws at the phase of defining requirement specifications were set as 1, the cost would be 2 in a small-scale system if the requirement flaws were detected in the test, and the cost would be 20 in a large-scale system. Inconsistencies of the cooperative behavior shown in Table 3 are flaws which are highly likely to be missed unless model checking is applied in the phase when the required specifications are defined. Considering the whole system development, the man-hours required for bridge method and model checking are highly cost-effective.

6.2 Applicability of this methodology

The methodology in this research is not specialized to the development of particular technological systems, but it can be applied universally to the development of any technological system. The reason is that in designing a system, achieving a function of the system by finding components which compose the system based on the system specification and having the components cooperate is a common concept for all technological systems. Also, this methodology can deal with unique problems related to the cooperative behavior in an applicable system. The reason is that it has the bridge method where attributes and model checking tools are selected according to the characteristics of the cooperative behavior.

However, attentions must be paid in the application of this methodology. This methodology employs model checking to verify whether the cooperative behavior by the components is consistent. Model checking is a method to verify whether given properties are valid or invalid in all possible state transitions which can be achieved by the models using a computer exhaustively. In cases where there are numerous states of the models in model checking, state explosion may occur where model checking does not get completed since the number of state combinations is too large. This means there is a possibility that the verification of the cooperative behavior by model checking may not get completed when the cooperative behavior by the components becomes extremely complex as a result of architectural designing. In this case, it is necessary to conduct re-architectural designing to prevent the cooperative behavior by the components from getting extremely complex, or reduce the number of the states in the models for the specifications related to the cooperative behavior.

6.3 Issues

We are able to comfirm the effectiveness of this methodology on an industrial case study. However, there are some issues which must be solved in the future.

The first issue is a problem of the bridge method in this methodology. In bridge method, the properties which must be satisfied by the cooperative behavior are extracted. In general, the properties to be satisfied by a target of model checking are liveness and safety[27]. Liveness is a property where “the verification target will eventually reach a desirable state”. Safety is a property where “the verification target will never reach an undesirable state”. The liveness property is often the specifications which must be achieved

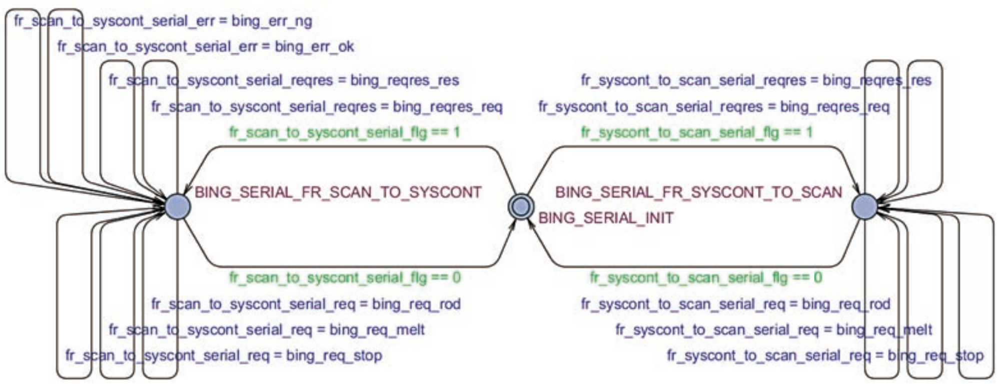


Fig. 13 Cooperative behavior model for interface specification between the measurement and integrated control subsystems

by the verification target. Therefore, the liveness of the verification target can be extracted from the specifications of the verification target or the specifications based on the verification target. However, most of the property related to safety of the verification target is not defined in the specifications of the verification target or the specifications based on the verification target. Extracting safety of the verification target depends highly on the experience and skill of engineers who use this methodology. Particularly, extracting the safety property which must be satisfied by the cooperative behavior tends to be dependent on engineers due to the complexity of the cooperative behavior.

The second issue is a problem of model checking in this methodology. In model checking, the models are developed based on the specifications related to the cooperative behavior extracted from the component specifications and interface specifications among components. The component specifications and the interface specifications are often described in natural language. Therefore, in many cases, the extracted specifications are modeled manually and errors may creep into the models. This is an issue for model checking in general.

The third issue is also a problem of model checking in this methodology. In model checking, the fomulae are developed based on the properties which must be satisfied by the cooperative behavior according to the expression form of the model checking tool. The formulae of the model checking are expressed by temporal operator[Term 37] (G: globally, F: finally) called temporal logic[Term 36], path quantifier[Term 38] (A: all, E: exists), and logic operator[Term 39] (OR, AND, NOT). However, since specialized knowledge is needed to use temporal logic, it is difficult to develop the formulae based on the properties to be satisfied by the cooperative behavior. This is also an issue for model checking in general.

7 Summary and future work

In this paper, we present the methodology where the system specification is decomposed into the component specifications and the interface specifications among components for the consistent cooperative behavior among the components which compose the system. Bridge method is developed to synthesize architectural design method and model checking, and the actual example of the bridge method is presented. The results of applying this methodology to an industrial robot are shown. From the application results, it is demonstrated that this methodology is effective for the complex system used in industry. We plan to present this methodology to the industrial fields through the Graduate School of System Design and Management, Keio University[28] (Keio SDM) to which the authors belong. The Keio SDM is a graduate school where people of various fields of both humanities and sciences study. Engineers who work in the frontline of product development on systems of aerospace, information, robot, and electronics attend Keio SDM. By presenting this methodology to the engineers attending Keio SDM, we can make contribution to industry. However, there are rooms for improvements in this methodology. In the future, we will solve issue 1 which is listed in this paper. We will aim to develop a methodology of higher quality.

Terminologies

Term 1. System: a combination of interacting elements organized to achieve one or more stated purposes.

Term 2. Electronic equipment system: a system equipped with multiple processors which digitally process information (e.g. cellular phone).

Term 3. Information system: a system for business activities where multiple computers engaging in data processing are connected with a network (e.g. business system).

Term 4. System of systems: a composite system which is formed by multiple systems with different purposes.

Term 5. Cooperative behavior: a cooperation with processings of the system component and the other system components through the interface among components.

Term 6. Consistency of cooperative behavior: a consistent implementation of the cooperative behavior by the components in correspondence to the system specification.

Term 7. Systems engineering: technological methodologies to achieve systems which satisfy the required quality within a given budget and time period. It is standardized as know-hows and rules independent of the technological fields.

Term 8. Architectural design method: a design method to allocate functions and performances required of a system to the system components, and to define the specifications of the components and the interface among the components.

Term 9. Model checking: a verification method to verify whether a given property is valid or invalid in all possible state transitions which can be achieved by the models which represent the state transitions of the system, using a computer exhaustively.

Term 10. Formal method: a developing and verification technology where specifications are expressed using the language of mathematical logic to guarantee the correctness of the specification.

Term 11. IEC 61508: an international standard which determines compliance items needed to build the functional safety in the process industry, machine manufacturing, traffic transportation, medical device, and others, using electrical, electronic, and programmable electronic systems.

Term 12. Structured analysis and structured design (SA/SD) method: a design method where a system is decomposed into components by focusing on data flows of the system.

Term 13. ISO 15288: one of the systems engineering standards. The tasks and procedures are defined for each process of the entire system lifecycle from the conceptualizing phase to the dismantling phase.

Term 14. ANSI/EIA 632: one of the systems engineering standards. The tasks and procedures are defined for each process of the system lifecycle from the conceptualizing phase to the transition to operation phase.

Term 15. IEEE 1220: one of the systems engineering standards. The tasks and procedures are defined for each process of the system lifecycle from the system requirement analysis phase to the system test phase.

Term 16. Test method: a verification method for verifying behavior of actual products against the test cases.

Term 17. Simulation method: a verification method where a target to be verified and peripheral environment of the target are simulated as models on a computer, and behavior of the models is verified against the test cases.

Term 18. Deadlock: a state where two or more processing units wait for each other to complete each processing, and as a result, all processings fail to move on further.

Term 19. Functional designing: a work where functions defined as a system specification are decomposed and refined, and performances defined as the system specification are allocated to the decomposed and refined functions.

Term 20. Physical designing: a work where system components are specified, and the functions and performances decomposed and refined in functional designing are allocated to the components.

Term 21. Functional analysis: the process which corresponds to functional designing, defined in chapter 6 section 3 in IEEE1220.

Term 22. Synthesis: the process which corresponds to physical designing, defined in chapter 6 section 5 in IEEE1220.

Term 23. Bridge method: a method which is presented in this paper to connect architectural design method and model checking seamlessly.

Term 24. Traceability matrix: a table which summarizes the correspondence of upper and lower level specifications.

Term 25. Finite automaton: a behavior model composed of finite number of combinations of the state, transition, and operation.

Term 26. Timed automaton: a behavior model where temporal variables are incorporated into finite automaton. It allows modeling of the time passage as transition conditions.

Term 27. SPIN: a model checking tool based on finite automaton. State transitions of the system are modeled using PROMELA (process meta language) which is a language similar to C. It can be downloaded from <http://spinroot.com/>.

Term 28. UPPAAL: a model checking tool based on timed automaton. State transitions of the system can be modeled in an intuitive manner using GUI (graphical user interface). It can be downloaded from <http://www.uppaal.com/>.

Term 29. Industrial robot: an industrial-use machine with the auto-control functions for manipulation or transportation. It can be programmed to conduct various work routines.

Term 30. Subsystem: an entity possessing the structure of a distinct, local system, while being part of a system.

Term 31. Subsystem Component: an element or a part which composes the subsystem.

Term 32. COTS (commercial off the shelf): software and hardware products which are available on the market.

Term 33. Teaching pendant: a device used for programming acitons and emergency stop of an industrial robot.

Term 34. Console: an input and output device used for operating the system. It is composed of input device such as a keyboard and output device such as a monitor display.

Term 35. QCD: an abbreviation for quality, cost, and delivery of development.

Term 36. Temporal logic: a theory of rules and expressions to understand and express the problem in relation to time. Temporal operator, path quantifier, and logic operator are combined to express the properties such as “P is always valid” or “Q is eventually valid.”

Term 37. Temporal operator: operators to express “G: globally” and “F: finally” in temporal logic.

Term 38. Path quantifier: operators to express “A: all” or “E: exists” in temporal logic.

Term 39. Logic operator: symbols which express logic operation. It includes “NOT: negation”, “AND: logical product” and “OR: logical sum.”

References

[1] International council on systems engineering (INCOSE): *INCOSE Systems Engineering Handbook version 3.1*, 1.5 of 6, INCOSE, USA (2007).

[2] N. G. Leveson: *SAFEWARE: System Safety and Computers*, 515-553, Addison-Wesley Professional, USA (1995).

[3] H. Shimizu: Arian 5 no bakuhatsu jiko to sofuto uea anzensei ni kansuru kokusai kikaku (Explosion of Ariane 5 and the international standard for software safety), *Anzen Kogaku (Journal of the Japan Society for Safety Engineering)*, 41 (1), 39-42 (2002) (in Japanese).

[4] Ministry of Land, Infrastructure, Transport and Tourism: FDP shisutemu no shogai no gen’in chosei no kekka (Result

of the cause adjustment of FDP system failure), MLIT (online), http://www.mlit.go.jp/kisha/kisha03/12/120312_.html (2009-09-22) (in Japanese).
[5] A. Katoh, N. Kohtake, S. Haruyama and Y. Ohkami: Moderu kensa o mochiite kumikomi shisutemu ni okeru sofuto uea to hado uea no kyocho dosa ni kansuru yokyu shiyo no fuseigo o kenshutsu suru shuho (A Model Checking Methodology for Detecting Inconsistency of Specifications concerned with Cooperating Behavior between Software and Hardware in Embedded System), *IPSJ Symposium Series*, 2009, 65-70 (2009) (in Japanese).
[6] A. Katoh and Y. Ohkami: FPGA to sofuto uea ni okeru kyocho dosa no seigosei ni kansuru hyoka shuho no teian (An Approach for Verifying Correctness of Co-operations between FPGA and Software in Electronic System), *IPSJ SIG Notes*, 2009 (31), 105-112 (2009) (in Japanese).
[7] E. M. Clarke, O. Grumberg and D. E. Long: Model checking and abstraction, *ACM Transactions on Programming Languages and Systems*, 16 (5), 1512-1542 (1994).
[8] Institute of Electrical and Electronics Engineers (IEEE): *IEEE standard for system and software engineering - System life cycle processes*, IEEE 15288-2008 (2008).
[9] American National Standard Institute (ANSI)/ Electronic Industries Alliance (EIA): *ANSI/EIA Standard for Process for Engineering a System*, ANSI/ EIA 632-1999 (1999).
[10] Institute of Electrical and Electronics Engineers (IEEE): *IEEE standard for application and management of the systems engineering process*, IEEE 1220-2005 (2005).
[11] E. M. Clarke and J. M. Wing: Formal methods: State of the art and future directions, *ACM Computing Surveys*, 28 (4), 626-643 (1996).
[12] International Electrotechnical Commission (IEC): *IEC standard for functional safety of electrical/electronic/ programmable electronic safety-related systems*, IEC 61508-SER Ed. 1.0 (2005).
[13] T. DeMarco: *Structured Analysis and System Specification*, Yourdon Press, USA (1978).
[14] M. Arisawa and T. Saitoh: *Moderu Shimyureshon Giho (Model Simulation Methodology)*, 16-17, Kyoritsu Shuppan (1997) (in Japanese).
[15] V. K. Rompaey, D. Verkest, I. Bolsens and D. H. Man: CoWare – A design environment for heterogeneous hardware/software systems, *Proceedings of the European Design Automation Conference*, 252-257 (1996).
[16] T. Doran: IEEE 1220: For practical systems engineering, *IEEE Magazines Computer*, 39 (5), 92-94 (2006).
[17] M. Sipser: Course Technology Ptr (SD), *Introduction to the Theory of Computation*, 29-90, The Netherlands (1996).
[18] R. Alur and D. L. Dill: A theory of timed automata, *Theoretical Computer Science*, 126 (2), 183-235 (1994).
[19] G. J. Holzmann: The model checker SPIN, *IEEE Transaction on Software Engineering*, 23 (5), 279-295 (1997).
[20] K. G. Larsen, P. Pettersson and W. Yi: UPPAAL in a nutshell, *International Journal on Software Tools for Technology Transfer*, 1 (1-2), 134-152 (1997).
[21] Japanese Industrial Standards Committee: *Sangyo yo manipyuretingu robotto - yogo (Industiral Manipulating Robot – Terminology)*, JIS B0134 (2008) (in Japanese).
[22] J. P. Elm: A study of systems engineering effectiveness – Initial results, *Proceedings of the Systems Conference 2008 2nd Annual IEEE*, 1-7 (2008).
[23] B. Boehm, R. Valerdi and E. Honour: The ROI of systems engineering: Some quantitative results for software-intensive systems, *Systems Engineering*, 11 (3), 221-234 (2008).
[24] E. C. Honour: Understanding the value of systems engineering, *Proceedings of the INCOSE International Symposium*, 1-16 (2004).
[25] A. K. Kludze: The impact of systems engineering on complex systems, *Proceedings of Conference on Systems Engineering Research* (2004).
[26] B. W. Boehm: *Software Engineering Economics*, 38-40, Prentice-Hall, USA (1981).
[27] B. Alpern and F. B. Schneider: Defining liveness, *Information Processing Letters*, 21, 181-185 (1985).
[28] Graduate School of System Design and Management, Keio University: Homepage, Graduate School of System Design and Management, Keio University (online), http:// www.sdm.keio.ac.jp/ (see 2010-04-18).

Authors

Atsushi Katoh

Completed the courses in Electric System at the Graduate School of Science and Technology, Kumamoto University in 2000. Joined an electric appliance company and engaged in research and development of a small network device in a ubiquitous environment. Worked on independent verification and validation (IV&V) of spacecraft software in space development field since 2006. Also engaged in research on systems engineering at Keio SDM. Won the Research Award of the Information Processing Society of Japan in 2009. Member of the Information Processing Society of Japan. In this paper, was in charge of the research plan, selection and synthesis of the methods, application to the industrial case, and discussion.

Masataka Urago

Completed the doctoral program at the Department of Mechanical Sciences and Engineering, Graduate School of Engineering, Tokyo Institute of Technology in 1998. Doctor (Engineering). Became an assistant at the Tokyo Institute of Technology in 1998. Appointed to associate professor of Keio SDM in 2008. Engages in research on systems engineering as well as computer modeling and mathematical computation of engineering problems. Member of the Japan Society of Mechanical Engineers and the International Council on Systems Engineering (INCOSE). In this paper, was in charge of the selection and synthesis of the methods.

Yoshiaki Ohkami

Completed the doctoral program at the Department of Electrical Engineering, Graduate School of Engineering, Tokyo Institute of Technology in 1968. Doctor (Engineering). NASA Fellow, professor of the Tokyo Institute of Technology, professor of Keio University, and Research Director, Japan Aerospace Exploration Agency (JAXA). Became the Director of Keio SDM in 2008. Engages in research on dynamics and control of complex systems and strategic systems engineering. Fellow of the Japan Society of Mechanical Engineers and the International Council on Systems Engineering (INCOSE). Member of the Japan

Society for Aerospace and Space Sciences, Institute of Electrical and Electronics Engineers, Inc. (IEEE), and American Institute of Aeronautics and Astronautics (AIAA). In this paper, was in charge of research strategy planning and research integration.

Discussions with Reviewers

1 Novelty of the issue and outcomes

Question (Kanji Ueda, AIST)

In chapter 2, you say the reason for synthesizing the methods of different research or technological fields is that you can expect to produce a new research or technological field as some new technologies are generated from the synthesis. What kind of results did you obtain from this research?

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

This paper claims novelty, but the readers outside of this specialty cannot understand immediately whether it is novel. I assume that there had been methods proposed to improve the reliability of the system, and I think you can emphasize the novelty if you explain the situation before this research was carried out. Similarly, I think you should explain why such critical technology was never pursued before, and why it had been difficult.

