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Biomedical Micromachines

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Biomedical Engineering (BME) has two facets: one is to apply scientific and engineering expertise to medical science and medical treatment, while the other is to apply the wisdom of living organisms to engineering. The figure shown below makes a comparison between the hierarchal structure of a bio-system and that of an artificial device. As the figure shows, the bio-system is typically characterized by:

① Being a molecular machine: The constituents of a living body, including DNA, protein, enzymes, polysaccharides, and fat, are functional molecules with unique characteristic performances, working, respectively, as a machine sharing a variety of roles, such as information suppliers, sensors, effectors, and actuators.

② Being a cell device: According to reports, the human body consists of 60 trillion cells. However, each cell, tens of microns in size, independently metabolizes, functions, conforms to the environment, and even proliferates, thus offering various design principles for micromachines.

③ Being an information-built-in system: Information basically necessary for the bio-system does not come from the outside, but is inherent in itself. This information emerges whenever necessary, thus enabling life to continue.

④ Being a bioholonic system: Various cells, tens of trillions in number and with over 200 types, work jointly, integrated toward a goal of life maintenance, to make up a bio-system. These cells never follow instructions from the outside or commands from a cell of supreme power (the president cell), but have integrated function as a decentralized and autonomous system harmonized as a whole although they may appear to be working separately. This is known a bioholonic, which Dogen, a famous priest, interprets in his book "Syobo Genzo" as "Life is a representation of integrated mechanisms as a whole". It may well be considered as a model in the multi-parallel unit control of micromachines.

⑤ Homeostasis (dynamic equilibrium): Life may well be regarded as an ability not only to independently establish an extremely orderly state with a nearly-zero entropy, but also to maintain this state. This orderly state is maintained not statically, but dynamically accompanied by metabolism. Even when damaged, it tries to restore the structural and functional order via self-reparation action. Homeostasis originally stands for a dynamic equilibrium of the physiological state exhibited by body temperature, blood pressure, hormones and so on. In a broader sense, however, it may represent a state in which the orders of function, structure, and form are maintained stably in an incessant flow of energy and mass.

⑥ Inherent time clock: As the words, chronobiology and circadian rhythm, indicate, the bio-system has an inherent clock, ticking away mostly for the reversibly repetitive phenomenon with a cycle of 24 hours as well as for the irreversible phenomenon of aging. The human erythrocyte lasts 120 days on average. However, the blood stem cell produces erythrocytes at a speed of over 2 million per second to make up for this short life. This instance clearly shows that a standard clock is necessary to coordinate the work among the many units. A life flows wholly under the control of the uncertain passage of time, but timing will be indispensable for its wisdom.

If we want to develop a new technology to be truly useful in BME, it is necessary for the respective fields in BME to closely associate and fuse with each other toward the same image. Under consignment to MITI and NEDO, we are to establish an ME-collaborative Laboratory System in order to conduct effective development and evaluation of BME technologies and devices in Japan. It is expected that consistent fusion of various BME technologies in the above system will lead to the development of BME in the 21st century, and further to the birth of BME-induced micromachines.

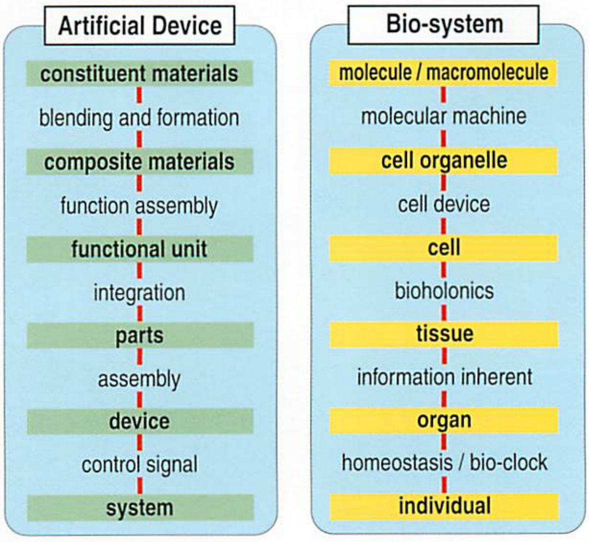

Fig. 1 Hierarchal architecture of Bio-system and Structure of Artificial Devices

New World of Micromachines Based on Supramolecular Assemblies

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1. Introduction

It was only in 1990 that Japan Advanced Institute of Science and Technology was founded as a national university with postgraduate courses specifically designed to answer the need for new research education toward the 21st century.

The School of Materials Science was opened seven years ago with a target for the research of an interdisciplinary area encompassing the three areas of physics, chemistry, and biology. Yui Laboratory, started simultaneously, focuses mainly on the study of the design of supramolecular assemblies for the drug delivery system and the chemomechanical system. This study stems from a grand concept of our laboratory to design new performance macromolecules that can only be obtained by building new molecules after the pattern of the mechanism and activity of a living body.

What are supramolecules ?

Supramolecular assemblies, unlike the familiar straight chain macromolecules, are composed of a group of molecules formed by non-covalent-bond molecular interaction, and which, comprising entirely new functions and properties, are expected to become the raw materials of the next generation. A typical supramolecular assembly is polyrotaxane, characterized by the structure in which straight chain macromolecules pass through many cyclic molecule cavities. Ogata et al. synthesized a pseudopolyrotaxane with cyclodextrin for the first time by polycondensation of an inclusion complex prepared from cyclic molecules and monomers. Particularly in recent years, Harada et al. for example, are actively studying the formation of pseudopolyrotaxane from a-cyclodextrin (α-CD) and poly(ethylene glycol) (PEG) or the synthesis of polyrotaxane with bulky substituents introduced into both terminals. In both of those studies, however, attention is focused on the design of this characteristic structure only on the basis of the recognition of molecules among the components. This means that no performance design has been made thus far with the structure in question being positively taken advantage of.

Since its launch, our laboratory has been studying a new biodegradable macromolecule with supramolecular structure with the intention of realizing a new function distinctly remote from the function and the point at issue, fatal to the biodegradable drug carrier based on the conventional structure. Furthermore, it is vigorously designing a stimuli-responsive polyrotaxane that moves in a similar way to the mechanism of driving the muscles in a living body as a molecule driving element. This kind of molecular design is very important for the basic study of new macromolecular micromachines. This study of the supramolecular assembly will be described below; specifically, the drug carrier design using a biodegradable polyrotaxane and the chemomechanical system design using a stimuli-responsive polyrotaxane.

2. Possibility of biodegradable Polyrotaxane as a Drug Carrier

Our laboratory is designing a biodegradable polyrotaxane into which an enzymatically degradable group is introduced as a molecule with bulky terminals. That is, L-phenylalanine (L-Phe) is introduced to both terminals of the PEG chain that has passed through many cavities of α-CD, via enzymatically degradable peptide bonding. It is possible to improve water solubility to a marked degree by chemically modifying the α-CD in the polyrotaxane in various ways, for example, by hydroxypropylation (HP) of α-CD. The resulting polyrotaxane has some 20 to 40 PEG molecules that have passed through α-CD depending on the molecular weight of PEG (2000 - 4000) used, and is characterized by easy dethreading of α-CD from the PEG chain after the terminal peptide groups have been degraded [1].

In the design of an enzymatically degradable mac-

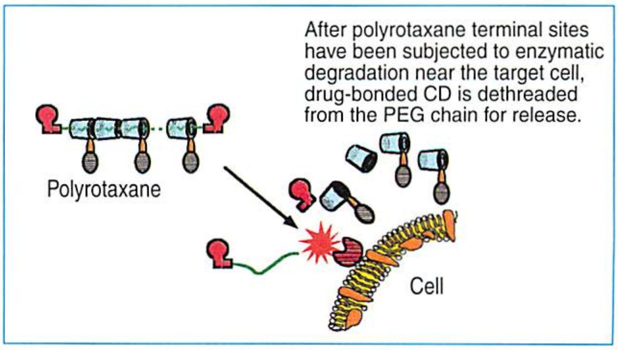

Fig. 1 Drug carrier using a biodegradable polyrotaxane

romolecule, it is considered possible to degrade the macromolecule using the enzymes that emerge specifically in the tissue and cell or disease-derived enzymes. It has been pointed out, however, that, in the case of conventional macromolecular drug, in which drugs are introduced to the main chain of the macromolecule via oligopeptide spacers, the drug is found to be less enzymatically degradable due to the molecular association between the oligopeptide spacers. It may therefore be safe to say that the macromolecular drug into which drugs are introduced to the side chain of the macromolecule in a manner as described above is inevitably accompanied by structure-related problems.

The biodegradable polyrotaxane in our laboratory has taken up is characterized by its supramolecular assemblies, and prescribed so that HP-α-CD is released by the enzymatic degradation of the terminal groups although HP-α-CD and the biodegradable groups are not bonded. It follows then, that if drugs are introduced to this HP-α-CD, it is possible to release the drugs by taking advantage of the dissociation of the supramolecular assembly with the degradation of the accompanying terminal groups. (Fig. 1).

Polyrotaxane has been found to be associated with drugs bonded under a physiological environment, through molecular interaction in an anisotropic state by the static and dynamic light scattering measurements of the biodegradable polyrotaxane.

It is already known that the polyrotaxane as above-described is completely enzymatically degradable irrespective of the number of associations. This is noteworthy, because it is in contrast with the fact that the conventional macromolecule drugs, association-dependent, become less enzymatically degradable. The biodegradable polyrotaxane is therefore characteristic as a drug carrier.

