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Synthesiology

English edition

ARGUS: Adaptive Recognition for General Use System

Toward the use of humanoid robots as assemblies of content technologies

Thermoelectric hydrogen gas sensor

Demonstration of optical communication network for ultra high-definition image transmission

Paper supplement to "Study on the PAN carbon-fiber -innovation for modeling a successful R&D management"

Synthesiology editorial board

2011

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MESSAGES FROM THE EDITORIAL BOARD

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

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

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

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

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

Addendum to Synthesiology-English edition,

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Synthesiology Editorial Board

Note 1 : The period was named "nightmare stage" by Hiroyuki Yoshikawa, President of AIST, and historical scientist Joseph Hatvany. The "valley of death" was by Vernon Ehlers in 1998 when he was Vice Chairman of US Congress, Science and Technology Committee. Lewis Branscomb, Professor emeritus of Harvard University, called this gap as "Darwinian sea" where natural selection takes place.
Note 2 : *Type 2 Basic Research*
This is a research type where various known and new knowledge is combined and integrated in order to achieve the specific goal that has social value. It also includes research activities that develop common theories or principles in technology integration.
Note 3 : *Full Research*
This is a research type where the theme is placed within the scenario toward the future society, and where framework is developed in which researchers from wide range of research fields can participate in studying actual issues. This research is done continuously and concurrently from *Type 1 Basic Research* (Note 4) to *Product Realization Research* (Note 5), centered by *Type 2 Basic Research* (Note 2).
Note 4 : *Type 1 Basic Research*
This is an analytical research type where unknown phenomena are analyzed, by observation, experimentation, and theoretical calculation, to establish universal principles and theories.
Note 5 : *Product Realization Research*
This is a research where the results and knowledge from *Type 1 Basic Research* and *Type 2 Basic Research* are applied to embody use of a new technology in the society.

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ARGUS: Adaptive Recognition for General Use System

— Its theoretical construction and applications —

Nobuyuki OTSU

[Translation from *Synthesiology*, Vol.4, No.2, p.70-79 (2011)]

In recent years, the need for computer vision systems is increasing in various fields, such as security and visual inspection. It is crucial there to realize simple and high-speed practical vision systems. The present paper addresses the author's theoretical research and its applications developed thus far in working toward this goal. First, the problem of the conventional approach is pointed out, and the general framework of pattern recognition, in particular the feature extraction theory, is referred to as the theoretical foundation. Next, a scheme of adaptive vision system with learning capability is presented, which comprises two stages of feature extraction, namely, Higher-order Local Auto-Correlation and multivariate data analysis. Several applications are demonstrated, showing the flexible and effective performance of the proposed scheme.

Keywords **:** Vision system, pattern recognition, feature extraction, adaptive learning

1 Introduction

In recent years, there have been great expectations for vision systems (computer vision). They are useful in various fields including surveillance cameras for crime prevention, appearance inspection of manufactured goods, CT scans and tissue examination in medicine, robot vision, and analysis and evaluation of movement in sports studies as well as image searching on the Internet. Furthermore, as an important aspect of vision systems, it should be noted that collection and processing of various images has become easier, owing to the technological development of CCD cameras, various sensors, computers, and visualization techniques.

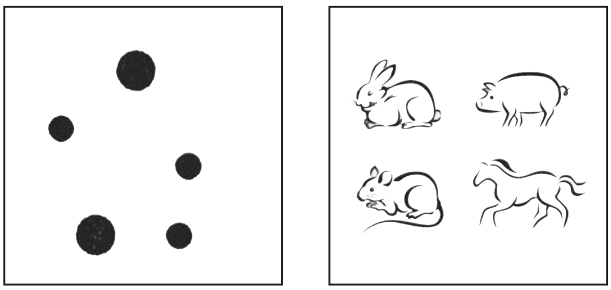
With developments in the field of vision systems, image recognition research has been pursued vigorously on an international level, but automation and implementation has been difficult. In addition, only distinct ad hoc methods and expensive specialized systems have been developed, and there is still a reliance on human abilities under actual settings. As a result, the implementation and distribution of a cheap, PC-based vision system that is versatile and delivers high speed is highly desirable.

With the above objective, this paper discusses the pattern recognition theory developed by the author thus far[1], focusing on feature extraction theory[2] and the Adaptive Recognition for General-Use System based on it that was proposed as a practical system construction method[3][4], as well as various practical developments[5][6]. Moreover, the effectiveness and importance of the theoretical approach in particular is demonstrated when considering a construction method for recognition (generally, information) systems.

2 Ordinary approaches and pattern recognition

First, let us consider the pattern recognition problem of image measurement and recognition. Fig.1-a) shows the image measurement (enumeration) task where there are round particles of two different sizes and the total number of each is enumerated. The method usually considered is similar to the following sequential method. First, the screen is scanned to segment individual particles, and then the radius is measured for the approximating circle of each particle; in this manner, the size of the particle can be determined from the radius, and the particles can thus be counted. However, this method will clearly result in an increase in the calculation time, proportional to the number of objects.

On the other hand, Fig.1-b) is the image recognition problem that identifies what each object (animal) is. It is usual to consider the characterizing features (parts) that distinguish these four objects. In the context of each model, ears, tails,



a) Image measurement　　b) Image recognition

Fig. 1 Examples of vision tasks[6]

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and body type among other features are compared (or quantified) as partial images in order to reach a final decision. However, overall recognition is dependent on the recognition of parts, which implies that the overall recognition will be incorrect if the part recognition is erroneous.

Thus, most ordinary approaches are “serial and procedural types” that first segment each individual object in this manner from the image, and then perform recognition according to a pre-prepared model. However, because the pattern generally has different variations, the model must also be made proportionately more complex in various ways. Moreover, accumulation of errors at each stage of processing in serial procedures results in overall vulnerability; a large amount of calculation is involved and it is difficult in practice to obtain the required recognition performance. The problem lies in the tendency to consider this as a logical procedure in an ad hoc manner at the image level. In a way, it is an approach dominated by the Neumann-type computer programming paradigm.

As the antithesis of this method, from the late 1980s, the “parallel and adaptive (learning) type” method was proposed using neural networks[7]; in addition to the study of the theoretical aspects, various applications have been attempted, especially in pattern recognition and control. However, because of the constraints that the elements are nonlinear and have bounded values [0, 1], information representation and feature extraction usually tend to be ambiguous. In recent years, additional problems such as the arbitrary nature of the model and the learning speed and convergence have been indicating the need for a change toward the nonlinear multivariate analysis, such as the kernel method[8].

To examine a new methodology for visual systems, recognition systems in general, it is necessary to theoretically reconsider the general framework of the underlying pattern recognition mechanism, especially information representation and feature extraction.

2.1 General framework for pattern recognition

In pattern recognition, recognition is accomplished by multiple extraction (thus represented by the vector $\boldsymbol{x}$) of some feature values effective for recognition (generally functionals $x_i = \phi_i[f]$ defined as functions of the function f) from the pattern, a signal expressed by a function f localized in space-time. Typically, as shown in Fig.2, the framework comprises a two-stage process of “feature extraction” and “recognition”. Recognition can be divided into classification and clustering. Classification is the determination of whether the input pattern corresponds to one of the several known categories, and is called supervised learning because the answer is given in the learning stage. Clustering is called unsupervised learning, which discriminates the input pattern into several clusters (categories). Many techniques have been proposed regarding classification, and it is already theoretically known that the minimum error rate classification method is the Bayesian decision rule, which decides on the category C_j with a maximum posterior probability $P(C_j|\boldsymbol{x})$. This implies that the feature extraction at the first stage is important as the requirement which dominates the recognition system efficiency, however various ad hoc or heuristic techniques have been suggested until date.

2.2 Feature extraction theory

The author has conducted a theoretical study of these feature extractions[2]. General framework for feature extraction comprises “invariant feature extraction” as the geometrical aspect and “discriminant feature extraction” as the statistical aspect. In principle, it is important that feature extraction comprises these two stages in this order. Fig.3 thus demonstrates the general framework for pattern recognition, as a natural consequence of this theory.

2.2.1 Invariant feature extraction (geometrical aspect)

The observed image f as a pattern is subject to various continuous geometrical transformations (generally, projective transformations) such as translation, scaling, and rotation due to the relative position and movement of the observer and the object. However, recognition results are independent of these and remain invariant. In

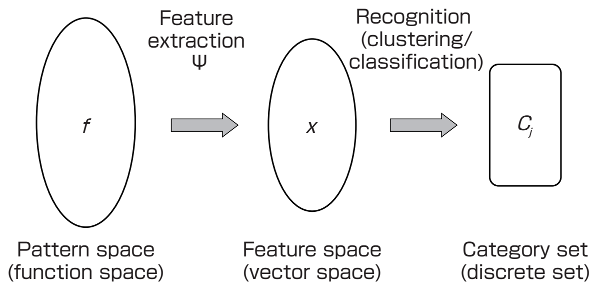


Fig. 2 General framework for pattern recognition (typical)

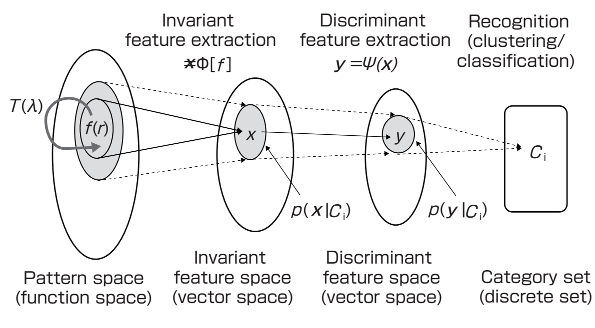


Fig. 3 General framework for pattern recognition (detail)

invariant feature extraction theory, such a geometrical transformation that operates on the pattern function f and keeps category correspondence invariant (called an invariant transformation) is represented by an operator $T(\lambda)$, under which the invariant feature values, and thus the corresponding invariant functionals $x = \phi[f]$ are pursued.

$$\phi[T(\lambda)f] - \phi[f] = 0 \qquad (1)$$

Using operator analysis based on Lie group theory, the invariant features, corresponding to the given invariant transformation, are found as elementary solutions of the partial differential equation, derived as a necessary and sufficient condition[1][2]. In this manner, the pattern, as the fundamental features for recognition through abstraction of extraneous information, can ideally be treated in unity as a single point x in the invariant feature vector space.

2.2.2 Discriminant feature extraction (statistical aspect)

However, actual patterns are subject to variations and noise and are distributed according to a probability distribution $p(\boldsymbol{x}|C_j)$ for each category class C_j. The next stage of the discriminant feature extraction theory considers a mapping $\boldsymbol{y} = \Psi(\boldsymbol{x})$ of the invariant feature vector $\boldsymbol{x}$ to a new feature vector $\boldsymbol{y}$ with reduced dimensions and derives an optimum mapping that optimizes an evaluation criterion for $\boldsymbol{y}$, such as discrimination of the category classes. So-called multivariate analysis methods (such as discriminant analysis) are usually formulated as linear mappings, whereas a neural network or a kernel method is used for some type of nonlinear mapping.

In fact, the ultimate optimum nonlinear discriminant mapping is easily obtained in the following formula using variational calculus[1][2].

$$\boldsymbol{y} = \Psi_N(\boldsymbol{x}) = \sum_{j=1}^{K} P(C_j|\boldsymbol{x})\boldsymbol{c}_j \qquad (2)$$

This result shows that pattern discrimination is closely related to Bayes posterior probability $P(C_j|\boldsymbol{x})$, and suggests the essential framework of Bayesian inference behind pattern recognition. Here, $\boldsymbol{c}_j$ are the vectors that represent each category in the target mapping Y, and in the case of discriminant analysis, they are derived as eigenvectors of the between-class stochastic matrix in the original space X. It is understood that the dimensions of the optimum discriminant space obtained are essentially determined by the number of classes, therefore coming to K-1 dimensions.

In real-life applications, it is necessary to make appropriate simplifications according to practical requirements considering these theoretical frameworks.

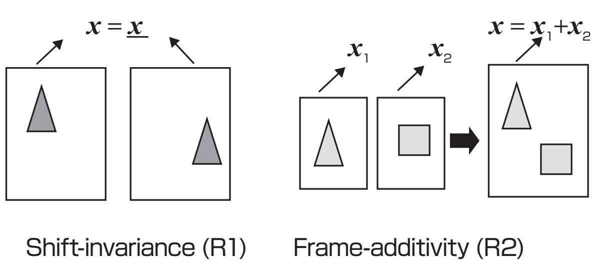


Fig. 4 Shift-invariance and frame-additivity[6]

3 Approach and conditions for a constructing method

While considering the approach toward a flexible vision system and a constructing method, the following three points can be mentioned as basic conditions that are required for the vision system (Fig.4).

R1: Shift-invariance,
R2: Frame-additivity,
R3: Adaptive trainability.

The results of such recognition or measurement should be the same regardless of where the recognition or measured object is in the image frame. Thus, the first condition R1 demands that a feature $\boldsymbol{x}$ extracted from the pattern does not depend on the position of the object (it is invariant under a parallel shift). Size scaling, rotation, and other transformations can also be considered as invariant transformations. However, since a parallel shift is the most fundamental, it was made a required condition.

The next condition R2 requires that features for the entire screen are the sum of local features for individual objects. This is also a consequence of R1, and is a required condition where feature representation is a convenient representation (linear) for recognition (especially counting), and the processing afterward becomes simple and high speed.

Unlike the ordinary method where feature extraction is given as a heuristic procedure and the construction method changes in accordance with the change in recognition tasks, the last condition R3 requires that a new feature $\boldsymbol{y}$ suited to the task is automatically constructed (synthesized) from the initial feature $\boldsymbol{x}$ in an optimal manner using the learning acquired from the example; in addition, the condition requires that the method is a general-purpose formulation that is adaptively optimized with a structure indifferent to changes in the task.

In addition, for such a feature extraction method constructed to meet these required conditions, it is desirable for the computation amount to be low and that real-time processing is possible.

4 Adaptive Recognition for General-Use System(ARGUS)

An "adaptive image recognition system for general use"[Note 1] has been devised that meets these basic demands and is implemented using the simplest form for the aforementioned pattern recognition, especially for the framework of feature extraction theory[3][4]. This system comprises a two-stage feature extraction following the theoretical framework of feature extraction (Fig.5).

4.1 Invariant feature extraction (HLAC/CHLAC)

The most basic features were considered to be parallel shift-invariant (position-invariant), for an initial feature in the first stage, namely, feature extraction that is invariant from a geometrical aspect. This is because recognition is essentially independent of the position $\boldsymbol{r}$ of the spatio-temporal pattern $f(\boldsymbol{r})$.

As position-invariant features, the auto-correlation function $r(\tau) = \int f(t) f(t+\tau)\, dt$ in the field of time series analysis of audio, has been known for a long time. This extracts the relative relationship (correlation) in a wave profile pattern that does not depend on time position. The higher-order expansion of this, Nth order auto-correlation function is known mathematically,

$$x(\boldsymbol{a}_1, , , \boldsymbol{a}_N) = \int f(\boldsymbol{r}) f(\boldsymbol{r}+\boldsymbol{a}_1) \cdot \cdot \cdot f(\boldsymbol{r}+\boldsymbol{a}_N)\, d\boldsymbol{r} \qquad (3)$$

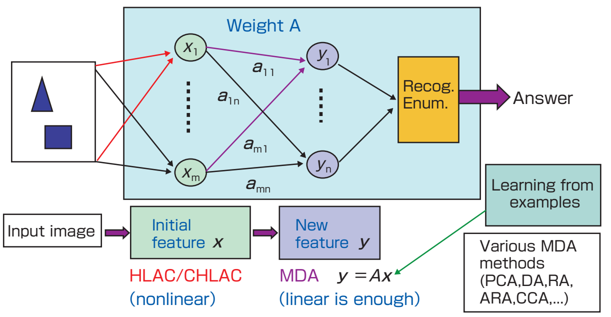


Fig. 5 Adaptive Recognition for General-Use System (ARGUS)

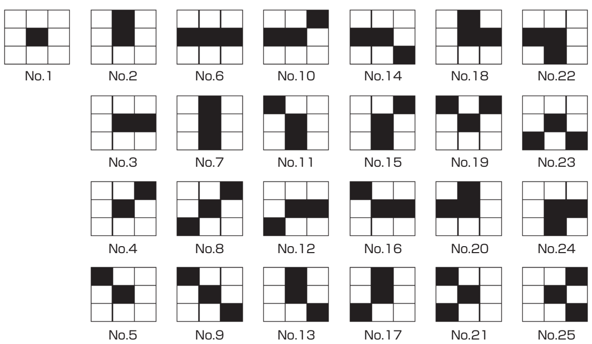


Fig. 6 Local 3 × 3 masks up to the 2nd order [3][4]

and the 2nd order (generally even-order) autocorrelation functions form a complete system. As such, several interesting properties pertaining to pattern recognition applications, have been discussed[9]. For an image, $f(\boldsymbol{r})$ is the gray-scale value at the reference point (image pixel) $\boldsymbol{r}$, and $\boldsymbol{a}_i$ is the relative displacement around the reference point $\boldsymbol{r}$. However, the number of feature values becomes exponentially large according to the combination of N displacements, and their computation is almost impossible. Thus, combinations of limited orders and displacements are used in a practical application.

In fact, patterns in the real world are spatio-temporally localized and the local relative relationships are essencial. Moreover, this localization also satisfies frame-additivity (R2). Therefore, as nonlinear features that satisfy both R1 and R2, Higher-order (Nth order) Local Auto-Correlation (HLAC) features, obtained from the higher-order auto-correlation function in Eq. (3) limited to a localized displacement, were devised and adopted[3][4].

HLAC: For an actual 2D image (a still image) $f(x, y)$, restricting the order to 2nd order and displacements to a local 3×3 region, there are 25 patterns of local masks for taking inequivalent and independent sum of products when considering the shift variance (Fig.6). For the full screen (or a sub-region) XY, scanning each of the local masks shown in Fig.6 and finding the sum of products of the pixel values corresponding to black dots gives the HLAC feature vector $\boldsymbol{x}$. Its dimension is 35 for a gray-scale image (e.g., for mask No. 1, distinguishes f , f^2, f^3), and for a binary image (0/1, white/black), it degenerates to 25 dimensions (e.g., for mask No. 1 yields $f = f^2 = f^3$ as idempotent)[Note2].

CHLAC: In the case of a moving image (3D) $f(x, y, t)$, since there are three-dimensional (solid) numerical data over XYT formed from the two-dimensional still images lined up along the time axis, features are extracted for CHLAC (Cubic HLAC), which naturally expanded HLAC by including the time axis[11]. Fig.7 shows an example of a local 3×3×3 mask for CHLAC. There are 251 independent local mask patterns. As with HLAC, the CHLAC feature vector $\boldsymbol{x}(t)$ is obained by finding the sum of products using

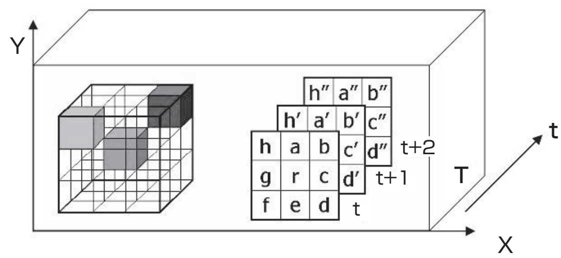


Fig. 7 Example of CHLAC mask (hr'b") [5][11]

the masks over the solid frame *XYT*. The dimension is 279 for a gray-scale moving image and 251 for a binary moving image.

The feature extraction methodology using the integral features of HLAC (CHLAC) is a fundamental and general-purpose feature extraction method for "object shape (and movement)" and satisfies the required conditions R1 (shift-invariance) and R2 (frame-additivity). Employing these methods, the recognition object can always be captured and represented in a unified manner as a single point (a vector) $\boldsymbol{x}$ in an invariant feature space.

4.2 Discriminant feature extraction (MDA)

In the next stage of adaptive learning (satisfying R3), statistical discriminant feature extraction, various multivariate data analysis (MDA) techniques are applied as linear mappings (Fig.8). This refers to adaptively deriving a new feature $\boldsymbol{y}$ optimized for the given recognition task, as the weighted linear sum of the elements of the HLAC or CHLAC feature vector $\boldsymbol{x}$ (R3: adaptive trainability) (Fig.5) ; since the mappings are linear, this secures the required condition R2 (frame-additivity).

A similarity can be found in neural networks, but owing to its nonlinearity R2 is not preserved. In addition, it requires an iterative solution for optimization and takes much computation time. On the other hand, MDA has the advantage that by learning through examples, the weights optimal for the tasks are easily obtained in an analytically explicit form[Note3].

4.3 Characteristics of the ARGUS recognition system

This formulation comprising these two stages of feature extraction does not require segmentation or positioning of the object, and is unique in not requiring any knowledge or model of the object. Thus, the formulation has a versatility that makes it applicable for various recognitions, measurements or enumerations of still and moving images. Moreover, since it basically performs only the multiply-accumulate operation, even CHLAC can run on a normal PC with an extremely high processing speed (2 msec/frame).

5 Application examples

5.1 Simultaneous recognition (/enumeration) of multiple objects

As an example of recognition of still images, an application for the enumeration task of simultaneously recognizing multiple objects is presented (Fig.9). This can be easily realized by utilizing factor analysis (FA), based on the shift-invariance

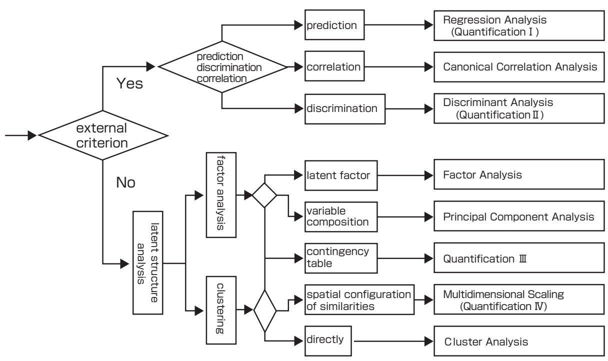
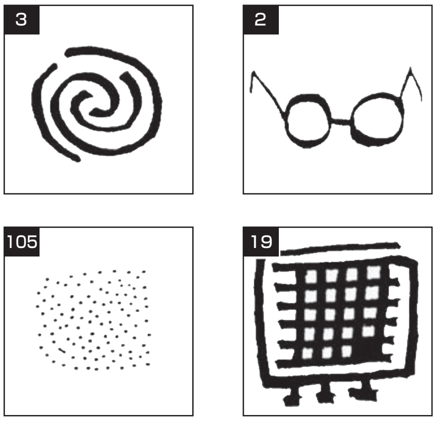


Fig. 8 Multivariate data analysis method (by objective)
Whether an external criterion exists corresponds to being supervised. A quantification method is for the case of qualitative data (Yes/No, 1/0).

Fig. 9 Simultaneous recognition (/enumeration) of multiple objects[5][6]



a) Number of objects b) Number of holes

Fig. 10 Recognition (/enumeration) of topological characteristics[5][6]

Fig. 11 Example of the JAFFE facial expression dataset (3 people)[14]

and the additive properties of HLAC features. Once each of the patterns on the left in Fig.9 are presented to the system, the system instantly responds to the test image (on the right) with the numbers y_i of each as $\boldsymbol{y} = (F'F)^{-1}F'\boldsymbol{x}$. This is by virtue of additivity, where the feature vector $\boldsymbol{x}$ for the entire right-hand diagram can be decomposed into the linear sum $\boldsymbol{x} = \sum_{i=1}^{6} y_i \boldsymbol{f}_i = [\boldsymbol{f}_1, \ldots, \boldsymbol{f}_6]\,\boldsymbol{y} = F\boldsymbol{y}$, which has as its coefficient the number of feature (factor) vectors $\boldsymbol{f}_i$ for each pattern.

5.2 Recognition (/enumeration) of topological characteristics

Next, as an example of recognition that is independent of shape, recognition outcomes for topological characteristics are given in Fig. 10. By learning from examples using multiple regression analysis (MRA), the system correctly answered the number of objects (a) or the number of holes (b)[4]. Interestingly, from the examples, the system learned the Euler number that underlies the basis of topology (number of points − number of lines + number of planes)[Note4] and used it for recognition.

5.3 Recognition of faces and facial expressions

HLAC is not limited to binary images and can be directly applied to gray-scale images as well. Face recognition was done as such an example[12][13]. By integrating with discriminant analysis (DA), the HLAC features extracted from each layer of a pyramid of images representing multi-resolution, even the simple classification method MDD[Note5] achieved a high recognition rate of more than 99 % among 119 people[13]. Furthermore, the method was applied to the difficult task of facial expression recognition for seven facial expressions by nine people (JAFFE Dataset[14], Fig.11). Using the MDD and the discriminant analysis that takes into account the position based weighting of HLAC features, a high recognition rate of more than 80 % was achieved[15].

5.4 Recognition of person and motion

Using CHLAC features that are a natural expansion from HLAC features when moving images are considered, both object and movement can be recognized in a moving image. Videos of four motions (walking/running to the left/right) by five persons were converted to binary images based on frame difference and thresholding, and the CHLAC features were extracted. Fig.12 shows the results after applying discriminant analysis to person and motion, respectively[11]. Each cluster (category) is well grouped and separated,demonstrating the effectiveness of CHLAC features. Even with a simple classification method MDD, recognition rate of almost 100 % was obtained.

5.5 Recognition of gait

In recent years, the concept of "gait" has attracted attention as a key in the identification of individuals(terrorists, etc.) by surveillance cameras from a distance. Application of CHLAC and discriminant analysis together with the *k*-NN decision rule to the Gait Challenge Dataset (Fig.13) of 71 individuals compiled by the NIST in the United States has achieved the best performance in the world thus far, significantly surpassing the top five methods[16](Fig.14).

5.6 Abnormality detection

When there are multiple objects in an image, CHLAC has the additive property in which the sum of the features of each object becomes the features of the whole; therefore, the feature vector for usual (normal) motion will be

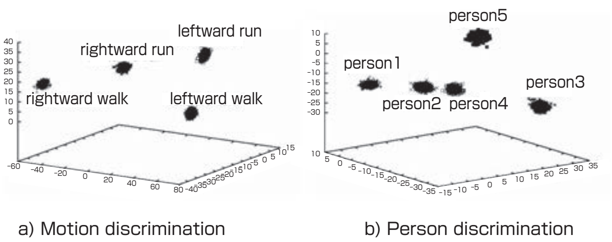


Fig. 12 Obtained discriminant feature spaces[11]

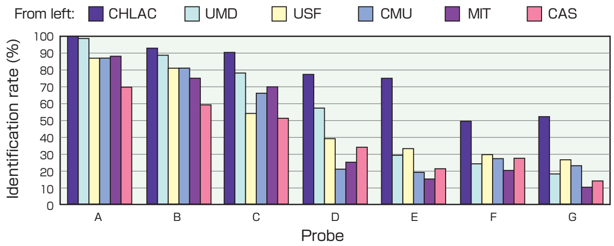


Fig. 14 Comparative experiment of "gait" recognition[5][6][16]

Fig. 13 Gait video and frame difference

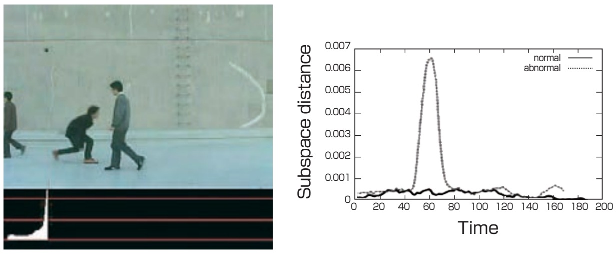


Fig. 15 Example of abnormality detection (Here, "falling down" is abnormal.)

distributed in a linear subspace (usual motion subspace) S_N in the feature space (with 251 dimensions). Accordingly, once S_N has been derived using principal component analysis (PCA) while learning on a regular basis (unsupervised), abnormal behavior does not require prior definitions, and can be detected and recognized immediately with high speed and accuracy, as a deviation (in distance or angle) from S_N[17] (Fig.15). Because of its additivity, capability for detecting abnormalities remains constant even for multiple persons (Fig.16).