Answer (Atsushi Katoh)

I would like to explain the background of this research by focusing on the cooperative behavior by the system components. Normally, the cooperative behavior by the system components is verified in the system test that is conducted at the final phase of system development. When any inconsistency of the cooperative behavior is detected there, it is necessary to return to the upstream of the system development for correcting, and correction is often quite costly. Also, re-designing in the final phase may compromise the reliability of the system. Therefore, the cooperative behavior by system components must be designed and verified thoroughly in the upstream of the system development. At that point, there was no proposal for a methodology to achieve this. The reason is that the cooperative behavior by system components was not viewed from the perspective of system reliability, and the incorporation of system quality in the upstream of the system development was a relatively new concept. I shall add these points in chapter 1.

As results of conducting this research, the following four outcomes were obtained. First is the establishment of this methodology where the system specifications are decomposed into the component specifications and interface specifications among components for consistent cooperative behavior. Second is the clarification that bridge method is needed to synthesize architectural design method and model checking, and the presentation of an actual example for the bridge method for the cooperative behavior. Third is the expansion of the ranges of application and research of model checking, by applying the method that was mainly used in software development to system development. Fourth is the proposal of this methodology to the robot industry.

2 Cooperative behavior

Comment (Kanji Ueda)

You use the expressions "cooperative behavior by the components" several times, but I think the general readers may have difficulty understanding the meaning. Also, you use "consistency/inconsistency of the cooperative behavior" as self-explanatory terms. Please state the definition or the meaning of the cooperative behavior, and provide explanations.

Comment (Motoyuki Akamatsu)

You do not describe the means for determining the attributes of the cooperative behavior, extracting the properties to be satisfied by cooperative behavior, and for considering safety. Therefore, I don't think the robot engineers, for example, can see whether they can use this. I think you should provide explanations that give some hints for the people of the robot industry to use this methodology.

Answer (Atsushi Katoh)

In this paper, the cooperative behavior by components is defined as "a cooperation with processings of the system component and the other system components through the interface among components". The consistency of cooperative behavior is defined as the state where "a consistent implementation of the cooperative behavior by the components in correspondence to the system specification is conducted". The inconsistency of cooperative behavior is defined as the state where "the definition of the consistency of the cooperative behavior is not satisfied". These are added to chapter 1.

The attributes of the cooperative behavior are determined based on the properties to be satisfied by the cooperative behavior and the specifications related to the cooperative behavior. For the measurement and integrated control subsystems in the applied case, we were concerned about the lacks in the messages and processings of the specifications related to the cooperative behavior. Also, there were temporal limitation specifications such as within 100 ms and timing of messages and processings, among the properties to be satisfied by the cooperative behavior and the specifications related to the cooperative behavior. Therefore, the two points presented in subchapter 4.2 were determined as the attributes. We will add these to section 5.2.2.

The properties that must be satisfied by the cooperative behavior are extracted using the traceability matrix that summalizes the correspondence between the system specifications and the component specifications obtained by decomposing the system specifications.

Confirming safety of the cooperative behavior is the topic of this research. Safety means a property where the system will never reach an undesirable state. Since it is difficult to identify "all the states where the system is undesirable", it cannot be denied that there may be a fault in the safety confirmation for the cooperative behavior. We plan to investigate the solution to this issue by combining a safety analysis method such as fault tree analysis (FTA) with this methodology.

3 Selection of methods

Question (Kanji Ueda)

There are many expressions of "according to IEEE 1220…". What is its relationship to the methodology developed in this research? Also, the reason why you employed IEEE 1220 is not clear.

Comment (Motoyuki Akamatsu)

Please explain what other methods there were of system design methods other than architectural designing. Please also explain methods other than IEEE 1220 that you did not employ for architectural designing. Also, to clarify the scenario for selecting IEEE 1220 among several other architectural design methods, it will be easier to understand if you describe what disadvantages there were in the other methods.

It is explained in chapter 1 that model checking is a method to exhaustively verify the models that express the state transitions of the system. Please explain whether model checking method used here was originally developed in this research or is an application of an existing method.

It is written that the checking tool based on finite automaton was selected as the model checking tool, and you describe the advantages. Please describe what other tools there were and what their disadvantages were. Similarly, if there were other candidates in the selection of UPPAAL, please describe them.

Answer (Atsushi Katoh)

In this research, we employed the research policy of selecting the methods for which the effectiveness has been already established, to efficiently establish a high-quality methodology. In constructing this methodology, we applied architectural design method that has been recognized as being effective and is standardized. Other system design methods include structured analysis and structured design (SA/SD) method. While architectural deign method is not appropriate for system design focusing on specific technological elements such as data or service, it is a universal design method independent of any particular technological systems. Therefore, we selected architectural design method as our system design method. The representative system engineering standards for architectural design method include ISO 15288, ANSI/EIA 632, and IEEE 1220. Since the tasks and procedures are finely defined for each process in IEEE 1220, we employed IEEE 1220. These standards are compared in chapter 3.

Model checking is a method that has already been established as a verification method. The research was started in the early 1980s, and today, it is widely used in software development. Model checking is "a verification using models", but it has become a proper noun for the verification method. We will add these points to chapter 1. The system verification methods other than model checking include test method and simulation method. However, model checking can exhaustively verify whether the properties to be satisfied for the state transitions are valid or not. Therefore, we employed model checking as our system verification method. We will compare these in chapter 3.

There is a verification method called theorem proving in the formal method. Theorem proving is a method where the system specifications and designs are described in a language that is mathematically defined in terms of semantics, and are given exact proof. While theorem proving enables exact verification of a system, great efforts are needed because some parts must be done interactively with humans. The authors think that theorem proving is not a verification method that has been applied in industry and the effectiveness has not been demonstrated. Therefore, we excluded it from the candidates of verification methods of this research.

The representative types of model checking include finite automaton and timed automaton, which is an extended finite automaton. Model checking and the tools to be applied must be selected according to the characteristic of the verified target. In a case of verifying general state transitions where the situation change is triggered by some external event, we select a model checking tool corresponding to finite automaton. SPIN is a representative model checking tool. In a case of verifying state transitions including temporal limitations, we select a model checking tool that corresponds to timed automaton. UPPAAL is another representative model checking tool. If the target that can be verified by model checking for finite automaton, it can also be verified using a model checking tool for timed automaton. However, it does not work the other way around. We will add these points to chapter 4. In the applied case, it was necessary to verify the temporal limitations of the cooperative behavior. Also, for the model checking tool corresponding to timed automaton, the authors determined that only UPPAAL possesses the applicable quality in the industrial case.

4 Industrial application of the outcomes

Comment (Kanji Ueda)

I think the significance as *Type 2 Basic Research* will increase if you address how the result of this research was actually used in the industrial application, what is the prospect, and the limit of application if it is used.

Comment (Motoyuki Akamatsu)

The important point of this research is that this methodology must be used by the people in industry who actually work to develop the system. In that sense, I would like to see an explanation on what targets these outcomes can be used, and the range of its application. Also, please state your thoughts on the ways of diffusing this methodology.

Answer (Atsushi Katoh)

I think the methodology in this research can be applied to the development of any technological systems, without specializing in particular technological systems. The reason is that when a system is designed, the function is achieved by finding the components that compose the system based on the system specifications, and then have the components behave cooperatively, and this is a common concept for all technological systems. Also, this methodology can deal with the unique issues of cooperative behavior in the applied system. The reason is that this methodology has the bridge method where the attributes and the model checking tool are selected according to the characteristics of the cooperative behavior.

Currently, the authors are planning and developing a new product for the industrial robot jointly with an industrial robot company. The industrial case study in chapter 5 describes these efforts. As of writing of this paper, the industrial robot is being developed according to the specifications that were verified for consistent cooperative behavior by applying the methodology of this research. I think this research amounts to *Type 2 Basic Research* because of the contribution to increase the reliability of industrial robot. These points are added to chapter 5.

However, cautions must be taken when applying this methodology. This method employs model checking to verifiy consistency of the cooperative behavior by components. When there are numerous states in model checking, state explosion may occur where model checking cannot be completed due to the huge number of combinations of the states. This means that if the cooperative behavior by components becomes extremely complex due to architectural designing, the verification of the cooperative behavior may not get completed in model checking. In such cases, it is necessary to do re-architectural designing to ensure the cooperative behavior by components will not become extremely complex, or the number of the states in the models for the specifications related to the cooperative behavior must be reduced. We will describe these in the newly added section "Applicability of this methodology" in chapter 6.

This methodology will be spread throughout industry by Keio SDM to which the authors belong. We will add this to chapter 7.

5 Advantages and disadvantages of the selected methods

Question (Motoyuki Akamatsu)

In chapter 3, you describe the selection of the methods. You mention architectural design and SA/SD methods for achieving function "a", and state that you selected architectural design method because it is a universal design method, although it is not suitable for system design focusing on specific technological elements such as data or service. Since the elemental technologies are selected according to the research goal, can you clearly state the goal, and then explain that you selected architectural design method as a result of comparing the advantages and disadvantages?

The goal of this research, I assume, is to construct a universal methodology, but when universality is set as a goal, you will also have a problem that the methodology cannot be applied to individual problems. I think the solution to this is the bridge method, but if this is so, please explain this clearly (this is also relevant to discussion 3).

Answer (Atsushi Katoh)

I shall clarify the objective (goal) of the research. The objective of this research is to establish a methodology for decomposing a system specification into component specifications and interface specifications among components whose cooperating behavior is consistent with each component, which is not specific to particular technological systems. We will add this to chapter 2. The system design method with function “a” mentioned in chapter 3 includes SA/SD and architectural design methods. In the SA/SD method, the system design is done focusing on the data (such as business information) that are stable against the changes in the system environment. This enables the construction of a system with maintainability and expandability. However, because it is a method developed primarily for information systems, it is not very suitable for designing anything other than the information system. On the other hand, architectural design method has no procedures or tasks specifically defined for a certain designing, and therefore requires more efforts compared to specific design methods. However, architectural design method is a universal design method independent of some particular technological systems. Therefore, considering the research objective of developing a methodology not specific to particular technological systems, we selected architectural design method as the system design method with function “a”. The process of selecting architectural design method from the system design methods, and the advantages and disadvantages of the SA/SD and architectural design methods are revised in chapter 3.

As you indicated, I do think there is a problem that this methodology will be difficult to apply to individual problems because it is not specific to any technological systems. For this methodology, the attributes and the model checking tools are selected according to the characteristics of the cooperative behavior in the applied system using the bridge method. The issues unique to the applied system for the cooperative behavior are handled in this manner. We will add these to subchapter 6.2.

6 Bridge method

Comment (Motoyuki Akamatsu)

You mention that one of the outcomes of this research is that you clarified the fact that the bridge method is necessary. Please describe the research scenario for the bridge method, such as why the bridge method is necessary, what requirements it has to satisfy, and why you named it bridge method.

Since architectural design method and model checking were developed based on two different ways of thinking, I assume that the outputs from architectural design method were insufficient for model checking, and I think it is natural that you needed a technology to convert each other to connect the two items with different concepts. Therefore, to clarify the originality of this method, please address whether this is simply a conversion method, or a method developed to verify the cooperative behavior.

Answer (Atsushi Katoh)

In this research, the system verification is conducted for the cooperative behavior by components at the phase of system design. Therefore, we focused on the cooperative behavior, and saw it was necessary to seamlessly connect the outputs of architectural design and the inputs of model checking. Therefore we developed the method to derive the component specifications and interface specifications among components related to the cooperative behavior, the properties to be satisfied by the cooperative behavior, and the model checking tool to be applied. This technology is called bridge method because it bridges architectural design method and model checking. I believe the bridge method is novel because it focuses on the cooperative behavior, and we clarified the specific method for synthesizing the system engineering standards such as IEEE 1220 and model checking. We will add these to subchapter 4.2.

National electrical standards supporting international competition of Japanese manufacturing industries

— Realization of a new capacitance standard and its traceability system —

Yasuhiro Nakamura * **and Atsushi Domae**

[Translation from *Synthesiology*, Vol.3, No.3, p.213-222 (2010)]

A capacitor or a condenser is one of the most basic electrical devices and is used in various electrical equipments. Recently the electrical equipment industry has been requesting the quality of capacitors to be compatible with international standards; among other things, it is strongly demanded that the traceability of a capacitance standard should be consistent with the national standards. To respond to this need from industry, we have developed a new national standard of capacitance based on the quantized Hall resistance and also established its traceability system in cooperation with the accredited calibration businesses. A remote calibration system of capacitance has also been developed to disseminate the standard quickly and to reduce calibration costs.

Keywords : Capacitance, condenser, electrical standard, traceability, remote calibration

1 Introduction

The manufacturing industry for electronic parts and modules including the laminated ceramic capacitor, chip inductor, EMI filter, and thin-film resistor element is one of the major industries in Japan. For example, capacitor alone has estimated market scale of 800 billion to one trillion yen. The demand for capacitors is increasing due to the increased and diversified performance of the digital home appliances such as the flat panel television, cell phones, and personal computers, as well as increased use of electronic elements in automobiles. Moreover, there is a high expectation for high-volume battery capacitor as the next-generation energy device, and further demands are expected in the environment and energy fields[1]. Currently, the global share of Japanese electronic parts industry for capacitors is estimated at about 70 %, but the shares of other Asian electrical companies are rapidly increasing.

The main customers of the electronic parts companies, or the main supply destination of the electronic parts, are the major manufacturers of automobile, electrical appliance, or communication device industries. These industries are demanding increased reliability of electronic parts and modules from the perspective of safety, security, and energy saving. At the same time, there is a strong demand for compatibility with the international standards such as the ISO/TS 16949 (international standard for the quality management system of the automobile industry) and ISO/IEC 17025 (international standard for the capability of the testing and calibration laboratories). The establishment of metrological traceability to the national standard is mandatory. For the Japanese electronic parts companies, to meet the demands of their customers, the establishment of measurement traceability and the compatibility to international standard for the testing device in their manufacture line are pressing issues.

To respond to the demands of the Japanese industry, the National Institute of Advanced Industrial Science and Technology (AIST) is developing the national standards of various electric quantities such as voltage and resistance, establishing these as standards with international compatibility through international comparisons, and is building a system for widely disseminating the metrology standards to the site of production of the Japanese industries through the Japanese calibration laboratories. The quantities of impedance such as capacitance, inductance, and AC resistance are the most fundamental physical quantities among many electric quantities. However, with the enhanced performance of electronic devices as well as the improved performance and increased electronic parts in automobiles, the demand for highly precise standards, particularly for capacitors, has risen in the last ten years. Therefore, the standard setting and realization of the capacitor or the capacitance standard were reviewed starting from zero, and R&D was conducted to establish a new capacitance standard and to build the metrological traceability system.

By disseminating the world's highest electrical standards, including the capacitance standard to the Japanese electronic parts companies, the metrological traceability can be guaranteed for every electronic part. We wish to support the global competition and the technological development of the Japanese electronic parts industry as well as the Japanese core industries such as electrical, communication, and automobile industries that are the destination of these

National Metrology Institute of Japan, AIST Tsukuba Central 3, 1-1-1 Umezono, Tsukuba 305-8563, Japan (current affiliation: Planning Headquarters, AIST Tokyo Headquarters, 1-3-1 Kasumigaseki, Chiyoda-Ku, Tokyo 100-8921, Japan) * E-mail : y.nakamura@aist.go.jp

Original manuscript received January 28, 2010, Revisions received July 12, 2010, Accepted July 14, 2010

electronic parts. We hope to contribute in strengthening the international competition power of the industries.

2 Scenario

2.1 Establishment of the development goal of the national standard

In developing a new national standard, it is necessary to establish the goal of the development, such as "What level of uncertainty (precision) should the national standard for the newly developed capacitance target?" and "What is the expected secondary measurement standard that will be the subject of calibration?" At the time we started the development, the mainly used secondary measurement standard capacitors, which were calibrated from the national standard (primary measurement standard), were air capacitors or mica capacitors. These were used because the temperature coefficients were small or the devices themselves were small and easy to handle. They were used widely in the corporate standard labs, but the expected uncertainly was of 1 ppm (1 μF/F) level. The electronic parts companies or the capacitance measuring instrument manufacturers that demanded high-precision capacitance standard owned the fused-silica capacitor that had higher precision and stability than the air capacitor, and wanted standard for this type of capacitors. The fused-silica capacitors were capable of achieving uncertainty of 0.1 ppm level. Therefore, we set the fused-silica capacitor as the subject of calibration and developed the national standard for capacitance.

The developed capacitance standard was compared with the standards of the national metrology institutes (NMI) of other countries to check its equivalency, and then to establish the international compatibility. Surveying the uncertainties of the capacitance standards realized at the NMIs of countries that realized the world's top-level capacitance standard, specifically, the National Institute of Science and Technology (NIST, USA), Physikalisch-Technische Bundesanstalt (PTB, Germany), National Measurement Institute of Australia (NMIA, Australia), and Laboratoire National de Métrologie et d'Essais (LNE, France), it was found that these NMIs have established the standard of uncertainly of 0.1 ppm or less[2]-[5]. We decided that the world's top-level standard must be achieved in assuming a highly precise and stable fused-silica capacitor as a calibration subject (secondary measurement standard), and to support the global competition of the Japanese industries. Therefore, we set the development goal: "the establishment of a national standard with standard uncertainty of 0.1 ppm or less".

2.2 Scenario for the dissemination of standard to industrial sites

To disseminate the capacitance standard to the manufacturers' production site and to build the metrological traceability system, we believe the role of the private calibration laboratories is mandatory. Currently, many NMIs around the world develop and organize standards required by industry and provide wide-ranging calibration services. (For example, the NIST and PTB provide about 330 types of electrical standards, while Standards and Calibration Laboratory [SCL, Hong Kong] provides about 200 calibration services[6].) However, it is not necessarily the best policy for AIST to organize and provide the standards for all ranges to meet the demands of industries. This is because there are several highly capable calibration labs and precision machine manufacturers in Japan compared to other countries. In building the metrological traceability system, if it is possible to maximize the calibration abilities of the cooperating laboratories in Japan, it will be possible to realize the stable dissemination of standards to the far corners of the industrial sites. At the same time, it will enable AIST to slim down its function and to allocate the resources efficiently. With this background, a standard provision system was considered for the capacitance standard and is shown in Fig. 1.