3. Possiblity of Stimuli-responsive Polyrotaxane as Driving Element

It is possible to design a stimuli-responsive macromolecule with a mechanism entirely different from that of the conventional one if a cyclic molecule can be moved along a linear macromolecule chain in polyrotaxane. This is entirely different from the conventional stimuli-responsive macromolecule in the deformation mechanism, thus enabling the design of a driving element excellent in terms of response rate and energy conversion efficiency.

Accordingly, our laboratory is analyzing the movement of β-CD in response to the temperature after the synthesis of polyrotaxane with bulky substituents introduced to both terminals of ABA-type block copolymer composed of PEG and polypropylene glycol (PPG) that has passed through the cavities of β-cyclodextrin (β-CD). The findings obtained thus far reveal that β-CD spreads over the block copolymer at a low temperature of 10°C, and assemblies at the PPG site in the center at a higher temperature of 50°C (Fig. 2) [2]. This new driving mechanism based on the basic principle of movement of a cyclic molecule in polyrotaxane in response to the stimulus is similar to the sliding motion of actin and myosin as seen in the muscle contraction in a living body. Since the design of a driving element is under way on the basis of the systematization of stimuli-responsive polyrotaxane (Fig. 3), it may be safe to say that a supramolecular structured micromachine will be created in the near future.

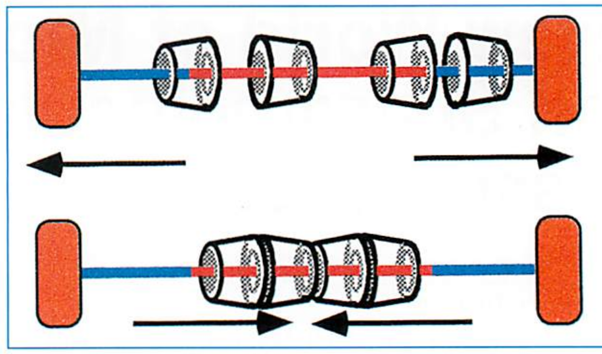

Fig. 2 Reversible function of β-CD sliding along a polymer chain

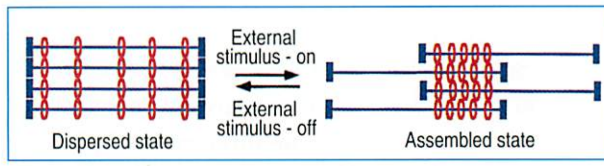

Fig. 3 Chemomechanical architecture utilizing stimuli-responsive polyrotaxanes

4. Conclusion

As described above, the possibility of designing a macromolecular micromachine has been introduced through the design of a supramolecular structured performance macromolecule. The foregoing concepts are unexceptionally pioneering research themes. The author would therefore like to contribute to the creation of a supramolecular structured micromachine by pursuing this study further.

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Research on Basic Micromachine Technology for Fiscal Year 1998 (Part I)

Since 1992, the Micromachine Center has taken up a various seeds of technology as themes for joint research by academic governmental and industrial sectors, aiming to reinforce basic technologies by searching for technology seeds, especially in the scientific and technological fields, that are necessary to build various micro systems. In fiscal 1998, research has been carried out on nine themes. The following articles are summary reports on five themes among them.

Investigative Studies of High-precision Micro-processing Technology and the Motion Measurement of Micro-mechanisms

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To promote the commercialization of micromachines or micromechanisms, it is necessary to 1) process high-quality components, 2) understand the physical properties of the materials necessary for design, and 3) evaluate the resultant three-dimensional motion of the micromechanisms. The above three points were therefore taken up for the studies.

First, the problems indigenous to micro-processing were unravelled. That is, the energy generally required for removing a unit volume becomes proportionately larger as the unit volume to be processed becomes smaller. This makes it difficult to remove the material by concentrated mechanical stress as in machining. In addition, the material to be processed should be considered as anisotropic and heterogeneous, though it can be assumed as isotropic and homogeneous in macro-processing, thus making it even harder to process. To obtain the desired results, it is necessary to have a comprehensive understanding of the properties of the materials to be processed as well as to select the most appropriate processing method or to devise a combination of processing methods.

Fig. 1 shows the approximate relationship between the processing size and the attainable accuracy of various processing methods. The processing size on the x-axis is the length measured in the direction of processing as the figure shows, indicating a processable range (length) under general processing conditions. In laser processing and atomic manipulation, however, the length in the horizontal direction against the material is employed because the operation like cutting are often used. The y-axis gives overall processing accuracy, an accuracy achievable, including a scattering when processing more than once. The processing methods that are located in right-hand and lower side in the figure can process over a wide dimension range with high resolution. The characteristics of each processing method are shown with specific range because they vary with the processing device and conditions. It should be noticed that the data about characteristics has not been verified and presumptions are included.

Here, a relative accuracy ratio is introduced, which can be obtained from the ratio of the minimum value of the overall processing accuracy on the y-axis of the figure to the maximum value of the processing size on the x-axis. In mechanical processing including cutting and grinding, accuracy to the extent of 1 μm, can be achieved over a wide processing range in order of the meter: thus a relative accuracy ratio to a level of 10^{-6} can be achieved. In some of the other micro-processing methods shown in the figure, however, accuracy is limited to a low level of 10^{-3} - 10^{-4}. Full knowledge of these processing characteristics and a combination of appropriate processing methods are considered essential to the stable manufacture of micro-parts, and to the success of micromachines. Moreover, when we come to consider the influence of the material structure, it appears desirable to positively utilize the regularity of single crystals or to employ isotropic, homogeneous amorphous materials rather than to use polycrytals considered discrete.

Next, the problems about the material properties related to micromachine parts are arranged, and the investigation of the recent evaluation methods was instigated.

Finally, a measurement method for the three-dimensional motion of micro-parts was also investigated. A method was proposed in which images captured by a high-speed video camera on a microscope were analyzed. Images of micro-objects are generally weak in contrast and obscure in outline. It was found that an appropriate preprocessing and filtering is necessary to improve the final accuracy.

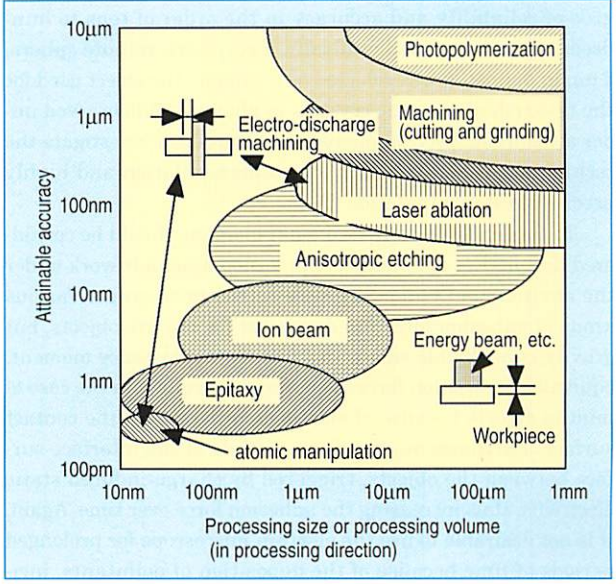

Fig. 1 Comparison of processing characteristics

Investigative Study of High-precision Assembly Technology

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Along with the development of various sensors and medical equipment now under study in the micromachine project, emphasis has come to be placed on the technology of assembling microparts below 100 μm in size. This is not only because the advanced semiconductor microprocessing technology has enabled the realization of steric structures without assembly, but also because the technology of assembling those processed steric structures has been recognized as being indispensable in terms of the practical mechanical system. Accordingly, the investigative study in question aimed at a possibility of enlarging the range of microparts that can be assembled.

At present, a system has been employed for mounting precision information equipment, in which a variety of parts can be assembled with a high degree of accuracy and at high speed chiefly on the basis of the information obtained through the high-speed visual processing of optical microscope images. However, it sometimes becomes impossible to process object parts by the optical sensing method because of its physical limits when they become immeasurably small. With this case taken up as an example, highly precise assembly may be considered possible if an electron microscope is used instead of the conventional optical microscope. However, this process is nothing but an extension of manual work, because the assembly under the electron microscope now in practice is carried out manually on a trial-and-error basis. Automation is therefore required via optimal skill by visual control, based on the granule dynamics under the electron microscope, if the above practice is expected to evolve further into the technology of manufacturing the granules.

This investigative study has clarified a technique of automatically manipulating granules with the intention of assembling microparts in the order of micrometers with a high degree of reliability and accuracy in the order of tens to hundreds of nanometers. Specifically, a polymeric minute sphere, 2 μm in diameter, was selected as a sample, the object used for the research of photonic crystals in physics, and observed under a scanning electron microscope in order to investigate the techniques of highly reliable pick-manipulation and highly precise place-manipulation.

To this end, we discussed what element should be considered first for the automation of precision assembly work under the environment of a scanning electron microscope. Various kinds of adhesion force are dominant for minute objects, but gravity is negligible small. In addition, a resistance moment, equivalent to friction force, also works for rolling in the case of minute objects because of elastic deformation at the contact surface. Furthermore, bonding proceeds at the interface surface between the objects, triggered by charge-induced static electricity, thus increasing the adhesion force over time. Again, it is not desirable to use the electron microscope for prolonged periods of time because of the deposition of pollutants, incidental to observation. It was decided to clarify what factor is responsible for the result of the method of manipulating minute objects by the analysis of the dynamic system of minute objects, heretofore carried out manually, so that effective pick- and place-techniques can be established even under the electron microscope. It was also decided to establish a three-dimensional positioning technique using scanning electron microscope images and force sensors to realize the above objective. Generalized Hough conversion was employed for measuring the relationship of the relative position in in-picture direction between the handling tool and the object. This method enabled measurements with an accuracy of 10 to 40 nm to be made, although this was dependent on the shape of the object to be measured. An accuracy to the extent of 100 nm was also realized by contact detection based on force detection relative to the direction of depth.