This abnormality detection system is already put into practice with surveillance cameras in elevators[Note6].

This system, where usual cases are learned as a statistical distribution in the CHLAC feature space and abnormalities are detected as deviations from such distribution (unusual), does not necessitate any model or knowledge of the objects. Accordingly, the system can be applied not only for abnormality detection from footage taken by surveillance and car-mounted cameras, but also for various other abnormality detection scenarios. For example, using the HLAC feature space for still images, it can be applied to various appearance inspections such as in the field of manufacturing semiconductor substrates (Fig.17).

Moreover, abnormality detection using HLAC is equally applicable in the medical field for various kinds of tissue examinations, especially in the pathological diagnosis of cancer. Cancer is a cell abnormality. The pathological diagnosis of cancer is conducted under a microscope by a pathologist who determines the degree of change found in the structure and the cells of organ tissues. However, this requires a wealth of experience and knowledge, and experienced pathologists are in short supply with their ever-increasing workload. Thus, there is great demand for system development to support pathologists, in the form of alleviating the burden of screening tests through automation,and preventing oversights through crosschecking. When this method was applied to actual lymph node metastasis in stomach cancer, it was possible to obtain analysis results that were close to those obtained by a experienced pathologist[18](Fig.18). Currently, we are collaborating with university hospitals and cancer centers with the goal of setting up a support system for pathological diagnosis.

5.7 Time series data analysis

In general, sensing data, not limited to images, is represented by N-dimensional (Ch.) time series data, $\{\boldsymbol{s}_i(t)\}_{i=1}^{N}$, $t = 1, \ldots, M$. Although it is possible to consider these as an $N \times M$ two-dimensional matrix(image) and extract HLAC features, the order of the dimension (Ch.) subscript i is generally optional. Accordingly,if for example a combination of any three is taken arbitrarily, this gives

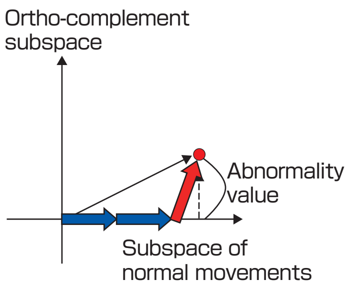


Fig. 16 Deviation from the subspace of usual motions

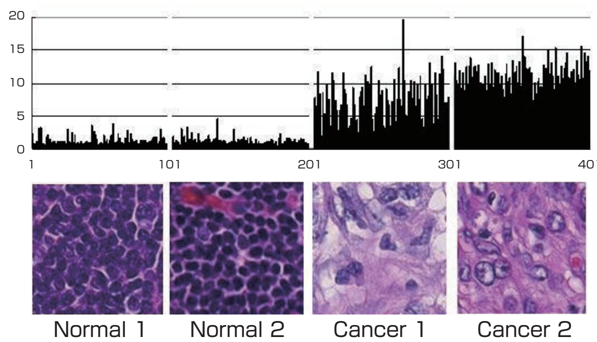


Fig. 18 Example of application to cancer detection (The upper figure shows abnormal values for each specimen.)[18]

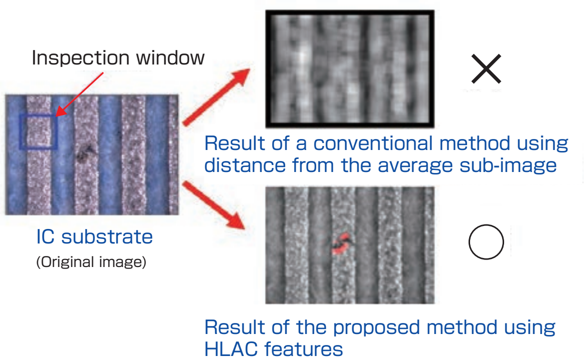


Fig. 17 Example of application to substrate inspection

Fig. 19 Correspondence learning[24][25]

$K={}_NC_3$ two-dimensional ($3{\times}M$) matrices, and taking HLAC features from each 3 × 3, a feature vector with K × HLAC dimensions is obtained. By performing multivariate analysis on this (PCA, DA), analysis of such time series can be conducted (abnormality detection and discrimination). This method has been applied to abnormality detection in electrocardiograms[19] and in the analysis of the movement of a multi-fingered robot hand with multiple degrees of freedom[20].

Moreover, causal relationships, which can be interpreted as the asymmetric interrelationship (correlation) among time series data, are important in many fields. Granger Causality[21] has been proposed as an analysis index using a linear auto-regression model, but the present paper expands this model to a polynomial auto-regression model[22] (which therefore involves Higher-order Local Auto-Correlation features). Furthermore, by introducing a weighting function *w(t)* (a Causality Marker) to indicate the existence of a causal relationship, we have proposed a method that automatically extracts where a causal relationship exists[23].

5.8 Correspondence learning

Correspondence learning is connected to a wide range of common applications. Retrieval through impressions and interactive searching as well as automatic evaluation (prediction) become possible by approximating (canonical correlation analysis (CCA) or multiple regression analysis (MRA)) through learning the correspondence between the expression of a person's judgment or evaluation (external criteria) toward a pattern (still or moving images), such as the qualitative expression in the form of keywords or impression (sensitivity) vocabulary $\boldsymbol{y}$[Note7] or rating y, and the feature vector expression (HLAC/CHLAC) $\boldsymbol{x}$ of a pattern. Figure 19 shows applications to retrieving of family crests by impressions (CCA)[24], and to the automatic evaluation of exercise (MRA)[25].

The former has been further applied to general image annotation and retrieval[26], and the latter to the automatic indexing of sports video images[27], as well as to the judgment of beef meat quality (BMS) based on ultrasound video images[28].

6 Effectiveness of the theoretical approach

This paper has thus far given an outline of an Adaptive Recognition for General-Use System (ARGUS) constructed to fulfill basic required conditions, based on feature extraction theory in pattern recognition. This paper has also discussed the system's application, focusing on a variety of practical applications in visual systems.

Unlike the scientific approach in physics and chemistry (elucidation of phenomena), in engineering applications, and in particular information technology, construction methods designed for realizing functionality are highly flexible and tend to become ad hoc and arbitrary. Thus, it is important to design proper and novel solutions from a theoretical perspective based on the fundamental requirement conditions of application demand.

By considering the fundamental framework of pattern recognition based on a theoretical standpoint, the method in this paper comprises a twostage method of Higher-order Local Auto-Correlation (HLAC/CHLAC), which is a geometrical invariant feature extraction, and multivariate data analysis, which is a statistical discriminant feature extraction. By using the latter, it is possible to learn from examples appropriate to the task. The method requires neither any model of the object nor prior knowledge, and the shape and movement of the object pattern are distinguished as points in discriminant feature space. Since segmentation of the object is also unnecessary and the computation is small with a fixed quantity of the sum of products, even moving images can be processed at far greater speeds than real-time operation on a normal PC. The features of this method are as follows:

- non-model base methodology → high versatility.
- basic initial features (HLAC/CHLAC) → applicable to a wide range of data formats.
- statistical learning (MDA) → task adaptability and increased accuracy.
- parallel sum of products operations → possible to process large amounts of data at high speed.

Almost as expected, through a variety of applications, it has outperformed the schemes that have been developed thus far. This can be attributed greatly to the method that is substantiated by theory, in particular the predominance of the Higher-order Local Auto-Correlation features and its essence. In contrast to being restricted to a two-point relationship of usual autocorrelation, by increasing to higher orders of threepoint relationship, the features obtained have become specific, e.g., curvature (convexity/concavity) rather than local straight-line direction for a contour in still images, and acceleration rather than velocity in moving images. These basic and essential initial features do not use an arbitrary iterative procedure or logical decisions (such as threshold processing and conditional branching, etc.). Rather, they use a multivariate data analysis technique and are integrated into new effective features in a parallel and comprehensive manner, forming a robust system with low information loss.

HLAC/CHLAC are fundamental general-purpose features, i.e., statistics (correlation and frequency) of spatio-temporally localized "patterns". In that sense, this constitutes a precedent for such trends as "from a model collation base to local feature statistics," which are representative of the recent HOG and SIFT features. In addition, not limited to images, it is widely applicable to the multi-channel time series data for audio and various kinds of sensor information and the like, as well as to general three-way data. Future goals include extension from quantitative data to qualitative (categorical) data, and the development of technique is already underway[29].

The application of this method is expected in a wide range of computer vision applications, such as automatic (unattended) video surveillance for intelligent security cameras, various appearance inspection systems, image annotation and retrieval, robot vision, motion analysis, and evaluation in sports and rehabilitation. At the moment, we are promoting its medical application through collaborative research with university hospitals and cancer centers, specifically toward an automatic inspection system for cancer using microscopic images. In addition, centering on an AIST-approved venture (United Technologies Institute), applications are being developed for the commercial viability of semiconductor substrate inspection and various kinds of visual inspection for agriculture and livestock fields, including inspection of rice quality and forecast of estrus and delivery in milk cows in local consortium projects.

The practical application of this method requires adjustments such as pre-processing and parameter tuning (correlation width). Future topics include automation of those settings, accumulating such knowledge base.

Acknowledgements

This study significantly progressed under the guidance of graduation and master's degree theses at the Department of Mechano-Informatics, the University of Tokyo, where I (the author) served concurrently. I hereby offer my appreciation to my dear students. I am especially indebted to the great contribution made by Dr. Takumi Kobayashi (currently in the Information Technology Research Institute, AIST) for the subsequent collaborative research and wish to offer my appreciation. I am also indebted to Dr. Takio Kurita (currently in Hiroshima University) for his work in the early HLAC experiments, and to various postdoctoral fellows as well as the Dr. Sakaue group and the Dr. Higuchi group for their contributions in recent years to the development of applications. Lastly, I would like to thank all of those concerned.

Notes

Note 1) Initially, it was intended to be called ARGUS (Adaptive Recognition for General Use System), after the giant of Greek mythology with a hundred eyes. In recent years, although HLAC/CHLAC has often been used as an abbreviation for this methodology, this actually refers to the first-stage feature extraction, and therefore is not appropriate. As such, the system/methodology as a whole will be referred to as ARGUS.

Note 2) HLAC features of a binary image are closely related to the image spectra due to the N +1th vector in perceptrons[10]. Here, combinations of "black" (1) and "white" (0) have been considered, and at first glance, it may appear that our approach that considers only "black" would not be sufficient, but it actually is. For example, ■□ , with $f_0 = f(\boldsymbol{r}) = 1$ and $f_1 = f(\boldsymbol{r}+\boldsymbol{a}_1) = 1$, and logically $f_0 \cdot \bar{f}_1 = f_0 \cdot (1-f_1) = f_0 - f_0 \cdot f_1$, is represented in the range of the linear sum of feature values due to the masks (No.1 and No.3).

Note 3) This method was proposed[2][3] prior to the back propagationlearning method[7] in neural networks.

Note 4) HLAC features count the number of those topological geometry elements and their coefficients are adaptively determined in the second stage by multiple regression.

Note 5) Minimum Distance Decision: the method whereby the distance from the unknown input feature vector to the center of each class is measured, and the class with the shortest is identified.

Note 6) Helios Watcher (KK Hitachi Building Systems), http://www.hbs.co.jp/lineup/elevator/hw_outline.html

Note 7) A vector with elements of 1or 0 to express positive or negative response for each corresponding word.

References

[1] N. Otsu, T. Kurita and I. Sekita: *Pattern Recognition - Theory and Application, Behaviormetrics Series 12*, Asakura Shoten, Tokyo (1996) (in Japanese).

[2] N. Otsu: Mathematical studies on feature extraction in pattern recognition, *Research Report of Electrotechnical Laboratory*, No.818, 210 pages (1981) (in Japanese).

[3] N. Otsu, T. Shimada and S. Mori: Shape feature extraction using *N*th order auto-correlation mask, *IECE Technical Report*, PRL-78 (31) (1978) (in Japanese).

[4] N. Otsu and T. Kurita: A new scheme for practical flexible and intelligent vision systems, *Proc. IAPR Workshop on*

Computer Vision (MVA1988), 431-435 (1988).
[5] N. Otsu: Towards flexible and intelligent vision systems - from thresholding to CHLAC, *Proc. IAPR Conf. on Machine Vision Applications, Invited talk*, 430-439 (2005).
[6] N. Otsu: CHLAC approach to flexible and intelligent vision systems, *Proc. ECSIS and IEEE Symposium on Bio-inspired Learning and Intelligent Systems for Security (BLISS 2008), Invited talk*, 23-33 (2008).
[7] D. Rumelhart, G. Hinton and R. Williams: Learning representations by back-propagating errors, *Nature*, 323 (9), 533-536 (1986).
[8] J. Shawe-Taylor, N. Cristianini: *Kernel Methods for Pattern Analysis*, Cambridge Univ. Press, Cambridge (2004).
[9] J. Mclaughlin, J. Raviv: *N* th-order autocorrelations in pattern recognition, *Information and Control*, 12, 121-142 (1968).
[10] M. Misky and S. Papert: *Perceptrons*, The MIT Press (1969).
[11] T. Kobayashi and N. Otsu: Action and simultaneous multiple-person identification using Cubic Higherorder Local Auto-Correlation, *Proc. 17th Int. Conf. on Pattern Recognition (ICPR)*, 741-744 (2004).
[12] T. Kurita and N. Otsu: Face recognition method using higher order local autocorrelation and multivariate analysis, *Proc. 11th ICPR*, 213-216 (1992).
[13] F. Goudail, E. Lange, T. Iwamoto, K. Kyuma, N. Otsu: Face recognition system using local autocorrelations and multi-scale integration, *IEEE Trans. PAMI*, 18, 1024-1028 (1996).
[14] M. Lyons and S. Akamatsu: Coding facial expressions with gabor wavelets, *Proc. 3rd IEEE Int. Conf. on Automatic Face and Gesture Recognition (FG1998)*, 200-205 (1998).
[15] Y. Shinohara and N. Otsu: Facial expression recognition using fisher weight maps, *Proc. 6th IEEE Int. Conf. on Automatic Face and Gesture Recognition (FG2004)*, 499-504 (2004).
[16] T. Kobayashi and N. Otsu: A three-way auto-correlation based approach to human identification by gait, *Proc.6th IEEE Int. Workshop on Visual Surveillance*, 185-192(2006).
[17] T. Nanri and N.Otsu: Unsupervised abnormality detection in video surveillance, *Proc. IAPR Conf. on Machine Vision Applications*, 574-577 (2005).
[18] K. Iwata, et al: Cancer pathological diagnostic imaging support system using Higher-order Local Auto-Correlation feature method, *Proc. ViEW2009*, B-6H, 32-37 (2009) (in Japanese).
[19] H. Araki, M. Murakawa, T. Kobayashi, T. Higuchi, I. Kubota and N. Otsu: Abnormality detection in multichannel time-series data using Higher-order Local Auto-Correlation features, *Journal of the IEEJ*, 129 (7), 1305-1310 (2009) (in Japanese).
[20] R. Fukano, Y. Kuniyoshi, T. Otani, T. Kobayashi and N. Otsu:Acquisition of unknown object property for manipulation by a compliant multi-fingered hand, *Journal of Robotics and Mechatoronics*, 17 (6), 645-654 (2005).
[21] C. W. J. Granger: Investigating causal relations by econometric models and cross-spectral methods, *Econometrica*, 37, 424 (1969).
[22] K. Ishiguro, N. Otsu, M. Lungarella and Y. Kuniyoshi: Comparison of nonlinear granger causality extensions for low-dimensional systems, *Physical Review E*, 77 (3) (2008).
[23] K. Ishiguro, N. Otsu, M. Lungarella and Y. Kuniyoshi: Detecting direction of causal interactions between dynamically coupled signals, *Physical Review E*, 77 (2) (2008).
[24] T. Kobayashi, K. Morisaki and N. Otsu: Evaluation of image retrieval performance by using subjective impression, *Journal of the IEICE*, J91-D (4), 1025-1032 (2008) (in Japanese).
[25] Y. Morishita, T. Kobayashi, K. Morisaki and N. Otsu: A method of motion evaluation using time weights and external criteria, *Technology Research Report of the IEICE*, PRMU-107 (539), 371-376 (2008) (in Japanese).
[26] H. Nakayama, T. Harada, Y. Kuniyoshi and N. Otsu: High-performance image annotation and retrieval for weakly labeled images, *Proc. Pacific-Rim Conf. on Multimedia*, 601-610 (2008).
[27] F. Yoshikawa, T. Kobayashi, K. Watanabe and N. Otsu: Start and end point detection of weightlifting motion using CHLAC and MRA, *Proc. 1st Int. Workshop on Bio-inspired Human-Machine Interfaces and Healthcare Applications*, 44-50 (2010).
[28] T. Kobayashi, K. Watanabe, T. Higuchi, T. Miyajima and N. Otsu: Recognition of dynamic texture patterns using CHLAC features and linear regression, *International Journal of Database Theory and Application*, 2 (4), 13-26 (2009).
[29] T. Kobayashi and N. Otsu: Image feature extraction using gradient local auto-correlations, *Proc. European Conf. on Computer Vision* (ECCV), 346-358 (2008).

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Discussions with Reviewers

1 Expansion of the theory and application to the industrial world

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

I understand from the fact that ARGUS was a robust method backed by theory, that the technique could be widely applied. As a *Synthesiology* paper about research based on such a theory, could you perhaps write about essential points or difficulties regarding the research of this theoretical basis? Also, after trying a variety of applications, could you possibly record if they generally went according to theory, or if not, whether you experienced difficulties? If it is the former case, it would greatly help the readers if you could explain why the theory went well.

Answer (Nobuyuki Otsu)

I have responded to the extent possible.

2 Selection of elemental technologies

Question (Kanji Ueda, AIST)

This paper, being *Type 2 Basic Research* for a theoretically based technique which applies to real problems, is of a type that had not yet appeared in *Synthesiology*. I would like to ask about the selection of elemental technologies for this theoretically based constitutive research. How did you choose components to achieve a practical target? Please explain whether they are just components derived by deduction from existing states, or if there are hypothetical components.

Question (Motoyuki Akamatsu)

In subchapter 4.1, you discuss how you developed an adaptive general-use image recognition system as a system satisfying the required conditions from R1 to R3, and how you adopted HLAC and CHLAC as a technique to extract feature values satisfying shift-invariance. In the process of their adoption, I believe there were other techniques considered as candidates. Could you write the rationale for how you came to the conclusion that, compared to those other techniques, HLAC is superior? Also, what is written here as a reason why HLAC was adopted, is the point that patterns are localized and their localized relative relationship is essential. I am afraid readers not specialized in this field may not immediately understand the relationship between focusing solely on local features and shift-invariance. It would be helfpful if you could add a little postscript .

Answer (Nobuyuki Otsu)

In a recognition system, the feature extraction from the object pattern is an important component in determining the performance. In contrast to choosing a variety in an ad hoc way (hypothetically so to speak or by trial and error), as has been the case up to now, higher-order local auto-correlation and multivariate data analysis were adopted as concrete components, which from a theoretical basis gives a two-stage framework comprising geometrical invariant feature extraction and statistical discriminant feature extraction, and which satisfies the basic required three conditions for achieving practical implementation objectives. In that sense, one can think of them as components derived in a deductive manner from theory, and also as hypothetical yet essential components that satisfy both theory and requirements.

There actually are not many alternatives for features that simultaneously satisfy the basic required conditions (especially R1 and R2), and yet are generic features not based on any model. As you pointed out, simply examining local features does not imply shift-invariance. Rather, because “relative” relationships are extracted as autocorrelation, this implies shift-invariance. I have supplemented the explanation as much as possible within the given space.

3 Requirements for vision systems

Question (Motoyuki Akamatsu)

As basic conditions required in a vision system, you listed “R1: shift-invariance, R2: frame-additivity, R3: adaptive trainability,” but the grounds for citing these was not clearly written. Could you please write the scenario in which these theoretical developments were selected? Also for geometrical invariance, I believe that other choices could also be considered, such as invariance with size, invariance with inclination, and relative position invariance between features. Moreover, for invariant feature extraction, it is mentioned that the functional is investigated which gives feature values invariant under geometrical transformations. Is it correct to understand that since this targets a vision system, geometrical invariance is an essentially important property? Finally, about frame-additivity, I do not think additivity will be satisfied in the case where there is overlapping, so is this a choice made mainly from processing time?

Answer (Nobuyuki Otsu)

The shift-invariance refers to invariance under a parallel shift. This does not mean that “the distance between camera and physical object hardly changes,” but rather that due to changes in the camera direction, the physical object undergoes a geometrical transformation which is a parallel shift within the screen frame, and its position changes, and that features which are invariant to such kinds of basic translation are essential in recognition. Of course, as you pointed out, other size (scale) transformations and rotations can be considered as invariant transformations, but what I am saying here is that the parallel shift (or position) invariance is the most fundamental. To avoid any misunderstanding, I have made a slight revision. The invariant feature extraction theory that seeks features invariant under geometrical transformations (functionals) is not something which is restricted to vision but also includes audio signals, and is a theory which we can generally consider as universal.

Frame-additivity, as you mentioned, does not strictly hold true for cases of overlapping, but I will risk asserting that it is important to leave the requirements as they are even in those cases. This, as you have pointed out, has implications from a processing time viewpoint, but the feature representation is a convenient one (linear) in terms of recognition (especially enumeration), and also the required condition to make the subsequent processing simple. I have supplemented the explanation.

4 The meaning of adaptive learning

Question (Kanji Ueda)

There could be several rules in using the word “adaptive learning,” but could you clarify its meaning in the context of this paper?

Answer (Nobuyuki Otsu)

To start, the prerequisite information in pattern recognition is not perfect. Based only on a finite number of examples given as learning samples, recognition is conducted on unknown test samples (an infinite number if possible). As you pointed out, there is certainly some ambiguity in the terminology “adaptive learning.” First, even if the pattern recognition is limited to the recognition object, there is adaption according to variations in the pattern. This is related to feature extraction and the learning process. Also, the adaptive learning in this paper is used in a meta-sense in that it is adaptive learning to a given recognition task. In the case of model-based learning, the model needs to be replaced when the task changes, whereas this method adapts to the task, with no model required at all and the components as they are, and it is optimally constructed (using weights) by learning through examples for the multivariate data analysis technique, the statistical feature extraction of the latter stage. I have thus revised this area to make it a little easier to understand.

5 Percentage of correct answers in pattern recognition

Question (Kanji Ueda)

Why does the percentage of correct answers not achieve 100 %? Or, in what kind of cases is 100 % possible? Recognizing fully that your research gives superior results compared to other researchers and researches until date, this is a question designed to deepen the discussion of the research as a *Synthesiology* paper.

Answer (Nobuyuki Otsu)

Real-world patterns, e.g., for an “a/i” in audio, or a “dog/cat” in an image, have diverse variations and noise, and feature (observed) values from them, such as frequency or color, are generally distributed stochastically. Using this visualization, even when categories are discriminative,the bases of those distributions near to as much extent as possible and could overlap at their frontal boundaries. Therefore, it is normal if 100 % is not achieved even for learning samples. Of course, the more the valid features are extracted in large numbers and integrated, the more close to 100 % it will approach asymptotically, However,it is more realistic to keep the feature extraction down to a finite number from a cost standpoint. It is a question of cost effectiveness.

If it is a simple identification problem, then apparently 100 % correct answer is possible. For example, in the identification and classification of 100 yen and 10 yen coins by using their feature values (e.g., diameter and weight), the fact that they are definitely different as a rule, allows for its implementation in vending machines (though sometimes there are erroneous recognitions). This paper has presented a scheme incorporating a general purpose approach aimed at more difficult, advanced recognition problems.

6 Application examples

Question (Motoyuki Akamatsu)

8 application examples were discussed in Chapter 5, and I understand that the argument as a general purpose system is based on such examples, However, in these examples, HLAC and CHLAC are the only ones that are common, and for discriminant feature extraction by multivariate data analysis, different techniques have been used, namely factor analysis, multiple regression analysis, discriminant analysis, *k*-NN classification, principal component analysis, AR model, and canonical correlation analysis among others. Although there are partial explanations such as what technique is optimum for each task, I look forward to an organized description of the basic thinking and theory behind the proper use of techniques depending on the task. I believe this would promote the understanding of the reader in terms of which technique to apply in solving their task.

Answer (Nobuyuki Otsu)

As you pointed out, I have used HLAC/CHLAC features as basic initial features (invariant features), and various multivariate data analyses for their optimum integration (linear weighted sum) corresponding to the task. As I think your concern is important in helping understand the readers who are unfamiliar with multivariate data analysis, I revised to include a correspondence table that had previously been omitted owing to limited space.

Toward the use of humanoid robots as assemblies of content technologies

— Realization of a biped humanoid robot allowing content creators to produce various expressions —

Shin'ichiro NAKAOKA *, Kanako MIURA, Mitsuharu MORISAWA, Fumio KANEHIRO, Kenji KANEKO, Shuuji KAJITA and Kazuhito YOKOI

[Translation from *Synthesiology*, Vol.4, No.2, p.80-91 (2011)]

A significant feature of humanoid robots is their potential to make various expressions as humans do, and this feature will allow the use of humanoid robots as assemblies of content technologies. Technical issues required for the practical use of humanoid robots are discussed in terms of robot hardware, motion expression generation, vocal expression generation and integrated GUI (Graphical User Interface), and the development of technologies to solve the issues and their integration have been carried out. As a result, we have produced HRP-4C, a life-size biped humanoid robot with realistic human-like appearance, and Choreonoid, an integrated software interface that allows us to choreograph motions with robots as done with CG characters. Experiments on creating contents with these technologies verified the potential of humanoid robots as assemblies of content technologies.

Keywords : Biped humanoid robots, content technology, entertainment, cybernetic human HRP-4C, motion creation, key pose, Choreonoid, VOCALOID

1 Humanoid robot as content technology

Among several types of robots, the humanoid robot enchants people, because of the sense of wonder created by the fact that an artifact made in the image of humans can actually move like a human, the expectation that it may take over the various tasks like a human, and because it has been referenced in various works of fiction. Driven by this fascination, various humanoids have been developed. In 1996, Honda developed the P2, a life-size humanoid capable of bipedal walking[1], and the development of humanoids have become active ever since. These robots made frequent appearances in public events and the media, and as a result, the expectation for the practical utilization of humanoids has increased.

One of the applications of robots for which people have high expectations is to have the robot assist various tasks in everyday activities, and there have been many researches on humanoids to fulfill this demand[2][3]. If the objective is to freely move around within the human environment and to use the tools and devices that humans use, it rationally follows that the robot should have a similar form as humans. However, there is a large gap between the ability of the tasks that people expect from robots and the current technological level of robots, and at this moment the practical utilization in this direction is no where in sight.

However, there is a great potential for the practical utilization of humanoids, where the robots are made to perform certain acts to be viewed and heard by an audience. There are many thoughts on how such performances could be used, but seen from the technological perspective, many performances can be captured within the framework of "content technology". Here, "content" means a set of information and experiences that may be valuable to the audience, viewer, or consumer. If the humanoid can be used as an expression of contents, this can be called the "content technology" that supports the expression and execution of the contents.