In this system, AIST develops and establishes the national standard for the basic range and provides this to the Japanese calibration labs. The calibration labs expand the calibration range based on the disseminated basic range standard, and then disseminate them to the industrial sites. In this case, the role of AIST is limited to regularly disseminating the highly precise basic range standard to the upper-tier calibration labs, and this enables simplifying its calibration work. Also, by limiting the range of the standards provided, the AIST resources can be focused and concentrated, and this in turn enables achieving higher precision and efficiency of the calibration devices. The method for disseminating

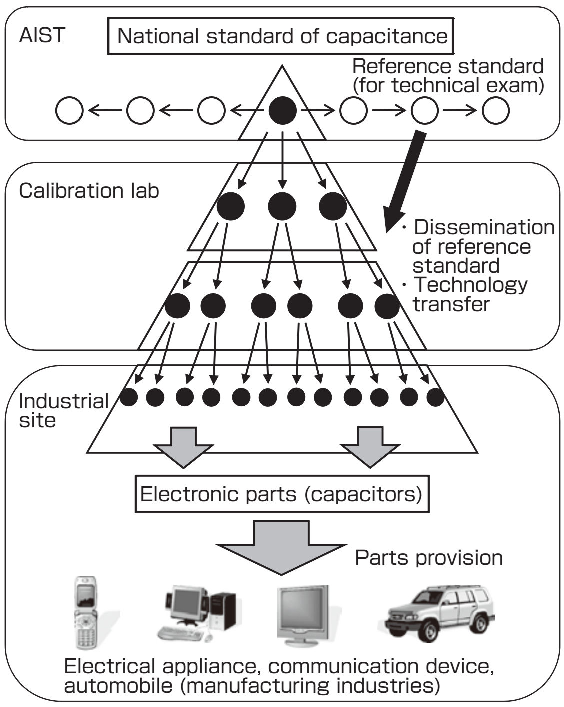


Fig. 1 Scenario for the system of capacitance standard provision

the standards is based on the Japan Calibration Service System (JCSS) of the Measurement Law. This builds the hierarchy of standard dissemination as shown in Fig. 1. The high-precision basic range national standard of AIST is expanded by the calibration labs of each tier, and is disseminated promptly to the site of production. Specifically, AIST develops and organizes the 10 pF, 100 pF and 1000 pF capacitance standards, and disseminates these to the upper-tier calibration labs. The upper-tier calibration labs may, for example, expand the calibration range to 1 μF based on the 10 pF standard, and this is provided to the lower-tier calibration labs. The lower-tier calibration labs may further expand the calibration range to provide the capacitance standard to the sites of production. By building this system, the necessary range of capacitance standard can be disseminated to the manufacturers' site of production when needed, while maintaining the link to the national standard. This means that the metrological traceability system of the measurement device or the capacitor at the site of production to the national standard can be established efficiently.

In building this standard dissemination system, the role of calibration labs at each tier, particularly the role of uppermost-tier calibration labs, is extremely important. Therefore, AIST must not only develop and disseminate the national standard, but also provide support to improve the technical skills of the calibration labs. Also, a standard (reference standard for skill examination) will be necessary to evaluate and judge the technical skills. This is because if the calibration lab expands, for example, to 1μF or 10 μF based on the 10 pF national standard, it is necessary to check whether the expanded result is correct or wrong. Therefore, as shown in Fig. 1, the range of the capacitance standard can be expanded to some extent at AIST (i.e. expansion to 1 μF or 10 μF based on 10 pF, 100 pF and 1000 pF), and these are used as reference standards to check the techniques of the calibration labs. To plan and organize all the standards that must be developed, the standard organization plan is created for each fiscal year as shown in table 1. The resource allotment is planned according to this plan to develop and realize the standards. Since the understanding and cooperation of the Japanese calibration labs are necessary to achieve this system, we set out to build consensus by actively exchanging opinions with industry at committees and research presentations for standards.

3 Development of the capacitance standard

3.1 Selection of the method

Two methods have been recognized in the world as ways to realize the capacitance standard. One is the method of using the specially shaped capacitor called the cross capacitor. As shown in Fig. 2, according to A.M. Thompson and D.G. Lampard, if the four electrode rods arranged parallel to each other, and the value per unit length of the capacitance (cross capacitance) between the two sets of opposing electrodes are

Table 1 Organization plan for the capacitance standard

Capacitance to be disseminated	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
10 pF		○								
100 pF	○									
1000 pF		○								
0.01 μF				○						
0.1 μF				○						
1 μF				○						
10 μF						○				
100 μF									○	
1000 μF										○

set as C_{12} and C_{34}, the average values of C_{12} and C_{34} can be expressed in the following equation[7]:

$$(C_{12}+C_{34})\ /\ 2 = (\varepsilon_0 \ln 2)\ /\ \pi \qquad (1)$$

As seen from the above equation, the average value of the cross capacitance per unit length is dependent only on the permittivity ε_0 between the electrodes. If the entire cross capacitor is placed in a vacuum, the cross capacitance per unit length will be 1.953549043… pF, and this is not dependent on the shape of the electrode. This means that if the length of the electrode rod is determined accurately, the capacitance can be determined by the length standard of the cross capacitor. However, the condition that makes equation (1) valid assumes that the four electrode rods are infinitely long. Therefore, the capacitance for unit length of electrode rod of infinite length is expressed by equation (1). Therefore, to actually realize the cross capacitor, it is necessary to insert a separate guard electrode between the four electrodes. The area where the guard electrode is inserted will have capacitance zero. When the guard electrode is moved in this state, the capacitance increases or decreases in accordance to the distance transferred. If the cross capacitance for the transferred distance of the guard electrode is calculated, it will follow equation (1). Many NMIs have established the capacitance standard using this method[2]-[5]. However to fabricate the actual cross capacitor, the precise machining of the electrode rods is extremely important. The surface roughness and the degree of parallelness of the electrode rods will directly affect the uncertainty

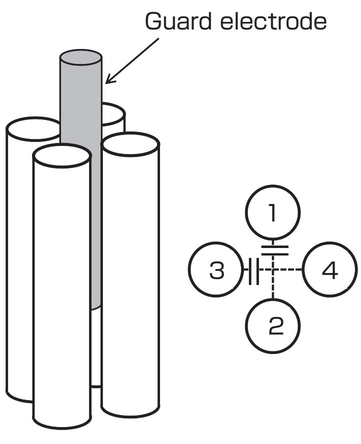


Fig. 2 Cross capacitor

of the cross capacitance. Also, the capacitance measurement by cross capacitor requires experience and skill, and it is not easy to realize the standard of 0.1 ppm or less using this method. While the leading countries of cross capacitor, NMIA (Australia), NIST (USA), PTB (Germany), and LNE (France) have realized the standard for 0.1 ppm or less using this method, the uncertainties at other NMIs are over 0.1 ppm. Also, the Electrotechnical Laboratory (currently AIST) had fabricated and realized the cross capacitor before, but has not achieved uncertainty 0.1 ppm or below[8].

Another method for realizing the capacitance standard is the method using the resistance standard based on the quantized Hall resistance, as shown in Fig. 3. Since 1990, it has been agreed worldwide that the standard for DC resistance will be determined by the quantized Hall resistance. The Electrotechnical Laboratory (current AIST) has disseminated the resistance standard based on the quantized Hall resistance, by organizing and developing the quantized Hall resistance standard according to the agreement (Recommendation of the 77th Comité International des Poids et Mesures [CIPM], 1988)[9]. If the origin of the standard is set in the quantum effect, same results should be obtained any time, anywhere, and by anyone. Particularly, the equation for expressing the quantum Hall effect is shown by equation (2). As it can be seen from the equation, absolutely no other standards are necessary to determine the quantized Hall resistance R_H (h is the Planck's constant, e is the elementary charge of electron, and i is the integer that represents the degree of quantization).

$$R_H(i) = h / ie^2 \qquad (2)$$

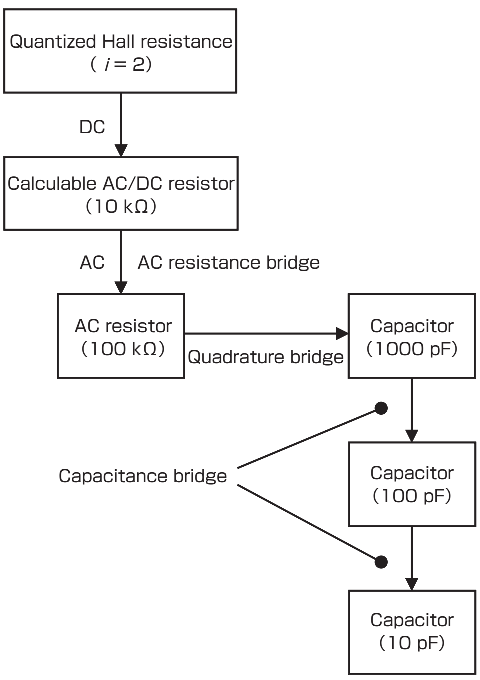


Fig. 3 Capacitance standard based on quantized Hall resistance

This is an advantage that differs greatly from the cross capacitor method where the length standard will always be required to determine the capacitance no matter how precisely the electrode rods are fabricated. Also, as mentioned above, the quantized Hall resistance is the origin of the DC resistance standard. If it is possible to derive the capacitance from the quantized Hall resistance, then sharing and efficient use of the devices can be achieved, and the maintenance and management will be easier after developing the standard. Therefore, we decided to employ the method of deriving the capacitance standard from the quantized Hall resistance.

3.2 Development of the new method to respond to the demands

To derive the capacitance from the quantized Hall resistance, various bridge circuit and special resistors are necessary, as shown in Fig. 3. Specifically, these include the AC resistance bridge, quadrature bridge, capacitance bridge, and a specially shaped resistor that can calculate the AC/DC difference. The capacitance can be derived from the quantized Hall resistance by developing these devices at high precision, and then using them to sequentially measure from resistance to capacitance. In this series of measurements, the quadrature bridge that converts the resistance to capacitance is particularly important in determining the final uncertainty of the capacitance standard. Figure 4 shows the circuit configuration

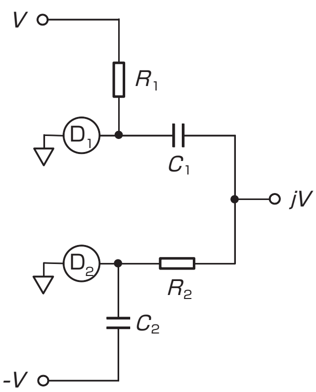


Fig. 4 Quadrature bridge

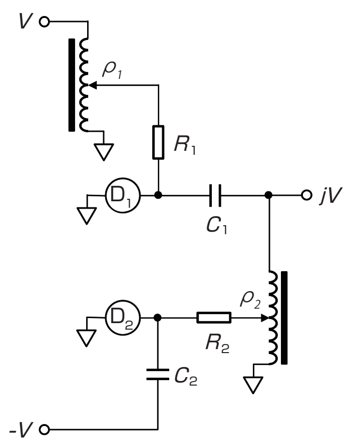


Fig. 5 Multi-frequency quadrature bridge

of the quadrature bridge. From this diagram, the equilibrium condition of the quadrature bridge is as follows:

$$\omega^2 C_1 C_2 R_1 R_2 = 1 \qquad (3)$$

Here, ω is angular frequency, C_1 and C_2 are capacitances, and R_1 and R_2 are resistances. In determining the capacitance based on the resistance of the quadrature bridge, the bridge balance frequency is determined uniquely. (As it is apparent from equation (3), when the resistances R_1 and R_2 and the capacitances C_1 and C_2 are set as fixed values, there will be only one bridge balance frequency ω.) Therefore, the capacitance derived from the quantized Hall resistance is limited to the value at a certain frequency. (Normally, to attain $C_1 = C_2 = 1000$ pF and $R_1 = R_2 = 100$ kΩ, the equilibrium frequency is $\omega = 104$ rad/s, or about 1.592 kHz.) This is a disadvantage against the capacitance standard using the cross capacitor (since, in principle, the cross capacitor is not dependent on frequency).

As shown in Fig. 1, the direct supply destination of the developed capacitance standard is the upper-tier calibration labs that disseminate high-precision calibration service. We conducted a survey for the needed calibration frequency of the capacitance standard of the measuring instrument manufacturers and private calibration labs that were candidates of upper-tier calibration labs, and found that "the request is calibration at 1 kHz". However, using the circuit shown in Fig. 4, the capacitance derived from the quantized Hall resistance is limited to the value of 1.592 kHz. There was a general thinking that the difference between 1 kHz and 1.592 kHz, or 592 kHz, could be ignored, but we decided to satisfy the industrial demands before we started to disseminate the standard. It was necessary to measure and evaluate the frequency characteristics around 1 kHz for the fused silica standard capacitor that will be the subject of calibration. Revisions were made to the circuit in Fig. 4, and we devised a quadrature bridge with new circuit configuration where the bridge balance frequency can be varied. Figure 5 shows the circuit for the multi-frequency quadrature bridge. When two inductive voltage dividers are added to the conventional circuit (Fig. 4), the bridge balance condition of the bridge can be expressed by equation (4).

$$\omega^2 C_1 C_2 R_1 R_2 = \rho_1 \rho_2 \qquad (4)$$

Here, $\rho_1\rho_2$ is the voltage ratio of the newly added inductive voltage dividers. By taking the partial pressure ratio $\rho_1\rho_2$ arbitrary, in principle, the quadrature bridge will reach bridge balance at all frequencies. In practice, the bridge was built by using $\rho = n/8$ (n = 1, 2, 3, …), and we created a multi-frequency quadrature bridge where the bridge balance frequency was $1.25n/2\pi$ kHz[10]. Using this bridge to measure the frequency characteristic of the fused silica capacitor, as shown in Fig. 6, it was found that capacitance change occurred according to the frequency variation around 1 kHz in a certain type of capacitor (GR1408). We obtained new findings that refuted the general thinking of, "there was no frequency dependency between the range 1.592 kHz and 1 kHz in fused silica capacitor"[11]. At the same time, for the AH11A standard capacitor that was assumed to be the major secondary standard, it was confirmed

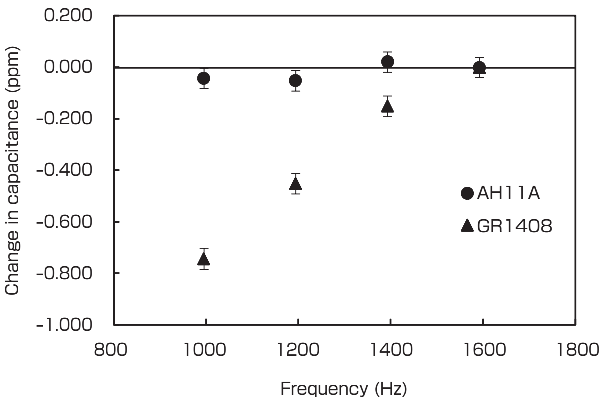


Fig. 6 Frequency characteristic of the fused silica standard capacitor

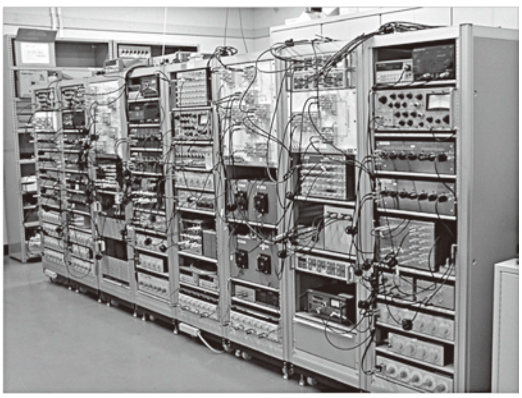


Fig. 7 Capacitance standard based on quantized Hall resistance (national standard)

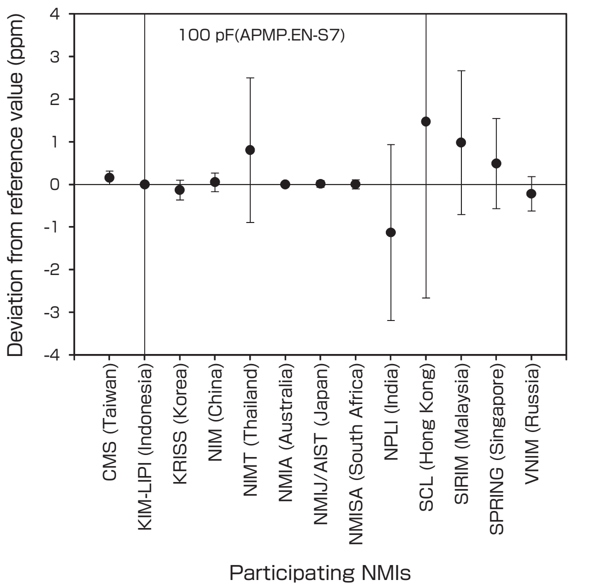


Fig. 8 Result of the international comparison of capacitance standard

that the capacitance change by frequency can be ignored[12]. Therefore, we developed the "capacitance standard based on quantized Hall resistance" that incorporated the new circuit configuration with added variable frequency to the quadrature bridge (Fig. 7). When the uncertainty of the developed capacitance standard was evaluated, the estimated standard uncertainly was 0.04 ppm, and we were able to achieve the goal of 0.1 ppm or less. This result was confirmed in the international comparison (Fig. 8), and after the technological peer review by the specialized researchers of the NMIs of other countries, it was demonstrated that the international equivalency was attained (CMC registration[6]). Currently, the institutes other than AIST that have realized the capacitance standard based on the quantized Hall resistance are National Physical Laboratory (NPL, UK), Center for Measurement Standards (CMS, Taiwan) and the Bureau International des Poids et Mesures (BIPM), but all of them use the conventional circuit as the quadrature bridge.