Taking the adhesion force and rolling resistance moment into consideration, and also the dynamic system in which the adhesion force continues to increase over time after contact, a method was studied to select a minute sphere with a high degree of reliability and to place it with a high degree of accuracy. In the selection process, it is important to peel off the interface between the object and the substrate. To this end, it is effective to employ a method to eccentrically push a portion, slightly out of the center of the sphere, toward the substrate. Again, it is effective for high-accuracy placement to employ a contact-point shearing method by which to move the tool in the direction of the pushing force rather than in the direction of the tangent line against the surface of contact between the handling tool and the sphere. It was made clear experimentally that, when a 2-μm-diameter sphere was pushed in eccentrically at an eccentricity of 100 to 200 nm, selection was successful without even a single failure in the trials numbering 10 to 20 times, and that an object can be set in position with an accuracy of 140 nm when the contact-point shearing method is used in such manner as to push the object in a direction 10 to 20 degrees against the contact surface. The foregoing means that correct understanding micro-world dynamics, considered uncertain to date, enables the behavior of minute objects to be controlled only by choosing the orbit of the manipulator in an appropriate manner.

Henceforth, it is necessary to 1) generalize a manipulating technique so that it can be applied to various objects with different components and shapes, 2) develop handling tools for easy manipulation by controlling not only the orbit but also the charged state or static electricity of an object, and 3) establish a more profound understanding of the adhesion force of minute objects under an electron microscope environment.

Investigative Study of the Flow of Liquid in Minute Pipelines and Flow Resistance Reduction Technology

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In this study the possibility of reducing loss from liquid flow and the problems involved were investigated. A flow is laminar because of the microscale flow site. This also led to the investigation of the peculiar phenomenon of a macromolecular flow with emphasis placed on a highly water-repellent wall considered to be effective for resistance reduction.

The devices included in the minute pipeline are a valve, a pump, and a sensor. The applications of these devices are predominantly medical as in chemical analysis and chemical injection.

With the understanding that the minute pipeline is in a range of 10 to 100 µm in scale, specific examples of application were instigated only to find that investigation has scarcely been made relative to the changes in flow resistance that accompany miniaturization, the problems involved, and the effect of resistance reduction. An ink jet stream was therefore taken up as one example of the application of a flow in a minute pipeline as shown in Fig. 1, to investigate the influence of pressure loss on the flow site. The circular pipe is about 10 µm in diameter, the velocity of the jet stream is about 52 m/s, and the flow is laminar with a Reynold number of Re ≒ 300. The objects of reduction are viscous friction losses at the outlet and inside the tube. The findings revealed that about 60% of the pump pressure applied to the system was lost, an indication that the reduction of loss in a minute pipeline poses a serious problem. The method of manufacturing a highly water-repellent wall and its characteristics were therefore investigated. As one of the methods of manufacturing the highly water-repellent wall of a minute pipeline, the plating method was taken up. A concrete example is shown, in which plating was applied to a minute crack. This method resulted in a highly water-repellent wall with a film thickness of several mm and a contact angle of about 170°. Although it is conditioned by the use of aluminium as its base material, it became apparent that this method could be used for a minute pipeline. On the other hand, low molecular weight PTFE particles were selected for their water repellency, to formulate solvent-based water-repellent paint from a particle-dispersed composite material. A study was made of the paint relative to the problems of its water repellency and adhesiveness and the mechanism of its water-repellency. It was then revealed that the presence of a gas phase in the interfacial phenomenon observed at the interface between a liquid and a solid carries weight when the mechanism of water repellency is considered.

On the other hand, the Navier-Stokes equation was employed, relative to the characteristics of the effect of reducing the resistance affecting pressure loss in the highly water-repellent circular pipe, to analyze the pipe friction coefficient, in which Navier's hypothesis on fluid slip was used as the boundary conditions. Fig. 2 shows the findings, which reveal that the pipe friction coefficient of the highly water-repellent around the pipe, λ, depends on the dimensionless number, S (= µ/aβ), including not only the Reynold number, Re, but also the viscosity, µ, the radius, a, and the sliding coefficient, β. In the future, it will become necessary to measure or predict the value, β, at the microscale site. Furthermore, the effect of the addition of water-soluble polymers on friction reduction was investigated from the viewpoint of changing the physical and flow characteristics of liquid. As already pointed out, this is a problem related to an apparent slip on the pipe wall.

As described in the above, this study presented controversial points for achieving the effect of reduction of liquid resistance in minute pipelines as well as the problems to be solved. The necessity of verification through future experiments has thus been clarified.

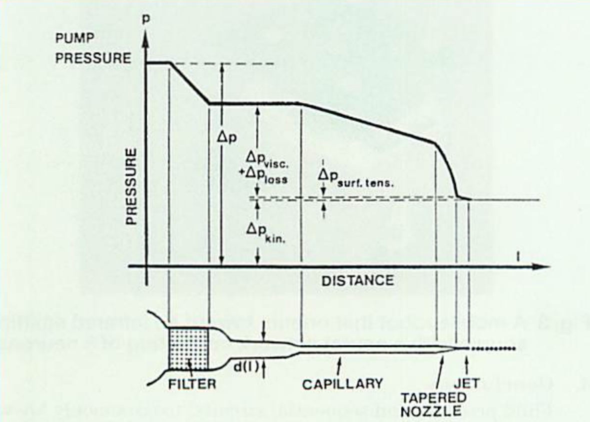

Fig. 1 Ink Jet Loss

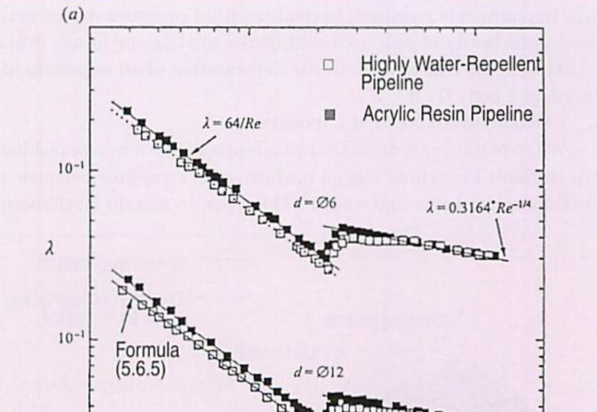

Fig. 2 Loss of Pressure in Circular Pipe with a Highly Water-Repellent Wall

The Mechanism and Control of the Organism Motion

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1. Introduction

We often find a hint, latent in an organism as small as a micromachine, for designing it. In this context, two examples will be cited that are applicable to the mechanism and control of the micromachine motion.

2. Utilization of body fluid pressure

The larva of a butterfly and a moth, or an earthworm moves by deforming itself with its body fluid. For example, as shown in Fig. 1, an earthworm has a structure called a muscular hydrostatic system, in which a somite is lengthened when the annular muscle contracts due to the pressure of body fluid in the body cavity. The somite is thickened by the contraction of the traversing muscle. In addition, asymmetrical friction is caused between the bristles of the earthworm and the earth surface, enabling the earthworm to move in a particular direction.

This induces us to devise a method of driving a microma-chine by utilizing the pressure of a fluid. When a pressurized fluid is poured into a fluid-filled deformable vessel from the outside, the vessel expands and deforms in all the directions of expansion. However, when the vessel is covered with a knit in a special manner, it expands, but contracts in one direction. This well-known mechanism was once commercialized as an artificial muscle, but scarcely used because of the difficulty involved in fluid control. In conventional robots for which highly accurate positioning and motion performance were required, sturdy and powerful actuators capable of highly accurate positioning were preferred to the ones, soft and easily deformed by external force.

Accurate positioning is also required for the mechanism of micromachine motion in some cases. However, a simple on-off mechanism is allowed in other cases. Accordingly, we made a prototype of an artificial muscle driven by pneumatic pressure from a thin silicon tube 1 mm in diameter. As described above, this concept is well known. However, one point worthy of attention is that the artificial muscle was slimmed down and shortened.

Incidentally, an artificial muscle works in one direction only under fluid pressure. It therefore becomes necessary, when reciprocating motion is required, to combine fluid-pressure-driven artificial muscles as in extensor and flexor muscles or to use other actuators. This can be seen in the deformation of an organism induced by a body fluid.

3. Utilization of Neural Circuits

When installing motion control circuits inside a micromachine, it is difficult to include a high performance computer because of the limits in volume and weight. However, in mobile mechanism control, for instance, it suffices to move a leg orderly with a sequential circuit made in the electronic circuit. The neural circuit of an organism, equivalent to the sequential circuit, is considered the so-called recurrent network. This is located in the brain as a network program an individual inherited from his parents, that is, a union of central nerves.