Humanoids possess potential attractiveness as an assembly of the content technologies. In fact, "the ability to enchant people", as mentioned above, is directly linked to the value of the contents. The robot is a machine that is controlled by a computer, and it is possible to do things that flesh-and-blood humans cannot do in the production, expression, and execution of the contents, such as combining with various information technologies and implementing special physical functions. Since most of the contents that people demand are geared to humans, the humanoids are more befitting in terms of general interest contents compared to the robots with non-human forms.

The above characteristic overlaps with the character animation in computer graphics (CG). In fact, the CG characters are utilized in various forms, and are becoming essential parts of the content technology. The robots are distinct from CG characters in that they are entities in the

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real world. This allows a sense of reality and involvement as well as physical interaction that is not possible with CG characters.

We believe that the use of humanoids in the content technology is a valuable application that allows optimization of its characteristics, and therefore we must engage in such a realization. As accomplished by the digital content technologies such as CG, computer music, and game devices, contents with new values can be created, and the industries of related technologies can be vitalized. If the humanoids can be widely utilized in such applications, continued investments can be expected, and that may lead to the development of other applications including the aforementioned support of daily human activities.

2 Objectives and issues of the research

The contents featuring humanoids did exist before. The technical demonstrations of the state-of-art humanoid were one such example, as the audiences were surprised and entertained by some specific actions of the humanoid. However, these were basically created by the robot developers and focused on the technological prowess of the robot. Also, it did not have the value or the breadth that would create sufficient income.

In practice, the producer of the contents should be the "creators" who are the specialists of content production. The "establishment of the content technology of the humanoids" is to be able to incorporate the humanoids into the contents that are created by the creators of various fields, to express things that do not merely fall in the realm of robot technology. Unless this is achieved, the humanoids are unlikely to be used widely, as seen from the situation of the current content technology. However, the conventional humanoids and the peripheral technologies were not realistically usable for the creators due to the difficulty of use and the limitations of expressions.

The objectives of this research are to improve the situation by developing, integrating and verifying the elemental technologies that would be the foundation and to set a path for the commercialization of the humanoids as a content technology.

We set the following technological issues as those we must solve.

Robot hardware
Develop a life-size, bipedal humanoid with human-like appearance throughout the body, as hardware with expressive ability unseen before.

Motion expression support technology
Create a technology as a method for generating diverse motion expressions, to enable choreography of the whole body movement of the bipedal humanoid through operation similar to the key frame animation for the CG characters.

Voice expression support technology
Incorporate the voice synthesis technology to enable the easy creation of the diverse expressions of speaking and singing, along with the movement of the mouth.

Integrated interface
Develop a software interface that enables integration of the above technologies and the current information and content technologies.

To solve these issues, it is necessary to engage comprehensively in the development, selection and integration of the various elemental technologies as shown in Fig. 1.

After overcoming these technological issues, another important issue of this research is to verify whether the expressions produced by a creator who is not a robot researcher are acknowledged as new contents unseen before. By combining the technological foundations that we created and the ideas and skills of the creator, it is possible to pioneer diverse contents utilizing the humanoid. This is our expected scenario.

In this paper, we describe the individual technological issues, the background for setting them and the technologies that were actually developed and integrated to solve the issues. Then the work on the verification of the technologies as well

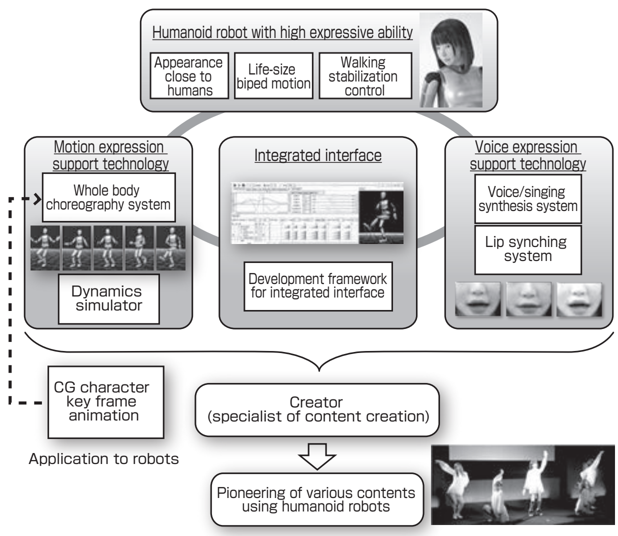

Fig. 1 Outline of research

as the future prospects will be explained.

3 Robot hardware

3.1 Issues of the form and appearance of the robot

While many conventional humanoids claimed to have "human form", most of them could be identified as robots from their form and appearance. While these were effective in the contents that intentionally featured the "robot-like form and appearance", such contents were for minor audiences. If a robot has the form and appearance like humans and possessed expressive ability like humans, it can be used in many categories of contents.

Considering the above points, we set the following two conditions as the issues for robot hardware. The robot:
(1) must be life-sized and capable of stable bipedal motion, and
(2) must have an appearance similar to humans throughout its entire body.

Advanced technology is necessary to fulfill the condition (1), and many humanoids do not fulfill this condition. Some of the examples are humanoids supported by stands and wheels, those connected by cables to external devices, and those that are small in size. While these robots may not possess expressive abilities similar to humans in terms of the whole body action and scale, many robots that fulfill the condition (1) have recently been developed by robotics institutions[1][4]-[9]. However, the appearances of these robots are very "robot-like", and do not fulfill the condition (2). We present examples of the conventional bipedal humanoid that our research group had developed in Fig. 2. Albert HUBO[12], a bipedal humanoid with a realistic head, was developed, but this had the conventional robot-like appearance except for the head. On the other hand, looking only at condition (2), robots that are so close to humans in appearance, so much so that one may not be able to make the distinction, have been developed[13][14]. However, only the upper body moved in such robots and they do not fulfill the condition (1). Therefore, this issue could be cleared if the two technologies were integrated in one robot.

The reason why the robot that fulfills the condition (1) has a robot-like appearance is not only because it was designed so intentionally, but also it is due to the mechanical limitations of size and form of the torso, appendages, and joints. In the conventional robots that fulfill the condition (2), the controller and the power source that drove the multiple joints at high speed to ensure human-like appearance were placed externally to the robot body. To fulfill the two conditions simultaneously by incorporating the mechanism for autonomous bipedal motion in a slender human body to give them a human-like appearance is a difficult technological issue.

The mechanical dolls, as exemplified by the "Audio-Animatronics" of Disneyland, may be called humanoids used in the context of content technology. However, these do not fulfill the condition (1) as they are limited to specific motions and are set in specific places, and do not have the general-use capacity that allow them to be used outside of their original settings. Therefore, they are different from the "content technology" that we have in mind.

3.2 Development of cybernetic human HRP-4C

We set out to solve these issues, and succeeded in the development of cybernetic human[Note 1)] HRP-4C[15][16] as shown in Fig.3. As seen in Fig. 3, HRP-4C is a life-size (height 158 cm) humanoid with an appearance similar to a human being throughout the body. Moreover, HRP-4C has all the mechanisms necessary for motions contained within its body, and is an autonomous robot with bipedal motion. The size and form of the body is close to the average young Japanese woman. It has a slender body compared to a conventional bipedal humanoid. Its total weight is 47 kg[Note 2)].

There is an 8 degrees-of-freedom (DOF) in the head, 3 in the neck, 6 in each arm, 2 in each hand, 3 in the waist, and 7 in each leg. The total joint freedom is 44 ways. The 8 DOF in the head allows changes in the facial expression, movement of the line of sight, and movement of the mouth when speaking. The 3 DOF in the waist allows its smooth movement. In terms of movement, these allow expressive ability close to humans compared to the conventional robots.

As mentioned earlier, the creation of such hardware was a technologically difficult issue. For the development of HRP-4C, a small distributed motor driver combined with a distributed control system, and newly developed ankle joint driving mechanisms were introduced to the design technology nurtured in the development of HRP-2[6] and HRP-3[11]. The actuator and battery were downsized to enable the design with reduced weight capacity. As a result of the integrated effort, we solved the issues and

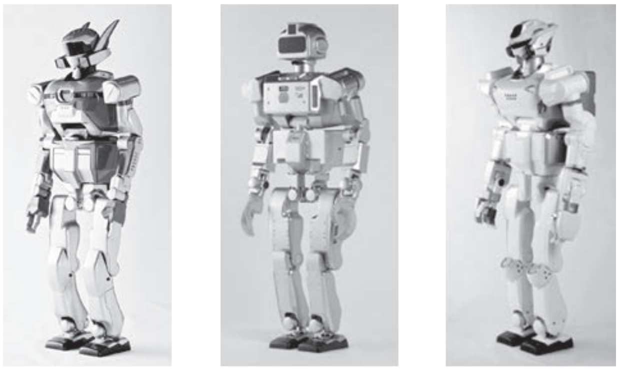

Fig. 2 Conventional biped humanoid robots
From left, HRP-2[6], HRP-3P[10], and HRP-3[11].

achieved the size and weight reductions of the mechanical and electric systems.

3.3 Improvement of the walking stabilization system

To achieve a form similar to humans for the legs in HRP-4C, as seen in Fig. 4, the sole of the feet is smaller compared to the conventional bipedal robots, and the ankle-center is placed close to the heel. In bipedal robots, when the position of the zero-moment point (ZMP) of the sole approaches the edge of the sole, it topples along the edge[17]. Therefore, to prevent falling, it is necessary to keep the ZMP between the sole and floor accurately within the sole, but this becomes difficult to control as the surface area of the sole becomes smaller. We succeeded in obtaining sufficient stability by introducing the new walking stabilization system[18] based on the linear inverted pendulum tracking control that we have been studying as basic research to increase the ability of the bipeds to cover uneven ground.

4 Motion expression support technology

4.1 Issues in choreography of the movement

In addition to the form and appearance of the robot, the movement of the body is, of course, an important element of expression for the content. The function that will be basic for the content technology is that the robot engages in a series of movements designated by the content creator.

The problem is how to choreograph such movements with the robot. In the life-size bipedal robot, the conventional method was to individually develop a program for some specific movements, or to set the commands for the basic preset movements. However, these were non-intuitive tasks that required specialized skills, and the resulting movements tended to be monotonous. Instead of such methods, an easy to understand, efficient method was needed to enable choreography of the various movements as desired by the creator.

We shall take another look at the animation technology for CG characters. The humanoids and CG characters are similar in the point that the desired motion is choreographed to the human-like physical model. The CG character animation is a practical technology that has been used in many moving image contents over the years. Therefore, the technology to choreograph the humanoids in similar ways to the CG characters may be used realistically in the content technology of the humanoids.

The basic methodology in CG animation is called the “key frame animation”. Here, “frame” means the images in sequential order that switches at tens of frames per second to generate the animation. In this method, the key frames are set when the character’s key poses are selected. The poses that fill the areas between the key poses are automatically created for the other frames. This results in the character’s motion. This allows choreographing detailed motions to the character directly, while skipping the between work. The setting of the poses that determine the motion is intuitive and easy to understand.

While this method had been used in the software system intended for use in robots, it was insufficient for “bipedal” robots.

In fact, most systems do not take into account the physical interaction between the robot and the floor in the real world, in processing the generation of the movement from the key poses. In such cases, the movement may be physically impossible for the robot to stay in balance on the feet, and the robot may fall when it is made to carry out the movement. This is the point that differs greatly between the robot and the CG character. In this system, if the robot is small and light and the relative sole size is large, the range where it can stay in balance without falling may be wide, and falls can be prevented depending on the adjustments of the key poses. Because of the size condition, the system was limited to the field of hobby robots, and it was not realistic for our purpose.

The only system that considered the physical behavior

Fig. 3 Cybernetic human HRP-4C
Name is “Miim”.

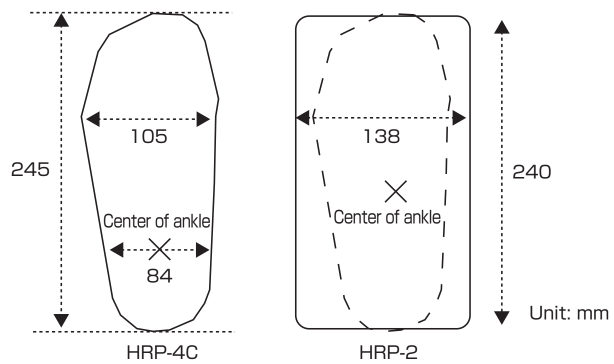

Fig. 4 Size of left soles and the central position of the ankles of HRP-4C and HRP-2
For comparison, the sole of HRP-4C is shown as dotted lines over the sole of HRP-2 on the right.

between the robot and the floor was the SDR Motion Creating System[19] that enabled various movements in a small, 58-cm-tall biped humanoid QRIO[20]. However, in this system, movements could be made from the key poses only for the upper body, and the movement of the lower body could be set only by the specific command and the parameters provided by the system. In this case, the movement of the lower body was limited to the ones allowed by the preset commands, and the task of creating the movement of the whole body was complex. In another light, the fact that a stable movement could be possible only by such a method highlighted the difficulty of the problem.

Until now, the system that allowed the creation of whole body motion of a life-size bipedal humanoid in a way similar to the key frame animation did not exist. We thought such a system would be the fundamental technology for the motion expression of humanoids, and set our topic as the integration of the key frame animation technology and the bipedal robot technology.

4.2 Development of the whole body motion choreography system

As a technology to solve the aforementioned issues, we succeeded in developing the whole body motion choreography system for bipedal humanoids[21]. The interface for the system and the example of the motion created by this system are shown in Fig. 5.

The interface of the system handles the whole body, without dividing the body into the upper and lower parts. As shown in the middle row of Fig. 5, the user can set the key poses on the CG model of the robot. The result will be a stable movement where the robot keeps balance on its feet. The

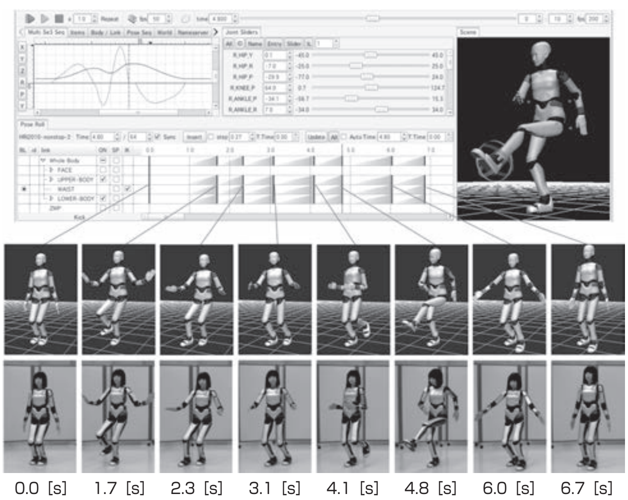

Fig. 5 Editing screen for the whole body choreography system and examples of the created key poses
In this example, eight patterns of key poses are needed to create an action of about 7 seconds where the robot makes the pose, takes a step, and does a kicking motion.

robot can execute the motion without falling as long as there is no self-collision or exceeding of the limits of the joint angle speed (the user will be prompted to correct them when such events occur).

To realize this, we devised an interface design never seen before. The greatest characteristic is that the system determines the horizontal position of the hips at each key pose so the robot can stay in balance. This determination is done instantly as the user enters or corrects the key pose. The result is presented on the spot to the user in the form of the correction of the hip position in the key pose. The supplementation between the key poses is also done to generate a balanced movement. In another word, the system allows only well-balanced choreography. While this maneuver is done, the user does the same operation as in the ordinary key frame animation, and the robot can be choreographed in a manner just like a CG character. It is also possible for the user to explicitly indicate the weight placement of the robot to the floor as the ZMP between the sole and the floor in the key pose, to obtain the desired horizontal movement of the hips within the balanced range.

Such design was not self-evident, and the fact that we reached this design was important in overcoming the issue. Also, implementation of this design was difficult. While providing a simple interface to the user, the system must integrate various complex computations such as the detection of sole landing status, the transition of target ZMP, the transition of supplementary space, the addition of supplementary key poses, and the calculation of center of gravity path that matches the target ZMP. Moreover, these have to be done at high speed.

In overcoming such implementation issues, we were able to utilize the technology of OpenHRP3[22], the dynamics simulator for robots that we have been developing. The various calculation processes for robotics implemented in the simulator were developed to handle practical simulation in terms of execution speed and precision, and it was useful for the implementation of this system. The dynamics simulation method that we developed for OpenHRP3[23] could accurately verify the behavior of the bipedal robot on the floor. By incorporating this into our system, we could directly verify the adequacy of the implementation to the system, and were able to increase the development efficiency.

This system was confirmed to be effective for HRP-4C. By combining the whole body motion created with the walking stabilization system[18] mentioned in subchapter 3.3, stable execution was confirmed to be possible for HRP-4C, as in the example of Fig. 5. To be able to construct such complex movements in a life-size humanoid with small soles, as in HRP-4C, was a major accomplishment. Also, as shown in Fig. 6, it was possible to create the changes in facial expressions[24]. In this system, the operation of the actuators in the head can be reflected in real time on the robot, and therefore, the changes of the fine facial expressions, which was difficult to render perfectly by CG, could be made directly. This system can bring out the expressive ability of the movement of HRP-4C.

4.3 Method of using the motion capture

In the CG character animation, a method with which actions of an actual person are incorporated by motion capture is also widely used. A method for applying captured human whole body motion to the whole body motion of the bipedal humanoid was developed[25]. Using this method, the whole-body performance of a Japanese folk dance called Aizu Bandaisan was done by HRP-2[6].

Comparing the motion capture method and the method developed in this research the former is, of course, more applicable in recreating the human actions. However, it must be noted that due to the limitations of the method and the limitations of the robot's movements, the human action cannot be completely reproduced in the robot. On the other hand, to express the action unique to a robot or to create high quality action within the limit of the robot's motion capacity, the latter method that choreographs the robot directly is more applicable. Moreover, the former requires a skilled performer that can move in a certain way, as well as specialized equipment and a studio, while the latter does not require such equipment and can be done easily on a PC.

Considering the above characteristics, for the objective of the creation of new contents using the humanoid and the diffusion of its use, the method of this research will be used as the base. It is highly significant that this was realized for the first time. On the other hand, the motion capture method can be also useful, and one of the future topics will be to integrate the two methods.

5 Voice expression support technology

The voice of the robot is an important expression element for the content. Research has been done on the speech mechanism simulating the human vocal cord[26]. However, this is a large mechanism including the lungs, and cannot be currently installed in a humanoid like HRP-4C. Therefore, production of some voice source through the speaker is adequate as the source of speech. In this case, to make it look as if the robot is speaking, the robot's mouth must move according to the voice source (lip synching). To obtain the vocal source, there are methods of using the human speech or using the voice synthesis technology. The difference of the characteristics of the two is similar to the difference between the two methods for creating the actions as mentioned in subchapter 4.3. In that sense, use of the voice synthesis will be more appropriate for our purpose.

(a)Smile (b)Surprise (c)Anger

Fig. 6 Examples of expression creation

From the above considerations, the issue for voice expression would be to enable various speech and singing expressions with the voice synthesis technology in linkage with the mouth movement.

To solve this issue, we developed a system using the VOCALOID[27], the song synthesis technology of Yamaha Corporation with whom we worked jointly, as the voice expression of HRP-4C[28]. The VOCALOID was developed to synthesize the singing voice, and is a technology that generates a singing voice very close to humans. Moreover, the VOCALOID-flex technology, where the technology is applied to produce natural speech with rich intonations, is available, and diverse voice expressions are possible. The system allows the robot to lip synch the voice data of the VOCALOID, and this enables easy creation of natural speech and singing performances by the robot.

6 Integrated interface

For the implementation of the whole body motion choreography system mentioned in subchapter 4.2, it was necessary to implement the various functions including the management of various data, the display and operation of the 3D models, the sequential display of the key poses, and the dynamic simulations in a collaborative format, in addition to the essential key pose processing. To create the integrated expressions of the robot and to have the robot perform them, it is necessary to link the choreography system and voice expression support technology to the robot hardware, and to provide an interface that allows easy use by the user. Moreover, the usefulness as a content technology will increase further if the information and media technologies for the robot expression including the existing technologies and those that will be developed in the future can be collaboratively used. The motion capture technology mentioned in subchapter 4.3 is an example of such a useful technology.

To realize the above, we developed the "Choreonoid framework", a software framework for the development of the integrated interface. The interface for the technology developed and selected in this study was implemented on the framework, and resulted in the integrated software Choreonoid[Note 3].

The Choreonoid framework is based on the C++ language, is compatible with programs written in C or C++, and is capable of realizing the algorithms and interface that require high-speed processing. Also, it is designed based on the architecture called Model View Controller and the signal mechanism, and while keeping the maintainability and expandability by increasing the independency of the objects, it is possible to execute complex associations between the objects[29]. New functions can be added as plug-ins and the new plug-ins can easily collaborate with the existing functions and other plug-in functions. Due to such characteristics, the Choreonoid surpasses the framework of the content technology, and is expected to be used widely as an environment to develop higher layer robot software.

7 Experiment in content production

In this research, to promote the technology, it was necessary to actually produce the contents using the Choreonoid and HRP-4C, and to verify and improve the technology. Considering the objective of this study, it was important to have the content created by professional creators rather than by us. By doing so, the practicality of the system could be verified, and new contents could be pioneered.

As a joint activity with Dr. Masaru Ishikawa, Project Researcher of the Information and Robot Technology Research Initiative, The University of Tokyo, we asked Mr. SAM, a famous dancer and dance creator, to create an entertainment content using HRP-4C. This was supported by the DC-EXPO (DIGITAL CONTENT EXPO)[Note 4] 2009 and DC-EXPO 2010, and the resulting performance was presented at the exposition. We shall now describe the efforts at the DC-EXPO 2010 that was done after the development of Choreonoid.

At the DC-EXPO 2010, to fully verify the technologies described in this paper, we tried to develop a content where the HRP-4C would sing and dance, as shown in Fig. 7. In this content, HRP-4C gave a three-minute demonstration of a dance, choreographed by Mr. SAM, and a song “Deatta Koro No Youni (Like When We First Met)” by Every Little Thing, a Japanese music group.

Fig. 7 Demonstration of singing and dancing by HRP-4C

The dance motion was created entirely by Choreonoid based on Mr. SAM’s choreography. We told Mr. SAM the robot’s motion capacity, and then had him choreograph freely within the possible motion range. The dance motion included various poses and actions using the entire body as shown in Fig. 8, and the richness of expression was unseen in any previous performance by a robot. We changed the wig of HRP-4C and dressed HRP-4C in a costume to match the dance, and the stage lighting was also carefully planned. Mr. SAM’s choreography included the total combination performance with four human back dancers.

For singing, we asked the cooperation of YAMAHA Corporation, and obtained the voice data and lip synch data through the VOCALOID. The VOCALOID sound source was CV-4Cβ of the Crypton Future Media, Inc. Using the VocaListener technology of Nakano and Goto[30], tuning was based on the song by Ms. Kaori Mochida, the singer of the original song (voice track of the vocal part by Ms. Kaori Mochida supplied by avex trax). This ensured expressive singing close to that of a human being. The lip synch data was produced automatically and was created efficiently from the voice data by using the VOCALOID linkage function explained in chapter 5.

This dance demonstration generated news mainly on the Internet since it was presented on October 16, 2010. As an example for its newsworthiness, the movies uploaded to YouTube by some audiences recorded over 2 million view counts and over 1,500 comments in 10 days after the presentation. One of the movies had the 6th highest view counts for YouTube Japan in the year 2010. Immediately after

Fig. 8 Example of various movements and poses actually done in the dance

the great response on the Internet, we received several offers for appearances of HRP-4C from various places including overseas. This showed that the expression created by the creator using the technology in this study was recognized as a totally new content, and demonstrated the effectiveness of our scenario.

The entry of the key poses on the Choreonoid was done by one of the authors, and the time required for entry was about 80 hours. A rather large amount of time was required for the three-minute performance, but this was mainly because the person did not have any experience creating CG character animation. Needless to say, verification by professional creators, including the key pose entry work, is necessary and we plan to have professional CG creators work directly on Choreonoid to create the contents.

8 Future prospects

Since the press release in March 2009, HRP-4C has received requests and suggestions for its use from various places. It gave the opening speech in the "SHINMAI Creator's Project" of the 8th Japan Fashion Week in Tokyo held in March 2009, was a model for the wedding dress in Yumi Katsura Paris Grand Collection in Osaka held in July 2009, and dressed up as a VOCALOID character such as "Hatsune Miku" and gave singing demonstrations at the Yamaha Corporation booth in CEATEC JAPAN 2009 in September 2009[31][29].

What is significant here is that the requests from the general public for HRP-4C do not stop at asking the robot developer to operate the robot, but are active requests where the requesters propose what they wish the robot to perform. This was unseen in the previous robots such as HRP-2, and in this sense, the strategy for the form and appearance of the robot mentioned in subchapter 3.1 was successful.

With the motion expression and voice expression support technologies that were developed in this study, the contents utilizing the expressive ability of the humanoid, as in the dance at the DC-EXPO 2010, became possible, and we are now able to respond to the various proposals for the use of HRP-4C. To verify this further, we believe we must continue the work, as mentioned in chapter 7, with several creators.

While engaging in such promotional activities, there are still many things that must be done technologically. In the area of bipedal motion, movements that include sliding and jumping as well as more human-like walking with the knees straight cannot be done in the current Choreonoid, but these are necessary to increase the range and quality of the contents. While there are examples where such motions are accomplished individually[32]-[34], the creation of movements that freely combine these elements still remains as a difficult issue.

The improvement of autonomy is an issue necessary to present a more natural motion. For example, the movement of the eyes must be automated to look more natural. In striking a pose, rather than stopping completely, it will look more natural if slight swaying was generated automatically.

Further improvements are necessary in the robot technology as a whole. The robot must move adaptively to the surrounding environment in some contents, and research results on environmental recognition and motion planning based on it or on human interactions are needed. Also, in contents that require use of props, manipulation ability is necessary.

The various technologies for the robot can be developed one step at a time as the contents are created. Therefore, the effort of pioneering the contents using the humanoid is effective in developing the robotics technology and applying them to industry. If the ability of the robot increases as a result, the path to the practical use of humanoids outside the content technology, including daily activity support, may be opened.

With the above experience behind us, we plan to continue the R&D for the humanoid as a content technology.

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Notes

Note 1) This is a term that denotes a humanoid robot that has an appearance and form similar to humans, is capable of walking and moving in a manner extremely close to humans, and is capable of interaction with people using voice recognition and other functions.

Note 2) This is the latest specification as of writing of this paper. This stands true for the other descriptions in this paper.

Note 3) The name "Choreonoid" is a combination of "choreograph" and "humanoid", and expresses the choreography function which is the core of this software.

Note 4) The DIGITAL CONTENT EXPO (DC-EXPO) is an international event organized by the Ministry of Economy, Trade and Industry and the Digital Content Association of Japan. It has been held in October since 2008, at the National Museum of Emerging Science and Innovation and the Tokyo International Exchange Center.

Note 5) More accurately, we used the "NetVocaListener" service developed by the Yamaha Corporation that obtained the license for this technology from AIST.

References

[1] K. Hirai, M. Hirose, Y. Haikawa and T. Takenaka: The development of Honda humanoid robot, *Proceedings of the 1998 IEEE International Conference on Robotics and Automation, Leuven, Belgium*, 1321-1326 (1998).

[2] E. S. Neo, T. Sakaguchi, K. Yokoi, Y. Kawai and K. Maruyama: A behavior level operation system for humanoid robots, *Proceedings of the 6th IEEERAS International Conference on Humanoid Robots, Genoa, Italy*, 327-332 (2006).