4 Establishment of the metrological traceability system

4.1 Development of the reference standard for technical review and technology transfer

The capacitance standard developed by AIST is disseminated to the industrial sites based on the standard dissemination system shown in Fig. 1. Also, the metrological traceability system for capacitance is established. However, as mentioned above, the standards provided by AIST are only for 10 pF, 100pF and 1000 pF, while at the sites of production, the capacitance standards for the range from 1 pF to 100 μF are required. Therefore, expansion of the calibration range is necessary at the calibration labs of each tier in Fig. 1. The candidates of calibration labs include the capacitance measuring instrument manufacturers and quality control divisions of the electronic parts companies, and these calibration labs must develop the expansion method on their own using the capacitance standard provided by AIST, and realize and provide the capacitance standard in the range needed at the industrial sites and by the customers. In this case, the calibration labs will undergo the technical review based on JCSS for the technical adequacy of the expansion method. For this review, a reference standard (standard with known value) is necessary to judge whether the expansion result is correct or wrong. For example, when a calibration lab conducts the calibration for 1 μF using a method it developed on its own based on the value for 10 pF provided by AIST, to judge whether the calibration result is right or wrong, a standard for 1 μF with a known value is necessary. Therefore, AIST developed the standards for 0.01 μF, 0.1 μF, 1 μF and 10 μ F (medium-capacitance standard) as reference standards for the technical review, other than the standards for 10 pF, 100 pF and 1000 pF (low-capacitance standard), and disseminated them to the National Institute of Technology and Evaluation (NITE) that conducts the technical review for JCSS. To develop the medium-capacitance standard, the technology where all the measurement systems are coaxial four-port bridge was employed. By doing so, the capacitance could be expanded or the lower impedance could be handled. By employing the coaxial four-port bridge, the influence of the measurement cable could be removed and the effect of the parasitic impedance could be reduced. The developed medium-capacitance expansion system is shown in fig. 9. The uncertainties of the medium-capacitance expansion system were estimated at standard uncertainty of 0.38 ppm for 0.01 μF and standard uncertainty of 2.0 ppm for 10 μF. We hence developed the capacitance expansion system with sufficient precision as the reference standard for technical review[13][14].

To technically support the expansion of the calibration range by the calibration labs, the medium-capacitance expansion technology developed at AIST was transferred to the Japan Electric Meters Inspection Corporation (JEMIC), which is one of the calibration labs[15]. (Specifically, the medium-capacitance expansion system that was the same as the one at AIST was developed at JEMIC through joint research with AIST.) As a result, expansion of the capacitance range using the medium-capacitance expansion system was achieved at JEMIC, which was then accredited as a JCSS calibration lab upon review by NITE. Active technical instructions and advices were given on the analysis method of uncertainty for the range expansion to other calibration labs, and now, there are three JCSS labs (uppermost-tier calibration labs) accredited for the capacitance standard. (For overall electrical standard, currently there are about 50 JCSS accredited labs, and nine labs including the above three are accredited as the uppermost-tier calibration labs.)

4.2 Development of the new dissemination method and analysis of the standard dissemination status

As mentioned earlier, the presence of the calibration labs is indispensable in establishing the metrological traceability system of the capacitance standard. We drafted a scenario for disseminating the national standard from AIST to the

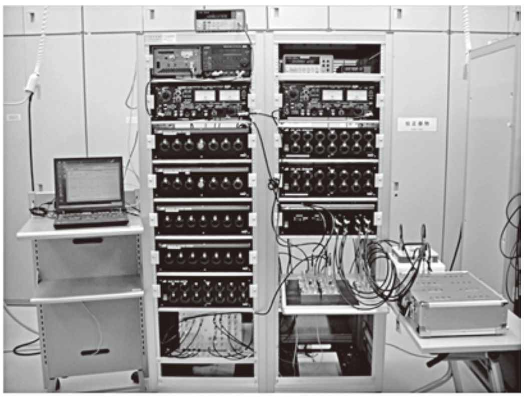


Fig. 9 Medium capacitance expansion system

industrial sites through the calibration labs. In the current situation, the accreditation of the JCSS calibration labs for capacitance is progressing, and the standard dissemination system according to the initial scenario is being realized. However, the sites of production are where the metrological traceability is truly needed, and our goal is achieved only when the demands of the industrial sites are satisfied. Therefore, we thought a survey and analysis of the state of the metrological traceability system at the industrial sites were necessary. We surveyed the demand for standard dissemination system of the industries, and found that with the current dissemination system, it was difficult in terms of time and cost to guarantee the metrological traceability to each and every measuring device at the site of production. In the current system where the measuring device that must be calibrated is transported to the calibration lab for calibration (carry-in calibration), the production line where the measuring device is used must be stopped while the device is being calibrated, and this is not practical for the production line that is normally in operation 24 hours. Also, when all of the several hundred or several thousand measuring instruments used at a site of production were to be calibrated, the calibration fee will be enormous and is not realistic. Therefore, we determined that it was difficult to establish the metrological traceability system to the industrial site according to the initial scenario.

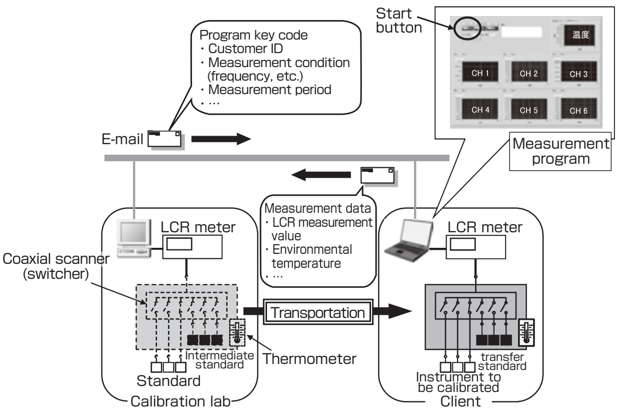


Fig. 10 Conceptual diagram of the remote calibration for capacitance standard

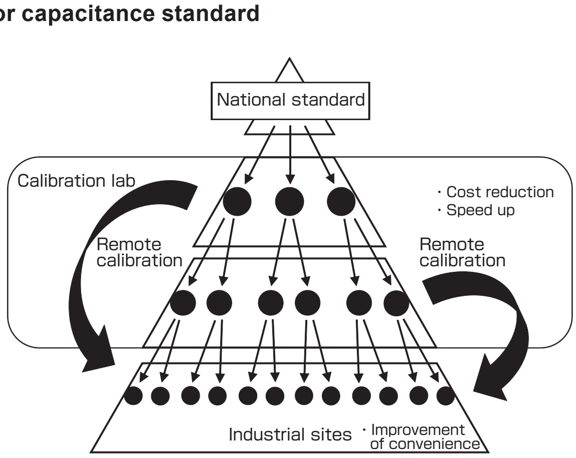


Fig. 11 Quickening the service dissemination by remote calibration and rationalization of the traceability system

Therefore, we conducted an R&D on a remote calibration method as a new dissemination method that may reduce the calibration time and cost[16]-[18]. Figure 10 shows the conceptual diagram for remote calibration of the capacitance standard. This calibration method uses an intermediate standard. Normally, to receive the calibration service, the clients must send or bring their instrument to be calibrated at their own expense and responsibility to the calibration lab. In the remote calibration shown in Fig. 10, the client uses the transfer standard and the measuring device sent by the calibration lab to conduct the measurements necessary for the calibration of the instruments on their own. Specifically, as shown in the figure, the transfer standard that has been previously calibrated by the calibration lab is sent to the client. At the same time, a switching device called the coaxial scanner is also sent. The client connects the commercial LCR meter, personal computer (PC), and the instrument to be calibrated to assemble the (remote) calibration system, starts up the measuring program installed in the PC beforehand, and conducts the measurement. The calibration system and the measurement program are designed to conduct the measurement automatically from beginning to end, and the client does not need any special training or skills. The measurement results obtained by the client are automatically sent to the calibration lab by e-mail. The data is analyzed by the calibration lab, and the result is returned to the client by e-mail. In remote calibration, the client does not have to transport the instrument outside to receive the calibration service. This will eliminate the cost needed for the transportation of the instrument, and can minimize the period during which the instrument cannot be used due to calibration. By incorporating the remote calibration method in the standard dissemination system, it will be possible to disseminate the standard to the sites of production directly from the upper-tier calibration labs, and this will rationalize the metrological traceability system as well as speed up the dissemination (Fig. 11).

The external appearance of the developed remote calibration system is shown in Fig. 12. In developing this system, considering the diffusion to industry and the reduction of the

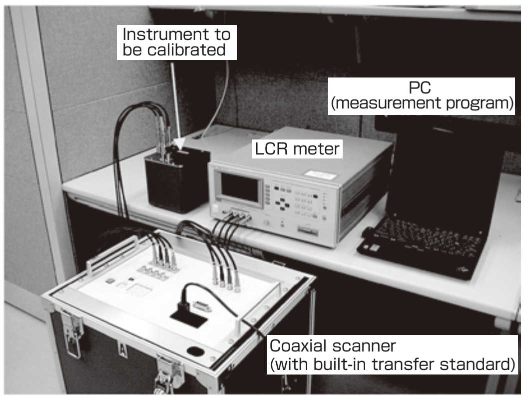


Fig. 12 LCR standard remote calibration system

introductory cost, commercially available measuring devices that were used widely in industry were employed in parts of the calibration system. Also, the system was designed to be used by clients (users) without special knowledge of calibration. For sending and receiving of the data and setting of the measurement conditions, particular care was taken for data protection and security measures to prevent intervention by the user. Also, the system allowed the remote calibration of all impedance standards (LCR standard) including inductance (L), AC resistance (R), and capacitance (C). Figure 13 shows the results of the demonstration experiment of the remote calibration using this system. The results were equivalent to those of the conventional carry-in calibration. Based on these results, we are investigating the practical use of the system, and are currently discussing the introduction of the remote calibration system with a Japanese electronic parts company. There are several thousand inspection meters for LCR parts at the production site of this company, and we expect to be able to provide the metrological traceability guarantee to all measuring devices through remote calibration. Also, active technological transfer and practical use are provided to other companies, to advance the quick dissemination of the capacitance standard to the industrial sites and to enable the establishment of the metrological traceability system.

5 Future issues

A series of R&D were conducted to support the competitive power of the Japanese industry by developing the world's top-level capacitance standard that is internationally compatible, and to establish the metrological traceability system by building the system for disseminating the standard to the industrial sites through the calibration labs. To present, three JCSS calibration labs are registered and accredited, and these labs are capable of conducting calibration in the range of 1 pF ~ 100 μF. Thus the basic standard dissemination system was established. However, to establish the true metrological traceability system, it is necessary to build a system that can disseminate the standards needed at the sites of production quickly and at low cost. As one of the

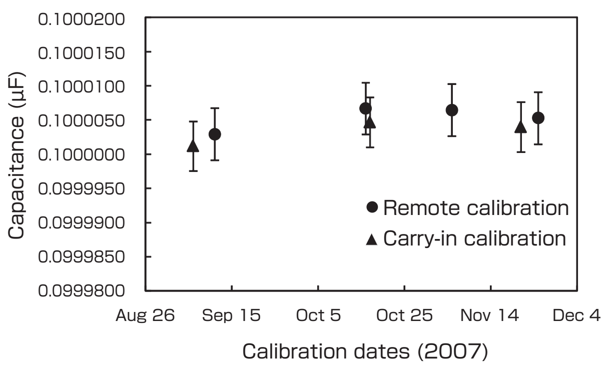


Fig. 13 Experimental results of remote calibration (comparison to carry-in calibration)

solutions, we considered the remote calibration system, and conducted R&D for the remote calibration system for the impedance standards (LCR standard) including the capacitance standard. While it has been technically demonstrated by experiment to be ready for practical use, to diffuse this system to industry, there are unsolved issues such as cost reduction of the system and the JCSS accreditation of the remote calibration method. However, a system that disseminates the national standard established by AIST to all the corners of industrial sites should be the issue in the future. We shall consider new methods of dissemination as well as the remote calibration method proposed in this paper, and the issue for the future is the establishment of a more efficient and rational metrological traceability system.

References

[1] Japan Economic Center: *'10 Kondensa Gyokai No Jittai To Shorai Tembo (2010 State of the Capacitor Industry and Its Future Prospect)*, Japan Economic Center (2009) (in Japanese).
[2] H. Bachmair, T. Funck, R. Hanke and H. Lang: Realization and maintenance of the unit of capacitance with the PTB cross capacitor during the last ten Years, *IEEE Trans. Instrum. Meas.*, 44, 440-442 (1995).
[3] G. Trapon, O. Thevenot, J. C. Lacueille and G. Geneves: Realization of the farad at BNM-LCIE, *CPEM '98 Conference Digest*, 448-449 (1998).
[4] G. W. Small, B. W. Ricketts, P. C. Coogan, B. J. Pritchard and M. M. R. Sovierzoski: A new determination of the quantized Hall resistance in terms of the NML calculable cross capacitor, *Metrologia*, 34, 241-243 (1997).
[5] A. Jeffery, R. E. Elmquist, L. H. Lee, J. Q. Shields and R. F. Dziuba: NIST comparison of the quantized Hall resistance and the realization of the SI ohm through the calculable capacitor, *IEEE Trans. Instrum. Meas.*, 46, 264-267 (1997).
[6] BIPM: *Calibration and Measurement Capabilities - CMCs (Appendix C)*, The BIPM key comparison database (http://kcdb.bipm.org/AppendixC/default.asp) (2009).
[7] A. M. Thompson and D. G. Lampard: A new theorem in electrostatics and its application to calculable standards of capacitance, *Nature*, 177, 888 (1956).
[8] K. Shida, T. Wada, H. Nishinaka, M. Kobayashi, G. Yonezaki, T. Igarashi and T. Nemoto: Determination of the quantized Hall resistance value by using a calculable capacitor at ETL, *IEEE Trans. Instrum. Meas.*, IM-36, 214-217 (1987).
[9] T. Endo: New electrical standards based on quantum effects - Josephson effect voltage standard and quantum Hall effects resistance standard, *Oyo Butsuri (A Monthly Publication of The Japan Society of Applied Physics)*, 59, 712-724 (1990) (in Japanese).
[10] Y. Nakamura, A. Fukushima, Y. Sakamoto, T. Endo and G. W. Small: A multifrequency quadrature bridge for realization of the capacitance standard at ETL, *IEEE Trans. Instrum. Meas.*, 48, 351-355 (1999).
[11] Y. Nakamura, M. Nakanishi and T. Endo: Measurement of frequency dependence of standard capacitors based on the QHR in the range between 1 kHz and 1.592 kHz, *IEEE Trans. Instrum. Meas.*, 50, 290-293 (2001).
[12] Y. Nakamura: Measurement of frequency dependence of fused-silica standard capacitor, *AIST Today*, 3 (1), 17 (2003) (in Japanese).
[13] A. Domae, Y. Nakamura and Y. Ichikawa: Calibration of standard capacitors of 0.01 μF - 1 μF at NMIJ/AIST, *CPEM*

Conference Digest 2004, 608-609 (2004).
[14] A. Yonenaga, A. Domae and Y. Nakamura: Standard capacitor calibration using the four terminal-pair impedance bridge and evaluation of its uncertainties, *Sansoken Keiryohyojun Houkoku (AIST Bulletin of Metrology)*, 6 (2), 101-117 (2007) (in Japanese).
[15] S. Sakagami: 4Tanshitsui Kyapashitansu Burijji no Seibi (Organization of a four-port capacitance bridge), *JEMIC Keisoku Sakuru Nyusu (JEMIC Metrology Circle News)*, 32 (3), 16-17 (2003) (in Japanese).
[16] Y. Nakamura, A. Yonenaga, N. Sakamoto and A. Shimoyama: Remote calibration of standard inductors, *IEEJ Trans. FM*, 126, 1183-1186 (2006).
[17] Y. Nakamura: Teishuha Impidansu no Enkaku Kosei Ni Tsuite (On remote calibration of low-frequency impedance), *JEMIC Keisoku Sakuru Nyusu (JEMIC Metrology Circle News)*, 36 (1), 1-6 (2007) (in Japanese).
[18] S. Matsuzawa, T. Shimodaira, K. Hanaoka, A. Shimoyama, S. Sakagami, A. Domae, K. Kito and Y. Nakamura: Feasibility study on remote calibration of impedance standards for industrial use, *CPEM Conference Digest 2008*, 348-349 (2008).

Authors

Yasuhiro Nakamura

Completed the doctoral course at the Graduate School of Engineering, Doshisha University in March 1994. Doctor (Engineering). Joined the Electrotechnical Laboratory, Agency of Industrial Science and Technology (current AIST) in April 1994. Became Section Chief of Electricity Standards Section 1, Electricity and Magnetism Division, National Metrology Institute of Japan (NMIJ) in October 2005; Division Head of Electricity and Magnetism Division, NMIJ in April 2007; and Principal Researcher of NMIJ in April 2009. Engages in R&D and standard provision of various electrical standards including the capacitance standard. Senior Principal Planning Officer of Planning Headquaters in October 2010. Received the Ichimura Prize in Technology (for Contribution) in 2002. In this paper, was in charge of the development of the capacitance standard based on quantized Hall resistance, the development of the remote calibration method for LCR standard, and planning and organization of the overall concept.

Atsushi Domae

Graduated from the Department of Electric and Electronic Engineering, Toyohashi Institute of Technology in March 2000. Joined the Electrotechnical Laboratory, Agency of Industrial Science and Technology (current AIST) in April 2000. Became the researcher of Electricity and Magnetism Division, NMIJ in April 2001, and person-in-charge of capacitance and AC resistance calibration in May 2006. Engages in R&D and standard dissemination of the capacitance and AC resistance standards. In this paper, was in charge of the development of the medium capacitance expansion system.

Discussions with Reviewers

1 Overall assessment

Comment (Katsuhisa Kudo, Safety and Environmental Protection Division, AIST)

You clearly defined the R&D goal in response to the demand of industry, and the scenario for standard dissemination all the way to the industrial site is very clear. The R&D was conducted according to a clear research road map based on the research potential that you accumulated over the years, while understanding the developments conducted at the NMIs around the world. Then, you established a highly original, world's top-level capacitance standard. You also developed an effective standard dissemination method to disseminate the primary measurement standard to the industrial sites, and contributed in establishing the traceability system for the capacitance standard that is one of the best in the world.