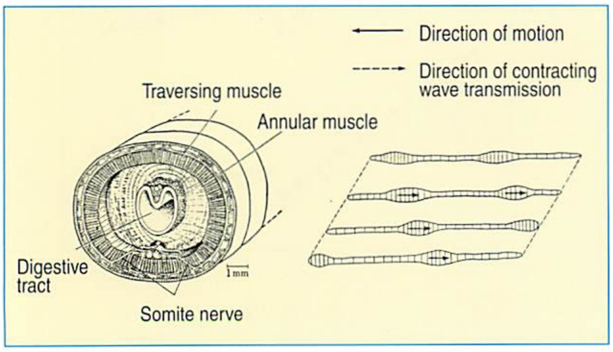

Fig. 1 The structure of an earthworm and peristalsis
Source: Literature 1

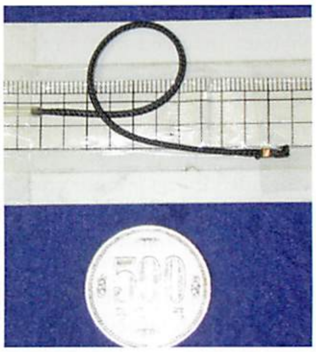

Fig. 2 Pneumatic artificial micro-muscles

The design of a logic circuit can be used when applying a sequential circuit to micromachine motion, in other words, for a rhythm generator. In addition, when environmental information comes into a neural circuit with a sensor, a system that interacts with the environment can be established. For instance, a machine can orient toward an external stimulus, such as an infrared emitting source.

Fig. 3 shows a mobile machine with a neural circuit including 8-neurons, and a sensor that detects infrared signals. This machine is modeled on the behavior of a male, triggered by the pheromone of a female silk worm moth. The way it moves toward the infrared emitting source is similar to the behavior of a silk worm moth.

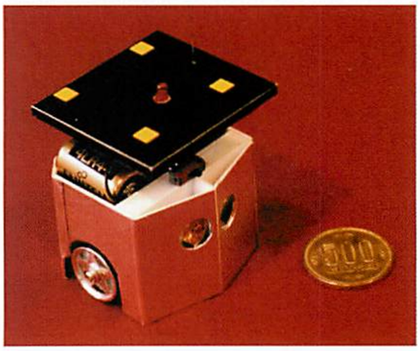

Fig. 3 A mobile robot that orients toward an infrared emitting source with a neural network consisting of 8 neurons

4. Conclusions

Fluid pressure and sequential circuits, too commonly known in the field of engineering, look fresh when a micromachine is related to a small organism. Besides, an organism with a lot of somites has many degrees of freedom. It is interesting to note, however, that many degrees of freedom do not always mean being ingenious.

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Investigative Study of the System Composed of many Functional Micro-elements

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The remarkable progress of recent micromachine technology has enabled the manufacture of a variety of steric microstructures. In addition, many products have been commercialized, including ink jet printers and micromirror-based displays. However, the microactuator now manufactured with micromachining technology is low in generating power when used alone, with its motion limited only to simple reciprocation or rotation. As symbolized by a swarm of ants or bees, many a little thing can only accomplish useful work in many cases when grouped together and do it in much finer way than their macroscopic counterparts.

Accordingly, the following items were investigated on a system composed of many functional microelements and the task those elements can accomplish in cooperation:

(1) The concept of an autonomous distributed microsystem and its application examples as an outline of a microsystem composed of many microelements.
(2) On the system whereby many actuators carry objects in cooperation: actual examples of a distributed control algorithm, a distributed image recognition algorithm and its implementation on integrated circuits, and the array of conveyance actuators based on various driving principles.
(3) As a future-oriented study, the cooperation-controlling algorithm of grouped microrobots, the results of simulation, and the macro-model experiments of interaction among many mobile robots.
(4) An active catheter as a system in which microactuators are connected linearly in series.
(5) As a distributing microsystem that controls fluid or acoustic characteristics, an active skin that controls the flight of an aeroplane by controlling the vortexes on the wings with actuators arranged on the surface of the aeroplane, and a trial to control the acoustic characteristics of a room with micro-resonators distributed on the wall.
(6) An arrayed optical microsystem to attain desired optical characteristics with actuators arranged in array over the entire focal plane or specular surface.
(7) As arrayed actuators for producing a large output or displacement via series-parallel connection of minute power-generating elements, the arrays of artificial muscle actuators, distributing electrostatic actuators, and scratch-drive actuators.

As Fig. 1 shows, the findings of the above investigation revealed that three courses can be considered to be the research direction on the system composed of many functional microelements. The first is to establish a microsystem rendered intelligent to a higher degree, represented by an autonomous-distributed microsystem. The second is to identify the application for which fine control is required over a wide range and to study microsystems that satisfy the requirements as seen in a spatial light modulator, a display, fluid control, acoustic control, and an active catheter. The third is to achieve large output and displacement by creating actuators with many power-generating microelements arranged in array. The future prospect of micromachine technology has thus been envisioned in the above three courses so that a remarkable effect can be achieved by gathering a multitude of minute elements.

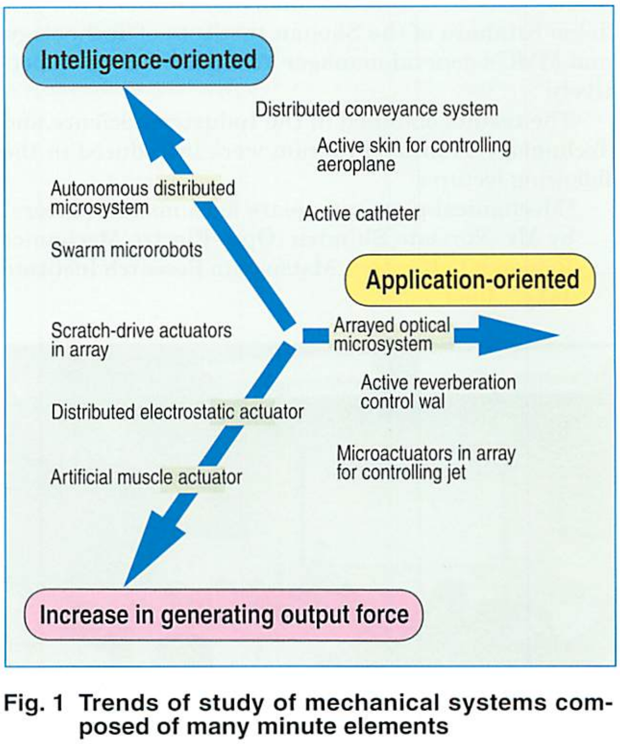

Fig. 1 Trends of study of mechanical systems composed of many minute elements

Iwate Mciromachine Seminar

The Iwate Micromachine Seminar was held on the afternoon of Friday, September 3, 1999 at Hotel Espoie Iwate in Morioka City. The seminar was sponsored by the Micromachine Center (MMC), Iwate Industrial Research Institute, Iwate Mechanics and Electronics Study Group, Center for Cooperative and Development. Iwate Univ, Iwate Network System, and Iwate Techno Foundation.

The seminar began with an introduction speech on micromacchine technology, which was followed by reports on four specific examples from the Industrial Science and Technology Frontier Program's development of Micromachine Technology, led by the Micromachine Center.

During an intermission, Mr. Takeshi Harada and Mr. Osamu Toyama explained the portable micromachine technology exhibits, brought to the site,"Microfluid Operation Devices", made by Hitachi, Ltd., and "Tip-Anticulation Endoscope using SMA Micro Coil", made by Mitsubishi Cable Industries, Ltd. This offered the participants a good opportunity to understand the outline of the micromachine technology.

Mr. Takatoshi Kohno, Deputy Director General of the Iwate Industrial Research Institute, and Professor Shigeyuki Mori of Iwate University, presided over the first half and the second half of the seminar, respectively. The seminar began with greetings from Mr. Isao Ohtawara, Director General of the Iwate Industrial Research Institute, followed by lectures on "MMC Activities", "Features of Micromachines", and "An Outline of the Second Phase of the Micromachine Project" by MMC's Executive Director Takayuki Hirano, Professor Tokio Kitahara of the Shonan Institute of Technology, and MMC's general manager Yuichi Ishikawa, respectively.

The results obtained in the Industrial Science and Technology Frontier Program were introduced in the following lectures.

"Mechanical planetary gears for a micro-reducers" by Mr. Norisato Shimizu (Opto-Electro Mechanics Research Laboratory, Matsushita Research Institute Tokyo, Inc.)

"Holonic mechanism and group control" by Mr. Shigetoshi Shiotani (Machinery Laboratory, Mitsubishi Heavy Industries, Ltd.)

"Research and development of microfluid operation technology" by Mr. Takeshi Harada (Mechanical Engineering Research Laboratory, Hitachi, Ltd.

"Environment recognition devices" by Mr. Osamu Toyama (Central Research Laboratory, Mitsubishi Cable Industries, Ltd.

In Iwate Prefecture, the sponsors of this seminar, acting as the nucleus of the core technology support organization of the regional industries, are setting about dealing with the development of the leading technologies in the fields of mining and manufacturing, textile, and fermentation industries in cooperation of the industrial, academic, and governmental sectors, and positively engaged in the activity of creating in-prefecture enterprises by carrying out need-oriented technical consultation as well as researches and tests. Furthermore, they are supporting research and development and technical exchange by offering industrial facilities and equipment to researchers and engineers.

In Iwate Prefecture, there are many steel-related manufacturers and a multitude of enterprises with techniques applicable to micromachines and micromechanisms such as micromachine technology, precise metal mold processing, and biotechnologies.

Circumstanced as such, 31 persons from 25 companies, related to precision machinery, precision electronic, and laser processing industries, and 35 participants from universities, technology support organizations, and research laboratories, a total of 66 persons, in the Prefecture and the Northeast, participated in this seminar which attracted public attention as a chance of applying effectively the machine technology, a fusion of varied technologies, as seen in micro science and engineering and functional microelements, to a variety of fields in industry, society, and daily life. The lectures promoted lively question-and-answer sessions, and the result was a very meaningful and informative seminar for all involved.