[3] K. Okada, M. Kojima, S. Tokutsu, Y. Mori, T. Maki and M. Inaba: Integrating recognition and action through task-relevant knowledge for daily assistive humanoids, *Advanced Robotics*, 23 (4), 459-480 (2009).

[4] Y. Sakagami, R. Watanabe, C. Aoyama, S. Matsunaga, N. Higaki and K. Fujimura: The intelligent ASIMO: System overview and integration, *Proceedings of the 2002 IEEE/RSJ International Conference on Intelligent Robots and Systems, EPFL, Lausanne, Switzerland*, 2478-2483 (2002).

[5] S. Kagami, K. Nishiwaki, J. Kuffner, Y. Kuniyoshi, M. Inaba and H. Inoue: Online 3D vision, motion planning and bipedal locomotion control coupling system of humanoid robot H7, *Proceedings of the 2002 IEEE/ RSJ International Conference on Intelligent Robots and Systems, EPFL, Lausanne, Switzerland*, 2557-2562 (2002).

[6] K. Kaneko, F. Kanehiro, S. Kajita, H. Hirukawa, T. Kawasaki, M. Hirata, K. Akachi and T. Isozumi: Humanoid Robot HRP-2, *Proceedings of the 2004 IEEE International Conference on Robotics and Automation, New Orleans, LA, USA*, 1083-1090 (2004).

[7] I. W. Park, J. Y. Kim, J. Lee and J. H. Oh: Mechanical design of humanoid robot platform KHR-3 (KAIST humanoid robot -3: HUBO), *Proceedings of the 5th IEEE-RAS International Conference on Humanoid Robots, Tsukuba, Japan*, 321-326 (2005).

[8] Y. Ogura, H. Aikawa, K. Shimomura, H. Kondo, A. Morishima, H. ok Lim and A. Takanishi: Development of a humanoid robot WABIAN-2, *Proceedings of the 2006 IEEE International Conference on Robotics and Automation, Orlando, Florida, USA*, 76-81 (2006).

[9] S. Takagi: Toyota partner robots, *Journal of the Robotics Society of Japan*, 24 (2), 208-210 (2006) (in Japanese).

[10] K. Akachi, K. Kaneko, N. Kanehira, S. Ota, G. Miyamori, M. Hirata, S. Kajita and F. Kanehiro: Development of humanoid robot HRP-3P, *Proceedings of the 5th IEEE-RAS International Conference on Humanoid Robots, Tsukuba, Japan*, 50-55 (2005).

[11] K. Kaneko, K. Harada, F. Kanehiro, G. Miyamori and K. Akachi: Humanoid Robot HRP-3, *Proceedings of the 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, Nice, France*, 2471-2478(2008).

[12] J. H. Oh, D. Hanson, W. S. Kim, I. Y. Han, J. Y. Kim and I. W. Park: Design of android type humanoid robot Albert HUBO, *Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, China*, 1428-1433 (2006).

[13] H. Ishiguro: Android science: Conscious and subconscious recognition, *Connection Science*, 18 (4), 319-332 (2006).

[14] D. Sakamoto, T. Kanda, T. Ono, H. Ishiguro and N. Hagita: Android as a Telecommunication Medium with a Human-like Presence, *Arlington, Virginia, USA*, 193-200 (2007).

[15] K. Kaneko, F. Kanehiro, M. Morisawa, K. Miura, S. Nakaoka and S. Kajita: Cybernetic Human HRP-4C, *Proceedings of the 10th IEEE-RAS International Conference on Humanoid Robots, Paris, France*, 7-14(2009).

[16] K. Kaneko, F. Kanehiro, M. Morisawa, T. Tsuji, K. Miura, S. Nakaoka, S. Kajita and K. Yokoi: Hardware Improvement of Cybernetic Human HRP-4C for Entertainment Use, *Proceedings of the 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, San Francisco, California, USA*, (2011), accepted.

[17] M. Vukobratovic, B.Borovac, D.Surla and D.Stokic: Biped Locomotion: Dynamics, Stability, Control and Application, *Scientific Fundamentals of Robotics,* 7, Springer-Verlag (1990).

[18] S. Kajita, M. Morisawa, K. Miura, S. Nakaoka, K. Harada, K. Kaneko, F. Kanehiro and K. Yokoi: Biped walking stabilization based on linear inverted pendulum tracking, *Proceedings of the 2010 IEEE/ RSJ International Conference on Intelligent Robots and Systems, Taipei, Taiwan* (2010).

[19] Y. Kuroki, B. Blank, T. Mikami, P. Mayeux, A. Miyamoto, R. Playter, K. Nagasaka, M. Raibert, M. Nagano and J. Yamaguchi: Motion creating system for a small biped entertainment robot, *Proceedings of the 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems, Las Vegas, Nevada*, 1394-1399 (2003).

[20] Y. Kuroki, M. Fujita, T. Ishida, K. Nagasaka and J. Yamaguchi: A small biped entertainment robot exploring attractive applications, *Proceedings of the 2003 IEEE International Conference on Robotics and Automation, Taipei, Taiwan*, 471-476 (2003).

[21] S. Nakaoka, S. Kajita and K. Yokoi: Intuitive and flexible user interface for creating whole body motions of biped humanoid robots, *Proceedings of the 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, Taipei, Taiwan*, 1675-1682 (2010).

[22] S. Nakaoka, N. Yamanobe, H. Hirukawa, K. Yamane and Y. Kawasumi: OpenHRP3: A robot simulator implemented as distributed objects, *Journal of Robotics Society of Japan*, 26, 5, 399-406 (2008) (in Japanese).

[23] S. Nakaoka, S. Hattori, F. Kanehiro, S. Kajita and H. Hirukawa: Constraint based dynamics simulator for humanoid robots with shock absorbing mechanisms, *Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems, San Diego, CA, USA*, 3641-3647 (2007).

[24] S. Nakaoka, F. Kanehiro, K. Miura, M. Morisawa, K. Fujiwara, K. Kaneko, S. Kajita and H. Hirukawa: Creating facial motions of cybernetic human HRP-4C, *Proceedings of the 10th IEEE-RAS International Conference on Humanoid Robots, Paris, France* (2009).
[25] S. Nakaoka, A. Nakazawa, F. Kanehiro, K. Kaneko, M. Morisawa, H. Hirukawa and K. Ikeuchi: Learning from Observation Paradigm: Leg Task Models for Enabling a Biped Humanoid Robot to Imitate Human Dances, *International Journal of Robotics Research*, 26(8), 829-844, SAGE Publications (2007).
[26] K. Fukui, Y. Ishikawa, K. Ohno, N. Sakakibara, M. Honda and A. Takanishi: Three dimensional tongue with liquid sealing mechanism for improving resonance on an anthropomorphic talking robot, *Proceedings of the 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, Kobe, Japan*, 5456-5462 (2009).
[27] H. Kenmochi and H. Ohshita: Singing synthesis system “VOCALOID” - Current situation and to-do lists, *Information Processing Society of Japan Technical Reports*, 2008-MUS-74-9, 12, 51-58 (2008) (in Japanese).
[28] M. Tachibana, S. Nakaoka and H. Kenmochi: A Singing Robot Realized by a Collaboration of VOCALOID and Cybernetic Human HRP-4C, *InterSinging 2010, Tokyo, Japan*, WA01 (2010).
[29] Shin'ichiro Nakaoka: Choreonoid as a Software Framework for Implementing Graphical Robotics Applications, *Proceedings of the 29th Annual Conference of the Robotics Society of Japan, Tokyo, Japan* (2011), to appear.
[30] Tomoyasu Nakano and Masataka Goto: VocaListener: A Singing-to-Singing Synthesis System Based on Iterative Parameter Estimation, *Proceedings of the 6th Sound and Music Computing Conference (SMC 2009)*, 343-348 (2009).
[31] K. Miura, S. Nakaoka, S. Kajita, K. Kaneko, F. Kanehiro, M. Morisawa and K. Yokoi: Trials of cybernetic human HRP-4C toward humanoid business, *Proceedings of the 6th IEEE Workshop on Advanced Robotics and its Social Impacts, Seoul, Korea*, WA01 (2010).
[32] K. Miura, S. Nakaoka, M. Morisawa, F. Kanehiro, K. Harada and S. Kajita: Analysis on a Friction Based ``Twirl'' for Biped Robots, *Proceedings of the 2010 IEEE International Conference on Robotics and Automation, Anchorage, Alaska, USA*, 4249-4255 (2010).
[33] Ryosuke Tajima and Keisuke Suga: Motion having a Flight Phase: Experiments Involving a One-legged Robot, *Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, China*, 1726-1731 (2006).
[34] Y. Ogura, K. Shimomura, H. Kondo, A. Morishima, T. Okubo, S. Momoki, H. ok Lim and A. Takanishi: Human-like walking with knee stretched, heel contact and toe-off motion by a humanoid robot, *Proceedings of the 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, China*, 3976- 3981 (2006).

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Discussions with Reviewers

1 Overall composition in terms of synthesiology

Comment (Masaaki Mochimaru, Digital Human Research Center, AIST)

[Composition of the paper in terms of synthesiology]

In terms of synthesiology, I see this paper as an integration of the three elemental technologies of life-sized, realistic humanoid (platform as hardware), motion expression support technology (whole body motion generation + dynamic simulator), and singing expression support technology (voice synthesis technology + lip synch technology). Verification was then done for whether the performance created by the integrated technologies would be recognized as an unprecedented new media content. As a synthesiology paper, I think you should clarify this position and organize the chapters along this line.

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

[Diagram that allows understanding of the whole picture in terms of synthesiology]

The elemental technologies that include the completion of cybernetic human HRP-4C, the creation of Choreonoid, the whole body movement software, the realization of facial expression creation function, and the development and use of dynamic simulator are extremely important. As I see it, the final objective was achieved by integrating these technologies. I think the reader's understanding will be improved if you provide a diagram that describes the elemental technologies in blocks, showing the relationship between the elemental technology blocks and how they were combined and synthesized to approach the final goal. I think this is also extremely important from the perspective of "synthesiology" as an academic study.

[Description of technological difficulties in integration]

I think you should explain the major difficulties that had to be overcome in integrating the technologies.

[Feedback from integration to elemental technology]

In conducting the integration, I think you had to have feedback for the correction and improvement of the individual elemental technologies. Please give us an actual example of a feedback that provides a clear case study that will be useful to the readers.

Answer (Shin'ichiro Nakaoka)

[Composition of the paper in terms of synthesiology]

The description was altered based on the comment from the reviewer. For the composition of the chapters, the four technological domains that were the issues in achieving the objective of this research were briefly summarized in chapter 2. The details of the issues and the efforts to solve them were described in the chapters for the four technological domains.

[Diagram that allows understanding of the whole picture in terms of synthesiology] Figure 1 was added to show the outline of this research.

[Description of technological difficulties in integration]

In the large framework of "robot hardware", "motion expression support technology", "voice expression support technology", and " integrated interface" as elemental technologies, the difficulties were to select the necessary elements, and to figure out how to integrate them as a whole. On the other hand, in the individual framework of robot hardware and motion expression, it was difficult to integrate the "human-like appearance" and "bipedal motion". It was also difficult to integrate the "CG key frame animation" and "maintaining stable motion of the bipedal robot". The descriptions of these difficulties were included in the corresponding chapters.

[Feedback from integration to elemental technology]

There were actual case studies of feedbacks. Particularly, from such feedbacks, it became necessary to improve the walking stabilization system, and I added the details in subchapter 3.3.

2 Contents industry for humanoids

Question (Naoto Kobayashi)

You described that you are aiming to commercialize the humanoid as a content medium. At this point, other than the "singing and dancing", "fashion show host", and "model" that were given as content examples in this paper, what other demands do you expect in the future, and what is the projection of the market scale of this industry (humanoid content industry or humanoid amusement industry)? What other technologies, opportunities, or additions do you think would help such an industry to grow further?

Answer (Shin'ichiro Nakaoka)

Other than the examples in the paper, the specific contents using HRP-4C include theatrical performance, message video for a coming-of-age ceremony, presentation at trade shows, and others. The HRP-4C greeted the heads of the nations in the exhibit of Japan's state-of-art technology during the summit meeting of the Asia Pacific Economic Cooperation (APEC) forum held in 2010. Including the examples in the paper, the range of application of the HRP-4C in "communication", "presentation" ,"expression", and "performance" is wide, and there is no end to the contents when meeting specific demands. This part is the work of the creators, and we would like to consult with the creators of various fields.

In terms of industry, we are considering the use of robots in the framework of the current contents industry or the amusement industry. This expectation is described as the "idol robot" in the Technological Strategy Map 2010 of the METI, and this extends to the industries of music, motion pictures, dramas, amusement parks, and tourism. The market for live entertainment is 1 trillion yen (2007). Within this market in Japan, the initial goal for the share of robots (robot hardware, software, operation service, etc.) will be to attain a multibillion-yen scale within Japan. After that, with the technological advancement mentioned in "8 Future prospects," this industry can evolve further by expanding the application of the robots. On the point of opportunities and nurturing the industry, here again, collaboration with the creators will be important.

3 Uniqueness of the Japanese culture

Question (Naoto Kobayashi)

Do you think the affinity people have for humanoids may be rooted in the unique Japanese culture? In other cultures, the responses people have for this type of robots may be different. What are the positive and negative responses in international academic societies?

Answer (Shin'ichiro Nakaoka)

The responses we received directly from the researchers at the international academic societies were mostly positive, regardless of nationality. I think this is mainly because the researchers evaluated the technology itself, and the robot researchers love robots to begin with. Therefore, the responses of different countries cannot be measured from the responses at the academic societies. On the other hand, we received comments on the Internet through the video upload sites, and they were not entirely positive. Several English comments written most probably by people overseas said, "This robot will eventually start attacking people" or "It will be used for war". There were hardly any such comments written in Japanese, and I did feel the difference in culture here. We do have many, many comments, and if we do some statistical analysis, we might get an accurate picture of the differences in perception.

4 Technological evolution of the humanoid and the limitation on the attractiveness of the contents

Question (Naoto Kobayashi)

Currently, people are attracted to the fact that a humanoid is moving like a person, and this is provided as a content. In the future, as the technology advances, the humanoids will be able to do things humans cannot do. It was great news when the computer won the chess game against a human for the first time, but people gradually lost interest. I feel that the contents featuring humanoids may reach a point where people start losing interest. What do you think is such a point and when do you think it would arrive? What kind of measures should you take to avoid this situation?

Answer (Shin'ichiro Nakaoka)

The factors that attract people to the contents featuring humanoid robots include the "interest for the robot itself" and the "interest in the contents". For the former, people will be continually interested in how the robots will become closer and closer to humans, and then eventually surpass humans. For the latter, the characteristics and the functions of the robot can be used in the expression and execution of the interesting and attractive contents. As the robots continue to evolve and become capable of doing what humans cannot do, the range of expression and execution of the contents will expand, and the content itself will become more attractive.

5 Strategy of humanoid R&D

Question (Naoto Kobayashi)

One of the strategies and policies of the humanoid R&D is to start with the use of the humanoid featured in the contents media, as in this study. The basic performances such as the motion ability, sturdiness, and safety of the humanoids are enhanced as they are used, and the improvement in the basic performance can be applied to other uses including the support of daily human activities. I think this strategy is appropriate. On the other hand, I think there is a powerful argument that a robot does not have to be humanoid in form when supporting human functions. Considering the psychological aspects, why do you think the humanoids are necessary?

Answer (Shin'ichiro Nakaoka)

If we increase the tasks that can be taken over by robots to support human activities, I think the physical form of the robot will necessarily become human-like, due to the reason given in paragraph 2 of "1 Humanoid robot as content technology". I also think the human-like form is effective for supporting people from the psychological aspects. It is a matter of how much one expects from robots. To respond to the high demands of human activity support, I think the "humanoid form" becomes necessary in addition to the various developments of the elemental technologies.

Thermoelectric hydrogen gas sensor

— Technology to secure safety in hydrogen usage and international standardization of hydrogen gas sensor —

Woosuck Shin*, Maiko Nishibori and Ichiro Matsubara

[Translation from *Synthesiology*, Vol.4, No.2, p.92-99 (2011)]

A thermoelectric hydrogen gas sensor developed for leak detection in hydrogen stations has shown good hydrogen selectivity and wide hydrogen detection concentration ranging from 0.5 ppm to 5 %. We have demonstrated high sensitivity and reliability of the sensor exceeding conventional technology through a field test of one year. We could optimize the following three constituent technology elements to meet the social needs, i.e. new principle integrating catalytic combustion and thermoelectric conversion technology, micro-fabrication technology to realize the principle and high performance ceramic catalyst for gas combustion. In addition, the sensor performance evaluation technology established during the development has been proposed for ISO standardization.

Keywords : hydrogen sensor, hydrogen station, field test, thermoelectric, catalyst combustor

1 Introduction

It was only 10 years ago in 2000 that we began the research and development of a new hydrogen sensor of thermoelectric principle presented in this paper. With the reorganization of the research environment into the National Institute of Advanced Industrial Science and Technology (AIST), we, the researchers working on material science and engineering explored the future of new materials research. The R&D level of leading industrial manufacturers or private sectors was already high, especially on devices, and also the process facilities and analysis equipment were highly advanced. We have tried to find the answer to differentiate ourselves from the basic studies of the materials in the university laboratories and we attempted to use new functional materials in the production of sensor elements or devices.

At the same time, a hydrogen-energy technology boom occurred, led by hydrogen fuel cells. For the goal of establishing a better leak detection sensor technology, which is the most important for the safe use of hydrogen, a novel sensor of a new working principle was developed in our laboratory. It is a “fusion of knowledge” of catalytic combustion gas using a catalyst which is the operating principle of a flammable gas, and a thermoelectric material being researched at that time. With a new principle of thermoelectric materials converting the local temperature changes caused by internal heating from burning gas to voltage, we jumped into the field of hydrogen sensors where so much had been developed up to that point.

Not limited to hydrogen sensors, a variety of performances is required with gas sensors. First of all, there are the detected concentration range, detection limit concentration, and performance such as selective gas detection. Most of the reports at related academic societies are concerned with materials research and device research and present arguments based on these detection performances. However, for sensors to be used in a real society, economy and reliability are required in addition to the detection performances. In particular, reliability is a subject that is most severely questioned when applied to a real sensor system.

We have developed a novel hydrogen sensor by continuously providing solutions to these challenges, the results showing the best performance in hydrogen leak detection applications. In terms of social receptivity of actual application of this sensor, we also have proposed international standards for hydrogen detectors.

2 Social demands for performance of hydrogen sensors

To ensure clean, safe to use hydrogen without the danger of its explosion, safety warranty technology is essential. At hydrogen-related facilities that require a high level of safety management such as hydrogen stations, hydrogen sensors are required to monitor changes in the concentration of hydrogen leaks continuously. In the hydrogen stations, large quantities of hydrogen are stored and frequently transferred to hydrogen cars, and the new technology of safe management of the stations is a challenge for a clean energy society. It is time to review the weaknesses of the current technology of safety sensors described below.

Most of the commercially available hydrogen sensors are

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semiconductor types or catalytic combustion types. In principle these sensors detect only a narrow range of concentration of gas, and hydrogen sensor technology of selective gas detection has not yet been achieved. The semiconductor sensors have been most extensively studied up to date because of their ultra-sensitive gas detection performance, and the majority of papers on gas sensors contribute to this technology. When improving the sensitivity of semiconductor sensors, the reliability problems always occur because the sensor is also very sensitive to the environmental noise, such as humidity. In addition, the accuracy of the sensor signals has another problem of signal drift (variation of the indication) [1], showing lack of reliability.

Catalytic combustion type sensors are widely used because they are robust with excellent stability. With this type of sensor, a slight rise in sensor temperature due to catalytic combustion of hydrogen gas increases the resistance of the platinum-coil heater, and this enables the detection of the hydrogen in the atmosphere. Catalytic combustion is a simple chemical reaction, and wrong signal outputs even in the presence of some environmental noise are extremely few. However, to achieve both reliability and sensitivity is difficult. The sensitivity of the detection signals of the catalytic combustion sensors which are the resistance rates of the sensor is significantly reduced in low concentration, and the practical range of concentration is in the detection range of a few percent from 1000 ppm[2].

Figure 1 shows the concept of a multi-level security system required in the hydrogen stations. In hydrogen-related facilities, if a system is established which can detect hydrogen concentrations before a specified concentration of hydrogen or fraction of flammable limit is reached, it will allow for single and/or multilevel safety operations, such as nitrogen purging or ventilation and/or ways to avoid shut-downs. Furthermore, in the stations, the system should have a sensor element which is robust against poisoning, which is caused by any interferential gas that permanently affects the sensitivity of a sensor, and is hydrogen selective against other flammable gases. In actual hydrogen stations, catalytic combustion type sensors are used for high gas concentrations as an alarm sensor, and semiconductor type sensors are also used for low concentrations as a monitoring sensor, respectively.

3 Elemental technologies for the gas sensor synthesis

3.1 Three elemental technologies for the three performances of the gas sensor

We have proposed a completely new principle of hydrogen gas sensor combining the catalytic combustion and thermoelectric conversion technology. This sensor uses the heat generated by combustion of gases within the catalyst in the same manner as conventional catalytic combustion type sensors. Rather than using a resistance change in temperature of the entire device, the changes in the local temperature inside the device are converted directly into voltage signals based on a thermoelectric conversion principle. We named this the thermoelectric sensor. Figure 2 shows three performances required for gas sensors or the 3S, correlating them with the elemental technologies: gas selectivity, high sensitivity, long-term stability.

1) new principle, of “integration of knowledge” - The thermoelectric conversion principle is the most fundamental idea which enables the wide-range selective gas detection, which is not possible with conventional technology[3].
2) microfabrication technology - For minimization of the heat capacity of the sensing element to catch a very small amount of heat for the detection of lower gas concentration, microfabrication techniques such as anisotropic etching of silicon was used. The thermoelectric sensor is a micro calorimeter with a catalyst combustor.
3) catalyst technology - Mounting a high-performance ceramic catalyst combustor on a specific position of the pattern on the micro thermoelectric devices has been accomplished.

By integrating these elemental technologies, a prototype of excellent hydrogen selectivity, of wide range detection up to 5 % hydrogen concentration from 0.5 ppm was realized and a year long stability field test proved that the same stability was realized as the current technology[4]. Typical characteristic of a high-sensitivity sensor is a trade-off between selectivity and stability, but thermoelectric gas sensor is able to satisfy both performances. Considering that the lower limit of catalytic combustion type sensor is about 500 ppm, the ppm-level detection performance of thermoelectric sensor is innovative. For the stability of the sensor, we have clarified with a scientific approach the factors causing degradation in the sensor response, and improved the stability of the sensor

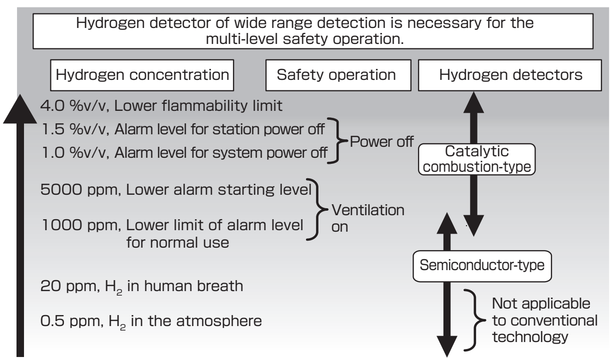

Fig. 1 Multi-level or multiple safety system for the operation of hydrogen facilities
Current safety technology of hydrogen leak detection lacks lower level stability and hydrogen selectivity.

by controlling the composition and thickness of the catalyst[5].

In the case of new born sensors, it is generally difficult to be accepted as a reliable technology for practical use. In order to demonstrate the reliability of the sensor, our thermoelectric sensors have been installed and tested for a year at Ariake hydrogen station in Tokyo. This field tests has validated the stable sensitive system-level safety operation, showing response to 100 ppm hydrogen in air[6].

3.2 The other elemental technology:technology of evaluation

Assembling each elemental technology, a sensor device is created. Then the method analyzing or checking the "workmanship" of the final product of the device also becomes an important issue. The device performance may satisfy the manufacturer, but it should be evaluated or tested for characteristics which are determined by social demands, customer needs or specifications. In this study, the following three testing methods were utilized as shown in Fig. 3:

・new test method to observe the surface temperature changes on the sensor device in the sensor operation using IR camera,
・standard test methods for the response speed (Appendix ISO CD26142),
・system technology to test the gas sensing performance for serial products.

As noted above, the thermoelectric gas sensor consists of two components of the ceramic catalyst and the thermoelectric device. The first test method is to evaluate the two different elemental technologies of the sensor separately to get a clear balance between the individual components. The second test method is a simple test method not using any special or complicated equipment so that anyone may evaluate the performance of sensor response in the same way. It is as simple as just filling the gas to be detected into a chamber with a capacity of 30 liters. This method is adopted as an appendix in the international standards issued in the year 2010 (ISO) as an evaluation method for the testing of sensor response time.

The third one is the test method for mass production. How much is the manufacturing cost of every single gas sensor element? Fabrication of small sensor elements costs little but testing of sensors costs much. The testing equipment for the materials properties is commercially available but the evaluation device for a “product” such as sensors is not commercially available. Sometimes the testing machine of the products is the most important secret or know-how for the manufacturers. So we started from an early stage of research and development efforts to develop a high-efficiency testing system as a top priority of mass production technology of the device.

3.3 The first step is to set a scenario

The integration of the elemental technologies mentioned so far is part of how the research progressed, aiming at solving various technical problems in order to meet the social demands. Figure 4 shows a chronological scenario of the thermoelectric hydrogen sensor development. We received a three-year research fund for the development from fiscal year (FY) 2000, and the achievement was the “knowledge” of fusing catalytic combustion and thermoelectric conversion as an elemental technology. The idea was very fragile, and as soon as we started, we found that even if the sensor was based on an excellent principle, to bring about satisfactory

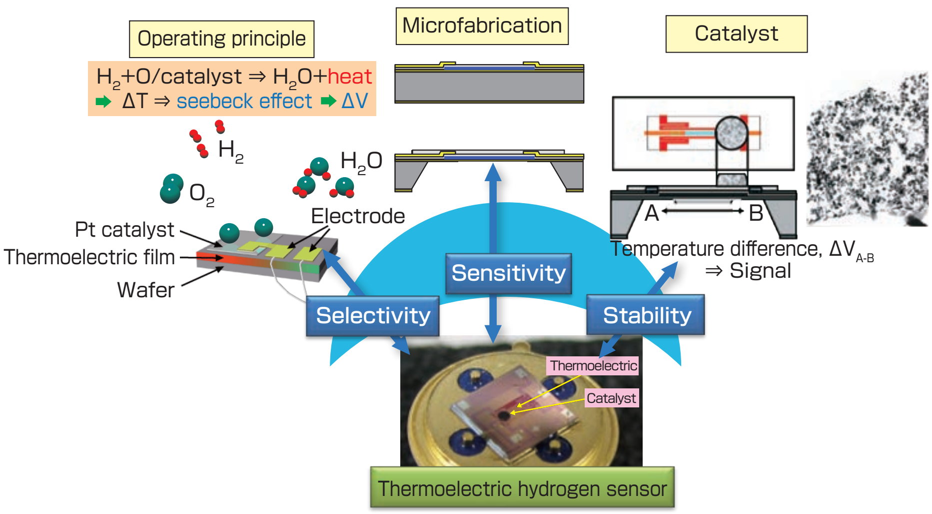

Fig. 2 Correlation between the sensor performances and elemental technologies
Three performance requirements, selectivity, sensitivity, and stability are of trade-off relations. Novel working principle of thermoelectric conversion of local temperature differences in sensor device induced by catalytic combustion can bring about the selective, stable, and sensitive detection.

performance, microfabrication was essential.