Comment (Akira Ono, AIST)

The development of the national standards for capacitance and the dissemination of these standards to the industrial sites are described in a birds-eye view along with the scenario. This is an excellent paper of the *Type 2 Basic Research* and *Product Realization Research*. It is not just the development of the national standards with the highest precision; the idea and the realization of the remote calibration to disseminate the standards to the industrial sites efficiently and rationally are also excellent outcomes of this research.

2 In reference to overall electrical standard

Comment (Katsuhisa Kudo)

The content of this paper is limited to capacitance standard. I got the impression that you are stating that the capacitance standard is particularly important in supporting the international competition of the manufacturing industries. In general, I think it is positioned as one of the core electrical standards, but does it have higher demand from industry compared to the voltage, current, or resistance standards? I think you should briefly refer to this in the "Introduction" to help the readers' understanding.

Answer (Yasuhiro Nakamura)

This paper focuses on the capacitance standard on which the authors have been mainly working to describe the scenario and the result of the R&D. As you indicated, capacitance is one of the core electrical standards, but other electrical standards such as the ones for voltage and resistance are also vital for supporting the international competition of the manufacturing industries. However, I thought the content may become unfocused if I talked about voltage and resistance standards, so in this paper, I intentionally emphasized the capacitance standard. As you indicated, I should discuss other electrical quantities in the "Introduction", and I added and revised the text accordingly.

3 Number of current calibration labs

Question (Katsuhisa Kudo)

In "2.2 Scenario for the dissemination of standard to industrial sites", the hierarchical structure of the calibration labs is shown in Fig. 1. You later mention three JCSS calibration labs, but it is unclear how many layers of Japanese calibration labs there are, or the number of calibration labs in each layer. Can you add some more figures in your explanations?

Answer (Yasuhiro Nakamura)

For the electrical standard, about 50 labs are accredited as the JCSS calibration labs. There are nine uppermost calibration labs (three labs for capacitance only) as shown in Fig. 1, and others are second-tier labs or below. I added the numbers of calibration labs to the text.

4 Situation at the NMIs of other countries

Question (Katsuhisa Kudo)

In “3.2 Development of the new method to respond to the demands”, you describe the method for deriving the capacitance from the quantized Hall resistance, and this is something to be proud of. Please add the percentage of the NMIs that derive the standard from cross capacitance and those that do from quantized Hall resistance, as well as any foreign NMIs that employ the method newly developed by AIST.

Answer (Yasuhiro Nakamura)

Among the NMIs that use cross capacitors, the ones that realize high-precision capacitance are NMIA (Australia), NIST (USA), PTB (Germany), and LNE (France), as described in the text. Other than these, NIM (China) and VNIIM (Russia) realize the standard using the cross capacitor. The ones that derive their capacitance from the quantized Hall resistance, other than AIST, include NPL (England), CMS (Taiwan), and BIPM. However in all cases, the capacitance standard is realized using the conventional quadrature bridge circuit, and the multi-frequency system of AIST is a step ahead internationally.

5 New method of standard provision

Question (Katsuhisa Kudo)

It is written in “5 Future issues” that you are “considering the development of a new dissemination method…”. While this may be a common issue for the metrological standards, do you have any ideas you can add?

Answer (Yasuhiro Nakamura)

Other than the “remote calibration method” described in this paper, another consideration is a system where a “long-term stable standard” is installed at the industrial sites, and this will enable calibration of the devices easily and at any time on site. For example, it may be possible to realize a “long-term highly stable standard voltage-current generation device” by combining the Josephson voltage standard and the thin-film thermal converter AC/DC standard. By developing such “technology that allows direct calibration at industrial sites” and then transferring this technology to industry, it may be possible to reduce the cost and time required for calibration. I think this will allow further rationalization of the traceability system.

Development of a sensor system for animal watching to keep human health and food safety

— A health monitoring system for chickens by using wireless sensors —

Toshihiro Itoh *, **Takashi Masuda and Kenji Tsukamoto**

[Translation from *Synthesiology*, Vol.3, No.3, p.231-240 (2010)]

We have been developing wireless sensor nodes for monitoring animal health and networks that care animal groups. “Animal Watch Sensors” - miniaturized, light, flexible and maintenance-free sensor nodes, will be utilized for the early detection of avian influenza outbreaks in poultry farms to defend human beings from an influenza pandemic. Key technologies to realize the sensor network system are ultra low power “event-driven” sensor nodes and a direct-conversion type receiver system for ultra short message communication. These technologies are developed by the integration of MEMS technology, life science and information technology.

Keywords : Wireless sensor nodes, sensor network, digital MEMS, event-driven, avian influenza

1 Introduction

The outbreak and pandemic of influenza (influenza A virus subtype H1N1) in 2009 is still fresh in our memory. There is now a rising concern for a new flu that may possess strong toxicity, through the reassortment and mutation of the avian influenza subtype H5N1 virus and the human influenza virus. According to the estimate by the Ministry of Health, Labour and Welfare, the death toll in Japan may reach maximum 640,000 people in case of a pandemic equivalent to the Spanish flu in 1918. Around the world, mainly in Asia, the outbreaks of bird flu and infection of humans have been confirmed. In Japan, the outbreaks of avian influenza subtype H5N1 were observed in Kyoto and Yamaguchi in January 2004 and in Miyazaki and Okayama in January to February 2007, and the virus remains a major threat to the safety of the humankind.

There are basically four measures that can be taken by the poultry farms against bird flu:

1) Strengthen measures to prevent virus invasion by enhancing hygienic control and wild bird control,
2) Strengthen surveillance monitoring at the farms,
3) Speed up diagnosis, and
4) Engage in early eradication of the virus through quarantine measures at affected farms.

The National Institute of Animal Health (NIAH) has been actively conducting the research for 3), or the development of genetic testing to detect the gene of the diversified bird flu virus. The research teams led by AIST are working on the development of 2), or the surveillance system for the farms. For the measures against bird flu infection at the poultry farm, if the period from infection to death is 1~2 days due to extremely strong virus toxicity, the outbreak can be detected in a relatively short time because the abnormal increase in bird deaths will be obvious and the farmers are obligated to report such abnormality. However, as shown in Fig. 7, strong toxicity means strong transmissiveness, and it is highly likely that the infection has spread widely by the time the situation becomes visible. This not only increases the loss of business but also is dangerous to the farmers themselves. On the other hand, if the toxicity is not strong, it may be difficult to tell it apart from other factors, and quick report may not be done if the number of bird deaths is within the range that does not obligate reporting. Moreover, the poultry farms have been scaling up rapidly in recent years, and along with the problems of aging farmers and lack of farmhands, signs of failing health among chickens that can normally be detected may be missed. It is desirable to introduce a technology that allows high-level monitoring of the health of chicken population, for the early discovery of bird flu outbreak from the perspective of maintaining public health and food safety, as well as increasing productivity.

With this background, this study is an attempt to develop a network system that monitors the health of the chickens at the poultry farms as shown in Fig. 1. Basically, this is a system where the wireless sensor nodes are attached to some percentage of chickens, or in the future to all chickens, to monitor their activity levels and body temperature, and to manage their health conditions. For example, if a node detects abnormal body temperature, the temperature change pattern can be referenced to the accumulated experimental data to automatically determine the possibility of bird flu infection,

Research Center for Ubiquitous MEMS and Micro Engineering, AIST Tsukuba East, 1-2-1 Namiki, Tsukuba 305-8564, Japan
* E-mail : toshihiro-itoh@aist.go.jp

Original manuscript received March 29, 2010, Revisions received May 24, 2010, Accepted May 25, 2010

or estimates can be made about whether the pattern of change is for the group or the individual, or whether it is an infection or some environmental control problem. Then, a warning is issued to the farmer or a report can be sent automatically to the veterinarian or the authorities, as needed.

We became aware of the necessity of downsizing, power reduction, and cost reduction of the node to realize the wireless sensor network system. The key is the utilization of the micro electro mechanical systems (MEMS) and its fusion with the related fields. MEMS are expected to be the main player of the "more than Moore" (advancement of the electronic device through diversification of its function) and has matured as the manufacturing technology for various sensing devices or man-machine interface devices. In this paper, we shall describe the experimental infection data obtained in this project, and explain the development concept of the ultra-low power (ULP) small wireless sensor node utilizing the MEMS technology.

2 Animal watch sensor nodes

As mentioned before, this study is a development of a monitoring system for chicken health that can be applied to the early detection of bird flu outbreaks. The developing wireless sensor node is called the "animal watch sensor node" because it is being considered for application to wild animals and pets, as well as livestocks other than chicken (Fig. 2). Table 1 shows the comparison of the human node and the animal watch sensor node that is expected to be used with relatively small livestock such as poultry. It is important to note that the node to be developed is totally different in requirements from the ones developed for humans, and the technological hurdle for low power consumption is fairly high.

Looking specifically at power consumption, the node lifespan must be about two years since the egg-laying hens are processed (as spent hen) in about 550 days[1]. Assuming the use of SR721, a silver oxide button battery weighing about 0.5 g that is also used in watches, since the official battery capacity of SR721 is 25 mAh, the average current consumption must be kept at 1.4 μA or less to ensure a two year operation. The wireless sensor node is usually composed of the sensor element, sensor interface circuit, microcontroller unit (MCU), wireless communication IC, and power source. As shown in table 2, the current consumption of the microcontroller and the wireless communication IC in standby mode only is about 1 μA even when low-energy consumption microcontroller is used. Therefore, achieving the current consumption of 1.4 μA or less is not simple, considering the current consumption of sensor and amplifier in standby and operating modes, as well as for the microcontroller and wireless transmission during operation. Therefore, in this research, the node with average power consumption of 1 μW level (current consumption 0.65 μA), or 1/1000 of conventional product, is achieved by reducing the power consumption of transmission and sensing, rather than by achieving further low-power consumption for the semiconductor elements such as the microcontroller. This means that the strategy of research is to achieve low energy consumption by methods such as raising the efficiency of sensing and transmission by dramatically reducing the standby power, minimizing the frequency and quantity of sensing and transmission, or increasing the efficiency of the antenna.

The most important concept in "minimizing the frequency and quantity of sensing and transmission" is the concept of "event driven". To simply reduce the frequency and quantity of sensing and transmission, intermittent operation is

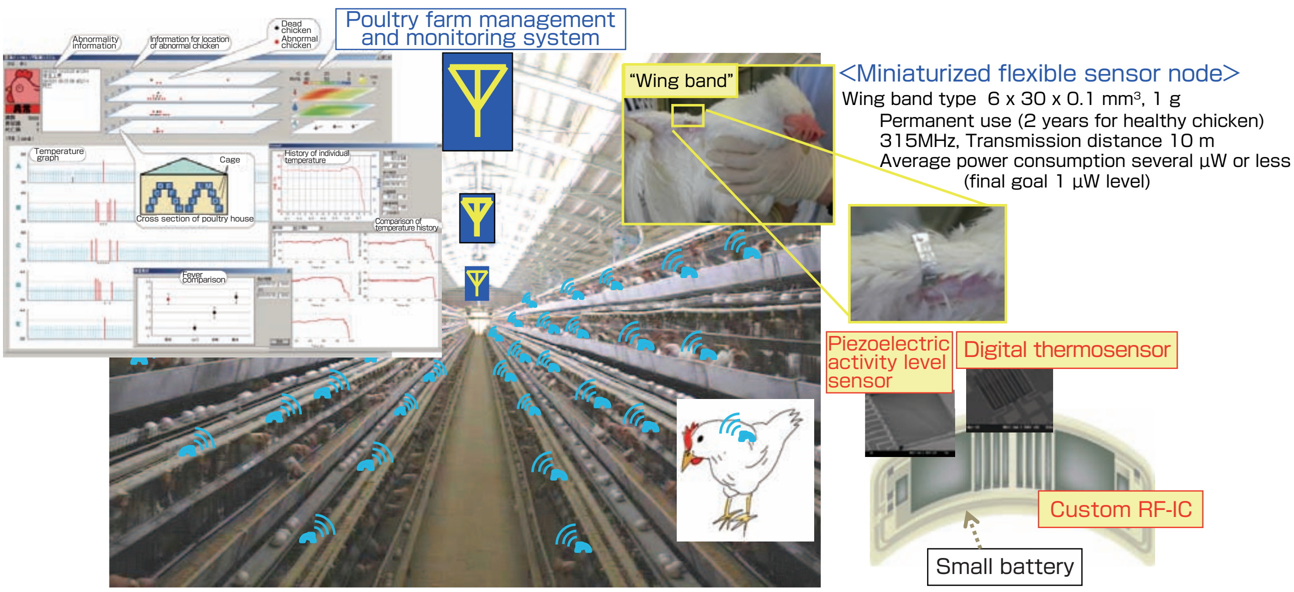


Fig. 1 Image of the chicken health monitoring system

sufficient. For example, if the chicken health management is to be done by temperature measurement, it is not necessary to take measurements every minute, but once in 30 minutes is sufficient. In this case, it is not difficult to keep the average current consumption to about 0.1 μA for sensing and transmission, and it is possible to keep the consumption at 1.4 μA or less even if combined with standby current consumption. However, like in the case of humans, there are diseases that accompany high fever and those that do not. We decide whether we should visit a hospital based on whether there is a decrease in activity, such as “I feel tired” or “I don’t have energy”, rather than basing the decision on temperature alone. Therefore, we thought that some kind of activity level sensor was needed for this animal watch sensor node. In fact, as shown in Fig. 7, in some H5N1 viruses with particularly high toxicity such as the Yamaguchi strain, death may occur without marked increase in temperature. In such cases, early detection is not possible by temperature monitoring alone, but it is known that infection estimate can be based on decreased activity level[3]. In the case where the activity level is monitored, only the activity status at the moment can be known if the measurement is taken once in 30 minutes, and it is difficult to determine whether the animal is active based on the figures of that moment only. Therefore, in this research, rather than the time-driven type where the activity is monitored and transmitted at certain intervals, we opted for the event-driven type where the monitoring and transmitting are done when an activity above some threshold takes place. The difficulty of an event-driven type is the selection of the appropriate event and setting of the threshold. One of the originalities of this research was we obtained the threshold by analyzing the data for the experimental infection of chickens and developed a suitable sensor accordingly.

Also, since the power needed for transmission is proportional to the amount of messages, the shortening of the transmitted message is important as well as the reduction in transmission frequency. Other than the data itself, the message includes the overhead, such as the preamble for clock synchronization

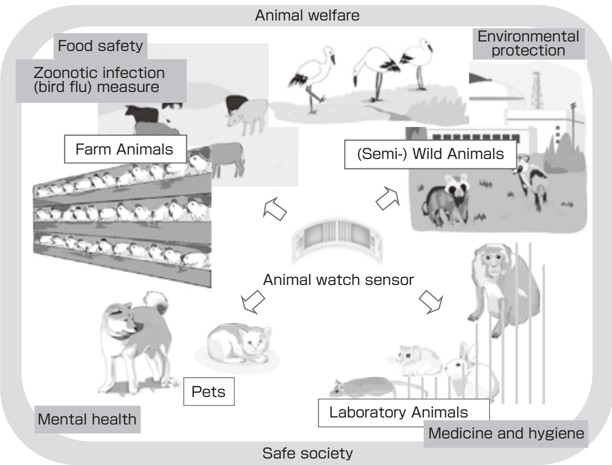


Fig. 2 Application of the animal watch sensor

Table 1 Comparison of the animal watch sensor node and the human health monitoring node

Main specs \ Sensor Node	Animal watch sensor node (mainly for chicken)	Human health monitoring node
Node size and weight	In case of chicken, few cm square, few g or less	Typically watch size, several ten g is acceptable as weight
Power source	Recharge impossible and basically, maintenance free	Charging frequency for cell phone is acceptable
Receiver and communication distance	At least 10 m communication performance necessary	Receiver is cell phone, communication distance is 1 m or less
Sensor type	As for now, thermosensor and activity level (acceleration) sensor	Thermosensor, activity level (acceleration) sensor, heart rate sensor, ECG sensor, etc.
Node cost	About 100 yen (1 US dollar or 1 euro)	Several thousand yen or more

Table 2 Example of the typical current consumption value of devices that comprise the wireless sensor node

	Microcontroller (MCU: MSP430)	Wireless communication (RF) IC
Sleep mode	0.8 μA[2]	About 0.2 μA
Operation (wireless transmission) mode	250 μA/MIPS[2]	About 650 μA (1 mW)

and the unique word for frame synchronization, and the ID (identification code for the node). In this study the overhead is eliminated by employing the new simultaneous multi-channel reception method, and the message is shortened by using the transmission frequency and baud rate as the ID[4]. Moreover, in theory, it is possible to create a minimal message with one-third the conventional content, composed only of the temperature data and parity bit (the simplest 1 bit error detecting code) by calculating the activity level from the transmission intervals[5].

As mentioned above, to achieve the chicken health monitoring system for poultry farms, the most important technical point is achieving the low-energy consumption of the wireless sensors. To achieve this, it is necessary to set the appropriate event and threshold by experimentally determining the activities and disease conditions of the chickens, and to develop the corresponding device and node system. Table 3 is a summary of the main elemental technologies to realize the system. In this research, the experimental animal infection and analysis using the wireless sensor node, the development of the low-energy consumption MEMS sensor suitable for the event-driven method based on the data obtained from the animal experiments, and the development of other elemental devices were done according to the development process shown in Fig. 3. Then, the prototype node was fabricated, the monitoring system for the experimental poultry house was created, and the issues in applying the system to the poultry house were extracted. In the future, the working node incorporating the developed elemental devices will be developed and a monitoring system using the nodes will be created. These will be used for the demonstration in the experimental poultry house.

3 Strategy for achieving ultra low power consumption of the nodes

To achieve a small (can be attached to the wing), lightweight (about 1 g), flexible and maintenance-free (2-year lifespan) wireless sensor node, we devised a new digital sensor using the MEMS switch[6][7]. This digital MEMS sensor is composed of an array of switch sensors, is capable of directly outputting digital signals without an AD conversion circuit, and can be used as a start-up trigger of the wireless sensor node in sleep (clock stop) modes. The individual switches that compose the sensor are micromechanical switches that use the MEMS technology, and do not require power for ON/OFF of the switch itself. Specific explanation will be provided using the digital bimetal thermosensor and digital piezoelectric accelerometer developed in this research.