Scene from the seminar at Hotel Espoie Iwate

Display of the portable micromachine technology exhibits

The Forthcoming Fifth International Micromachine Symposium

This year marks the fifth staging of the International Micromachine Symposium, which has become an annual autumn event. As it has been in the past, the symposium will be held in the Science Hall of the Science Museum at Kitanomaru Park in Tokyo, on October 28 (Thursday) and 29 (Friday).

On this occasion the symposium has been planned by the organizing committee (headed by Professor Naomasa Nakajima, Dean of the School of Engineering at The University of Tokyo), and the program committee (headed by Professor Tomomasa Sato of The University of Tokyo) decided on the specific program and the invited speakers. An advisory board has also been established, made up of nine Chief Delegates of countries in Europe and North America that participated in the 5th Micromachine Summit held in Glasgow this year, Scotland. The first day will see addresses from invited speakers. In Session 1 Opening at the start of the symposium, opening addresses from Ministry of International Trade and Industry, the Agency of Industrial Science & Technology, and the New Energy and Industrial Technology Development Organization, will be followed by a keynote address from Professor Takemochi Ishii, Emeritus Professor, The University of Tokyo, titled "What Micromachines will bring to the 21st Century." Professor Ishii will talk from wide-ranging perspectives about the future of micromachines and what they can contribute to man as we are approaching the 21st century. We are sure this will provide an outstanding opportunity for those engaged in micromachine technology R&D to consider the future of micromachines and the direction that they should take.

This will be continued during the morning of the first day by addresses from the following five speakers about industrialization.

Session 2 The Path to New Industries in the 21st Century
Prof. Fumio KODAMA (The University of Tokyo/Japan): "Market Perspectives of Micromachine in 21st Century"
Dr. Franz van de WEIJER (NEXUS/France): "Market Study on Multimedia and Peripherals"
Prof. Kiyoshi ITAO (The University of Tokyo/Japan): "Micromachines for Wearable Information Systems"
Prof. Tomomasa SATO (The University of Tokyo/Japan): "Pet Robot and Micromachine"
Prof. Hisayoshi SATO (Chuo University/Japan): "Trend on Standard"

Three sessions have been planned for the time after lunch.

In the first of these sessions we will call upon four people from overseas who will talk about the most recent developments overseas.

Session 3 Overseas Activities
Ms. Karen W. MARKUS (Cronos Integrated Microsystems, Inc./USA): "Recent MEMS Advances in USA"
Dr. Francois GREY (Technical University of Denmark/Denmark): "Nordic Collaboration in Micromachine Technologies"
Dr. Ronald B. ZMOOD (Royal Melbourne Institute of Technology/Australia): "Recent Developments in Collaborative Micromachine Research in Australia"
Prof. Nico F. de ROOIJ (University of Neuchatel/Switzerland): "Recent Activities on Micromachine Technologies in Switzerland"

This will be followed by presentations made by the following four people about new research for which great developments are expected.

Session 4 Innovative R&D
Prof. Eiichi TAMIYA (Japan Advanced Institute of Science and Technology/Japan): "Recent Research Trends in Biochips"
Prof. Tsuneo CHINZEI (The University of Tokyo/Japan): "Micromachine for Medical Therapy"
Prof. Yasunaga MITSUYA (Nagoya University/Japan): "Nano-Technologies of Magnetic Disk Drives"
Dr. Chih-Ming HO (UCLA/USA): "MEMS Transducers for Fluidic Control"

From the perspective that micromachine is a technology that has great possibilities for the future, Micromachine Center is devoting a great deal of effort to originating information for the next generation, such as holding picture contests for children. The final session was planned from such a perspective.

Session 5 Thinking of Micromachines –Message to Young Generation–
Prof. Atsushi KADOWAKI (University of Tsukuba): "Trends of Value-orientation of Young Generation"
Mr. Tatsuo HAYASHI (Japan Science Foundation/Japan): "Science Museum: MM for Use of an Educational Exhibition"
Prof. Chang-Jin "CJ" KIM (UCLA/USA): "MEMS Education Program at UCLA"

On the second day we will give a progress report on AIST's Industrial Science and Technology Frontier

(ISTF) Program "Micromachine Technology".

Firstly, after an overview from Mr. Yoshikazu Yamaguchi, Director for Machinery and Aerospace R&D, the Agency of Industrial Science & Technology, representatives from the three national research laboratories (Mechanical Engineering Laboratory, Electrotechnical Laboratory and National Research Laboratory of Metrology) will give presentations about research into micromachine technology and its future outlook. Next the research committee chairman of MMC and the four working group leaders will report on the survey of technical developments and give an overview of Phase II research and development under the ISTF Program. This will be followed by explanations of details of the latest results of the ISTF Program given by the researchers of each of the companies that are supporting members. The speakers and the titles of their addresses will be as follows.

Session 6 Current Status of Micromachine Technology Project in ISTF Program

Mr. Yoshikazu YAMAGUCHI (Director for Machinery and Aerospace R&D, AIST, MITI/Japan): "Overview of ISTF Program"

Dr. Shigeru KOKAJI (Mechanical Engineering Laboratory, AIST, MITI/Japan): "Research and Development on Micromachines at Mechanical Engineering Laboratory"

Dr. Shigeoki HIRAI (Electrotechnical Laboratory, AIST, MITI/Japan): "Research on Micromachine Technology at Electrotechnical Laboratory"

Dr. Toshio SAKURAI (National Research Laboratory of Metrology, AIST, MITI/Japan): "Research on Micromachine Technology at National Research Laboratory of Metrology"

Mr. Tatsuaki ATAKA (Research Committee, Micromachine Center/Japan): "The outline of the micromachine project"

Dr. Nobuaki KAWAHARA (Micromachine Center/Japan): "Experimental Wireless Micromachine for Inspection on Inner Surface of Tubes"

Mr. Hiromu NARUMIYA (Micromachine Center/Japan): " Experimental Chain-type Micromachine for Inspection on Outer Surface of Tubes"

Mr. Ryo OHTA (Micromachine Center/Japan): "Experimental Catheter-type Micromachine for Repair in Narrow Complex Areas"

Mr. Kazuyoshi FURUTA (Micromachine Center/Japan): "Experimental Processing and Assembling System (Microfactory)"

Mr. Hiroshi YAMADA (TOSHIBA Corp./Japan): "Advanced three-dimensional assembly technology for high density CCD micro camera system module"

Mr. Kensuke MURAISHI (Mitsubishi Materials Corp./Japan): "Development of Flexible Shaped Battery"

Dr. Ron PELRINE (SRI International/USA): "Recent Progress in Artificial Muscle Micro Actuators"

Mr. Hiromi TOTANI (OMRON Corp./Japan): "PZT Thin-Film Actuator Driven Two Dimensional Micro Optical Scanning Sensor"

Mr. Kouji TAKEMURA (Murata Manufacturing. Co., Ltd./Japan): "Microgyroscope for Experimental Catheter-type Micromachine"

Mr. Osamu TOHYAMA (Mitsubishi Cable Industries, Ltd./Japan): "Environmental Recognition Devices using Fiberscopes"

Dr. Hiroshi NAKAMURA (Yaskawa Electric Corp./Japan): "Development of Micro Servo Actuators for Microfactories"

The 10th Micromachine Exhibition "Micromachine '99" will be held on the first floor of the Science Museum from October 27. Displays will be on show from micromachine-related companies, universities and organizations, including supporting members of MMC. Practical examples of micromachine technology from the ISTF Program will be exhibited by supporting member companies and the three national research laboratories. Holding a micromachine exhibition in conjunction with this symposium will provide an outstanding opportunity for visitors to gain an effective understanding of micromachine technology. By showing their participant badge, participants in the symposium will be able to enter the Micromachine Exhibition at will.

The deadline for registration as a participant in this symposium is October 15. As long as seating is available, registrations on the day will be accepted, so we look forward to participation from as many people as possible.

Mitsubishi Materials Corp.

Motohiko Yoshizumi
General Manager
Corporate Research & Development Div.
Strategic Research & Development Planning Dept.

1. Dealing with Micromachine Technology

With the innovations in information communication technology and the spread of networks, the world is beginning to change toward the 21st century. In line with this, our life-styles are also changing with emphasis placed on the circulation of resources and living together with the environment rather than on mass production and consumption. With its management based on research and development, Mitsubishi Materials is considering answering the needs of the world by focusing on the key words, Energy, Environment, and Materials.

In addition, in the research and development of micromachine technology, the company is developing energy-saving microbattery (secondary battery) devices that enable large-scale work to be performed in small spaces.

2. Development of Micromachine Technology

As part of the research and development of the advanced technology of functional devices in the Industrial Science and Technology Frontier Program, the company is dealing with the miniaturization of batteries, one of the devices for energy supply, with the in-tube automatic environment monitoring system assumed as a model. For efficient use of the limited space of a micromachine, the battery should be miniaturized and flexible with an increase in energy density. In the second term, attention is focused on the development of a tape-like flexible shaped battery that can be pasted to or wound around the inside or outside of the wall of a micromachine to take advantage of a space, largest, but not efficiently used.

A battery that can be bent freely should be composed of flexible parts. The chemical reaction in the battery should also be compatible with the flexible materials. Figure 1 gives a schematic drawing of the concept of a tape-like flexible shaped secondary battery, in which typical flexible polymer materials are used for the cathode, anode, and electrolyte in the lithium-electrochemical system. A prototype of this battery was manufactured by packaging the main body of the battery with attention paid to the sealability of aluminium packaging material after elaborating the high-strength adhesion between the flexible current-collecting material, cathode sheet, anode sheet, and electrolyte sheet. Figure 2 shows the prototype, wound around a 2-cm-radius cylinder, in action. The battery is 14 cm long, 2 cm wide, and 0.5 mm thick. A battery, with an average voltage of 3.6 V and a discharge capacity of 100 mAh, can run a small motor for as long as five hours.