A five-year scenario of microfabrication of the sensor was drawn in 2002. One study cycle consisted of fiscal years of 2003-07. By integrating the elemental components, the necessary sensor performances were achieved, and as a result, we could harvest the output of research, such as papers, patents, transfer of technology one after another, and start a new cycle. The cycle of the development can be divided into four steps as follows, among which the third is the synthesis:

1) idea - to discover new ideas or to search social demands,
2) integration of knowledge - to quantify it in such experiments that embody it,
3) synthesis - to set the necessary properties (goals), to further development,
4) completion - summarize research results leading to the following research.

It takes a long time to organize the different elemental technologies. Based on a new idea for sensor performance improvement, new batch fabrication is processed, and then the performance of the manufactured sensor device is investigated, in relation to the improvement of the idea. By searching for new methods of development from the results obtained in this process, the leader of the research team could direct engineers who were responsible for each elemental technology to new directions. This feedback sometimes took a few months or one year. It is very similar to the practice of an orchestra. The most highly agile methodology practices in the development of thermoelectric sensors are the following two:

・laboratory design aimed at real application from the beginning (the full-automated process equipment and sensor testing systems)
・sharing of the whole development scenario and discussions within the laboratory with all the engineers.

In the process of the integration of knowledge, it is important to speed up the feedback of the fabrication and of the results of sensor tests. Our strategy was the improvement of both the process and analysis tools with a compact lab design. Though all the details of tools or lab layout cannot be described in this paper, we can explain a unique idea of our laboratory for manufacturing micro-sensor devices. We have succeeded in minimizing the clean room space very efficiently, and to integrate most of the process equipment within 5 meters radius. The sensor test was carried out next door. This high quick fabrication and tests realized the commercialization of the sensor after the 5 years research period.

Introducing full-automatic process equipment has brought good results in this research. Typically, especially at an early research stage, people tend to introduce an experimental facility which is designed specially for scientific researches. We, however, were able to develop a practical-looking production system by introducing a semi-generic one. Such equipment does not require a high professional staff with knowledge and is easy to maintain, and this led to a significant reduction in development costs.

The people who put out the results by running the facility are the members of the team. It is important to position the members in the right places, supplying an environment not

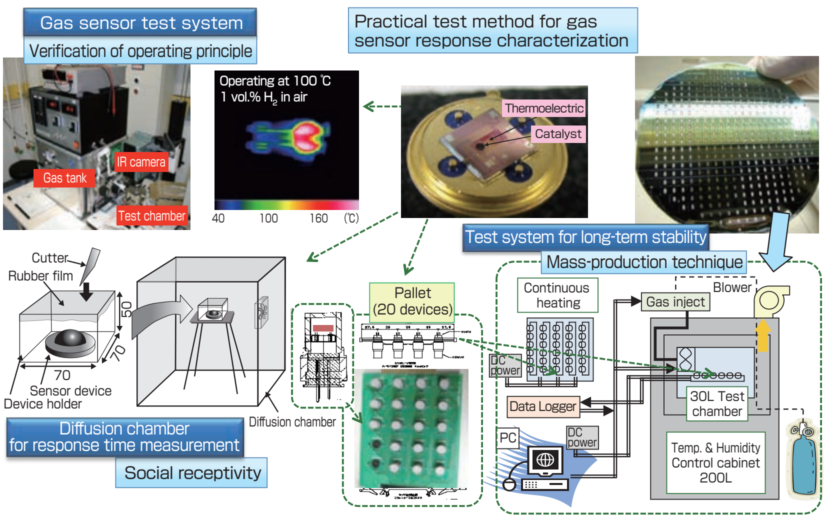

Fig. 3 Three test methods for sensor element
They are developed for checking the working principle, social receptivity and mass production, respectively.

bound by their expertise, encouraging the members to propel their corresponding special jobs. To direct them to a single goal keeping every core technology of each member is not easy, but it is possible to align their vector if the scenario is shared. In developing thermoelectric sensors, with all the members understanding the technological domains of others while holding firmly their own technological specialties, the organic collaboration between the members was achieved.

There is a concept called agile type often used in software development. As the waterfall type development is considered to be difficult to have communication among the staff, the agile type is currently widely used from the point of emphasizing communication among the members. Our research progress was close to the agile type but was not the same. A negative aspect of the agile type is the risk that the progress becomes slow dragged by too much discussion among members. We, however, built up the scenario at an early stage, and the whole image of development could be shared by the members.

For example, the supply and installation of the equipment, process and test facilities for the overall research period were carried out following the plan written in the proposal at the start. The leader of the project continuously showed the clear vision of the results after five years and also the five-year scenario to all the members. His work is similar to an orchestra conductor. The essential part is to share all the possible information and visions together.

4 How to make synthesis

4.1 Elements and boundary conditions

A simple combination of elemental technologies cannot make synthesis. Figure 5 shows the schematic plan of synthetic integration of each element. Natural phenomena and engineering components are listed on the left, and the observations and analysis are related tools to quantify their characteristics. It is important to bring out the full features of each element, resulting in performance which has an engineering or scientific value. When one integrates them into a new synthesis, specific and detailed boundary conditions are necessary. The boundary conditions are the various social demands.

For example, if you configure a catalyst and thermoelectric material for the applications to a generator and to a gas sensor, the conditions of configuration are largely different. For synthesis of the generator, it is important to obtain large electric voltage and current by high-calorie combustion. A catalytic material which can endure high temperature combustion needs to be selected and the device needs a complex flow channel for efficient fuel combustion. A large thermal capacity of the whole system is desired. Therefore, it is necessary to design a thermoelectric device that allows large electric current flow.

For the synthesis of a gas sensor detecting a wide range of gas from a few ppm to a few percent, ensuring reliable, linear sensor output, extremely high catalytic activity of the combustor is required which enables combustion even with low concentration gas. In order to detect slight temperature changes, a thermoelectric device which generates high voltage is required with a sensor structure of easy fast gas diffusion and sensor elements of minimized heat capacity for fast response.

In our sensor development, we configured and integrated the elemental technologies with the boundary conditions based on social demands as illustrated in Fig. 5. The conditions on the right such as high sensitivity, stability,

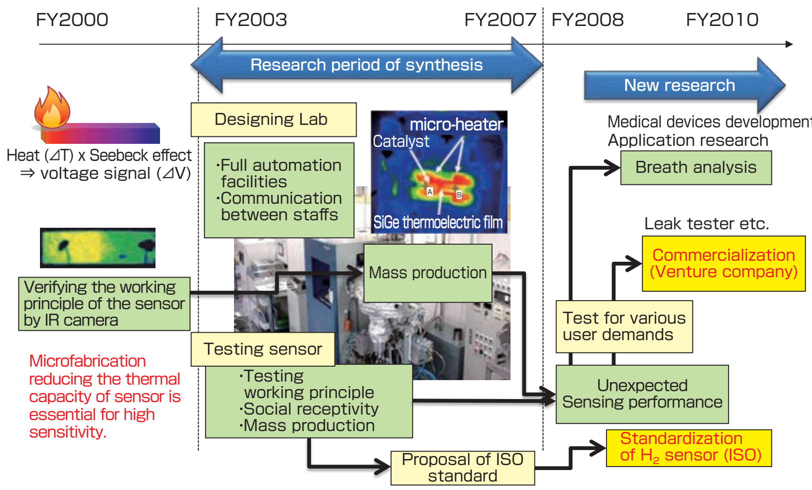

Fig. 4 Scenario of thermoelectric hydrogen sensor development

In FY2000, the operation of the new sensor was started with the NEDO grant, and the full development of hydrogen sensor technology was carried out under the national project of developing hydrogen infrastructure, FY2003-07.

and fast response could be determined by specific numeric target values requested from the user's needs. A prototype sensor is fabricated and its performance is evaluated, verifying the achievement against the targets. During this process, the elemental components are selected and integrated for the synthesis.

When we select the elemental technology by considering the boundary conditions, the knowledge of the past is sometimes insufficient, and it is necessary to confirm and to recognize the details by fabricating and testing the actual prototype device. At the start of the development of the sensors, we had a catalyst problem. The composition of the catalyst combustor followed the previously reported data in the papers, which said that a few nanometer thick catalyst film was selected for higher activity. However, after trial and error, thick film catalyst of much higher platinum content was found to be better by our experiment. This thick film catalyst made hydrogen combustion possible at room temperature[7].

The researchers in the field of catalyst science have wondered and were surprised by the very high amount of 20 ~ 40 wt% of noble metal, platinum, in the catalysts of our sensor devices. This was because their common knowledge of the catalyst was that several wt% of metal content was better to prohibit unwanted sintering of the metal during the operation. However, the catalyst of our design was found to exhibit a high activity and stability to detect the hydrogen gas in air[8]. Unlike the typical catalytic reactions, the catalyst for the sensors is required to be able to burn gas at extremely low concentrations of flammable gases, so that thick film type of high metal contents was integrated into the sensor. As a result, boundary conditions of gas sensor application stimulated the elemental technology of the catalyst to be something of a totally different quality.

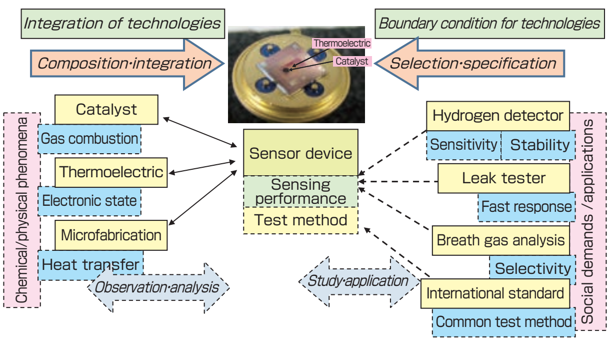

Fig. 5 In the synthesis of thermoelectric gas sensor, the elemental technologies have been configured and integrated with the boundary conditions of social demands.

4.2 Scenario for commercialization

After investment for research such as capital, facilities, and human resources, papers and patents are always desired as results of research. Of course commercialization of the new technology is an ultimate goal to complete the R&D. Especially for AIST, a research institute without any commercial product vending department, to complete R&D is to transfer technology obtained in the development to private companies as intellectual property such as in the form of patents.

In mass production technology of our prototype, it was easy to scale up the fabrication of sensors, as a result of the strategy described above. It was necessary to make technology transfer possible even with some companies that do not have their own semiconductor process facilities. We performed 4 inches or 6 inches wafer processes not only in the laboratory prototype manufacturing but also in a commercial foundry. In 2007, the foundry services in Japan still had little business experience, including the issue of acceptance of service and other contractual issues of technical problems, and it was very difficult to work out our first batch. The experience of the difficulty of the foundry process, and confirming the process yield was a big step toward commercialization. Fortunately, the Seebeck coefficient of the SiGe thermoelectric film pattern in our device which is the most important parameter of the sensor, was relatively process independent. Therefore, we established a manufacturing technology sensor device with reduced discrepancies in sensor performance.

4.3 Results over the scenario

Unexpected sensor performance triggered a start of new development which was not drawn in the scenario. A leak detector is one example in our research. The very promising thermoelectric hydrogen sensor capability detecting the gas leak of several-ppm level was over-specification in the application of safety sensors. However, this performance is necessary in new industrial application of leak detection, which is the technology to check the air tightness or sealing of the products, such as in fuel tanks, battery packs, water proof housings, etc. In this gas leakage test, currently helium gas is used, but hydrogen is now also used in place of helium because of recent instability of He import from the US. Recent testing equipment with 95 % nitrogen 5 % hydrogen gas as a gas alternative is now widely used, and with the high cost of helium, there is a strong need for cheap, sensitive, and selective hydrogen sensors.

Another development is a medical device to support human life, which aims to expand the application of the sensor which can measure hydrogen concentration in the breath[9]. Current technology used in medical centers is expensive, costs around 3 million yen, and it combines a semiconductor type gas sensor and a gas chromatograph. The thermoelectric sensor can detect ppm level hydrogen concentration, and can be a simple alternative solution, which does not need gas chromatograph, reducing the size, cost, and analysis time significantly. Currently, a prototype has been commercialized as an AIST venture, and is expected to be applied to various fields as well as to hydrogen-energy facilities such as hydrogen stations.

5 International standard making use of research output

The state of the market of hydrogen sensor strongly correlated to the spread of the hydrogen energy use and the social receptivity of hydrogen are also important issues for commercialization. However, the situation of the current market is inactive and conservative. The sensors of the old technology are already adopted in the present hydrogen stations operated in Japan, and the new technology cannot be accepted easily. Even though there is new demand for a wide range of hydrogen detection, the thermoelectric hydrogen sensor could just end up as a development study. To promote the application of our new sensor technology, we also carried out a study for the standardization of the gas sensor, making a new proposal for hydrogen sensors. The standardization work has been proceeded in parallel with the technology development of the thermoelectric sensor, propelled by the policy of the Ministry (METI).

We prepared a proposal based on the performance of our newly developed "thermoelectric hydrogen sensor with a wide range of hydrogen concentrations with hydrogen selectivity", and submitted it as a new proposal (NWIP) to the committee of ISO/TC197 (Hydrogen technologies) in 2005. This proposal was accepted and WG13 (Hydrogen Detectors, host country is Japan) started to discuss a new international standard of hydrogen detectors. This international standard was issued in June 2010. This was one example of proposed international standards development efforts utilizing the technology, and the best detection technology that satisfied many of the contents of the proposed standard was the thermoelectric hydrogen sensor developed by us. However, the draft did not pass as it was, and the final draft was edited and changed significantly from the 2005 draft. This International Standard set the performance requirements for hydrogen detectors as follows:

・measuring range, concentration calibration and alarm set points,
・stability (short and long term),
・time of response and recovery, selectivity, poisoning,
・temperature, pressure, humidity (standard test conditions),
・operation above the measuring range, power supply variation and interruptions.

The most discussed issue was the measuring range of the detector as shown in Fig. 6. In the related IEC standard on the inflammable gas detectors, only the upper limit of gas concentration is specified and this is declared to be the range. However, the tolerance required in the calibration is defined as 5 % of the upper limit or 10 % of the indication, and the error becomes seriously large in the low gas concentration range.

We have explained the importance of low-concentration detection for the multi-level safety operation, and proposed the standard of detectors covering a wide range of hydrogen concentration. This claim of our Japanese delegate was accepted and a committee draft containing the measuring range from 500 ppm to 2 % as shown in Fig. 6 was drawn. However, several countries did not agree to this, because their technology works well at high gas concentration. In the end, as the international standard is not intended to exclude any specific technologies that meet the performance requirements, the measuring range of the detector including the tolerance of the detection was decided to be declared by each sensor manufacturer.

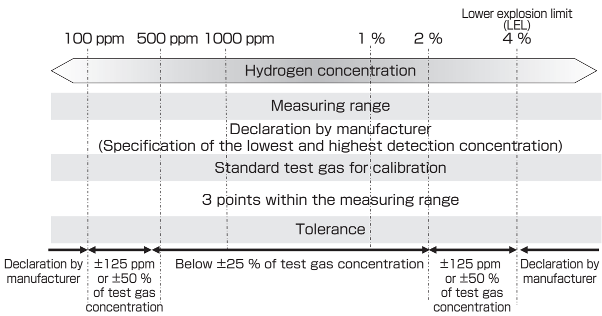

Fig. 6 Measuring range and calibration
It was extremely difficult to write down the measuring range of the hydrogen detectors to satisfy all the members in the ISO working group for hydrogen detectors. This figure shows the meeting material suggested and used in the final stage of the committee meeting, showing a range from 500 ppm to 2 %, which was the result of the previous meeting. This was finally rejected and the measuring range of the detector was decided to be declared by each sensor manufacturer.

6 Summary

We have invented a novel thermoelectric gas sensor, integrating the elemental technologies of catalytic combustion of hydrogen and thermoelectric conversion from thermal gradient to voltage, for gas-leak detection systems in hydrogen stations. By integrating various elemental technologies, completely new performances such as robustness, hydrogen-selectivenes, wide-range hydrogen detection from 0.5 ppm to 5 % in air, fast and linear response are realized, which are impossible by the current sensor technology. Furthermore, taking advantage of this new technology, we have proposed and published a new ISO international standard in 2010.

We are carrying out several application researches of the thermoelectric hydrogen sensors for various practical uses, expecting future spread of the related technologies and international cooperation including hydrogen energy use.

References

[1] ISO 5725-1:1994(JIS Z 8402-1) Accuracy (trueness and precision) of measurement methods and results - Part 1: General principles and definitions.
[2] JIS M 7626-1994, stationary type combustible gas alarm (1994).
[3] W. Shin, K. Imai, N. Izu and N. Murayama: Thermoelectric thick-Film hydrogen gas sensor operating at room temperature, *Jpn. J. Appl. Phys.* 2, 40 L1232-1234(2001).
[4] M. Nishibori, W. Shin, L. Houlet, N. Izu, T. Itoh, N. Murayama and I. Matsubara: New Structural Design of Micro-thermoelectric Sensor for Wide range Hydrogen detection, *J. Ceram. Soc. Japan*, 114, 853-856 (2006).
[5] M. Nishibori, W. Shin, L. Houlet, K. Tajima, N. Izu, T. Itoh and I. Matsubara: Long-term stability of Pt/alumina catalyst combustors for micro-gas sensor application, *J. European Ceramic Society*, 28,2183–2190 (2008).
[6] M. Nishibori, W. Shin, K. Tajima, L. Houlet, N. Izu, T. Itoh and I. Matsubara: Robust hydrogen detection system with a thermoelectric hydrogen sensor for hydrogen station application, Int. J. *hydrogen energy*, 34, 2834-2841 (2009).
[7] M. Matsumiya, W. Shin, N. Izu and N. Murayama: Nano structured thin-film Pt catalyst for thermoelectric hydrogen gas sensor, *Sens. Actuators B*, 93, 309-315 (2003).
[8] Y. Choi, K. Tajima, N. Sawaguchi, W. Shin, N. Izu, I. Matsubara and N. Murayama: Planar catalytic combustor application for gas sensing, *Applied Catalyst A*, 287, 19-24 (2005).
[9] M. Nishibori, W. Shin, N. Izu, T. Itoh, and I. Matsubara: Sensing performance of thermoelectric hydrogen sensor for breath hydrogen analysis, *Sen. Actuators B*, 137, 524-528 (2009).

Authors

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Received his BS and MS degrees in material science and engineering from KAIST in Korea in 1992 and 1994, respectively. Since 1998, after receiving his doctorate in applied chemistry from the Nagoya University, he has been employed at AIST. He is the group leader of the Electroceramics Processing Research Group, Advanced Manufacturing Research Institute, AIST. His research activity includes the thin film materials for gas sensor technology.

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Studied material science of the Earth's deep interior. After finishing her master's course in 1998 at Ehime University, she worked at Japan Synchrotron Radiation Research Institute (SPring-8/JASRI) and received her doctorate in 2004 in Earth science from Ehime University. She has been working at AIST in Japan since 2004. Her research fields are catalysts for gas sensors, in-situ analysis of materials using radiation source. In this paper she described the sensor fabrication process and applications.

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Received his BS and MS degrees in polymer chemistry from Osaka University in 1985 and 1987, respectively, and his doctorate of science in inorganic and physical chemistry from Osaka University in 1994. He is the director of Research Planning Office for Nanotechnology, Materials and Manufacturing, AIST, and the convener of the ISO/TC197/WG13 (hydrogen detection apparatus) and TC146/WG16 (Test method of VOC detector). His research interests include functional oxide materials, organic-inorganic hybrid materials, and gas sensors. In this paper he discussed the part of international standard working group for hydrogen detectors.

Discussions with Reviewers

1 Investigating social demands

Question (Norimitsu Murayama, Advanced Manufacturing Research Institute, AIST)

This report points out the importance of catching the clear social demands in the beginning of the research. What is your opinion on the method of grasping the social demands?

Answer (Woosuck Shin)

We first collected information from the domestic and oversea R&D reports and technology road maps, our team discussed the future social demands using the obtained information, and we finally made an analytical evaluation of the social demands we found.

2 Selection of elemental technologies.

Question (Hisao Ichijo, Tsukuba Center, Inc.)

The assembling and integration of the elemental technologies are clearly written in this paper. How do you make a choice?

Answer (Woosuck Shin)

Though it is simple and clear to choose each elemental technology from the boundary condition of the social demands, to select in detail and the way of integration is rather complicated. By fabricating and testing the sensors, we carried out the integration.

3 Originality of the research

Question (Norimitsu Murayama)

The originality of this research is the combination of catalytic combustion and thermoelectric conversion. How did you come about this idea?

Answer (Woosuck Shin)

Before the sensor research, I researched papers to take advantage of the thermoelectric research we had developed for the sensor application. I found a paper of 1985 reporting a bulk oxide gas sensor with Pt electrode on one side. Both the materials and designs of the sensors of the paper are developed and advanced in this research.

4 Research of commercialization

Question (Norimitsu Murayama)

In this research, mass production facilities are equipped from the beginning, which made easy commercialization. I wonder if this method can be applied to other researches or if it is more beneficial to specific research types.

Answer (Woosuck Shin)

The materials research is a fundamental issue and the research of the catalyst material in this research was also carried out in the usual chemistry laboratory. The most important role of the process and test facility foreseeing mass production is to reduce the barrier to real application. I think these mass production facilities could be applied to most research and will become more and more important in speeding up the research and development.

5 Publicity activities

Question (Norimitsu Murayama)

At first the application of the sensor was for the hydrogen stations, but it was changed and expanded to others such as leakage detection of air-tight tests and breath gas tests. To explore these unexpected applications, publicity activities need to be performed effectively. Which activity worked well in your case?

Answer (Woosuck Shin)

The press release and the material transfer were very effective to draw attention of society, and to lead to new applications.

Demonstration of optical communication network for ultra high-definition image transmission

— Proof-of-concept experiment of image distribution over the dynamic optical path network —

Junya KURUMIDA * and Shu NAMIKI

[Translation from *Synthesiology*, Vol.4, No.2, p.100-110 (2011)]

In order to overcome the limitation of low-power-consumption and communication capacity of the equipment forming the present communication network, National Institute of Advanced Industrial Science and Technology (AIST) has carried out a demonstration of a new prototype optical path network to support the super HD large-capacity image contents era, in collaboration with five IT- related companies and with the support of National Institute of Information and Communications Technology (NICT) and Nippon Hoso Kyokai Science and Technology Research Laboratories (NHK/STRL) . The experiment was a trial to demonstrate the performance of the dynamic optical path network developed mainly by AIST under practical conditions, using a network testbed of field optical fiber links connecting Akihabara, Otemachi and Koganei offices in Tokyo. The demonstration included the cross-border-connection with the optical packet and circuit integrated network realized by NICT and transmission of super HD video signals developed by NHK. In this paper, we describe the objectives, targets, technology syntheses based on the elemental technologies for the demonstration, and outcomes.

Keywords : Optical path network, optical packet and circuit integrated network, JGN2plus, distribution of high-quality images, super high vision (SHV)

1 Introduction

With the background of increased demand in communication mainly for the Internet, energy savings in optical communication is an immediate issue. The most important topic of communication system R&D fields today is to devise a network configuration that allows the viewers to obtain high-capacity information such as super high-definition (HD) images at home at their convenience, while maintaining low power consumption in the communication devices. Whenever a demand is made, the optical fiber path quickly switches to link the home and the information source to allow delivery of all sorts of information services. Such optically transparent network, where the home and the information source are connected by optical fiber only, is ideal because the communication bandwidth can be maximized to its theoretical limit without increasing the energy. This can then be used in various application technologies and services such as education, welfare, or medical care that employ super HD image transmission. Nowadays, the services based on the communication technology are handling large volumes of data, thus, high-speed data communication has become necessary. The optical fiber communication technology has a capability of handling such high-capacity data transmission, and it has become the foundation of the Internet and the advanced information society. On the other hand, there is a major problem in the sustainable development of such advanced communication services. It will be explained in the following chapter.

In August 2010, we conducted a demonstration experiment of the network that allows transmission of high-capacity information as typified by super HD videos on demand, by combining the elemental technologies for optical communication that were newly developed by AIST and five information technology companies. This enabled a proposal of the new network technology that overcomes the limitations of power consumption and communication capacity of the devices that configure the current network. In this paper, we describe the process of the technological considerations for synthesizing the individual elemental technologies and obtaining the functioning results.

2 Social demand for optical network

It is well known that the communication traffic on the Internet is increasing at the rate of 30~40 % every year in Japan. Assuming that this trend continues for about 20 years, the traffic will be about 1,000 times higher. This calls for the improvement of power efficiency. The number of Japanese Internet users surpassed 94 million people at the end of 2009, and the penetration rate is 78 %[1]. The technological background is that the performances of the communication equipment and PDAs have improved, well-developed

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application software has become available, and a click on the computer (including mobile terminals) connected to the Internet can trigger transmission and reception of high-capacity data. Video information services are provided through the Internet, and the major issue now is how to realize a network while considering the power efficiency to deal with the increased communication traffic. Particularly, the configuration of the optical network consisting of the optical fiber communication technology that is capable of supporting high-capacity data communication is emphasized. The followings are the reasons for the demand based on the social background. Until now, the measures for increased Internet traffic included the parallel installation of communication devices or shifting to equipment with higher communication speed. However, the increased installation of the conventional communication equipment that employed high-speed electric signal processing linearly increased the power consumption as the communication speed increased (power issue). Also, as the connection technology of the optical subscriber lines advanced and optical fibers reached the homes, there has been increasing difficulty in efficiently concentrating the diversified broadband services to the communication node (base station) (communication capacity and network configuration issues). To solve these issues, the important point is how the optical communication lines are developed and configured into a true optical network.

The Network Photonics Research Center, AIST proposes a new network called the “optical path network” that directly links the users with the optical path, and engages in R&D to solve the above issues. Particularly, the network where the optical network is switched flexibly to actively maintain the optical path in response to the high-capacity information request is called the “dynamic optical path network”. Specifically, we engage in the technological developments for transmission/reception of the video images, silicon optical path switch, and dispersion compensation, to create an optical network that realizes the broadband service based on the appropriate management and control of each device and device group. Figure 1 shows the conceptual diagram. To utilize the optical switch in the network, a mechanism for controlling the optical switch according to the network application is necessary. That is to say, a mechanism is needed where the mutual connections are made between the HD video server and display, teleconference systems are handled, and these are appropriately managed according to the optical path and storage information. Moreover, vertical integration (collaboration) is essential to introduce the silicon optical path switch and wavelength resource management technologies, and to consolidate and realize the technologies that are developed individually, from device level to application level. These efforts will enable the high-speed data communication without going through multiple electric signal processing, and a network that handles large-capacity information at low power can be configured. In this paper, we mainly describe how the elemental technologies were built up into a system, and how the demonstration experiment was conducted.

When the issues manifested in the network are solved by step-by-step approach, it will provide great advantage socially and economically. This may become a communication infrastructure for various services, including the information provision for automobiles and robots (including remote operation), as well as teleconferencing and remote sensing. Such new communication infrastructure will generate new social values in terms of applications software. For example, teleconferencing in which three-dimensional images are shared will decrease the movement of people or business trips, and highly realistic HD video service will decrease the necessity for people to actually go to a certain place. High-speed high-capacity communication infrastructure may provide the basic technology that supports tele-existence, tele-presence, and tele-immersion.