Figure 4 shows the schematic diagram of the digital bimetal thermosensor[7]. It is very simple in principle, and is composed of an array of bimetal cantilevers that come in contact with the opposite electrode above a certain temperature. Since the normal body temperature for chickens is about 41 °C, it can be considered that a fever is occurring due to some health abnormality if the temperature rises above 42.5 °C as in the case of infection by the Yokohama strain, as shown in Fig. 7. Therefore, a bimetal cantilever that turns ON at 42.5 °C or above is installed. When the contact is ON due to temperature increase, the node wakes up from sleep, and transmits a message that includes only the fact that the contact is ON as the sensing information. This is the basic thinking of the event-driven concept. In the case of the intermittent operation mode using a timer, the detection timing is determined by the set interval regardless of the occurrence of the temperature increase event, while in the event-driven node, the moment

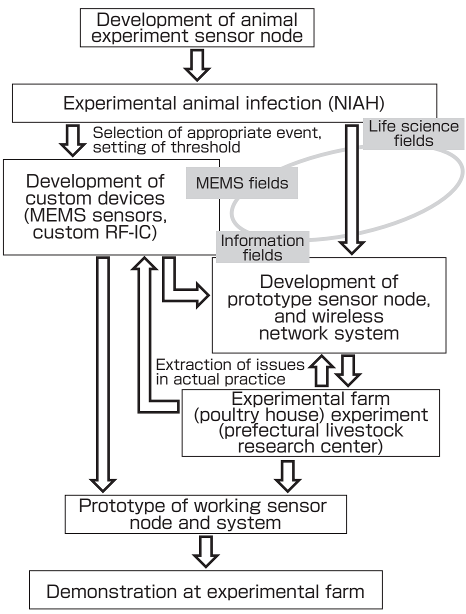


Fig. 3 Overall picture of the development process (outline of the scenario)

Table 3 Main elemental technologies for the chicken health monitoring system

ULP wireless sensor node	Digital bimetal thermosensor
	Digital piezoelectric accelerometer (activity level sensor)
	Custom RF-IC (event-driven type)
	miniaturized antenna (315 MHz)
	Flexible node packaging technology
Direct conversion receiver system	
Poultry house monitoring system	

of temperature increase can be detected instead of the temperature value. The event-driven type can be used to shift the node from the sleep mode to the emergency time-driven measurement mode, instead of sending one transmission at the occurrence of the event. For the event, the individual difference can be considered, as well as multiple bimetal cantilevers can be installed for each temperature value setting to detect the rough temperature change. For example, if the multiple bimetal cantilevers of different sizes are installed and the ON temperatures are set at certain intervals such as 0.5 °C, it can be used as a digital thermosensor. The meaning of “digital” here is that it is possible to detect the digital signal of 1100, or the four switches of ON, ON, OFF, OFF, if the sensor output is the digital signal itself, and this can be included in the message without alteration. The ON detection of a mechanical switch can be done with very low power, and the standby power of the sensor is basically the power for the semiconductor switch. While the bimetal switch can be fabricated without the MEMS technology, the use of MEMS technology is vital in order to achieve the downsizing and cost reduction of the bimetal thermosensor, since the multiple three-dimensional microstructure can be realized at once on a silicon wafer without an assembly process.

The activity level sensor can be constructed from the mechanical switch that turns ON when the acceleration of certain level or higher is inputted, but we developed a sensor where piezoelectric thin-film is formed over the cantilever, as shown in Fig. 5. Here, the technological details will not be provided[8][9], but the power is generated by the piezoelectric effect when the cantilever is activated, and the transistor can be turned ON or OFF using this power. In theory, a digital accelerometer with zero-power consumption is possible. As in the bimetal thermosensor, it is possible to arrange the cantilevers with different sensitivity, but it is also possible to arrange a series of the same cantilevers[6] or devise the circuit to extract the digital output that corresponds to a certain acceleration threshold with one cantilever[10]. From the result of the experimental infection using the experimental node that will be described in chapter 5, it is known that health abnormality can be detected 10 hours beforehand[3] by counting the number of occurrences of accelerations surpassing the threshold within a certain time (30 minutes, for example) and by comparing the number with the number for 24 hours beforehand, even for the Yamaguchi strain where no significant temperature increase could be seen. The activity level can be counted with low power if a generating piezoelectric sensor is used. To realize such a device at a small size and low cost, piezoelectric MEMS technology that combines the MEMS and piezoelectric thin film formation technologies is necessary.

As shown in Fig. 6, it is necessary to use the digital MEMS sensor that matches the event-driven type to achieve the ULP node, and also customize the semiconductor elements such as the microcontroller and the radio frequency integrated circuit (RF-IC). As mentioned before, the event-driven node that we developed in this research is a device “where the sensor directly sends out the digital signals, then the node wakes up from the sleep mode and transmits the digital signals wirelessly”. Therefore, the node does not require any high-grade arithmetic processing, and a RF-IC with simple processing function such as a sensor interface and a message writing function is sufficient. Conversely, if one is to install an over-spec universal microcontroller, realization of the chicken node is impossible in terms of power and cost. While the new technological development for semiconductor element technology is not necessary for the introduction of such custom-made RF-IC, there is no example anywhere in the world of RF-IC specialized for event-driven nodes, and it is a key device that must be designed and developed by us on our own. Of course, the increased flexibility of the substrate and downsizing and flexibility of the antenna are also important for practical use.

4 Image of the animal watch sensor

The specifications of the wireless sensor node scheduled for realization by the end of this research project (end of FY 2011) are as follows.

Size/weight of node: substrate (flexible) size 6 × 30 × 0.1 mm^3, weight (including batteries) about 1 g
Attachment method: Wing band
Sensor: digital bimetal thermosensor, digital piezoelectric accelerometer (activity level sensor)
Wireless transmission: frequency 315 MHz band (310~320 MHz), modulation GFSK, line-of-sight communication distance of 10 m or more
Standby power consumption: 0.5 μW or less
Power source: silver oxide battery (1.55 V)

This wireless sensor node transmits data but does not receive. The primary reason is because the reception standby power is large and it cannot fulfill the necessary specs for size and cost, but it is also because the node does not have to receive. The node must be able to receive if there is a need for communication between the nodes or for receiving the re-transmission request in case of a bad reception. For this system, since the frequency of data transmission is once every 30 minutes to 1 hour with short transmitted messages of 10 bits or less, there is hardly any chance of collision of the transmission signals even if there are over 10,000 nodes. However, in the event-driven system, high communication reliability is demanded because one data transmission is extremely important. In this research, the basic concept is to employ an advanced receiver in order to simplify the node system that is subjected to harsh boundary conditions.

With this way of thinking, we employed and are developing the direct conversion method as the reception method of this research. This method is also called the software-defined radio, where the frequency spectrum in the range 310~320 MHz as discussed above is received, stored on the memory, and then analyzed to read the message. We are developing the receiver system by fabricating the prototype of the simultaneous multi-channel receiver. Using this method, it will be possible to identify the nodes by frequency and transmission data rate, and

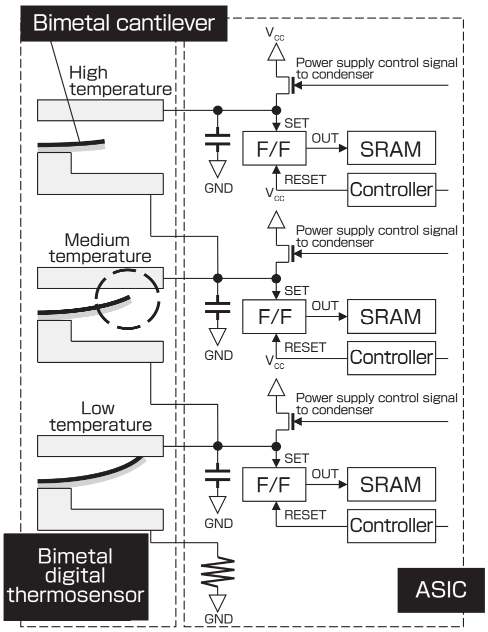


Fig. 4 Digital bimetal thermosensor

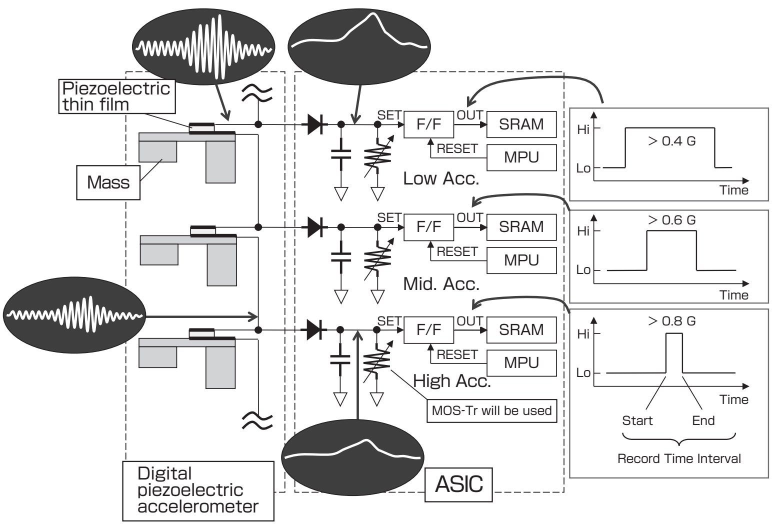


Fig. 5 Digital piezoelectric accelerometer

as mentioned earlier, data reception will be possible without the overhead such as the preamble. Also, by comparing the reception signal intensity of each node, the location of the node at 1 m or less precision can be known. This allows the detection of the outbreak and spread of the disease, as well as the location of the chicken with health abnormality without conducting ID management of the nodes. Another point of shortening the message is the estimation of activity level by reception frequency. For example, in the simplest model, a switch that turns ON when there is an acceleration that surpasses a certain threshold is installed, and one message is transmitted when the number of ONs reaches a certain level[11]. If the activity level is high, the transmission intervals shorten, and when the activity is low, the transmission intervals lengthen. Therefore, the reception interval represents the activity status. Although we cannot tell whether the activity level is abnormal from one transmitted data alone, the activity level monitoring with consideration of the individual differences will be possible by comparing with past data. Using this method, it will not be necessary to include data for the activity level in the message, and ultimately, only the output from the digital thermosensor and parity bit during signal transmission is necessary. For the development of this reception system, the fabrication of the prototype of the simultaneous multi-channel receiver and the confirmation of its operation, the check of the effectiveness of the basic message analysis software, and the development of the algorithm for identifying the node position have been completed. It has been experimentally confirmed that the node location identification can be obtained at 1 m or less precision in an ideal environment.

As explained above, downsizing and weight reduction, low power consumption (longer lifespan), and cost reduction are done by simplifying the node through the employment of the high-performance receiver system.

5 Experimental infection and prototype system

As mentioned earlier, one of the important points of this research is to study the disease state of the chickens to optimize the sensor node. At the start of this research project, although it was known that the bird flu that occurred in the Japanese poultry farms could be a threat to humanity, there was no study on how the body temperature changed when the chickens became infected by H5N1. The only data that existed were qualitative data on the daily behavior of chickens in good health and how that may change when infection occurred. The digital MEMS sensor or the event-driven node could be realized only by understanding the properties of the subject, or chicken characteristics in this study, and therefore the research team engaged in experimental infection.

In the experimental infection conducted by NIAH, it was shown for the first time from the results of the temperature behavior using the wireless sensor node[14] shown in Fig. 7, that "the fever development and time of death of chickens infected by the highly pathogenic avian influenza virus differ according to the strain"[12], and that "the transmissibility of avian influenza virus among the chickens is correlated to the amount of virus excreted"[13]. The prototype node used in the experiment had exterior size of a one-yen coin and weight of 3 g or less (including weight of the battery) to reduce the burden on the chickens in the experimental infection and poultry house experiment. It also included a thermosensor to measure body temperature and accelerometer to monitor the activity level, as well as the time-driven wireless module that obtained and transmitted the temperature and acceleration data at a certain time interval (can be freely set).

In the above experimental infection, the acceleration data as well as the temperature data were recorded. Based on these finding and data, an infection determination program was developed using both the temperature and activity level patterns. This was compared to the conventional data, and it became possible to discover (recognize) the possibility of infection early and automatically. Moreover, the number of probes and individual thresholds can be set in the digital thermosensor, and the activity level sensor can be set with appropriate acceleration threshold. Also, the virus

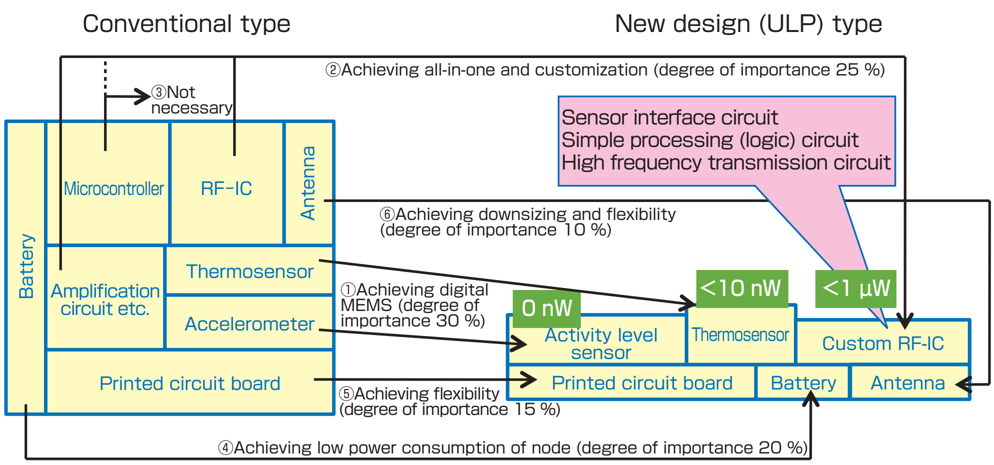


Fig. 6 Comparison of the ULP wireless sensor and the conventional sensor

transmission simulation program is created using the data for the rate of infection spread to study the relationship between the node concentration and the time required to discover the infection, and this is utilized in the development of the monitoring program[3]. In this simulation, if it is determined that an infection is suspected when three chickens behave abnormally, it is known that by attaching the sensors to 5 % of the chickens, detection can be done two days faster than the visual observation currently set by the government.

To extract the issues when such wireless sensing system is used in the poultry house, the above prototype node is made into a wing band so it can be easily attached to the chickens. Also, we are reviewing a health management system for poultry farms to monitor the heat stress during summer, by setting up the wireless network system in an experimental poultry house in the Ibaraki Prefectural Livestock Research Center[14].

6 Progress and prospect of the research

The objective of this research is to complete the practical level chicken health monitoring system by the end of FY 2011. While there are some differences in the progress of development of the elemental technologies listed in table 3, at this point, the overall achievement level compared to the initial goal is 60~70 %. For the digital piezoelectric accelerometer that is being developed as the key device among the elemental devices, we are ready to conduct demonstrations of the prototype node using the test device. For the digital bimetal thermosensor, the development of the new structure for manufacturing at the wafer level including the packaging process is in progress[15], and an investigation for a mass production process will be done in FY 2010. For custom-made RF-IC, design and a prototype are being done for scheduled completion in November 2010, and the node that is close to the final goal is to be completed within FY 2010. The technological issues include:

- Development of the software for the reception system, and
- Development of the low-cost wafer-level packaging technology for the digital MEMS sensor.

Particularly, the packaging technology greatly affects the manufacture cost of the digital MEMS sensor device, and it is necessary to optimize not only the packaging process but also the manufacturing process of the device itself.

The final goal of this research is the practical use, or the introduction to the sites of commercial poultry farming, rather than constructing a “practical level” system and demonstrating it. However, there are various issues that cannot be solved by technological development alone. In addition to the development of low-cost attachment and removal, there are issues of how to make this technology improve the farm productivity, and how to establish a government monitoring system.

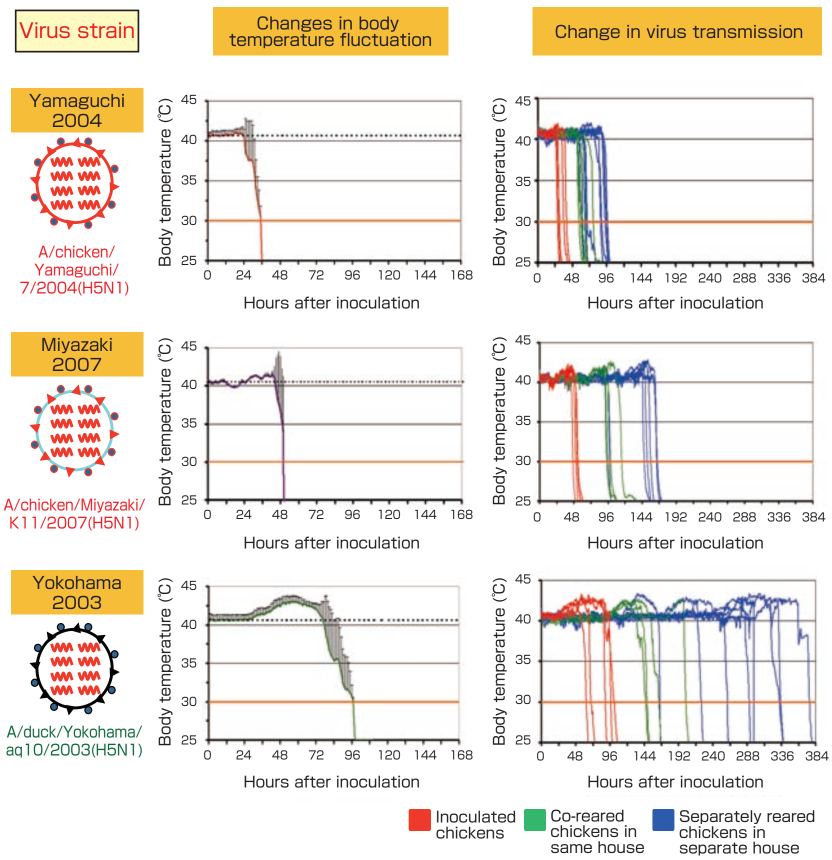


Fig. 7 Examples of data obtained by experimental infection

In this research, by focusing the research on the rather special use in the chicken health monitoring system, we are trying to reduce the cost of the active (type that does not require leader unlike the RF tag) wireless sensor node, which currently is no less than several thousand yen at least, to about 100 yen. We are also trying to downsize and reduce the weight to a band-aid level. Since this node cannot measure the vital signs, application to humans may be limited. However, monitoring the temperature and activity level (liveliness) is basic to health management, and we wish to consider the health monitoring of infants and the elderly who must be monitored continuously at hospitals and homes.