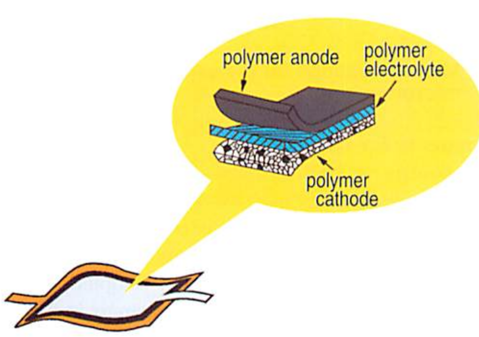

Fig. 1 Schematic of flexible shaped battery concept

Fig. 2 Flexible shaped battery folded round the tube

3. Prospect for the Future

Along with the contribution to the advancement of energy supply technology, one of the important micromachine technologies, the company is hoping to offer articles that suit the 21st century by utilizing the company's techniques of micromachining, micropackaging, and energy-related material application cultivated in the Industrial Science and Technology Frontier Program.

Murata Manufacturing Co., Ltd.

Yohei Ishikawa
Executive General Manager of
Yokohama Technical Center

1. Dealing with Micromachine Technology

The company is carrying forward the research and development of electronic components and materials based on the concept that "new quality electronic equipment begins with new quality components and new quality components begin with new quality materials". With the idea that micromachine technology also forms a part of the revolutionary basic technology over a wide area ranging from information and communication to automobile equipment, the company's Yokohama Technical Center has participated in the MITI's industrial technology project to tackle the problem positively. In the Industrial Science and Technology Frontier Program, attitude control technology using a micro-gyro is under study. In addition, the microgyro is making headway toward commercialization in line with the above study so that the results of the Industrial Science and Technology Frontier Program can be put to practical use.

2. Development of Micromachine Technology

The company is promoting the construction of the experimental catheter-type micromachine for repair in narrow complex areas in joint cooperation with Olympus Optical Industry and Omron in the Industrial Science and Technology Frontier Program. In the above project, the company is responsible for the attitude control of a system head, and is attempting to establish the control technology using the microgyro completed in the first term. Currently, the company is proceeding with the verification of the attitude control function by confirming the basic performance of the microgyro mounted on the system head.

The establishment of chip package process technology was an important problem for the device. However, packaging with an inner pressure of less than 200 Pa could be realized by vacuum anodic bonding technology, for which getter material is used, with the three-layer structure of glass-silicon-glass. With a prototype of the microgyro fabricated with the above technology, the verification of the attitude control function is under way.

In line with the above, the company is also promoting the advancement of microgyro element technology. With attention focused on the mechanical coupling between drive vibration mode and detection vibration one, which are considered to be responsible for restraining the performances including a resolution, the company is heading toward the measurement of the mechanical coupling, for which a two-dimensional laser displacement meter is used, and the study of the device structure with reduced mechanical coupling. Particularly noteworthy is that the company succeeded in developing a vibratory motion adjustment technology which is effective for mechanical coupling reduction.

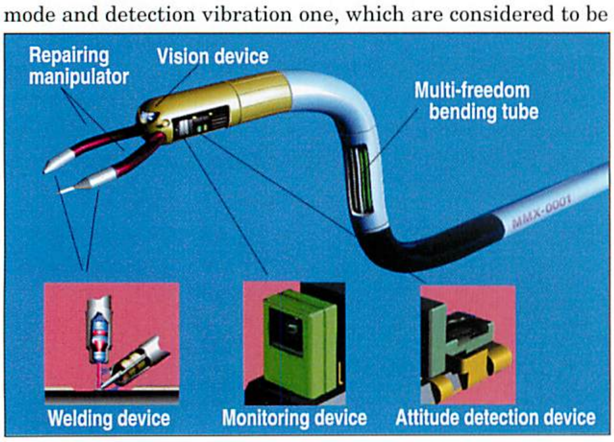

Fig. 1 Experimental catheter-type micromachine for repair in narrow complex areas

On the other hand, the company is developing a silicon gyro intended for general application so that the results of the Industrial Science and Technology Frontier Program can be put to practical use.

The company is developing a silicon gyro in the following manner: 1) Employment of a planar bidirectional vibrating resonator with the simple process and structure by the use of a three-layer structure of silicon-glass-silicon. 2) Design of a double frame structure effective for mechanical coupling reduction. 3) Combination with low pressure package process on a wafer level.

To date, a resolution of 0.8 deg/sec (rms), a linearity of less than 1%, and an impact resistance of 1500 G, 0.5 ms have resulted from the above study.

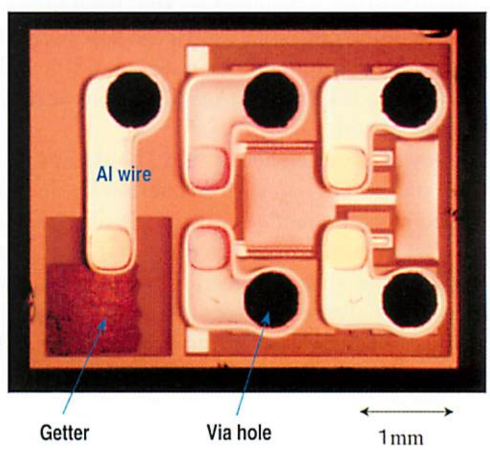

Fig. 2 Microgyroscope for the experimental catheter-type micromachine

3. Prospects for the Future

The company has promoted the establishment of micromachine technology with attention focused mainly on the microgyro. It is planning to commercialize the microgyro toward the 21st century not only by verifying the effectiveness of microgyro-induced attitude control after completing the experimental catheter-type micromachine for repair in narrow complex areas, but also by enhancing the degree of completion of technology.

1999 Micromachine Mission to Europe

In the course of holding the Micromachine European Seminars, we had the opportunity to visit research organizations in Europe.

Visited organization: CEA-LETI (Grenoble, France)
Date: June 24 (Thursday)
Conferred with: Dr. Jean-Frederic Clerc and others
Outline of visit:

LETI (Laboratorie d'Electronique de Technologie et d'Instrumentation) is one of the research organizations of CEA (Commissariatal & Energie Atomique), with some 80% of its research carried out under agreements with external organizations. It is also actively involved in technology transfer. In LETI's display room we were given explanations of pressure sensors, acceleration sensors, emissions sensors, DNA chips and optical gyro sensors. Research is being advanced centering on microoptical-related and microsensor-related fields.

Visited organization: University of Roma Tor Vergata (Rome, Italy)
Date: June 28, (Monday)
Conferred with: Prof. Arnaldo D'Amico and others
Outline of visit:

This university has a new campus created in the southeastern part of Rome in 1997. In the vicinity, construction of national research organizations in addition to the university is taking place, in striving towards a large-scale new research area. In Prof. D'Amico's laboratory, research into cell measurement using near-field optical microscopes, AFM, and chemical sensors (O_2, smell sensors) was taking place. The main target of smell sensors is quality control for food such as wine, meat and fish. Particular effort is being devoted to research into an "artificial nose" combining eight smell sensor elements and information processing by the neural network.

Visited organization: Scuola Superiore Sant' Anna; SSSA
Mitech Lab. and Arts Lab. (Pisa, Italy)
Date: June 29 (Tuesday)
Conferred with: Prof. Paolo Dario, Prof. Maria Chiara Carrozza
Outline of visit:

SSSA is a public university established in 1987, comprising an Faculty of Social Sciences and a Faculty of Applied Science, with 40 lecturers and 160 students. The Mitech Lab. (Microfabrication Technology and Systems Laboratory) and the Arts Lab. (Advanced Robotics Technology and System Laboratory) are organizations within SSSA. Their respective research themes are microtechnology and robot technology, and both lead by Prof. Dario, they are advancing research with no clear demarcation line between them. At Mitech Lab. we were given an explanation of microgrippers for ultrafine work and fluid devices. Mitech was devoting a great deal of effort to fluid devices under EUROPRACTICE II (micromachine project staged by EC). In the Arts Lab. research being engaged in includes support robots for disabled people, self-propelled large intestine endoscopes, VR systems for arthroscopic operations, and artificial limb systems using the electric potential of muscles. There are plans for Mitech Lab. and Arts Lab. to relocate to Pontdera, a city slightly distant from Pisa, in 2001.

At Leti

At Arts Lab.

Micromachine Seminars in Europe

From June 22 to July 4, 1999, seminars were held jointly with micromachine-related organizations and research organizations in France, Italy and Spain, as a part of the business exchange mission of the Japan External Trade Organization (JETRO). The purpose of these seminars was to communicate technical information from Japan, and for exchange with Europe's micromachinerelated organizations and experts. Details of the seminars follow.