3 Scenario of the demonstration experiment

In general, communication network is considered to be a social infrastructure equivalent to electricity, gas, and water. Usually, a new optical fiber network will not be installed from scratch in a city, except in areas where there is no existing network. Therefore, the new network must be implemented step by step by combining the existing and the new technologies. It is necessary to consider the incorporation of the super HD videos into the network for the future. Therefore, we shall discuss the issue from three perspectives. A) To incorporate the distribution of the super HD videos into the demo experiment, we think of a network configured by the coexistence of the super HD video distribution technology (bitrate < 43 Gb/s) and the elemental communication technologies for 1 Gb/s or 10 Gb/s that are already in commercial networks. There are two reasons for doing this. First is to demonstrate that the different communication rates can be handled simultaneously on the network, with focus on the super HD video distribution technology. Second is to demonstrate that it is possible to manage them on the network, to determine the services according to the request, and to actually switch the network for smooth distribution. Next, B) the configuration using the actual field optical fiber is considered. There are also two

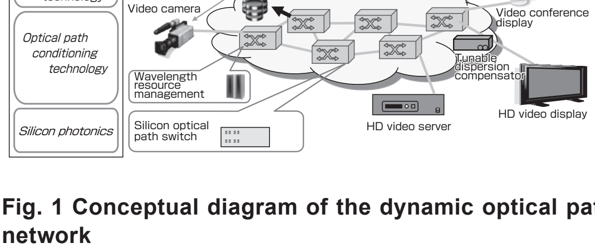

Fig. 1 Conceptual diagram of the dynamic optical path network

reasons for this. One is to check that the communication is possible by compensating all the nonlinear responses from the field optical fiber, and the other is to check whether the different networks configured by different elements can be mutually connected. Also, some modifications are made to the entire system to C) achieve low power consumption.

Above is the framework for the scenario of the demo experiment. The dynamic optical path network will be built based on this framework. One factor will be whether it is possible to achieve the high-speed high-capacity communication infrastructure geared for the near future by merely integrating and combining the aforementioned items. The aforementioned perspective mainly looks at the hardware, and that alone will not enable correct synthesis of the network. It is necessary to design the software and firmware to match the hardware. Figure 2 shows the configuration elements of the demo experiment. In the configuration elements, there are the following limiting conditions: to use the field optical fiber, to use the communication elemental technologies that we developed, and to add the resource management and control. Moreover there are two aspects of software and hardware for these conditions, and a consideration for a comprehensive configuration is necessary to conduct the demo experiment effectively.

The elemental technologies will be explained in the next chapter in more detail, but extra scenarios were considered in actually executing the demo. Although it might not be used in the demonstration, the network extendibility was added in the elemental technology as a backup in preparation of the worst-case situation. Such preparation is done not only in demonstration experiment, but is done in actual communication systems. Real systems are designed to be reconfigurable according to the status of the problem or have implemented functions that allow alternative functions. Considering the above, we created a scenario to demonstrate the mixed bitrates, mutual connection of heterogeneous networks, and provision of the HD video service according to requests.

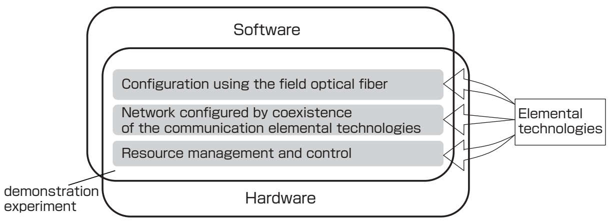

Fig. 2 Configuration of the demonstration experiment

Table 1. Configuration element of the demonstration experiment

Configuration elements	Name of technologies	Collaborating organizations	References	Notes
Resource management	(a) Optical path network	NTT / AIST	[2][3]	
	(b) Optical Packet and Circuit Integrated Network	NICT	[4]	
Communication line	(c) R&D testbed network	JGN2plus(NICT)	[5]	
	(d) Commercial optical fiber line (Akihabara – Otemachi)	–		
Node equipment and device	(e) PLC optical switch	–		Commercially available
	(f) Silicon photonics switch	AIST	[6]	
	(g) Current-injection-type silicon-based high-speed optical switch	Fujitsu Laboratories Ltd.	[7]	
	(h) Power-saving next-generation ROADM	NEC	[8]	
	(i) High-speed wavelength tunable laser	Trimatiz Ltd.		
	(j) Optical fiber amplifier (EDFA)	–		Commercially available
	(k) Parametric arbitrary wavelength converter	Furukawa Electric Co., Ltd./ AIST	[10]	
	(l) High-speed autonomous-control tunable dispersion	Furukawa Electric Co., Ltd./ AIST	[11]-[13]	
Terminal	(m) Super Hi-Vision transceiver	NHK	[14]	
	(n) Contents achieve server	–		General-use
	Video delivery server	–		General-use
	Display (monitor)	–		Commercially available
Contents	(o) Super Hi-Vision image	NHK		
	(p) Hi-Vision video	AIST		

4 Elemental technologies

The elemental technologies of the optical network demo experiment can be broken down into five parts. They are: network resource management, communication line as a medium through which the information is transmitted, nodes or equipment placed at their terminals, terminal device for transmitting/receiving, and the actual information (contents) that flow through the lines and devices. Table 1 shows the summary of the elemental technologies. In this chapter, the elemental technologies of configuration will be described according to Table 1, and the reasons for selecting them will be clarified.

4.1 Resource management

4.1.1 Optical path network (NTT and AIST)

The Network Photonics Research Center, AIST has engaged in the R&D of optical path network, and developed the technology to optimize the optical fiber dispersion and optical intensity of the communication path, to eliminate the effect of the various optical switches that are used to switch the communication path[2]. In this demonstration, the PLC type optical switch[Term 1] (Table 1(e)) was used for the node, which was connected by the optical fiber patch cord several meters long to form the optical path network.

The network and storage resource manager in the optical path network was realized by the collaboration between the Nippon Telegraph and Telephone (NTT) Corporation and the Information Technology Research Institute, AIST. The network resource manager was installed to manage the optical path and the resource manager that managed the reservation status of the performance-assured storage, and optimal server selection and optical path were set for the video on demand from the viewer[3].When the reservation from the viewer was received and the reservation time arrived, the optical path opened to start the content distribution for the viewer. It was also designed to handle the multiple bitrate signals containing 1 Gb/s, 10 Gb/s, and 43 Gb/s. The software that indicated the reservation status of the optical path was developed, and the user interface was provided at the same time.

4.1.2 Mutual connection to the Optical Packet and Circuit Integrated Network (NICT)

To demonstrate that the mutual servicing of heterogeneous network was possible, we conducted the demonstration jointly with the Optical Packet and Circuit Integrated Network of the National Institute of Information and Communication Technology (NICT). With the cooperation of NICT, the hand-over of the control signal was determined and was accomplished by exchanging the contents and service information at the connection node. High-quality service without delay or data loss could be provided through the Optical Packet and Circuit Integrated Network[4].

4.2 Communication line

While it was possible to configure the network without using the optical fibers that were already laid (field fiber), it was necessary to use the field fibers since fiber laying fell outside of our objective (scenario) of the demo experiment. However, renting the commercial optical fiber over long distances increased the cost burden. Therefore, we borrowed the R&D testbed network that is called JGN2plus[5] and incorporated it into the experimental system to obtain the practical communication distance. This allowed us to test the factors of communication instability and limitations that might occur in reality. Considering the geography and the convenience of this test bed, the use of JGN2plus was suitable for this demo experiment. The details will be explained in subchapter 5.1 along with the site of experiment.

4.3 Node equipment and devices

4.3.1 Silicon photonics switch (AIST)

Optical devices that have a capability of the low power consumption and integration in the network are attractive, and AIST is working on the development of the cross bar switch[Term 2] using the silicon photonics technology[6]. This switch was incorporated into the network node for the configuration that enabled the transmission of video data for the first time. Although the general-use PLC optical switch was employed as the switch for some of the communication nodes, this silicon photonics switch was incorporated since low power consumption and highly integrated multiple ports could be demonstrated.

4.3.2 Current-injection-type silicon-based high-speed optical switch (Fujitsu)

At the Fujitsu Laboratories, Ltd., the development of the small silicon-based optical switch that allows mixed integration with electrical circuit is being done for the future dynamic optical path network. Fujitsu achieved a high-performance device with extremely high optical confinement efficiency as well as small cross-sectional surface area, employing the nano wire rib waveguide transverse direction p-i-n diode structure. It also achieved the switching speed of ns with the lowest switching power in the world[7]. This switch was also incorporated into the network node for the demo experiment.

4.3.3 Power-saving next-generation ROADM (NEC)

The reconfigurable optical add/drop multiplexer (ROADM) is equipment that enables efficient operation of the super high-speed high-capacity optical transmission network, by combining the wavelength multiplexing method and path control. Currently, there is insufficient degree of freedom in the optical path setting in the node devices of the network in which ROADM is deployed. The equipment system that allows switching the transponder[Term 3] stored in the node at arbitrary wavelength and direction is important. NEC Corporation developed the transponder aggregator[Term 4] to increase the freedom of optical path setting, and this will ultimately improve the use efficiency of the transponder[8].

4.3.4 High-speed wavelength tunable laser (Trimatiz)

Since it is necessary to be able to dynamically switch the wavelength in the future optical networks, the achievement of high speed in wavelength switching will be the key. Trimatiz, Ltd. is developing the wavelength tunable light source device based on the wavelength tunable laser diode (T-LD) that allows switching of the wavelength at millisecond or less. This technology allows the single T-LD to be tuned stably at high speed and a device that allows 5 GHz resolution tuning of the C-band[Term 5] was achieved. This was installed in the input end of the NEC's ROADM equipment, to create a configuration that allowed the switching of the wavelength.

4.3.5 Optical amplifier

The optical amplifier (Erbium-doped fiber amplifier: EDFA[Term 6]) must be used to compensate the loss of the optical fiber communication line. The key point is to determine where in the network this device should be placed and the position is determined by the loss information on the optical fiber corresponding to the distance. In the optical path network, since the wavelength is switched dynamically, the EDFA must be capable of following the transient response[9], and therefore, we selected the amplifier which has a suppressing technology of the transient response.

4.3.6 Parametric arbitrary wavelength converter (Furukawa Electric and AIST)

The wavelength converting technology is essential to effectively utilize the wavelength resource in the future optical path network. Since the coherent wavelength conversion using the highly nonlinear fiber (HNLF) can maintain the state of the light phase after conversion, in principle, it is not dependent on the data modulation format or modulation speed[10]. Other than HNLF, there is the semiconductor optical amplifier method that can be used as the wavelength conversion technology, but HNLF was employed since the non-dependency on the modulation format would be useful in the future. In the demonstration, the wavelength conversion from the C-band to the L-bandTerm 5 was incorporated.

4.3.7 High-speed autonomous-control optical tunable dispersion compensator (Furukawa Electric and AIST)

Furukawa Electric Co., Ltd. and AIST proposed and demonstrated the tunable dispersion compensator that combines the wavelength dependent dispersion medium and the wavelength conversion by parametric process, called the optical parametric tunable dispersion compensator (P-TDC)[11]. By using the four wavelength mixing (FWM) of the HNLF[12] that has low dispersion slope with the principle of phase maintaining wavelength conversion, we achieved a gridless broadband function surpassing 1 THz that could not be achieved by the conventional tunable dispersion compensation technology. Projecting that the optical path will be dynamically switched in the future optical network, the high-speed tuning response of microsecond order is realized[13]. For the transmission experiment, this technology was applied to the field fiber of 105 km line through which the Super Hi-Vision signals are transmitted at 43 Gb/s.

4.4 Terminal equipment

4.4.1 SHV transceivers (NHK)

The Japan Broadcasting Association (Nippon Hoso Kyokai = NHK) leads the development of the device that enables the transmission and reception of uncompressed Super Hi-Vision (SHV) in the 24 Gb/s dual green method by the 43 Gb/s optical signal[14]. The network was configured via the 105 km field fiber. The long distance transmission was achieved by the high-speed autonomous control tunable dispersion compensation technology described in section 4.3.7.

4.4.2 Content archive server, delivery server, and display

The content archive server is the computer in which the image contents are stored, and this archive/delivery server functions by the command (section 4.1.1) of the network storage resource manager of the optical path network. The display was configured by devices that were readily available using the SHV monitor.

4.5 Contents

The contents we used were the SHV videos (NHK) and Hi-Vision videos. The former was SHV videos with 33 million pixels/frame, and these were about four times larger both horizontally and vertically than the regular Hi-Vision videos. With the cooperation of NHK, two SHV videos were set in the demonstration system, ready to be transmitted.

For the regular Hi-Vision (or HD), we purchased a general-use HD video camera and shot our own contents. The videos were set in the delivery server.

5 Demonstration experiment

Importance of demo experiment for communication technologies is basically to demonstrate that it is possible to deliver information from point A to point B, including the switching technology. The important factors of the experiment include the site where the transmitting/receiving terminals are located, construction of the experimental system based on the plan, and then to execute the transmission and switching of the actual video information. Considering these factors, we configured the demo experiment as shown in Fig. 3. The elemental technologies described in chapter 4 are also shown in the diagram. In this chapter, we describe how the elemental technologies described in the previous chapter were incorporated into the experiment.

Figure 3 shows the configuration where the two networks are mutually connected. The blue area on the left side is the NICT's Optical Packet and Circuit Integrated Network, and the green area on the right is the AIST's optical path network. NHK's SHV transceiver technology is set in the middle. This topologyTerm 7 was the result of discussing the points of mutual connection. The blue connection line indicates the optical fiber. The switch request method of the networks was predetermined. The network in the black dotted line on the right of the diagram were located entirely in Akihabara, and the line went to NICT's Optical Packet and Circuit Integrated Network via Otemachi, Koganei and then back to Otemachi, with connecting points NICT-EAST and NICT-WEST. After the control environment of the network was set up, and the stage progressed to the video distribution experiment (subchapter 5.2).

5.1 Site of the experiment and construction of the experimental system

Although it seemed that the demo experiment could be executed anywhere, we decided the site as we narrowed down the available filed optical fiber. Since it was necessary to use the R&D testbed network (JGN2plus) as mentioned in subchapter 4.2, we considered the appropriate terminal station. The east terminal of the JGN2plus was located in Otemachi (Chiyoda-ku, Tokyo). Therefore, we reached the conclusion that we could create the network relatively easily by connecting with the AIST Akihabara (Soto-Kanda, Chiyoda-ku Tokyo) through the commercial optical fiber. Although it was also possible to connect to the AIST headquarters in Tsukuba, Ibaraki, the more convenient AIST Akihabara was selected since there was no extension of the R&D testbed network to Tsukuba, and we wanted to conduct the demo experiment during the symposium. The distance between Otemachi and Akihabara was 1~2 km by line of sight, but the optical fiber actually used was 9.8 km. This was because the usable laid optical fiber traveled up to a certain floor of the building and then went into the underground common utility hole. After the optical fiber line between Otemachi and Akihabara was set, it was connected to NICT since the west terminal of JGN2plus was located at NICT (Koganei). This range was set up as the network. The distance between these points was about 42.7 km, and the round trip distance was 105 km from Akihabara. The demo site was located in two places, NICT (Koganei) and AIST (Akihabara). This distance was suitable as a network model connecting the area within a city. The major issue was to establish the communication by the 43 Gb/s optical modulation signal, the fastest signal used in the demo. Therefore, we planned the complete compensation for the effect of signal degradation by wavelength dispersion in the 105 km of optical fiber, using the high-speed autonomous control tunable dispersion compensator that we developed. However, since the transmission loss at 0.2 dB/km or more in the optical fiber and the loss due to optical connectors and parts were unknown, it was uncertain whether the optical S/N ratio would fall within the acceptable range of the receiver. Therefore, we prepared a backup plan to decrease the difficulty of the transmission for the video distribution demo based on the simplification of the topology.

The site of the demo experiment was set up on one of the floors of AIST Akihabara, as shown in Fig. 4. The hardware was placed in groups by elemental technologies. Although it was compared with Fig. 3, in practice, the design in Fig. 4 was completed first. As a result of giving priority to the size of the device and convenience of connection in a limited space, the layout was determined without inconvenience. As the actual hardware was prepared as in Fig. 4, the devices and equipment were connected by each function block. In building the experimental system, the connection process was the most important, and misconnection or major communication line loss were not acceptable. The connections were done accurately and at appropriate signal level using a switch port table.

5.2 Video distribution experiment

One of the highlights of the demo experiment was to see whether the path communication for 43 Gb/s, the fastest optical modulation signal, was possible over the 105 km transmission distance. This is the communication path shown as a red line in Fig. 3. When the path was tested by bit error rate tester, it did not become error free even when the optical signal intensity was raised, and we were concerned about the disturbances or interruptions in the SHV video. However, when the actual connection was made with the receiver with the appropriate optical power, the communication was established due to the signal error correction function of the device. Although the signal error correction function was nothing special, whether the 43 Gb/s path at transmission

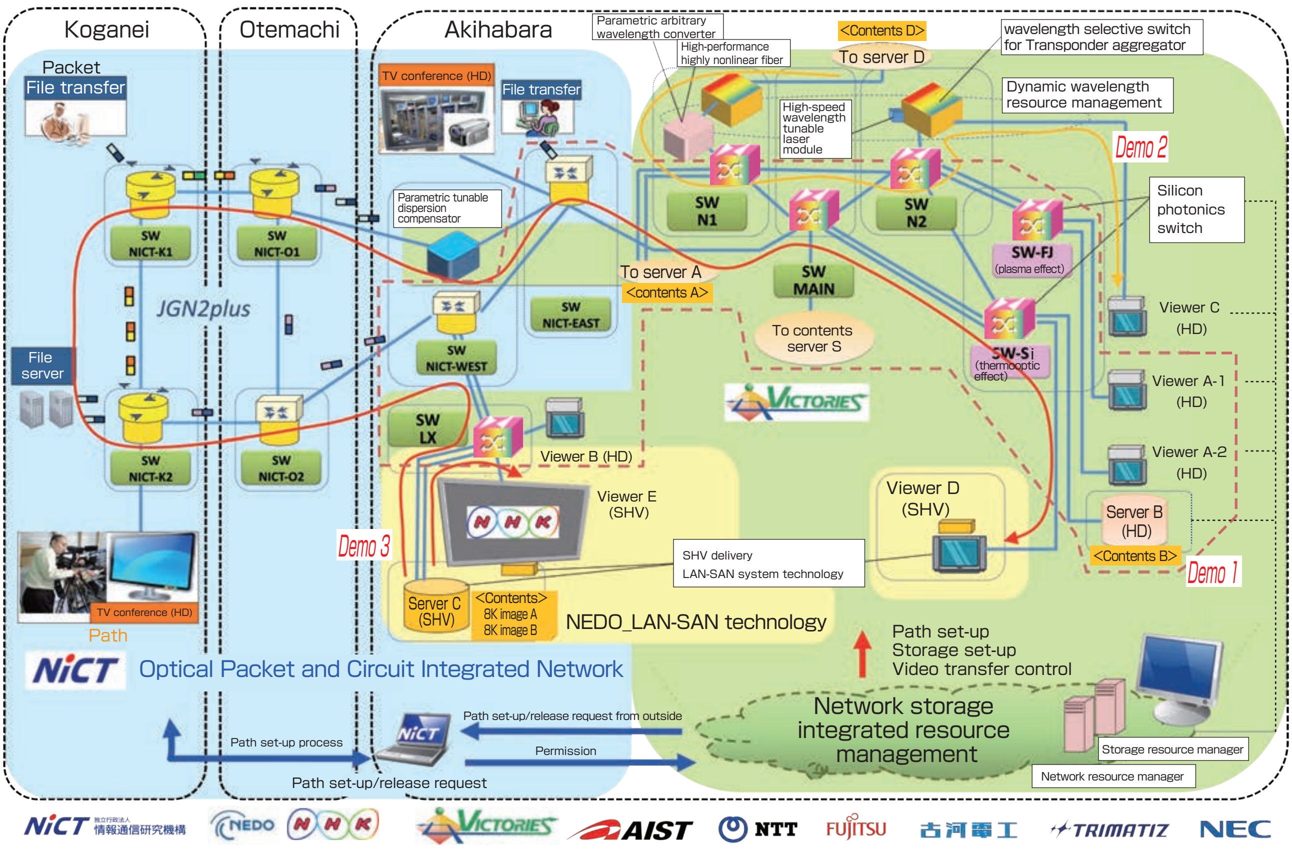

Fig. 3 Schematic diagram of the joint connection experiment for the optical network

distance 105 km would fall into the error correctable range could only be confirmed by the experiment, and this was a major point of the video distribution experiment.

After the long-distance, high-speed communication path was established, the issue shifted to how to create the scenes that would be viewed in the public demonstration experiment. This was discussed carefully with NTT that handled the network storage/resource management technology. We called this the demo scenario. In conducting a large-scale demonstration experiment network, the significance of the elemental technologies would be diminished unless we create a demo scenario that showed all the elemental technologies actually in function. The executed demo scenario consisted of the reservation of the image and its control including the storage management equipment, the protection including the node device image, the cooperation with the NICT Optical Packet and Circuit Integrated Network, and the reserved distribution of SHV.

The demo experiment was conducted at the 3rd Vertically Integrated Center for Technologies of Optical Routing toward Ideal Energy Savings (VICTORIES) Symposium held on August 25, 2010. Table 2 shows the flow of the demo scenario. The network was configured so all the elemental technologies would cooperate and be presented in about 30 minutes. Looking at both the demo scenario and Fig. 3, in Demo 1, it was demonstrated that the content request from viewer A-1 and A-2 were answered based on the network storage integrated resource management, and the HD video was transmitted with the optimization of the server in which the contents were stored and the optical path that linked to the viewer. In Demo 2, in addition to the format for distributing

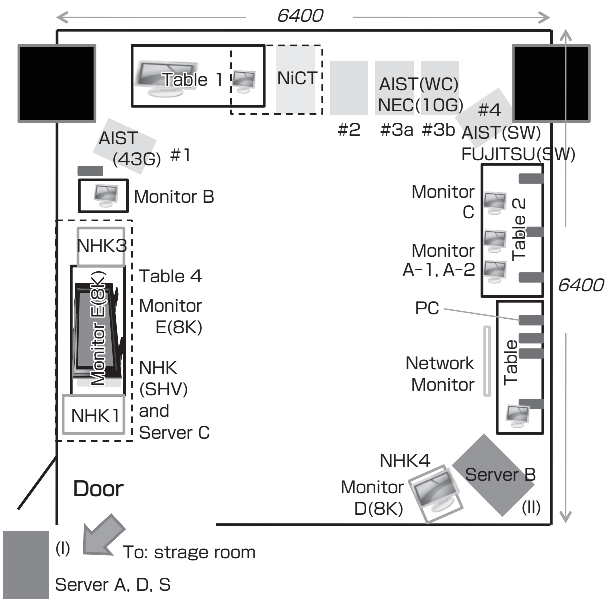

Fig. 4 Layout of the Akihabara site

Table 2. Demo scenario and elemental technologies

	Demo scenario	Elemental technologies
About 30 min	Demo 1: Reservation of the video and its control including the storage management device	(a), (e), (j), (n), (p)
	Demo 2: Protection (next-generation ROADM technology)	(e), (h), (i), (j)
	NICT Demo: Optical Packet and Circuit Integrated Network	(b), (c), (d)
	Demo 3: SHV video distribution by reservation (NHK), dissimilar network connection, silicon optical switch, tunable dispersion compensation	(b), (c), (d), (e), (f), (g), (j), (k), (l), (m), (o)

contents D in server D as requested by viewer C via the dynamic wavelength resource manager, the protection action in case of transponder failure was demonstrated. In Demo 3, it was confirmed that the SHV video information could pass heterogeneous networks without any problem, by setting the optical path including the silicon photonics switch and long-distance transmission and by estimating the SHV video request from viewers B and D. Figure 5 shows the actual open demonstration. The three small monitors shown in the center corresponds to viewers C, A-1, and A-2 from left. The large screen on the right of the three small monitors is the network storage integrated resource management screen.

6 Evaluation of the results and future developments

It was confirmed in the experiment that all of the elemental technologies cooperated using the demo scenario of subchapter 5.2. The three points mentioned in chapter 3 were confirmed: A) to execute the multiple communication rates on the network, to manage them on the network, and to distribute the contents by switching the network according to the requested service; B) to check that the communication can be established by compensating the nonlinear responses from the field optical fiber, and to check that the different networks configured by different elements can be mutually connected; and C) to achieve low power consumption.

The power consumption measurement of the specific network nodes was conducted while in function, and Fig. 6 shows the measured and the projected values. Assuming that the switch ports and nodes were set up for the same number of devices used in the demo experiment using the core router, it was

Fig. 5 Open demo experiment

estimated to be about 13.4 kW including the optical amplifier. In the demo experiment, the power excluding the server was 1.5 kW with room for expandability to Tb/s. Since the power of some office appliances that could not be isolated from the measured power source circuit was included, the figure was slightly larger than the sum of the ratings of the device groups. However, it was found that basically, the energy saving effect on the value of the power consumption would be more significant as the high-capacity communication data were stuffed. Specifically, when the transmission rate per port becomes100 Gb/s as the silicon photonics optical switch is realized, it is estimated that power efficiency 1,000 times higher may be achieved. Considering the increased communication demand such as for HD video expected in the future, we believe sufficient decrease of power consumption was achieved, as we are able to slow down the increase of power consumption. The optical path network can contribute to the achievement of low power consumption of the communication network.

There were several things that became clear for the first time after starting to build the optical path network. Viewing from the OSI model[Term 8], which is the basis of network connection, the first point is that the cooperation between the layers became complex. This is a complex involvement, starting from the switching occurring at the physical layer to the moment of display as the cache of the browser stores some of the images. We spent time establishing the communication in each optical path, such as in the line that used the media converter[Term 9], because the linkage function corresponding to the converter function behaved differently from the command of the resource management device. In the demo experiment, the issues related to the inter-layer cooperation were solved one by one to bring the system to function. We believe we need an opportunity for more specific demo experiments and mutual connections including the standardization of connection, in order to maximize the potential of the optical path network. Such findings could not have been obtained without the "vertical integration (collaboration)" where the technologies from devices to applications were convened and executed.

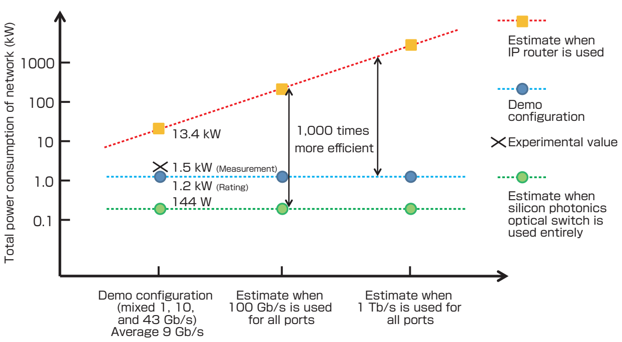

Fig. 6 Communication capacity and power consumption (including estimated values) in the demo configuration

In the future, it will be necessary to enhance the inter-layer cooperation and to compensate the differences in the wavelength and performances of the transceiver devices in the optical path network. Such R&Ds will be continued as the optical path conditioning technology at the Network Photonics Research Center of AIST.

7 Conclusion:the significance of the demo experiment

A new optical communication network that supports the high-definition high-capacity video era was demonstrated through the joint efforts of AIST, five IT related companies, NICT, and NHK Science and Technology Research Laboratories. It was highly significant that through the vertical integration (collaboration) that crossed the organizations, the potential of the new network was demonstrated in surpassing the limitations of the power consumption and communication capacity of the devices that configured the current network. We were able to realize some of the aspects of the new video information service by incorporating the elemental technologies for the newly developed optical communication, and we believe this was an important step in the evolution of the optical communication technology.