7 Conclusion

What became apparent when working on this research is the fact that the researches on MEMS and packaging technology are only part of the technologies needed to solve the entire issue. MEMS research is basically a research for the manufacturing process technology, and it is about “drilling an extremely narrow, deep, and straight hole”. However, as such technologies are becoming mature in the 21st century, we are facing the issue of what (for what purpose and for which specifications) we shall make. We thought one of the answers was a device that can be used in ultra-small wireless sensor node, and started this research. However, whether MEMS itself was really necessary for the chicken health monitoring was frequently discussed. Fortunately, we were able to position the MEMS technology as being absolutely necessary, but if the boundary conditions change (for example, if it is used for pigs and cows), whether MEMS is necessary must be discussed in each case.

In the beginning, the main issue of this research was the early detection of bird flu at farms, but as we talked with the livestock researchers, we started to consider the animal watch sensor from the perspective of animal welfare. With the upscaling of animal husbandry, the people of the metropolitan area are loosing the sense that they are consuming animal products, perhaps because the sites of production are far away from the city. Of course, livestocks are industrial animals and cannot be considered on the same level as pets and wild life. However, when one realizes that the eggs, milk, or meat are obtained from overweight animals that are fed high calorie food and may harbor risks of production diseases, we may want to reconsider whether we wish to consume such food. In Europe and the United States, the thinking of livestock welfare is spreading, and the approval system for Welfare Quality Products will be launched in 2010. In the evaluation committee for this system, the technological issues raised are “animal based measurement” or the assessment of “how the animals feel”. Therefore, we believe the animal watch sensor will become more important from the point of maintaining the welfare of the livestock, as an interface technology with animals.

While many of the concepts and technologies for the wireless sensor network described in this paper were generated by focusing on the application to the chicken health monitoring, the individual technologies can be applied to other fields such as environmental monitoring including agriculture and disaster prevention. I think another major product of this research is to recognize that conducting the research with focused application may be an efficient way for pioneering a field or for creating inventions.

Acknowledgements

The product of the R&D described in this paper was obtained by the research team for the “Development of the Animal Watch Sensor for Safety” of the Core Research for Evolutional Science and Technology (CREST), Japan Science and Technology Agency (JST). The research team includes: Kenji Tsukamoto, Senior Researcher, National Institute of Animal Health; Takashi Masuda, Special Appointment Lecturer, The University of Tokyo; and Ken Kobayashi, Zhang Yi, and Hironao Okada, researchers, AIST.

References

[1] http://www.toukei.maff.go.jp/dijest/tikusan/tiku06/ tiku06.html

[2] Texas Instruments MSP 430 Microcontroller http:// focus.tij.co.jp/jp/mcu/docs/mcugettingstarteddetail.tsp ?sectionId=97&tabId=1511&familyId=342

[3] H. Okada, K. Suzuki, K. Tsukamoto and T. Itoh: Wireless sensor system for detection of avian influenza outbreak farms at an early stage, *Proc. IEEE Sensors 2009*, 1374-1377 (2009).

[4] T. Itoh, T. Masuda, K. Nakamura and H. Okada: Low-power consumption wireless sensor node and sensor network system (Tei shohi denryoku musen sensa tanmatsu oyobi sensa nettowaku shisutemu), Patent Application 2009-232154 (in Japanese).

[5] T. Itoh, T. Masuda, K. Nakamura and H. Okada: Wireless activity level sensor node and sensor network system (Musen katsudoryo sensa tanmatsu oyobi sensa nettowaku shisutemu), Patent Application 2009- 232153 (in Japanese).

[6] K. Kobayashi, T. Itoh, T. Ikehara, M. Ichiki and R. Maeda: Accelerometer, avian influenza monitoring system (Kasokudo sensa, tori infuruenza kanshi shisutemu), Patent Application 2008-151562 (in Japanese).

[7] T. Ikehara, T. Itoh, Y. Zhang, M. Ichiki, K. Kobayashi and R. Maeda: Thermosensor, health management system (Ondo sensa, seitai no kenko kanri shisutemu), Patent Application 2008-151555 (in Japanese).

[8] T. Itoh, T. Kobayashi, H. Okada, T. Masuda and T. Suga: A digital output piezoelectric accelerometer for ultra-low power wireless sensor node, *Proc. IEEE Sensors 2008*, 542-545 (2008).

[9] T. Kobayashi, H. Okada, T. Masuda and T. Itoh: A digital output piezoelectric accelerometer using patterned Pb(Zr,Ti)O_3 thin films electrically connected in series, *22th IEEE International Conference on Micro Electro Mechanical Systems* (Sorrento, Italy, Jan. 25-29, 2009).

[10] K. Kobayashi, T. Itoh, T. Masuda, H. Okada, Y. Zhang and R. Maeda: Piezoelectric accelerometer (Atsuden kasokudo

sensa), Patent Application 2010-098993 (in Japanese).
[11] H. Okada, T. Kobayashi, T. Masuda and T. Itoh: Ultra-low power event-driven wireless sensor node using piezoelectric accelerometer for health monitoring, *Jpn. J. Appl. Phys.*, 48 (7), 070222 (2009).
[12] K. Suzuki, H. Okada, T. Itoh, T. Tada, M. Mase, K. Nakamura, M. Kubo and K. Tsukamoto: Association of increased pathogenicity of Asian H5N1 highly pathogenic avian influenza viruses in chickens with highly efficient viral replication accompanied with early destruction of cytokine responses, *Journal of Virology* 83 (15), 7475-7486 (2009).
[13] K. Suzuki, H. Okada, T. Itoh, T. Tada and K. Tsukamoto: Critical determinants of avian influenza viruses for transmissibility in chickens, *Journal of General Virology* 91, 2302-2306 (2010).
[14] AIST Press Release 2009.10.6 "Development of a chicken health monitoring system by using wireless sensor" (in Japanese).
[15] Y. Zhang, H. Okada, K. Kobayashi, T. Itoh and R. Maeda: Thermosensor using MEMS technology and its manufacturing method (MEMS no gijutsu niyoru ondo sensa oyobi korerano seizo hoho), Patent Application 2009-067117 (in Japanese).

Authors

Toshihiro Itoh

Completed the doctoral course at the Graduate School of Engineering, The University of Tokyo in 1994. Joined the Research Center for Advanced Science and Technology, The University of Tokyo, as assistant in 1994, and become lecturer and assistant professor. Joined AIST in 2007. Deputy director of the Research Center for Ubiquitous MEMS and Micro Engineering in 2010. Engaged in research for piezoelectric MEMS, MEMS probe card, MEMS packaging, wireless sensor node, and others. Research Director of the "Development of the Animal Watch Sensor for Safety" of the Core Research for Evolutional Science and Technology (CREST), Japan Science and Technology Agency (JST) since 2006. Engages in research for weaving MEMS as the Director of Macro BEANS Center, Bio Electromechanical Autonomous Nano Systems (BEANS) Project of the New Energy and Industrial Technology Development Organization (NEDO). In this paper, was in charge of the development of the MEMS sensor and the wireless sensor node.

Takashi Masuda

Completed the doctoral course in applied electronic engineering at the Graduate School of Electronic Science and Technology, Shizuoka University in 2001. Independent researcher at the Gunma Industrial Technology Center in 2002. Worked as chief researcher of the R&D Center, Taiyo Yuden Co., Ltd. and also as the special appointment lecturer of precision mechanical engineering at the Graduate School of Engineering, The University of Tokyo in 2006 to present. Has engaged in research and development of the elements and signal processing of humidity sensor, silicon piezoresistance pressure sensor, sapphire capacitance pressure sensor, and ball inclination sensor. Currently works on the development of the event-driven communication protocol in ultra low power wireless sensor, as well as the development of the piezovibration power generation system, ULP custom LSI, and small antennae for 300 MHz band, at the "Development of the Animal Watch Sensor for Safety" of JST CREST. For this paper, was in charge of the development of the ULP technology and the wireless network system.

Kenji Tsukamoto

Completed the master's course at the Graduate School of Agricultural Science, The University of Tokyo in 1982. Joined the National Institute of Animal Health, Ministry of Agriculture, Forestry and Fisheries in 1982. Worked as researcher, chief researcher, head, and senior researcher from 2007. Engaged in epidemiological survey of wild birds for avian influenza and genetic diagnosis method from 2004. Joined the "Development of the Animal Watch Sensor for Safety" of JST CREST as main joint researcher in 2006, and works on the analysis of changes in disease states of chicken infected with bird flu virus, as well as the analysis of molecular basis of avian pathogenesis. In this paper, mainly worked on the experimental infection and the development of the prototype system.

Discussions with Reviewers

1 Configuration of the wireless sensor node

Comment (Toshimi Shimizu, Research Coordinator (current affiliation: Deputy Director General), AIST)

The conceptual points and their degree of importance (or difficulty) of the newly designed wireless node corresponding to an event-driven type are unclear. As a plan, I think you should compare the configurations of the conventional wireless node and the newly designed one, list the issues for each element, and explain the importance (or difficulty) of each. I think that will enhance the understanding of the general readers including engineers who are not familiar with MEMS.

Answer (Toshihiro Itoh)

Revisions were made in Fig. 6 as you instructed.

2 Technical terms

Comment (Toshimi Shimizu)

The National Institute of Animal Health (NIAH) is listed as the joint research institute. As far as the reviewer knows, there are several veterinarians at the NIAH, and from veterinary standpoint, what are the recent research trends for preventing infection of chickens? Please also add some comments from the point of technical policy and measures of the Ministry of Agriculture, Forestry and Fisheries.

Answer (Toshihiro Itoh)

We added some explanation in the second paragraph "measures at the poultry farm…" in "1 Introduction".

Comment (Toshimi Shimizu)

There are several difficult English terminologies for the general readers including engineers. For example, "time-driven", "preamble", "parity bit", "direct conversion", "custom-made RF-IC", and "vital signs" are terms that may be used often in your field, but are incomprehensible to general readers. I think you should explain them sufficiently.

Answer (Toshihiro Itoh)

At least, for the terms you indicated, we added explanations as much as possible at first appearances.

3 Advantage of using the MEMS technology

Question (Jun Hama, Evaluation Department, AIST)

You explain that power consumpution of animal sensor can be extremely reduced by using MEMS technology,which allows creating an all-in-one structure, in addition to simiplifying the animal sensor. Can you specifically tell us the advantages of the manufacturing process for sensors?

Answer (Toshihiro Itoh)

A three-dimensional mechanical structure is necessary to achieve the switch sensor. The MEMS technology is good at creating the three-dimensional microstructure and the protective packaging structure all at once on the silicon wafer. It can be considered the only technology to realize such devices including small and low-cost three-dimensional mechanical structure. Specifically, the MEMS technology is mandatory for creating the oscillator with piezoelectric thin film and the encapsulation structure for the accelerometer, and for creating the bimetal cantilever array, contact, and encapsulation structures for the thermosensor.

4 Setting of the threshold

Question (Jun Hama)

How did you actually set the threshold to determine the abnormal activities? Please explain the decision process within the range you may disclose.

Answer (Toshihiro Itoh)

We conducted several experiments using dozens of chickens at NIAH using the wireless sensor nodes. Basically, we set the thresholds for temperature and acceleration by comparing the temperature and acceleration data of the chickens inoculated with the virus (with several virus strains) and the non-inoculated chickens.

5 Cost reduction

Question (Jun Hama)

To reduce the cost of the health monitoring system, I am sure you've done lots of devising, such as minimizing the sample number of chickens to which the nodes are attached in the technological development of an inexpensive sensor system. Is there any statistical difference in the total sample number of animals depending on the characteristic of the animals?

Answer (Toshihiro Itoh)

I am not sure there is any difference according to the character of the animals, but I've heard from the expert at NIAH that 0.3~1 % is probably sufficient as the number of samples to watch the health of the chicken population at a poultry farm. Also, by simulating the relationship between the sensor concentration and detection time (the time required from the first infection of the chicken to the determination of abnormality and reporting) using the experimental data, we think about 5 % is the minimum number needed.

6 Realization of the MEMS technology

Question (Jun Hama)

You are attempting the product realization and diffusion of the chicken health monitoring as one of the ways to pioneer the use of the MEMS technology. Please explain specifically the prospect for an outlet that emphasizes the superiority of the MEMS technology.

Answer (Toshihiro Itoh)

In general, I think the MEMS technology is a core manufacturing technology for all kinds of sensors that demand downsizing and cost reduction. Therefore, various sensor interface devices in an ambient society[Note)] will be realized by the MEMS technology. A system with a similar concept will be applicable to the health behavior monitoring of animals other than chickens. For other use such as monitoring the environment of some facility, it must be reconsidered from step 1 (including whether MEMS is necessary). However, the concept of making the nodes as "light" as possible so it can be spread widely and profusely while making the receiver system advanced, is effective for the application to environmental monitoring including agriculture and disaster prevention.

Note) Ambient society: While the "ubiquitous society" is a world where the necessary information can be retrieved "anytime, anywhere, by anyone", the "ambient society" is a world where the necessary information is provided by the environment that surrounds the person as it senses the person's situation.

Meta-engineering that promotes innovation

[Translation from *Synthesiology*, Vol.3, No.3, p.241-246 (2010)]

The Engineering Academy of Japan has the Committee on Technology Policy that proposes effective policy upon analyzing what kind of science and technology policies are necessary from the standpoint of engineering for society. Under this committee, a proposal for the science and technology on which Japan should focus was presented. Motoyuki Akamatsu, the executive editor of *Synthesiology*, interviewed Dr. Hiroshi Suzuki, the chair of the task force for this proposal. He discussed "meta-engineering" and the relationship to synthesiology.

***Synthesiology* Editorial Board**

Hiroshi Suzuki: Technology Executive, General Electric International, Inc.
Motoyuki Akamatsu: Executive Editor, *Synthesiology*

What is meta-engineering?

(Akamatsu)

The Committee on Technology Policy, the Engineering Academy of Japan, set forth "meta-engineering" as a "proposal for the science and technology on which Japan should focus". I read the proposal, and it states it is necessary "to propel radical innovation that does not stop at the application of science and technology to exposed issues". What exactly is meta-engineering?

(Suzuki)

In the United States, cloud computing, smart grid, and iPod and iPad are coming out as innovations. On the other hand, while Japan is said to be extremely good at engineering, capable of making excellent products, and has competent craftsmen, not so many innovations are coming out from Japan. We intended to explore the reason at first.

There are many definitions for engineering, and it is often defined as a way "to provide an optimal solution under a limited given condition". We asked ourselves whether that definition was sufficient. We may obtain a totally different answer that may lead to innovation, if we start openly by removing the limiting conditions, not by narrowing things down. In studying innovation, we decided to look at "converging technology (CT)", which is a way of thinking about science and technology in the United States and the European Union. If this fits well in Japan, we can think of a Japanese-style converging technology. That was the starting point of the task force.

What is the American-style converging technology?

(Akamatsu)

You mean you started from the research of converging technology, and found that it was not the goal in Japan, and you came up with the concept of "meta-engineering"?

In 2002, the National Science Foundation and the U.S. Department of Commerce released the "Converging Technologies for Improving Human Performance". Since then, Europe and other areas have offered various definitions.

(Suzuki)

CT, as well as meta-engineering, starts with identifying what the future challenges will be and exploring what sciences and technologies will be needed for them. In the final proposal of CT, the four fields of NBIC – nanotechnology, biotechnology, information technology, and cognitive science – are said to

Dr. Akamatsu (left) and Dr. Suzuki (right)

be the core technologies. It also says that any single field of them will not be enough to address global issues and that converging multiple fields will be necessary. “Converge” means “to bring together”. While the four fields of NBIC are originally independent, they should be converged keeping the original parts.

(Akamatsu)
Does that mean that they do not merge to create a new field?

(Suzuki)
It’s okay if a new field emerges, but the original fields must also remain.

It is “converg-ing” rather than “converg-ence” probably because the Americans want to express the dynamism that things are occurring this very moment. In some places like Europe and Korea, it is called “convergence technology”. I think this shows the character of the countries.

Japanese soccer is like Japanese innovation: why?

(Akamatsu)
The keyword of the American converging technology is the “expansion of capacity”, and it seems to be trying to create a future of technological utopia. On the other hand, Europe seems to be dealing with the problems at hand.

However, I feel there is no clear picture of the specific issues, or what must be solved by NBIC. In the task force, did you discuss what is insufficient about CT?

(Suzuki)
When we were discussing, the Japanese national soccer team came to my mind. They’ve got wonderful skills, are good at passing, and dominate the ball 60 % of the time in international matches. They are excellent at passing to switch sides. However, when they advance before the goal, no one shoots. They can’t score. They end up with a draw at best. The Japanese soccer shows the situation of the Japanese innovation. The countries that can score and win aren’t necessarily great at teamwork, though they certainly have wonderful individual skills. But they’re capable of those scoring shots, and show superior concentration when they have the chance to score.

In the United States where innovations continue to flow out, the Americans are great at picking out unseen issues. They find issues to which they want to find solutions, and then spend full-force effort to find the solutions. The Japanese are good at finding a solution for a given issue under limited conditions, but are very weak when they are told to “think of something” without any limits or conditions. You cannot score unless you approach the unseen issues and seek solutions. You must think what is behind the visible issue, what are the real issues, and what are the hidden issues.

We lack the ability to find unseen or potential issues, and then to solve them using science and technology. We thought those were the issues for Japanese engineering.

Japanese and American engineers think differently

(Akamatsu)
You mentioned that the Americans are good at finding the issues while the Japanese are good at solving problems under certain conditions. I think there are American and Japanese engineers working at General Electric. Do you see their differences?