<Addresses and Locations of Addresses by Japanese Speakers>

"Future Prospect of Micromachine": Takayuki HIRANO/Micromachine Center (France, Italy, Spain)

"The Prospects of National Micromachine R&D Project in Japan": Tatsuaki ATAKA/Seiko Instruments Inc. (Italy, Spain)

"In-pipe Wireless Microrobot": Naoki MITSUMOTO/Denso Corp. (France, Italy)

"Experimental Chain-type Micromachine for Inspection of Outer Tube Surfaces": Hiromu NARUMIYA/Group Manager, Mitsubishi Electric Corp. (Italy, France, Spain)

"Development of Microgyroscope": Kuniki OWADA/Murata Mfg. Co., Ltd. (Italy, Spain)

"Design and Fabrication of a Peristaltic Micro-Pump": Yoshihiro NARUSE/Assistant Chief Researcher, Aishin Cosmos Research Laboratory (France, Italy, Spain)

"Micro Sensors for Minimally Invasive Diagnoses and Therapies": Takashi MIHARA/General Manager, Olympus Optical Co., Ltd. (France, Italy, Spain)

<Overview of Individual Seminars>

1. Microsystems in Rhone-Alpes and Japan

Date: June 24, 1999 (Thursday)
Venue: LETI, Grenoble, France
Participants: Approximately 30 (companies, universities and research organizations within France (especially in the Rhone Alpes Region))
Content:

The seminar was organized jointly with CEA-LETI. French speakers gave addresses on micromachine initiatives in LETI, aratem (a research organization for instrument technology in the Rhone Alps Region) and SEXTANT Avionique (aircraft instrument manufacturer), activities of NEXUS, and CMOS based DNA chip. Many questions were fielded about business and implementation.

2. Italy-Japan Joint Seminar on Micromachines

Date: June 30, 1999 (Wednesday)
Venue: Scuola Superiore Sant'Anna, Pisa, Italy
Participants: Approximately 100 (Italian companies, universities and research organizations)
Content:

The seminar was organized jointly with Scuola Superiore Sant'Anna. With participation from more than 100 people, and coverage from two local television stations, the seminar was very well attended. From Italians, examples of applications of micromachine technology to printers and motor vehicles, and Italy's micromachine research framework were reported mainly by companies from Milan and Pisa.

3. Micromachine Seminar

Date: July 2, 1999 (Friday)
Venue: AIPA, Spain
Participants: Approximately 70 (mainly from Spanish companies)
Content:

The seminar was organized jointly with Tekniker. The venue was the Basque Region located in northwestern Spain. Spanish speakers reported on research frameworks and research cases at the National Microelectronics Center and Tekniker.

Seminar in Pisa, Italy

Seminar in Basque, Spain

Technical Terms in Micromachine Technology (v1.0) — Part 3

This is the third issue we publish a glossary of key terms excerpted from MMC Technical Report: Technical Terms in Micromachine Technology (MMC TR-S001(01)-1998), which was published by MMC. For more detailed explanations, please refer to the Technical Report.

Mechanochemical actuator
【メカノケミカルアクチュエータ】

[DEFINITION] An actuator that converts chemical energy directly into mechanical work.

[DESCRIPTION] Since a mechanochemical actuator uses chemical energy for the power source, its efficiency is independent of its size. Contracting and expanding force is obtained by changes of internal energy at different levels, from the molecule to polymer conformation, interaction between polymers, to polymer bridge, against the stimuli from the outside. Examples of application developed so far are robot hands, and artificial legs. Application to clamps that carry out mechanical operations at the molecular level is also expected.

[References] (2)(8) **[Related Terms]** Polymer actuator, Flagellar motor

Wobble motor 【ワブルモータ】

[DEFINITION] A variable gap electrostatic motor that generates rolling motion of the rotor on eccentric stator without slip.

[DESCRIPTION] Wobble motors are also called harmonic electrostatic motors. These motors consist of a rotor, a stator with electrodes for the generation of electrostatic force, and an insulation film on the rotor or stator surface. The rotor rotates in a reverse direction to the revolution. The rotation speed is (the revolution speed) × {(the stator circumference - rotor circumference) / (rotor circumference)}. Characteristics of the wobble motor include 1) the ability to easily provide low speed and high torque when the rotor circumference is very close to the stator circumference, 2) no friction and wear problems because of no sliding parts, 3) the ability to use diverse materials, 4) an easily increasable aspect ratio. On the other hand, the revolution of the rotor can cause unnecessory vibration. Production examples include a wobble motor that supports a rotor by a flexible coupling, and a wobble motor fabricated by the IC process and whose rotor rolls at the fulcrum.

[References] (4)(6) **[Related Terms]** Electrostatic motor

Ultrasonic motor 【超音波モータ】

[DEFINITION] A motor that uses ultrasonic vibration transmitted through the elastic mechanical members.

[DESCRIPTION] An ultrasonic motor stator is pressed to a rotor to transform ultrasonic vibration to mechanical output motion. Ultrasonic motors have the following characteristics: 1) a simple structure assisting miniaturization and light weight, 2) direct drive capability with high torque in the low-speed range, 3) a high power-to-weight ratio, 4) quick response, 5) good controllability, 6) the ability to maintain the rotor position because of a self-holding force when the power supply is off, and 7) no magnetic noise. On the other hand, problems include the friction and wear that occur between the stator and the rotor. Ultrasonic motors can be driven by standing wave or progressive wave. The former offers high energy conversion efficiency, while the latter gives excellent controllability because forward and reverse rotations are possible. Generally, ultrasonic motors are used in direct drive applications requiring low speed and high torque performance.

[References] (4)(6)(8)(14)(15) **[Related Terms]** Piezoelectric linear actuator, Piezoelectric element

Biosensor 【バイオセンサ】

[DEFINITION] A generic term for sensors that use organic substances in the device, that are intended for measurement of organism related subsystems, or that mimic an organism.

[DESCRIPTION] A typical biosensor consists of the biologically originated specific material such as an enzyme or an antibody that identifies the object of measurement and the device that measures a physical or chemical quantity change related to the identifying reaction. A semiconductor sensor or any of various types of electrodes (ex. ISFET, micro-oxygen electrode, and fluores-cence detection optical sensor) prepared by silicon micromachining tech-nology can be used as this device. Biosensors are used for blood analysis systems, glucose sensors, micro robots, and so on.

[References] (2)(4)(19)

[Related Terms] Ion sensitive field effect transistor (ISFET) , Microsensor

Pressure sensor 【圧力センサ】

[DEFINITION] A sensor for measuring pressure of fluids.

[DESCRIPTION] A typical pressure sensor consists of the pressure receiver diaphragm, fabricated by the silicon micromachining technology, especially the anisotropic etching technique, and the strain gauge built on the substrate. At present, the pressure sensor is the most successful micromachine in business terms, and has been used in automobile engine. High market demand is expected in the future, and research and development is brisk for further miniaturization, precision improvement, reliability enhancement, higher integration and so on. Apart from the strain gauge type, electrostatic type and vibration type sensors have been also developed.

[References] (2)(3)

Accelerometer 【加速度センサ】

[DEFINITION] A sensor for measuring acceleration.

[DESCRIPTION] This accelerometer, based on silicon micromachining technology, is typically composed of a soft spring and a mass. The accelerometer senses the displacement of the spring caused by the inertia of the accelerated mass, or detects acceleration from the measurement of the force required to cancel this displacement. Among today's silicon-made sensors, accelerometers hold particular promise as a next-generation product. There are many types of accelerometer such as semiconductor strain gauges, capacitance detectors, electromagnetic servosystems, and electrostatic servosystems. In addition, vibration detection-type accelerometers, which detect changes in resonance frequencies, and piezoelectric effect-type accelerometers, which use the piezoelectric effect, are also under development. Continuing development is aimed at applications in a wide variety of fields, including automobiles, robots, and the space industry.

[References] (2)

[Related Terms] Pressure sensor, Capacitive displacement meter, Integrated strain sensor

Integrated chemical analyzing system
【集積化化学分析システム】

[DEFINITION] A micro-chemical analyzing system integrating chemical sensors and fluid control elements.

[DESCRIPTION] A blood gas monitoring microsystem and an integrated chromatography system are manufactured as integrated chemical analyzing systems. A blood gas monitoring microsystem analyzes the pH of blood samples obtained intermittently from the body. One example of such a system integrates a microvalve, a pH ion sensitive field effect transistor (pHISFET), and other components on a silicon substrate. In the integrated chromatography system separation and analysis components are based on the difference in the adsorption among sample components. This system is commercially available in a shape that a number of valves, sensors, and columns (tubes) are integrated on a silicon substrate.

[References] (4)

Micro-gyroscope 【マイクロジャイロ】

[DEFINITION] A microscopic sensor for measuring angular velocity.

[DESCRIPTION] Micro-gyroscopes are expected to be applied as microrobot attitude sensors. Rotational and vibrational gyroscopes are based on Coriolis' force. Ring laser gyroscopes and optical fiber gyroscopes are based on the Sagnac effect. Among these types of gyroscopes, vibrational gyroscopes (the tuning fork- and resonant piece-types) are suitable for miniaturization and are being developed for miniaturized applications.

[References] (19)(20)

Ion sensitive field effect transistor (ISFET)
【ＩＳＦＥＴ】

[DEFINITION] A semiconductor sensor integrating an ion sensitive electrode with a field effect transistor (FET).

[DESCRIPTION] In the ion sensitive electrode section, the membrane voltage changes according to fluctuations of pH or carbon dioxide partial pressure in blood, for example. As the voltage amplifier, the ISFET uses an FET, a transistor controlling the conductance of the current path (channels) formed by the majority carriers using an electrical field perpendicular to the carrier flow. The ISFET is based on silicon micromachining technology integrating a detector and amplifier on a silicon substrate. In addition, an ISFET with mechanical components such as a valve has been developed. The ISFET is used in such fields as medical analysis and environmental instrumentation.

[References] (1)(4)(11)

Micro-Fresnel lens 【マイクロフレネルレンズ】

[DEFINITION] A micro-lens structure resembling flattened out narrow rings.