Acknowledgements

In conducting the demo experiment we wish to express gratitude to the major contributions of NICT and NHK. We thank the people of the collaborating companies, whose efforts led the demo experiment to success. We also thank the researchers of AIST who were in charge of the elemental technologies, led by Tomohiro Kudoh, group leader of the Information Technology Research Institute, AIST, who worked to install and start up the demo. We would also like to mention that this demo experiment would not have been possible without the guidance and support of Shingo Ichimura, vice-president, AIST and Hiroshi Ishikawa, director, Network Photonics Research Center, AIST.

Terminologies

Term 1. Planar light wave circuit (PLC) optical switch: PLC often refers to the planar quartz waveguide.

Term 2. Cross bar switch: the switch with two switching state, the bar and cross states, when considering the connection port with two inputs and two outputs. This electric switching method was originally used in the telephone switchboard before digital switching became common. Recently, it refers to the internal switch element that dynamically selects the route when the data is exchanged between the CPU and the memory within a device.

Term 3. Transponder: optical transmitting/receiving equipment that communicates at an arbitrary wavelength, by storing the client signal and converting it into frame format (such as OTN) appropriate for the backbone transmission networks.

Term 4. Transponder aggregator: a device that resolves the ROADM's issue of the limitation of wavelength and path in the optical route setting, and provides the degree of freedom in reconfiguring the optical route between the transmission line and the optical transmitting/receiving device (transponder). It is composed of the waveguide with wavelength selectivity and an optical matrix switch, and it enables the optical route setting where the arbitrary transponder connects to an arbitrary optical fiber transmission route at an arbitrary wavelength.

Term 5. C-band, L-band: the wavelength range used in optical communication. Conventional (C) band has the wavelength range of 1530-1565 nm, while long (L) band has the range 1565-1625 nm.

Term 6. Erbium-doped optical fiber amplifier: a device that amplifies the optical signal directly in the fiber without the electrical signal conversion, utilizing the principle where the optical signal of a certain range is amplified when the excitation light of a certain wavelength is applied to a fiber doped with rare earth element erbium.

Term 7. Topology: a term that indicates the position and connection. In general, it indicates the connection format of the computer network. Star-type and ring-type network topology are most commonly used.

Term 8. Open systems interconnection (OSI): the standardization and organization where the communication protocol is broken down into the seven-layer structure. It is known as the OSI reference model.

Term 9. Media converter: a device that connects the different transmission media and converts the signals mutually. The most common one is the device that converts the LAN cable (copper wire) to optical fiber.

References

[1] Ministry of Internal Affairs and Communications, 2010 White Paper on Information and Communications in Japan, (*White paper*), (2010).

[2] S. Namiki, T. Kurosu, K. Tanizawa, J. Kurumida, T. Hasama, H. Ishikawa, T. Nakatogawa, M. Nakamura and K. Oyamada: Super HD video transmission and extremely green optical networks for future, *IEEE Journal of Selected Topics in Quantum Electronics*, 17 (2), 446-457 (2011).

[3] K. Yamada, Y. Tsukishima, K. Matsuda, M. Jinno, Y. Tanimura, T. Kudoh, A. Takefusa, R. Takano and T. Shimizu: Joint storage-network resource management for super high-definition video delivery service, *Optical Fiber Communication (OFC) 2011, Conference on*, JWA1, (2011).

[4] H. Harai: Report of proof-of-concept experimental and live demonstration of optical packet & circuit integrated network over JGN2plus optical-fiber testbed, *IEICE technical report*, 110, 7-12 (2010).

[5] NICT, Advanced Testbed Network for R&D, *http://www.jgn.nict.go.jp/*.

[6] Y. Shoji, K. Kintaka, S. Suda, H. Kawashima, T. Hasama and H. Ishikawa: Low-crosstalk 2 x 2 thermo-optic switch with silicon wire waveguides, *Optics Express*, 18, 9071-9075 (2010).

[7] S. Sekiguchi, T. Kurahashi, K. Kawaguchi and K. Morito: Current-type silicon-based optical switch with silicon germanium waveguide, *IEEE Photonics Society 23rd Annual Meeting*, WW3 (2010).

[8] M. Sakauchi, I. Nishioka, S. Nakamura, T. Chu and Y. Urino: Demonstration of fast optical protection in ROADM system with one-chip color/direction- independent add/drop multiplexer employing silicon photonic circuit, *Optical Fiber Communication (OFC) 2009, Conference on*, JThA51 (2009).

[9] Y. Oikawa, Y. Horiuchi, Y. Tanaka, M. Shiga, N. Shiga and H. Nagaeda: Super-fast AGC-EDFA for the burst-mode systems without gain excursion in 20-ns and 21-dB ramped input, *2008 Conference on Optical Fiber Communication/National Fiber Optic Engineers Conference*, 1-3 (2008).

[10] S. Petit, T. Kurosu, S. Namiki, M. Takahashi and T. Yagi: Truly arbitrary wavelength conversion by cascaded four-wave mixing in low dispersion slope sbs suppressed highly nonlinear fibers, *2010 IEEE Photonics Society Winter Topicals Meeting Series*, 115-116 (2010).

[11] S.Namiki: Wide-band and -range tunable dispersion compensation through parametric wavelength conversion and dispersive optical fibers, *Journal of Lightwave Technology*, 26, 28-35 (2008).

[12] M. Takahashi, R. Sugizaki, J.Hiroishi,M.Tadakuma,Y. Taniguchi and T.Yagi: Low-loss and low-dispersion-slope highly nonlinear fibers, *Journal of Lightwave Technology*, 23, 3615-3624 (2005).

[13] K. Tanizawa, J. Kurumida, H. Ishida, Y. Oikawa, N. Shiga, M. Takahashi, T. Yagi and S. Namiki: Microsecond switching of parametric tunable dispersion compensator, *Optics Letters*, 35, 3039-3041 (2010).

[14] T. Nakatogawa,S. Okabe,M. Nakamura,K. Oyamada,F. Suginoshita, T. Ikeda and K. Shogen: Wireless and fibre-optic live contribution link for uncompressed super hi-vision signals, *The Best of IET and IBC, IET Journals*, 2, 31-36 (2010).

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Researcher, Optical Signal Processing System Research Team, Network Photonics Research Center (NPRC), AIST. He received the master's degree from the Graduate School of Engineering, Osaka Electro-Communication University in 1998 and the doctorate from the Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology. Doctor (Engineering). He worked at the Fujitsu Ltd., Photonics Research Institute of AIST, and University of California, Davis. He is with NPRC since 2009,and engages in R&D for device and system in the optical fiber communication technology field. Cooperated with Shu Namiki to oversee the entire demo experiment and managed the operation and wrote all chapters of this paper.

Shu NAMIKI

Leader, Optical Signal Processing System Research Team, Network Photonics Research Center, AIST. He received the master's degree from the Graduate School of Science and Engineering, Waseda University in 1988. Joined the Furukawa Electric Co., Ltd. in 1988. Engaged in research and product development of the semiconductor optical device, mode-locking laser, light amplifier, nonlinear fiber optics, and optical transmission. Visiting researcher at Massachusetts Institute of Technology, USA from 1994-1997. Joined AIST in 2005. Has coauthored over 200 publications, and served as member of several international conference programs, as well as member of International Organization for Standardization/International Electrotechnical Commission (ISO/IEC). Vice-chairman of the Editorial Board, IEICE Transaction B (Communications) of the Institute of Electronics, Information and Communication Engineers. Associate editor, Optics Express, Optical Society of America from 2005. Currently, advisory editor, Optics Express and deputy chief editor of IEICE Society. Doctor of Science. Fellow of the Optical Society of America. In this paper, considered the direction of the demo experiment and the outline of the elemental technology to be combined.

Discussions with Reviewers

1 Background of the paper

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

The main theme of this paper is that a demonstration experiment was conducted to realize the dynamic optical path network. Yet I think there is lack of explanation on what is a dynamic optical path network, and how it can realize low-power optical communication (also why that's not possible with packet communication). I think you should describe these to help the understanding of readers outside of the field.

Answer (Junya Kurumida)

I think you indicated an important point in the description. To clarify the optical path network, I added the following section in paragraph of chapter 2: "… a new network called the 'optical path network' that directly links the users with optical path, and engages in R&D to solve the above issues. Particularly, the network where the optical network is switched flexibly to actively maintain the optical path in response to the high-capacity information request is called the 'dynamic optical path network'." Also, as the reason for the realization of low-power optical communication, I added in chapter 2: "These efforts will enable the high-speed data communication without going through multiple electric signal processing, and a network that handles large-capacity information at low power can be configured."

To make the point clear for the readers, I added the following sentence in chapter 1 and the issues will be discussed in the following chapter: "On the other hand, there is a major problem in the sustainable development of such advanced communication service. It will be explained in the following chapter."

Comment (Hiroshi Tateishi, New Energy and Industrial Technology Development Organization)

I understand that the point of this paper is the demonstration of the low power consumption by using only optical components in the high-capacity network, the seamless mutual connection technology of heterogeneous networks and the implementation of the super high-capacity content distribution based on these technologies, in one model experiment. However, I cannot understand where the breakthrough point was, or how things were solved. Please organize and present the background and the outline of the research in an understandable manner. The press release* for this experiment on the AIST website is much clearer. After doing this, please describe the important points from the perspective of R&D. You have described what you have done in detail, but you did not explain "why they had to be done" or "what were the problems and how they were solved". Please consider these and write with a stance that you are trying to get some third-party people to understand.

Answer (Junya Kurumida)

Thank you very much for your important indication. I added the segment "…the new network technology that overcomes the limitations of power consumption and communication capacity of the devices that configured the current network" in the outline, and added the sentence "With the background of increased demand in communication mainly for the Internet, the energy savings in optical communication is an immediate issue". in the beginning of "1 Introduction" to clarify the background and outline of the research.

To solidify the perspective from R&D, I added the description about establishing the 43 Gb/s path communication, that is the highlight of this demo and is the fastest optical modulation signal at 105 km transmission distance, to the "5.2 Video distribution experiment". The three viewpoints of the scenario explained in chapter 3 were organized as A, B and C and were explained correspondingly in chapter 6.

*http://www.aist.go.jp/aist_j/press_release/pr2010/pr20100824_2/pr20100824_2.html

2 Demo experiment system and its significance

Comment (Naoto Kobayashi)

I think the elemental technologies are explained well. However, the part on the achievement of the demo experiment system and the significance of the successful research are expressed weakly, and the significance of this major accomplishment may not be communicated to the readers. Therefore I think you should do the following:

1. You should clearly show how the scenario shown in chapter 3 was realized in the demo experiment, as the result shown in chapter 3, "(1) to configure a network with coexisting communication elemental technologies such as 1 Gb/s and 10 Gb/s, (2) to configure the network using the already laid optical fiber, and (3) to work on these further to achieve low power consumption".
2. Since it is highly significant that the elemental technologies were integrated to create a system, I think you should tell the difficulties of the integration and how you were able to overcome them in more detail.

Comment (Hiroshi Tateishi)

In subchapter 5.1, you describe in detail the distance of the intermediate optical fiber, but you do not explain what that length means for the experiment, so I don't know how to interpret the information. Do you wish to say that in practice, implementing this distance is sufficient for the purpose of demonstration, or did it simply end up this way and there's not much technological meaning? Whichever the reason, when you give specific figures, the readers become curious about the meaning behind them.

Answer (Junya Kurumida)

Thank you very much for indicating the improvement points for the paper.

1. The three viewpoints explained in chapter 3, were clarified as A, B and C, with the introduction “we shall discuss the issue from the three perspectives” I matched them to the explanation in chapter 6.

2. Since I provided a specific figure for the distance of the optical fiber line in subchapter 5.1, I added the story about the difficulty of high-speed communication over distance: “This distance was suitable as a network model connecting the area within a city. The major issue was to establish the communication by the 43 Gb/s optical modulation signal, the fastest signal used in the demo. Therefore, we planned the complete compensation for the effect of signal degradation by wavelength dispersion in the 105 km of optical fiber, using the high-speed autonomous control tunable dispersion compensator that we developed. However, since the transmission loss at 0.2 dB/km or more in the optical fiber and the loss due to optical connectors and parts were unknown, it was uncertain whether the optical S/N ratio would fall within the acceptable range of the receiver. Therefore, we prepared a backup plan to decrease the difficulty of the transmission for the video distribution demo based on the simplification of the topology.”

In response to the above, I described the important point that we overcame in the demo experiment in subchapter 5.2: “One of the highlights of the demo experiment was to see whether the path communication for 43 Gb/s, the fastest optical modulation signal, was possible over the 105 km transmission distance. This is the communication path shown as a red line in Fig. 3. When the path was tested by a bit error rate tester, it did not become error free even when the optical signal intensity was raised and we were concerned about the disturbances or interruptions in the SHV video. However, when the actual connection was made with the receiver with appropriate optical power, the communication was established due to the signal error correction function of the device. Although the signal error correction function was nothing special, whether the 43 Gb/s path at transmission distance 105 km would fall into the error correctable range could only be confirmed by the experiment, and this was a major point of the video distribution experiment.”

3 Vertical integration (collaboration) and its concept

Comment (Naoto Kobayashi)

I think the “vertical integration (collaboration)” is one of the most valuable points in this research, and I think you should include a simple explanation along with a figure.

Answer (Junya Kurumida)

Thank you for your indication. I added Fig. 1 and the explanation for the figure as follows: “Figure 1 shows the conceptual diagram. To utilize the optical switch in the network, a mechanism for controlling the optical switch according to the network application is necessary. That is to say, a mechanism is needed where the mutual connections are made between the HD video server and display, teleconference systems are handled, and these are appropriately managed according to the optical path and storage information. Moreover, vertical integration (collaboration) is essential to introduce the silicon optical path switch and wavelength resource management technologies, and to consolidate and realize the technologies that are developed individually, from device level to application level.”

4 Evaluation of the result

Comment (Hiroshi Tateishi)

Chapter 6 is an important part for Synthesiology, but the description is insufficient. What are the meanings of the problems that occurred in the experiment and how were they solved? Moreover, what significance do they have in the future development? As of now, you’re saying, “When we did the experiment, many unforeseen problems occurred, but we could not solve all of them on the spot”. It is merely a report of the results without much information for the reader.

Also, there is no evaluation for “power consumption 1.5 kW”. When I see Fig. 6, I can understand that it can be reduced further compared to the electric signal processing, but you need the explanations for, “to which extent you have to decrease in practice?” and “were the results sufficient or insufficient?”

Answer (Junya Kurumida)

I added the description on the specific problems that occurred in the experiment and the solution process in the beginning of the video distribution experiment in subchapter 5.2. I added the process of establishing the communication with 43 Gb/s path, the optical modulating signal with highest speed in this demo, with 105 km transmission distance.

Also, in the beginning of chapter 2, I added the detailed description of the communication traffic and electricity: “Assuming that this trend will continue for about 20 years, the traffic will be about 1,000 times higher. This calls for the improvement of power efficiency.” Building on this comment, I added the following section as the evaluation of the power consumption in chapter 6: “Assuming that the switch ports and nodes were set up for the same number of devices used in the demo experiment using the core router, it was estimated to be about 13.4 kW including the optical amplifier. In the demo experiment, the power excluding the server was 1.5 kW with room for expandability to Tb/s.” and “Specifically, when the transmission rate per port becomes100 Gb/s as the silicon photonics optical switch is realized, it is estimated that power efficiency 1,000 times higher may be achieved. Considering the increased communication demand such as for HD video expected in the future, we believe sufficient decrease of power consumption was achieved, as we are able to slow down the increase of power consumption.”

Paper supplement to "Study on the PAN carbon-fiber-innovation for modeling a successful R&D management"

— An excited-oscillation management model —

Osamu NAKAMURA[1], Tsuguyori OHANA[2], Masato TAZAWA[3], Shinji YOKOTA[4], Wataru SHINODA[5], Osamu NAKAMURA[6] and Junji ITOH[7]

[Translation from *Synthesiology*, Vol.4, No.2, p.111-114 (2011)]

In the paper, "Study on the PAN carbon-fiber-innovation for modeling a successful R&D management", published in *Synthesiology*, Vol. 2 No. 2, pages 159-169, some errors and inaccurate expressions have been found, which do not sufficiently convey the authors' intentions and could lead to misunderstandings. The errata, additional references, and supplemental commentaries are presented as follows.

[Errata]

1. Page 155 left, subchapter 2.1(2)

Original: Originally, carbon fiber was developed in the United States in 1956, using rayon as the raw material.
Correction: In 1956, W.F. Abbott of the United States developed the carbon fiber using rayon as the raw material, and applied for the patent for the first time[1][14].

2. Page 157 right, subchapter 2.4(1)

Original: Toray Industries, Inc., which is currently highly successful in the commercialization of PAN carbon fiber, started production of carbon fiber in full force around 1968.
Correction: Toray Industries, Inc. decided to engage in commercialization in 1970, and started the production and sales of the carbon fiber in 1971 after obtaining the patent license from Dr. Shindo[15][16].

Corresponding to this correction, figures 1 and 3 are corrected as shown.

3. Page 158 right, subchapter 2.5(1)

Original: However, there were several cases where technological transfer to companies was done through official technical assistance or joint research, and some companies have expressed gratitude to GIRIO in the "company history".
Correction: However, there were several cases where technological transfers to companies were done through official technical assistance or joint research, and these were mentioned in places such as the "company history".

4. Page 160 right, subchapter 3.3

Original: They sought technical assistance "unofficially" …
Correction: They came to collect technological information …

[Additional references and place of insertion]

[14] T. Takamatsu: *Gijutsu To Bunmei: Journal of the Japan Society for the History of Industrial Technology*, 12 (1), 2 (2000) (in Japanese).
(Page 155 left, subchapter 2.1(2) as in Errata 1)
[15] http://www.fujimura-lab.mot.titech.ac.jp/class/CASE05-03TORAY(1).pdf
Y. Aoshima and T. Kawanishi (Hitotsubashi University Institute of Innovation Research), and METI "Promotion of the MOT Human Resource Training Program": *Technological development of Toray carbon fiber composite material "Toreka" by Toray*, page 3 (2005) (in Japanese).
(Page 157 right, subchapter 2.4(1) as in Errata 2)
[16] Toray Industries, Inc.: *Toray Gojunen Shi (Fifty Year History of Toray)*, 199,308(1977).
(Page 157 right, subchapter 2.4(1) as in Errata 2)
[17] J. Matsui: Carbon fibers, part 3: Birth of PAN based carbon fibers - Researches by Shindo and Watt, *Reinforced Plastics*, 43 (8), 298 (1997) (in Japanese).

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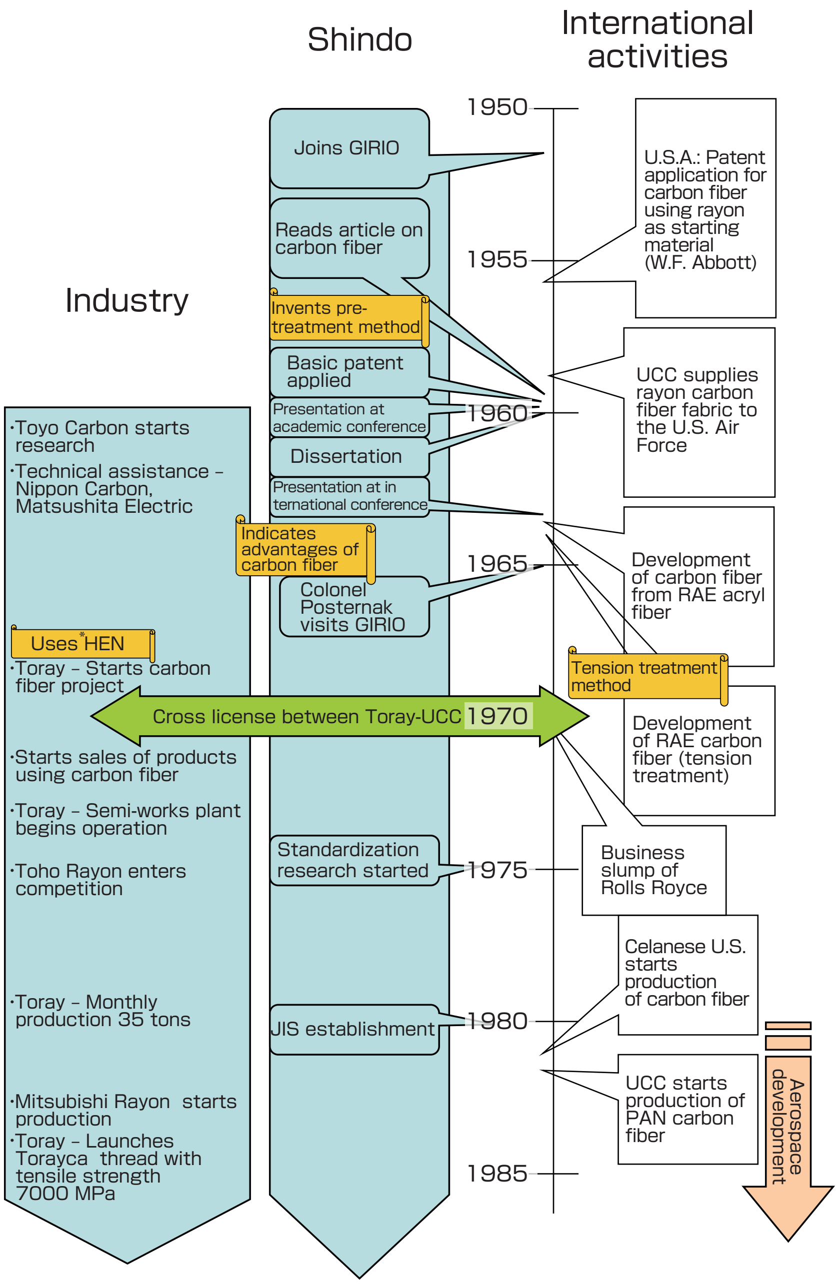
(Page 160 left, subchapter 3.3: Through the presentation of Dr. Shindo at the Carbon Conference in the United States in 1963, the British carbon researchers realized the advantage of using PAN fiber and started research of PAN carbon fibers[17]-[19].)
[18] A. Shindo: Special - Japan Innovation Story: Light, strong, and hard-to-stretch PAN carbon fiber, *Monthly Chemistry*, 65 (1), 22-25 (2010) (in Japanese).
(As in [17])
[19] D. Swinbanks: Graphitic carbon copies, *Nature*, 349, 97 (1991).
(As in [17])
[20] J. Matsui: Carbon fibers, part 6: Industrialization of carbon fibers – Toray Industries Co. 1968-1979, *Reinforced Plastics*, 44 (1), 31 (1998) (in Japanese).
(Page 160 right, subchapter 3.3: ...And technological transfers were done 10 years prior to the actual marketing of the product.)



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

Fig. 1 Flow of carbon fiber development

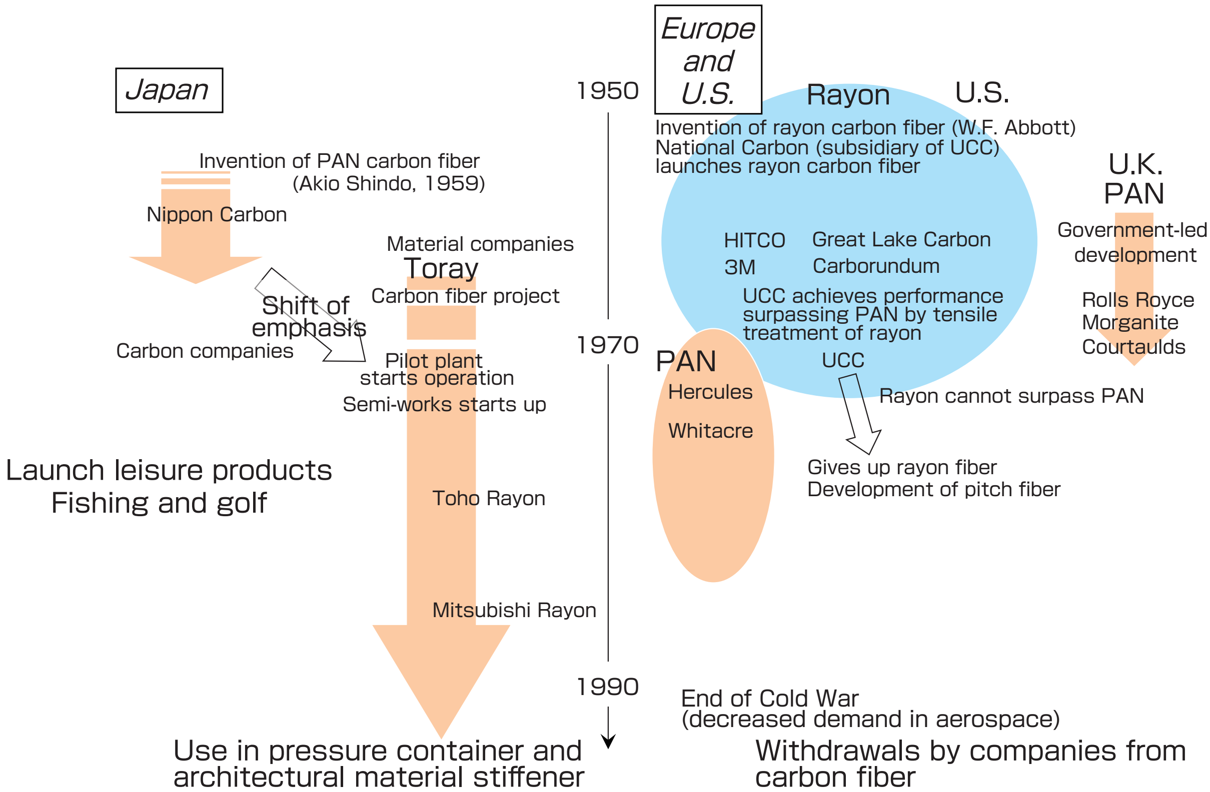


Fig. 3 Efforts by Japanese and overseas industries on carbon fiber

[Additional explanations]

As stated in the "Abstract" and "Introduction", this paper is an investigation and a construct based on the interviews to the people (listed in the "Acknowledgement") who were directly involved in the initial phases of the innovation, with focus on the internal motivation of the researchers and the actions taken by the GIRIO management, in the process where research results of a public institution were recognized by society, transferred to industry, and led the industrial transformation. Therefore, this paper is not a technological history that follows the whole development phases of the PAN carbon fiber.

1 "Strategic" research promotion at GIRIO

Page 155 right, subchapter 2.1(2)

Original: …It could be imagined that the results of PAN carbon fiber research was strategically announced…

The statement "strategically announced" is based on the analysis and interpretation from the interviews with the people involved. It is the authors' interpretation that the fact that the research was "announced" seems to indicate that there was some strategy rather than being a random course of events.

Pertaining to the research itself, it is clearly stated in several places that "the topics were determined according to personal interest and concern". This is part of the instruction given by the superiors at the time (in case of Shindo, the supervisor was Sengoku), and derives from the fact that "the degree of freedom for the research topic selection and how the research was carried out differed greatly by person". It is also clearly stated in the paper that for Shindo, "the development of carbon fiber was incidental upon seeing the newspaper article." The topic selection and new findings were dependent on the autonomy of the researchers or on some incidental encounters with newspaper coverage, and this is quite distinct from the recent MOT evaluations that emphasize that the "R&D must be conducted strategically and should be planned".

The "strategy" of the model discussed in this paper includes the spontaneous activities of the individual or group in the initial phases of the R&D. This means that the organization does not impede the activities or the diffusion of the products, but various measures (such as encouraging securement of intellectual property) are taken to incite and enhance the activities. This paper states that research, an individual spontaneous activity, and organizational strategy are not in antinomy, but are compatible, and moreover, innovation will be accelerated if the two work hand in hand.