(Suzuki)
I think they are different in the way they come up with ideas. When a Japanese company does business, it thinks, “We are capable of doing this. How could we make this into business?” However, in the GE style, the thinking is, “We, as GE, want to do this kind of business”. A project starts in a top-down style, where the top people think what we have, what we don’t have, and what we should do. In Japan, the bottom-up style is very strong, where the technology that the company possesses is molded into a new product.

(Akamatsu)
The bottom-up approach is a way “to capitalize one’s strength”, and this method was a textbook example of diversification during the period of rapid economic growth. In the case of GE, this isn’t necessarily the case.

(Suzuki)
That’s right. We often refer to “total available market (TAM)”. For example, GE was very strong in power generation, but withdrew from the electric power network business 20 or 30 years ago. However, there is an 80 trillion yen market for electric power around the world, and we decided to take up electric power network business again. The technology remaining at GE was for transformers, and there wasn’t anything for the breaker or the power system control. So we considered what we had to do to restart the business. Since we had hardly any technology left, what do we do to fill in the lacking technology? The options were: engage in R&D ourselves, acquire companies, or form partnerships with others.

In the case of a Japanese company, if it has the technology for the transformer, it tries to do electric business by making a line-up of peripheral products for the transformer. It is totally different.

(Akamatsu)
GE is not of the bottom-up style. I think the corporate

management is not in that style. Do you think there are differences in ways the on-site Japanese and American engineers come up with ideas when they're faced with "the company has this policy, and I want to do this"?

(Suzuki)
I think there is. I don't know the reason. Perhaps it is education. In the Japanese elementary school arithmetic class, they ask, "What is 5 plus 7?" However in the States, they ask "what two numbers do you add to get 12?" If it is 5+7, the only answer is 12. I think the Japanese students are fed this type of problems and have grown used to it.

I often use the example of a Japanese air conditioner. It is highly efficient. It uses intelligent inverters and heat pumps, and utilizes very fine technology. Also, the hybrid vehicles combine the gasoline internal combustion engine and the battery motor in a sophisticated manner. Since the Japanese are capable of such skills, they try to solve problems in that manner.

(Akamatsu)
I see, so you suggest meta-engineering because that is what is lacking in propelling innovation in the Japanese science and technology.

(Suzuki)
We decided to call the effort where the potential issues are found and solved by removing the limitations as "meta-engineering". We also considered the other names such as "holonic engineering", "comprehensive engineering", "ecological engineering", "transformative engineering", or "Japanese converging technology", etc.. However, since we wanted to redefine it as metaphysical engineering as a level above current engineering, we decided to call it "*konponteki* engineering" in Japanese. The word *konponteki* translates into "radical" in English, but that may also mean "aggressive" in Japanese, so we call it "meta-engineering" in English.

Dr. Hiroshi Suzuki

Meta-engineering is to circulate the four processes in a spiral

(Akamatsu)
You mentioned that the process of finding the issues is important in meta-engineering.

(Suzuki)
That is the starting point. We call them the four processes. First, one finds a potential issue or buried issue, and then finds the necessary science and technology to solve it. If the issue cannot be solved by current science and technology, the fields and technologies are integrated. Finally, the solution to the issue is implemented. Then, a new issue is found in this process. The image of the four processes turning round and round is important.

(Akamatsu)
On that "turning round". It seems that the process of finding a potential issue, selecting the necessary technologies, integrating them, and then solving the actual problem is a complete process in itself. Why do you have to return to the process of finding new issues?

(Suzuki)
One is that innovation is meaningless unless it continues. As the process turns round and round, society gets better cyclically, or the innovations occur continuously. We want that to happen.

(Akamatsu)
In that sense, it is a spiral rather than a cyclical feedback. It means that, the world may change by introducing new things, but some other potential issue arises because of that new introduction.

The most difficult part, I think, is the discovery of the potential issue, but what is the key point to this?

Point in discovering the potential issue

(Suzuki)
I cannot find a specific plan, but let us think in terms of marketing.

A salesman visits a client, and the client says, "I want to drink some juice". In a Japanese company, the salesman will purchase an expensive juicer and some fresh fruits, makes juice, and takes it to the client. The client is 100 % satisfied and may buy the cup of juice for 10 dollars. However, it actually costs 9 dollars to buy the juicer and the fresh fruits. The cup of juice sells for 10 dollars, so the profit is 1 dollar. In a Japanese company, this is evaluated highly because the customer satisfaction is 100 %.

However, when GE looks at the root of the issue, if the client says, “I want some juice”, the salesman will ask, “Why do you want juice?” When the client answers, “Because I’m thirsty”, the salesman comes back with water to sell. This will solve the issues of the client’s thirst. Another client may say, “I want cola”, but maybe he is just thirsty. Then, the salesman sells cups of water to, say, 10 thirsty clients. If he sells water for 1 dollar a cup, the sales will be 10 dollars. Since the original cost of water is low, for example, if the original cost of 10 cups of water is 5 dollars, the profit is 5 dollars.

As you can see, the way of doing business is different, but I feel that the process of asking “what is really necessary” is lacking in Japan. I think the engineers themselves must work on the issues with such an attitude. The Japanese look at “how”. The “how-to” books sell well at bookstores. But behind the “how” is a “what”, and one must investigate what is really important and “why” it is important to get to the hidden or potential issues. I think this is fairly close to synthesiology practiced at AIST.

(Akamatsu)
Taking the example of the juice, “what” is the level where the person is saying he wants juice, and “how” is what kind of juice should be made. But “why” will investigate the reason the person wants juice, and that’s because he’s thirsty.

In conventional engineering, “what” is given as a problem, and the engineer figures out “how” to make something. You are suggesting that the engineer must return to the cause of “what” and look into “why”.

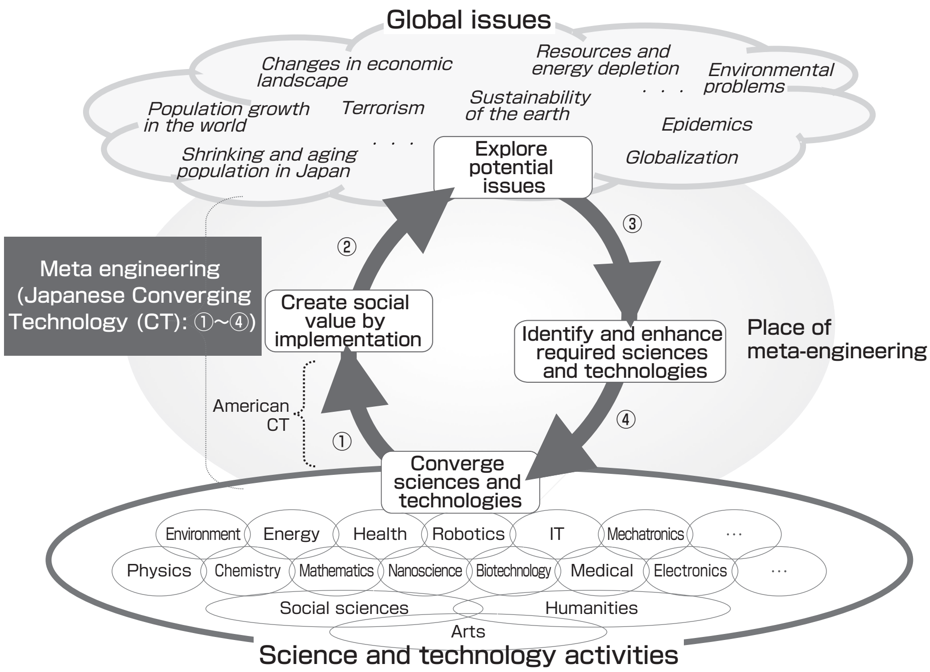
(Suzuki)
Discussions are continued in our task force, and I think there are two major points. One is education. How can we educate people who can realize such things through education? Another is to research meta-engineering itself. Including case studies, can we study it academically? Currently, we are pursuing these two lines.

In education, debate is always a part of the courses in the United States. The discussion progresses by changing the settings and perspectives. Debate is not preferred in Japan.

(Akamatsu)
To switch the perspective and discuss what should be done; I feel this type of training is insufficient in Japan.

(Suzuki)
The other day, there was a symposium on security by photographing the people on the streets, organized by the Engineering Academy of Japan and the Royal Academy of Engineering of U.K. From Japan, there were discussions about how pattern recognition could be accomplished by TV cameras and at what angles the cameras should be set. The U.K. started the discussion on the institution itself, of how to protect personal information while maintaining national security. I felt that the way of looking at things was fairly different.

(Akamatsu)
I think the engineering people in Japan are accustomed to not saying anything about the system. Their job is doing technological things.



(Suzuki)
Yes, exactly. They think that is the proper thing to do. I think it will be interesting to do education that removes that kind of framework.

(Akamatsu)
I think the shift in perspective is important, and engineers tend to get fixed perspective if they stay in one place too long. I'm sure there are many technologies in GE, but do people go to different sections?

(Suzuki)
At GE, mobility is fairly high. Someone in sales may go to marketing, or become in charge of acquisition, which we call business development, or do project management. People experience different types of work to enhance their own expertise. If one stays in a position for 18 months, you earn the right to move to another section.

(Akamatsu)
So it is a right. Are there incentives to encourage mobility?

(Suzuki)
We have an intranet web-site for recruitment. It is called COS or career opportunity system, and it shows which country, what position, and what kind of work types requires people. It allows people to obtain information about their destination easily. Also, the salary format changes when one changes position, and that can be a great incentive. If the person is capable, the salary increases for sure, and that is a powerful motivation. Of course, the person may also loose a position.

Contact point of synthesiology and meta-engineering

(Akamatsu)
When considering the promotion of innovation through meta-engineering, the discovery of the potential issues is important, and shifting the perspective is important to make such a discovery. What else do you think other than case study research will enable this?

Dr. Motoyuki Akamatsu

(Suzuki)
We don't have any specific ideas yet, and I don't know whether it is better to collect the successful innovation stories or find examples of failures of why something did not lead to innovation. Japan is good at manufacturing and many great products have been made, but what is its limit? It will be interesting to investigate this topic.

Returning to the "what" and "how", when we talk of *monozukuri* or "thing-making", it is the multiplication of *mono* or "thing" and *tsukuri* or "making". Japan concentrates on the "making" or the "how", whereas perhaps the "thing" or the "what" may be more important. I think both "what" and "how" are needed to do "thing-making".

In the Unites States, the emphasis is on the thing they make. Therefore, if they are not good at making it, the making part can be outsourced. If many things are made, they can figure out a way of doing it well. If things are multiplied, that eventually leads to great innovation.

(Akamatsu)
In a company, even if the engineer has an idea, this idea may not go into the process of product realization, or the decision-making manager may not give the go to any product other than the one that already exists. I feel there is a lack of decision-making ability to create products with totally different way of thinking. In that sense, are there some relationships between technological management and meta-engineering?

(Suzuki)
I think there is a close relationship. The management in technological management is not necessarily the same as the management of business. It is how one can use a certain technology well. In the example of "thing-making", I said it is the multiplication of the "what" and "how", and I think "technological management" is the multiplication of "technology" and "management". Even if you've got good technology, it won't be useful without good management, and good management won't be effective without good technology. It is necessary to build up this balance through multiplication. I think meta-engineering can play a significant role here.

(Akamatsu)
Then, can people who have been doing only management do meta-engineering? In synthesiology, we think that a person can take the next step because he/she is highly knowledgeable about the technology of the research subject. I think this is a prerequisite for a researcher, but how is it for meta-engineering?

(Suzuki)
Since we are discussing mostly about technology, I don't know whether it is directly linked. There was an interview article with Dr. Lester[Note)] in *Synthesiology*. What Lester and Piore mention in their book *Innovation*: *The Missing Dimension* is that "innovation will take place interpretively rather than analytically". We felt that Japan didn't have that perspective until now, and in that sense, I think it is important to extend engineering to interpretation rather than engineering for analysis only. Of course, people with expertise in engineering have the knowledge, so if they enter the interpretive process even if they had been engaging in analytics only, they may be able to attain meta-engineering. Of course, interpretation includes synthesiological thinking, and if analysis and synthesis can expand within the same background, I think it will lead to some interesting innovation.

(Akamatsu)
Another point. In the United States, the people involved work very hard to create their market. In Japan, research often ends when they come up with some good technology.

While this may simply be a conjecture and I may be wrong, when funding is received from the government, many companies think that they're fine as long as they come up with "technological development". The government provides funding for commercialization, and sometimes I think the companies should be responsible all the way to the market when they receive the funds.

(Suzuki)
Exactly as you say. They are looking only at the technological development. I think Japan should look at the whole system and recognize its importance.

(Akamatsu)
Looking at the *Synthesiology* papers, I feel that the researchers' strong will to take the technology to a certain level is absolutely necessary.

(Suzuki)
Yes. In that sense, I think meta-engineering can be proposed globally. Japan is very good at manufacturing, and therefore it should maximize the experiences accumulated as its strengths. Then, it should strengthen the weaknesses, and start off the process that spirals from the discovery of the potential issues, the identification and build up of the necessary science and technology, the integration of fields and technologies, to the creation of social values, and then back to the discovery of potential issues.

(Akamatsu)
What is the final goal? How can this technology be used to achieve the goal? One must always return to that standpoint and think. Moreover, I think to arouse innovation, you need the ability to think "persistently". I think I saw a glimpse of the relationship between meta-engineering and synthesiology. Thank you very much for the interesting discussion.

(This interview was conducted at GE Japan in Akasaka, Minato-ku on May 13, 2010.)

Note) Hope for *Synthesiology*: Discussion with Professor Lester, *Synthesiology*, 1 (2), 139-143 (2008).

Profile of Dr. Hiroshi Suzuki
Born in Tokyo on December 25, 1946. Graduated from the Electronic Engineering Department, The University of Tokyo in 1969. Completed the doctorate course at the Graduate School of Engineering, The University of Tokyo in 1974. Joined the Mitsubishi Electric Corporation in 1974. Worked at the Central Research Laboratory, and as manager of Electric Power System Technology Division, manager of Electric Power Technology, head of Electric Power System Engineering Center, and as director and advisory engineer. Joined the General Electric Company in 2003 as the technology executive for new business. He was vice-chairman of the Institute of Electrical Engineers of Japan, board member of the Engineering Academy of Japan, chair of Management of Technology Japan Branch. He is IEEE Fellow and vice-chairman of the History Committee for Electrical Engineering, IEEJ. Areas of specialization are energy system and technological management. Doctor of Engineering.

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. After receiving the manuscript, if the editorial board judges it necessary, the reviewers may give an interview to the author(s) in person or by phone to clarify points in addition to the exchange of the reviewers' reports.

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), keywords, 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, prior permission for citation must be obtained and should be clearly stated in the paper, and the sources should be listed in the reference list. A copy of the permission should be sent to the Publishing Secretariat. 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* (italic), Volume(Issue), Starting page-Ending page (Year of publication).
Book – [No.] Author(s): *Title of book* (italic), 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 Website and Publication Office, Public Relations Department, National Institute of Advanced Industrial Science and Technology (AIST)
Tsukuba Central 2, 1-1-1 Umezono, 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).

Inquiries:

Synthesiology Editorial Board
c/o Website and Publication Office, Public Relations Department, National Institute of Advanced Industrial Science and Technology (AIST)
Tel: +81-29-862-6217 Fax: +81-29-862-6212
E-mail: synthesiology@m.aist.go.jp

Letter from the editor

The goal of *Synthesiology* is to visibly organize the methodologies for overcoming the “valley of death” and the “period of nightmare” of R&D, and for establishing the “social technology” process in which the technology becomes accepted by society at its contact point. The methodologies are presented as assets common to humankind and the information is transmitted to the world. Particularly, we place importance on the description of the process by which technology is incorporated into society through integration and collaboration with other technologies from the perspective of synthesis.

In this issue, the methodologies for overcoming the “valley of death” and the process for establishing the “social technology” are described as a progress of research in the paper, “Development of novel chemical reagents for reliable genetic analyses - Process from an original idea to marketing of a chemical product used for life science.” This paper provides a few tips to conquer the “valley of death” as well as useful insights on social technology.

First, the paper recognizes that the DNAs that failed to bond with the linker could be removed by adding a function to the bonding area called the linker that bonds the synthesized DNA on the substrate, and describes the finding that the DNA becomes bondable through hydrophobic interaction with the target molecule. These were developed to meet the technical demands in the field of DNA chip that is being used for medical applications. The authors were able to discern the technological demand for raising the purity of the synthesized DNA and increasing the percentage of captured target molecules, and then proposed the idea for realizing them. This was an extremely effective factor.

The second effective factor was reaching commercialization by adding major improvement to achieve reliability and originality differentiating from conventional technologies. This was done through joint research with the private companies, and during the process of establishing the social technology of mass production and performance evaluation of the DNA chip. The points where the authors experienced hardships, overcame the valley of death, established the social technology by achieving mass production and reliability as well as originality differentiating from conventional technology, and finally realizing practical use, can be highly praised. I believe this paper will serve as useful reference for many technological developments.

Moreover, the authors mentioned that they tried out new ideas without being caught up in technological demands. Yet, I think expanding the function of the DNA chip by adding functions to the linker was a major social demand, and the authors were able to propose the new idea by understanding the new demands.

To be able to understand the process of establishment of a social technology and the ways to overcome the valley of death from the papers submitted to *Synthesiology* was a pleasant experience, where I almost felt like a participant of the R&D.

Editor
Akira Yabe

Synthesiology - English edition Vol. 3 No. 3, Dec. 2010
Edited by *Synthesiology* Editorial Board
Published by National Institute of Advanced Industrial Science and Technology (AIST)

Contact: *Synthesiology* Editorial Board
c/o Website and Publication Office, Public Relations Department, AIST
Tsukuba Central 2, 1-1-1 Umezono, Tsukuba 305-8568, Japan
Tel: +81-29-862-6217 Fax: +81-29-862-6212
E-mail: synthesiology@m.aist.go.jp
URL: http://www.aist.go.jp/synthesiology

Synthesiology Vol.3 No.3 December 2010
-English edition

Messages from the editorial board

Research papers

Interview

Editorial policy
Instructions for authors

"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".

Published by AIST