The statement "GIRIO … organized the infrastructure and raised people's enthusiasm (Page 155 right, subchapter 2.2)" given as an example of the managerial background that produced research results was confirmed through the interviews with the people involved, according to the descriptions in *Osaka Kogyo Gijutsu Shikenjo Gojunenshi (Fifty Years History of GIRIO)*[11]. This reference material records the increase in the number of research publications and patent applications, the building of the radiation chemistry lab, the opening of the technical consultation office, and the concentration from Daini (Osaka) to Ikeda. These are the indications of the managerial efforts. Moreover, the description "…and we could see that this was an organizational effort (Page 156 left, subchapter 2.2)" is based on the fact that the "research on fibrous graphite" set by the organization (GIRIO) was included amongst the "carbon material research" according to the description in the *1959 GIRIO Annual Report*[9].

Also, the principle of filing the patent application before publication at the academic society was followed. The importance of patents started to be recognized at the national research institutes and universities after 1999, when the Act on Special Measures for Industrial Revitalization (Article 30), a Japanese version of the Bayh-Dole Act, went into effect. This vitalized the procurement of intellectual properties by the public institutions, and their importance increased drastically. It should be particularly noted that the principle of "patents first" was executed shortly after World War II in the 1950s and '60s. The authors noted this point, and considered this as one of the proofs where the organizational strategy and individual spontaneity could be compatible.

2 Explanation of the actions for quick development for innovation

Page 158 left-right, subchapter 2.5(1)

Original: One of the authors has heard that when a corporate researcher obtained certain results after solving a problem or produced new proposals after getting help by technological information obtained from daily conversations at GIRIO, the researcher went on to company presentation without mentioning that the idea was picked up at GIRIO.

In the context of this paper, this expression is limited to the "results obtained by the individual effort of the corporate researcher based on the information gained through the daily conversations at GIRIO". This is not seen as a problem. Instead, the paper describes that there was a general awareness by GIRIO at the time, that even if there was a serendipitous inspiration based on the information obtained, the company may not necessarily make it clear that there was a contribution of the GIRIO information behind a certain result. If some source information leads to some inspiration or research development that produces an innovation, the range of opinion exchange will expand and the possibility of additional development grows when the source information and the thought process that lead to the inspiration are introduced in the course of the discussion, rather than reporting the conclusion only.

3 Explanation on the reduction of the "valley of death" in innovation

Page 158 right, subchapter 2.5(2)

Original: the primary group and the secondary group

This grouping was done for the sake of convenience by the authors, to enhance the reader's understanding. This refers to the necessity of background research in new material development, where one looks for something better than the primary material but can not find any, as this is a common occurrence in material research. (This is based on the information obtained from the interviews with Dr. Shindo and other people involved.)

When the new material is discovered and is recognized and praised by society, it is necessary to confirm whether the new material is truly better than the other materials in terms of competitiveness in performance, cost, reliability, and durability. Of course, such survey should be completed at the time of announcement, but further considerations are required taking into account the manufacturing process as well as the use and application of the material. The other companies of the same industry with different ways of thinking or companies of different industries will enter the research as they seek commercial opportunities. In case the standard of the material is not yet set, more companies may develop interest as they pursue the potential. Such a situation is included in the concept of "valley of death" in a wider sense. In this paper, the primary group and the secondary group are terminologies introduced to explain this phase. The companies that set the "product" and send it out to society comprise the "primary group", while the companies that are interested and seek different commercial opportunities are called the "secondary group". The "secondary group" is necessary to thicken the layer of the field, but often their projects fail to produce intended results. Such negative information are not released to society and become dead storage. In general, the range that can be covered by a single research or a single company tends to be limited. Therefore, to achieve innovations, the government must create a mechanism for efficiently overcoming such a "valley of death", though this may be a difficult order to fulfill.

As an attempt or a revision by the national institute, though the effect was partial, the authors took notice of the following: "The ways in which the results were presented to society (patent, papers, reporting sessions, and others) were always planned according to the progress of the research and contact with industry. To propel the results, the scale of the research funding was controlled carefully according to growth. (Page 159 right, subchapter 3.1(2))" The facts that GIRIO created the Shindo Lab and allowed the participation of new researchers may support this point. This was an organizational research management within GIRIO and the paper does not state that an organizational (systematic) research was executed involving the companies.

The "daily exchange with companies (Page 160 left, subchapter 3.2(2))" much like the recent innovation hub function may be useful for the above objective. It is rather questionable that such activities were done intentionally back then, but now, if the corporate researcher spontaneously visits the national institute to engage in dynamic discussions, the time needed to overcome the "valley of death" can be somewhat shortened.

4 Explanation of the PAN carbon fiber developers

Page 160 left, subchapter 3.3

Original: Through the presentation of Dr. Shindo at the Carbon Conference in the United States in 1963, the British carbon researchers realized the advantage of using PAN fiber and started research of PAN carbon fibers.

The following references are added as the basis of this statement.

In Reference [17], there is a description, "Shindo's research result was presented at the Carbon Conference in the United States held in June 1963, and this touched off the PAN carbon fiber researches in Europe and the United states." Also, the following sentence says, "The only conceivable reason that RAE UK started to work with PAN was because it was stimulated by Shindo's presentation."

There is a similar statement in Page 24 left of Reference [18]. The following description can be seen in Reference [19]: "W. Watt et al., *Nature* 213, 690-691 (1967) and *Nature* 220, 835 (1968); referenced Shindo's earlier work, and PAN carbon fibres were first made by Shindo and…."

5 Timeline from the first invention to the innovation

Page 160 right, subchapter 3.3

Original: …And technological transfers were done 10 years prior to the actual marketing of the product.

The time when the product was actually marketed is considered to be 1972, as described in Reference [20]: "The fishing pole and Black Shaft (author's note: name of the actual product) using the carbon fiber reinforced plastic was known in the world from around 1972." On the other hand, the "technical guidance" by Shindo *et al*. called the "manufacture method of graphite fiber" provided to Nippon Carbon Co., Ltd. and Matsushita Electric Industrial Co., Ltd. was given in 1960, and the timeline is as stated in the original text.

The point of this paper is to express the difficulty of the innovation. From the first invention (1959) to the achievement of something that was truly useful (product), diverse and voluminous researches as well as the work of individual researchers, efforts, and time were necessary. The paper does not attempt to describe the ten-year span in a strict manner like a chronology of technological history.

Third anniversary of *Synthesiology*

[Translation from *Synthesiology*, Vol.4, No.2, p.115-120 (2011)]

A roundtable discussion of the authors was held for the third year anniversary of *Synthesiology*. We asked the authors what they gained from writing for *Synthesiology*, and their thoughts on the "Discussion with Reviewers" that is the distinguishing characteristic of this journal.

***Synthesiology* Editorial Board**

Participants of the Roundtable Session

Hiroyuki YOSHIKAWA	Editor,Center for Research and Development Strategy of Japan Science and Technology Agency, AIST
Motoyuki AKAMATSU	Executive Editor, *Synthesiology*
Takeshi KOMAI	Institute of Geo-Resources and Environment, AIST
Makiko SUWA	Computational Biology Research Center, AIST
Yoshiki KINOSHITA	Collaborative Research Team for Verification and Specification, AIST
Koji WATARI	Planning Division, Research and Innovation Promotion Headquarters, AIST
Yasuhiro NAKAMURA	Planning Headquarters, AIST
Koji WAKITA	Geoinformation Center, AIST

Akamatsu

Unlike the conventional academic journals that publish the scientific findings or the results of basic research, *Synthesiology* asks the authors "to write the scenario of the research". In writing papers with a viewpoint quite different from the conventional way, I imagined that the authors might have encountered new findings or gains. Therefore, to commemorate the third year anniversary of *Synthesiology*, the authors got together with Dr. Yoshikawa to discuss their writing experiences.

First, please describe your paper and what went through your minds while you were writing.

What did you want to express in your paper?

Komai

My paper was "Development of a risk assessment system for soil contamination and the application to the social system: processes in synthesiology for practicing an advanced environmental risk management". This research spanned two fields: environment/energy and geology. Unlike the risk assessment for air and surface water, the methodology of the risk assessment for soil and ground water was not established anywhere in the world, and we developed a technology to assess how such contamination may affect human health. To tell you the truth, I wasn't really sure what the difference between a *Synthesiology* paper and a conventional paper exactly was. I described my research in chronological order, and I was sure I organized it cleverly in terms of synthesis. It was reviewed by Vice-President Ono and Dr. Togashi, and the result was terrible: "We have no idea what you are talking about." So, I abandoned the chronological order. What I wanted to express was just one point: "if we have such and such members and such and such composition, it can be realized as a product". In the conventional journals, we must remove such elements and concentrate on the logic only, so I don't think such papers can be readily understood by general readers. While academic papers are important, I think the writing style emphasizing synthesis will become increasingly important in the future.

Suwa

My research topic is "A bioinformatics strategy to produce a project structure of spiral development: comprehensive functional analysis of the drug design target genes", and it is a story of the database creation started in 2001 and the joint research using this database. There was an epic event in 2001 where the entire human genome was decoded. Among that genome sequence, we created a calculation pipeline which comprehensively searches for and conducts functional analysis of GPCR gene that transmits information received from the exterior to the interior of the human cell membrane and is a crucial target gene in drug discovery. The applied result was formed into the functional analysis database SEVENS. It took two years from the start of the research to the publication of the database, or the so-called product realization. I wrote in the paper that this product became the elemental technology for the next study, and major joint researches happened cyclically. In the field of bioinformatics, the time required to produce a result is relatively short. Moreover, we can choose practically any subject which allows us to move forward quickly, and we are able to expand the research plan with several joint researchers.

In writing the paper, the part I had most trouble with was to “show the research scenario”. In this research, I can’t remember ever making a scenario. If I had one it was for the first few years. From then on, the research developed spontaneously, and I just rode along. However, I do believe that as a consequence I was able to take the shortest route.

In a conventional paper, you write up the optimal data after everything is finished to make it look neat. Dr. Komai said, “I quit the chronological order and reorganized things”. In my case, the chronology itself bred new developments, so, in my case, I thought the chronological order was important. Another point is, in a conventional paper, I don’t think I can ever write failure stories. If I write, “I failed”, I won’t be allowed to continue. I find it interesting that this journal allows us to argue that the failures help the next step forward.

Another point that I found difficult was that I had to explain things, so people of other fields could understand. Dr. Akamatsu reviewed my paper and said, “This is totally incomprehensible”. To use terminologies that can be understood by people in any field, that was very difficult.

Kinoshita

With my colleague, Dr. Toshinori Takai, I wrote a paper entitled “A field-scientific approach to clinico-informatics: towards general models of technology transfers”. about the technical transfers conducted in the Research Center for Verification and Semantics, over six years, until March 2010. System verification is a technology to find and fix bugs or the faults in information systems. At the Electrotechnical Laboratory, before it was incorporated into AIST, we conducted research in semantics of programming. When AIST started, I thought that a person, like me, engaging in semantics research could contribute to society through research in system verification. If one follows a waterfall style model, however, taking steps from basics to application, the day will be over before making any contribution to society. Therefore, I decided to try concurrent engagement in both the academic research and the technological transfer. It did not seem impossible, as the people in universities engage in both education and research, and while not all their research link directly to education, they realize both. Moreover, some interesting things happen because of theinteraction between research and education. So, we decided to try doing research and technological transfer concurrently with industry-academia collaboration. The word “clinical” was borrowed from medicine as a way of drawing an analogy between system verification and a doctor’s diagnosis. Finally, “field science” is a term coined by the cultural anthropologist Dr. Jiro Kawakita, who wrote a book about abduction which also introduces the famous KJ method. In spite of the importance of abduction, it had not been discussed very much in the context of Full Research. So, we wanted to emphasize it in our paper.

Watari

I submitted a paper with a simple title “A strategy to reduce energy usage in ceramic fabrication: novel binders and related processing technology”. It is a write-up of an R&D for the ceramics manufacturing process in industrial operation. The point of the research is to understand the relationship between the binder and the energy consumption in ceramics manufacturing, and we implemented energy savings in manufacturing through this new binder technology.

In writing the paper, I had a personal battle of whether I should write about the results obtained with private companies. However, as I wrote, I understood that there was a story of how we created the scenario under what thinking and what were extracted among which elemental technologies, and I was finally able to finish the paper.

Dr. Yoshiki Kinoshita

Dr. Koji Watari

I also realized that difficult research topics and social demands could be solved by clarifying the topics and synthetic elements. I am extremely honored that I was able to publish in *Synthesiology* through the joint research with corporations. Thank you very much for the opportunity.

Nakamura

My paper is "National electrical standards supporting international competition of Japanese manufacturing industries: realization of a new capacitance standard and its traceability system". For example, the company that makes the scales is responsible for assuring the precision of the "size of an object". The company regularly checks that their standard is accurate, by bringing the company standard to the calibration laboratory. The calibration lab has its standard calibrated by an authoritative institute, and finally it is traceable to the national standard. As you can see, there is a "national metrology standard" for all physical quantities, and currently, almost all metrology standards are set by AIST, which maintains, manages, and provides them to industry. Therefore, our mission is to set the national metrology standard, to guarantee the correct values for measurements in industry, and thereby supporting the activities of the Japanese manufacturing industries in the international market. The capacitor is one of the major Japanese products, and recently large capacity capacitors are in demand for batteries. The precision level demanded for capacitance standard is increasing. I wrote about how we developed the new capacitance standard that matches the current demand although the national standard for capacitance existed before, and how the new standard was provided to society through the calibration labs.

When I am told to "write a scenario",I must look back on how I arrived here. Since the national standard is a standard of the highest order, it must have the highest precision possible. We always aimed for the world's best. Yet, by writing this paper and looking at the industrial demands and comparing the standards of other countries, I was able to think in terms of what would be the satisfactory specification that could be achieved in the shortest time and at the most reasonable cost. Another point is whether the provided standard is being delivered to the sites of production. At the production sites, the pressure of time and cost is extremely high, and many people say, "We don't need the national standard level precision at the production sites. Give us something that is easy to use, costs less, and can be used quickly, even though the precision is slightly poor". Therefore, I reviewed my scenario and conducted the desired R&D. The paper was written as a story that followed an actual case.

Wakita

The title of my paper is "Creation of seamless geological map of Japan at the scale of 1:200000 and its distribution on the web: for maximum accessibility and utilization of geological information". Seamless means that there are no joins. The Geological Survey of Japan, AIST created the geological maps for the wealth and military power of the nation in the Meiji period and for the exploration and development of the mineral resources for recovery after the World War II. After that, the objective for geological information research became vague, and geology started to concentrate on, for example, how the Japanese Archipelago was formed or how certain rocks and minerals were created, or the *Type 1 Basic Research* as stated by AIST. When I joined the institute, I seriously studied how the Japanese Archipelago was formed, and for a long time, I produced the geological maps as a result of that study. As a result, the geological maps of Japan became diverse according to the interests of the researchers in charge. Therefore, after the establishment of AIST, we set up the seamless geological map project where we reconsidered the geological map in terms of being useful to the users, recreated the maps using the latest information under a uniform standard, and the boundaries were joined digitally according to the latest findings. Several years have passed since the maps were completed and utilized, and I wrote in my paper describing the basic principles, the process of creation, and the ripple effects and responses. There is no place to publish a paper on how the database was created or how it was useful to society, and I thought it was an excellent opportunity. A long time ago, this field was a practical science that became pure science, and now it is returning to practical science. I am grateful that I am working in such a time, to be able to publish my work.

Dr. Yasuhiro Nakamura

Dr. Koji Wakita

What was gained from writing the paper?

Akamatsu
I think the common experience is that the authors look back on their studies and realize that they were actually following some story or scenario. I am interested to know whether this realization has been useful in conducting your other studies.

Nakamura
In case of standards, the focus tends to fall on the development and provision. Now, I can say to other people in the lab, “You must think of the scenario for how the standard will be diffused after it is provided”.

Akamatsu
That means that the process of actually diffusing the product was not shared among the researchers. I get a similar impression for geology.

Wakita
After writing the paper, for Phase 3, the project called the next-generation seamless was created, and collaboration with JIS and national standardization led to expanding utilization in the GEO Grid system. I feel the ripple effect in that, in collaboration with the information technology field, the user-orientation of how geoinformation can be utilized became clear among researchers including many young researchers.

Komai
The starting line is the desire to develop a methodology that will ultimately become a national standard, and that this is incorporated into the legal and social systems. How to diffuse it in society, while appealing to the ministries and agencies, solving the contamination problem without spending much money; these are the hard-and-fast rules of risk management.

However, I am having a lot of trouble now. The product realization was done and the social system started spinning, but things stagnated due to the “cost and risk” relationship. We plan to develop an economic model in Phase 3, but I feel that we’re hitting the second “valley of death”.

Kinoshita
We tried to conduct academic research and technology transfer concurrently. It seems this brought about cases where a great burden was imposed on the researchers involved. We did not want to be narrow minded, i.e., we did not want to think only about academic research nor to seek only for industrial values. Because of that, there were some cases where some researchers felt overloaded.

Akamatsu
I think the scientists may be thinking that the sociological methodologies that Dr. Kinoshita used to solve the on-site issues may not be that valuable. By understanding that there is a theory different than that in natural sciences and that it is part of how the discipline is done, the researcher may be relieved or may feel a bit more comfortable.

Kinoshita
Comparison of social and natural science is interesting. I, however, wish to compare quality and quantity. Where quantitative discussions are possible, those are preferable to qualitative discussions because they enable much more precise arguments. However, there often are many kinds of quantity to measure and it is not necessarily clear which is to be chosen. If that is determined injudiciously, the whole argument would be like a castle built on sand even if rigorous and detailed quantitative considerations are made on it. We are faced with systems with many kinds of quantities in computer science, probably many more than in physics and chemistry. So, analysis which justifies the selection of quantity to be measured is necessary before we start a quantitative theory. Such discussion will naturally be qualitative. Some people tend to say that qualitative argument is less precise than a quantitative one. It may be true, but a qualitative argument would be much more precise than a quantitative argument based on careless choice of the quantity. I wish to emphasize this point.

Komai
Currently, what troubles me the most is the “social approach”. Although risk assessment is a scientific approach, there is a

Dr. Takeshi Komai

Dr. Motoyuki Akamatsu

matter of whether the general public will accept the result of risk assessment. When I talk to the local government or company, it is about social acceptance, and I think AIST should step into that field. Well, there's a problem of how many people with sociology background can be employed here.

Yoshikawa
I've been thinking about the same thing for a long time, and that was why I set up "design science". I've been told that "design is not a discipline", and the individual designers just made things in solitude. There was no accumulation, and there were no advancements like in physics, and it's been viewed with some degree of discrimination because it cannot be expressed quantitatively, and therefore it's not a science. In a wide sense, there's a structure where the science department is important but the engineering department isn't. I am trying to think of the method for "making science out of qualitative issues". The fact that many issues can only be handled qualitatively means that it can be a major issue as the subject of science, and the researcher involved deserves respect.

Kinoshita
While I am not a physicist, I have a science background. In my field, many people who studied in faculties of science seek for qualitative discussions, and many people from faculties of engineering tend to seek for quantitative arguments, such as computer performance, etc. I think it's the people from faculties of science where the qualitative discussions are sought that are discriminated.

Akamatsu
In the case of Dr. Suwa, the goal is not set with quantitativeness alone, but qualitative element enters to form a cycle. I felt that the next step couldn't be taken unless some sort of spiral is set off.

Suwa
It's exactly as you say. While the qualitative factor cannot be explained clearly, it is there for sure, and the quality changes throughout the research process. If there is an academic demand at some point and the daily trendiness mixes in, a certain vector is formed. We must decide what we should do about the vector as we come across it. As a cycle, I think we return to the basics again and again.

Akamatsu
Dr. Watari emphasizes that the story is important.

Watari
I've been in charge of various projects in the Research and Innovation Promotion Headquarters, and the way of thinking of synthesiology was extremely instructive for understanding the start-up of a project and its topic. Recently, we're promoting another activity, the promotion of joint research with companies. As a recent trend, we find that it's difficult to determine the topic of joint research between the AIST and the company people. That is because they do not have the synthesiology to breakdown the subject based on the topics they are studying. To get the blooming results, we must think about which elemental technologies to select or which technologies should be developed as the target of basic research. I think synthesiology is necessary to send the technology into society, such as understanding the other's demand or creating a scenario through close communication. I feel that the study of building synthesiology may be the most important activity for AIST right now.

Kinoshita
Joint work with industry sometimes brings about a language barrier. In some cases, I found that there was some fundamental misunderstanding half a year after we started talking.

Watari
I think narrowing down the subject is a preliminary preparation stage, but the vocabulary is difficult even within AIST.

Akamatsu
I think it is good training to write for *Synthesiology* so people of other fields can understand.

Dr. Hiroyuki Yoshikawa

Dr. Makiko Suwa

Watari
Normally, I have no idea what the research papers of other fields are saying, but I can get the flow when I read *Synthesiology*. When I read the questions first, I can understand what other people consider as the main issue and what the point is. I think the good thing about *Synthesiology* is that a reader can understand a paper of any discipline if he/she has a basic knowledge of science.

Through the discussion with reviewers

Akamatsu
One of the characteristics is the discussion with reviewers. How do you feel about the quality of the discussion with the reviewers?

Komai
It was vey educational. I had about two exchanges, and when I wrote the scenario, everything became clear, and I am grateful for this experience. I have abundant dealings with companies, and the people of the companies are dead serious about manufacturing and product realization. I feel that the R&Ds at AIST do not have a scenario all the way to the final product realization. I feel that by writing the whole scenario, you can propose the research project with the fastest route to product realization.

Suwa
First, I was thinking I had to explain my research within the framework of AIST's Full Research. When I tried to fit it in, there were some kinks that I found rather uncomfortable. I was advised to "freely present what you designed", and I felt better about writing. It was very educational because I was able to look back on my research. I think the paper turned out excellently. However, I think this kind of discussion can be directed only to the employees of AIST. I assume you will be seeking submission from people outside of AIST. In conventional papers and journals, there isn't much exchange of opinions for the reviews, and I am worried that there aren't any people outside of AIST who will spend time on this.

Akamatsu
Dr. Yoshikawa, what do you think after hearing other people's comments?

Yoshikawa
Dr. Komai extends into the field of science and technology policy and system design, not just the new risk assessment technology for soil and ground water contamination. Dr. Watari covers various fields to realize the great objective of energy-saving process for ceramics manufacturing. I call this the "design of super-discipline", and the "synthesis" is possible when the individual researches are integrated. Dr. Suwa integrates wide-ranging researches in bioinformatics that is the combination of life science, information and communication, and ICT. Dr. Kinoshita's clinico-informatics discusses, in some sense, the design of synthesiology or the essence of synthesis. Dr. Nakamura engages in a wide range of research with the increasing importance of standard and globalization in the background. In Dr. Wakita's seamless geological map of Japan, accumulated knowledge was not written up as a research paper until now, but with this paper, the larger issue in the background was extracted.

I think that the science handled in *Synthesiology* has a universal structure, though rather abstract, in the background of diverse issues. From the accumulated papers, it may be possible for us to extract something that is different from the methodology of *Type 1 Basic Research*, but just as important; something that we can say "this is *Type 2 Basic Research*". That is something which I look forward to.

Expectation for *Synthesiology*

Akamatsu
Finally, please express your expectations for the journal *Synthesiology*.

Kinoshita
I've worked on the scenario based on the thought that whenever you discuss safety and reliability there is always risk assessment, and that dependable and reliable software should be constructed in a certain way. I've never thought of generalizing this to other fields of technology. So, Dr. Yoshikawa's comment was an eye-opener for me, and to pursue a common structure in these kinds of scenarios is interesting. Hopefully, there will also be other authors who will take part in the pursuit of this direction.

Suwa
If it is called science, it must be reproducible. I think it would be interesting to categorize the structure of researches in linkage with the results, to study how many percentages of researches succeeded or failed when some method was taken. Also, considering the trend in the world and the interaction with the exterior environment, I think it will be helpful to see the results of the research group in a certain era and the changes in reproducibility over time.

Akamatsu
That means that one may fail using the same method depending on the changes in the social situation. I hear suggestions that people would like to read stories of failures, but you'd have to be brave to publish that.

Wakita
In my field, recently we are discussing "geodiversity", and we hope to propose a new discipline as synthesiology of the fused disciplines. I hope you open roads for publishing cases of failures and successes of attempting such fusions.

Nakamura
I think that standard is a common infrastructure even in synthesiology, and I am impressed myself. I think the collaboration and fusion with other fields can be done through the keyword “standard”.

Watari
Recently, there’s talk within AIST that “fusion of fields is important”, but the major issues in society are all already fused. Since this is a good opportunity, I want people who wrote for *Synthesiology* to get their hands in practical science. I think the next step is to get down to practice, like when you break down a topic, you see there are such research elements, and you can actually do such projects.

Akamatsu
So, you mean don’t just write and feel important, but get down and do it !

Komai
I wish the young researchers would have this attitude. I speak to sociology students in collaborative lectures, and last year, I started talking about synthesiology, and they are showing great interest. To have an overview of the whole and to engage in solid synthesis are important for people studying social sciences as well as for those seeking employment in companies, and it is important that this thinking diffuses among the young people. Also, this year, I was a moderator at the Innovation School, and the post-doctorate level people of system science and bio fields were particularly interested.

Yoshikawa
I think the strategic projects are created based on the thoughts of *Synthesiology*, but I hope it becomes a bit more analytic so it can be appealing to people outside AIST. In the Fourth Science and Technology Basic Plan, we have the problem-solving innovation, but we have no methodology. I would like you to make a presentation, “Here is the methodology.”

Akamatsu
I would like to aim for not just writing papers based solely on what I practiced, but for providing verification as I re-practice making use of what I gained through writing the paper. Thank you very much for your participation today.

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
Revised August 5, 2010

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:

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Letter from the editor

Four research papers and a paper supplement are delivered here in *Synthesiology* Volume 4 Issue 2. The subjects of the papers cover diverse fields: information, robots, sensors, photonics, and materials. All papers are written in a manner to facilitate understanding of readers in different fields as well as general readers. The Editorial Board has received readers' comments responding to the questionnaire survey for each issue that state that one feature of the *Synthesiology* papers is that they are readily understandable by researchers in different fields.

A roundtable discussion about writing research papers for *Synthesiology* was planned for this issue with six authors and Prof. Hiroyuki Yoshikawa, former president of the National Institute of Advanced Industrial Science and Technology. The *Synthesiology* papers have a distinct and novel form completely different from those of conventional academic journals, so the participants of the roundtable discussion freely talked about difficulties, elaborations, and benefits coming from the writing of *Synthesiology* papers.

Many authors gave comments in the roundtable discussion that they realized through writing the *Synthesiology* papers that, for a series of their own researches, there were clear research scenarios in their minds which were related to each other in a consistent manner. As Editor-in-Chief of *Synthesiology*, I was able to confirm again the uniqueness and significance of *Synthesiology* from their comments. I also agreed with the comments that the approach in which elements are identified and integrated/synthesized is useful for planning and evaluating research projects as well.

It is another feature of *Synthesiology* that discussions are carried out between the reviewers and the authors. The discussions are presented in *Synthesiology* following the individual texts of their papers. It seems to me that these are good stimuli for the authors. It was pointed out that the discussions highlight the essences of the papers and help the readers' understanding.

I would be grateful if the readers would keep being interested in *Synthesiology*. If there would be an opportunity, I would like to suggest to you, the readers, to present your research in this new format of research papers. I believe that it will help you review your scenarios and add new perspectives to your own researches. We welcome contributions to *Synthesiology* from researchers in a wide range of fields of science and technology.

Editor in Chief
Akira Ono

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