[DESCRIPTION] As a micro-lens that has low aberrations, high efficiency, and high numerical aperture (NA), the micro-Fresnel lens is under research and development. The lens realizes a high NA by a single lens and is manu-factured by reproduction of an original lens pattern, which has been drawn by electron beam lithography on a glass substrate.

[References] (21)

Micro-battery 【マイクロバッテリ】

[DEFINITION] An ultra-small cell that convert chemical energy to electrical energy.

[DESCRIPTION] In the field of micromachines where energy supply is an important issue, research is focusing on such topics as micro-batteries, micro-generators, microwave energy supplies, propagation of vibrational energy, and optical energy conversion devices. Micro-battery research, which improves the energy density per volume and miniaturizes battery size, is developing thin film processes and machining technologies. In particular, R&D into packaging technology and electrolyte materials is advancing. As the volume of micromachines is small, rechargeable secondary batteries are desirable, and research is focusing on metal/hydrogen secondary batteries or lithium-type secondary batteries.

[References] (11)

Micro-teleoperation 【マイクロテレオペレーション】

[DEFINITION] A technology for remotely manipulating (teleoperating) a microscopic robot.

[DESCRIPTION] Micro-teleoperation systems are systems in which humans give instructions to microrobots to implement microscopic work. This remote manipulation technology, which makes the remote operator feels as if he/she is actually at the scene of the operation, is effective for operations requiring a precise manipulation in such fields as gene manipulation, cell manipulation, and microscopic surgery or microsurgery. In addition, micro-teleoperation is also effective for microscopic work such as inspection and repairs in areas that conventional machines cannot reach. As the operability of teleoperation systems is highly dependent on the arm control method, the development of a special micro-teleoperation arm control method is required. In particular, when manipulating objects in the microscopic world where dynamic behavior differs from the ordinary world, special control technology is required to realize a remote manipulation system where the operator can feel the operation just as in real world manipulation.

[References] (4)

Silicon process 【シリコンプロセス】

[DEFINITION] A generic term for ultra-precise processing technologies for silicon.

[DESCRIPTION] While the silicon process is broadly divided into surface micromachining and bulk micromachining, most of the technologies involved are the same. The silicon process starts with layer work and continues to a patterning process, microassembly, annealing, and packaging. Many technologies such as deposition, diffusion, chemical corrosion, and lithography are combined as working technologies. A feature of the silicon process is the ability to use batch processing on large wafers for mass-fabrication of components.

[References] (5)(6) **[Related Terms]** Surface micromachining, Bulk micromachining

Bulk micromachining【バルク微細加工】

[DEFINITION] A micromachining process by removing a part of substrate itself.

[DESCRIPTION] An example of bulk micromachining is a processing method based on etching by a chemical solution to remove unnecessary parts of a substrate. Covering the areas to be preserved with a mask of SiO_2 or Si_3N_4 ensures that etching cannot progress from the surface. Also, a boron-doped layer can stop the etching of the part underneath the surface layer. Recently, silicon fusion bonding has been used to fabricate still more complex structures.

[References] (3)(6) **[Related Terms]** Surface micromachining

Surface micromachining【表面微細加工】

[DEFINITION] A micromachining process by forming various substances in various microshape on the substrate surface.

[DESCRIPTION] Surface micromachining is a processing technique that applies for example chemical vapor deposition (CVD) to form various thin films on the substrate and uses a mask to perform selective removal of the substrate surface to produce movable parts and other structures. The dissolved layer that was deposited initially is called the sacrificial layer. A typical sacrificial layer material is phosphosilicate glass (PSG). This technology is applied to the fabrication of micro-beams, bearings, and links, etc.

[References] (3)(6) **[Related Terms]** Bulk micromachining, Chemical vapor deposition (CVD)

LIGA process【ＬＩＧＡプロセス】

[DEFINITION] An acronym for Lithographie, Galvanoformung und Abformung, the German for lithography, electroforming, and molding.

stances in various microshape on the substrate surface.

[DESCRIPTION] This process was developed at the Kernforschungszentrum Karlsruhe. While LIGA is a method of creating microstructures with a high aspect ratio by using deep lithography based on X-rays (synchrotron radiation) and electroforming, the electroplated microstructure can sometimes be used as a mold for plastic molding. Characteristics of the LIGA process include the ability to mass-produce high-aspect ratio microstructures with a line width of 1–10 μm and a height of several hundreds of micrometers, to allow the use of a wide range of materials including plastics, metals, and ceramics, and to combine with silicon semiconductor elements, etc.

[References] (1)(2)(3)(8) **[Related Terms]** Surface micromachining, Bulk microma-chining

Ion beam machining【イオンビーム加工】

[DEFINITION] A machining process based on the sputtering action of an accelerated ion beam.

[DESCRIPTION] The ions generated from the ion source are accelerated and introduced into the reaction chamber, and sputter the sample. This process can be used either as removal process of the sample, or as deposition process of the sample material on other sample. In case of removal process, variable three-dimensional shapes can be fabricated by adjusting the ion incident angle in relation to the sample, because the finished profile consists of edges parallel with the incident direction of the ions. By focusing the beam diameter to a submicrometer order, ultramicroscopic machining can be performed. Ar gas is generally used as the ion source. The sputtering rate (number of etched atoms/number of bombarding ions) depends on the atomic weight of the processing target. So, Kr gas and other gases are also used.

[References] (4)(7)(8) **[Related Terms]** Reactive Ion Etching (RIE), Ion beam-assisted machining

Micromachining (1)【マイクロ機械加工】

[DEFINITION] Technologies applying conventional machining technologies to the processing of microscopic components.

[DESCRIPTION] Micromachining includes micro-cutting and grinding, micro-plastic working, micro-forging, micro-electro-discharge machining and so on. Ultra-precision machining such as mirror finishing can be achieved, and also microscopic shapes like diffraction gratings can be fabricated by making tools and machine tools to highly precise and miniaturized specifications. Single-crystal diamonds can be polished into microscopic and sharp-edged tools and are widely used as machine tools.

[References] (6) **[Related Terms]** Micro-electro-discharge machining, Micro-cutting and grinding

Micro-electro-discharge machining【マイクロ放電加工】

[DEFINITION] A micromachining process using the discharge between micro-electrodes and the material.

[DESCRIPTION] While this technique uses the same principle as conventional electro-discharge machining, micro-energy discharge technology and micro-electrode production technology differ. That is, the floating capacitance between the electrode and the material being processed must be reduced and the electrode must be miniaturized by such methods as wire electro-discharge grinding (WEDG). With the WEDG method, electrodes with a diameter of 2.5 μm can be prepared and micro-holes can be processed with this electrode.

[References] (4)

Diffusion bonding【拡散接合】

[DEFINITION] A technique of bonding materials by heating below their melting points and pressing them to achieve solid state adherence by the mutual diffusion of their atoms.

[DESCRIPTION] As the materials are bonded in a solid state, far more accurate bonding is possible than with fusion bonding. This method is mainly used for bonding metals or bonding a ceramic to a metal. After bonding dissimilar materials, thermal stress occurs during cooling because of the difference in the coefficients of the thermal expansion of the materials. To avoid cracking caused by this stress, most diffusion bonding research is concerned with ways of reducing thermal stress. Methods of achieving this include sandwiching a third material with a coefficient of thermal expansion roughly halfway between that of the two materials, or a readily deformable material between them. Much research is being done into the insertion of a material whose coefficient of thermal expansion changes gradually across the thickness (functionally gradient material, i.e. FGM).

[References] (1)

THE FIFTH INTERNATIONAL MICROMACHINE SYMPOSIUM
Foundation of Industrial Technology in the 21st Century

Date: October 28 - 29, 1999
Venue: Science Museum, Tokyo
Organizers: Micromachine Center / Japan Industrial Technology Association
Supporters (Expected): Ministry of International Trade and Industry (MITI) / Agency of Industrial Science and Technology (AIST) / New Energy and Industrial Technology Development Organization (NEDO)
Cooperators (Expected): The Federation of Micromachine Technology / Micromachine Society / Research Committee on Micromechatronics / Japan Power Engineering and Inspection Corporation / Japan Robot Association / Japan Machinery Federation
Registration Fee: ¥15,000 (Including proceedings and reception party)
Application: Complete the symposium registration form and FAX to Micromachine Center by Oct. 15, 1999
Contact: Micromachine Center
(TEL +81-3-5294-7131 FAX +81-3-5294-7137)

PROGRAM

October 28, 1999

9:00 ~	Registration	
Session 1: Opening		**Chairman: Mr. T. HIRANO**
9:30	Opening Declaration	Mr. Takayuki HIRANO, Executive Director, Micromachine Center
9:30 ~ 9:35	Opening Remarks	Dr. Tsuneo ISHIMARU, Chairman, Micromachine Center
9:35 ~ 9:43	Guest Speech (Expected)	Mr. Shinichirou OOTA, Director-General,Machinery and Information Industries Bureau, MITI
9:43 ~ 9:51	Guest Speech (Expected)	Dr. Koji KAJIWARA, Director-General, AIST, MITI
9:51 ~ 10:00	Guest Speech (Expected)	Mr. Hideyuki MATSUI, Chairman, NEDO
10:00 ~ 10:45	Special Guest Speech: What Micromachine Technologies will bring to the 21 Century	Professor Emeritus Takemochi ISHII, The University of Tokyo/Japan
Session 2: The Path to New Industries in The 21st Century		**Chairman: Prof. H. MIURA**
Market Frecast		
10:45 ~ 11:05	Market Perspectives of Micromachine in 21st Century	Prof. Fumio KODAMA, The University of Tokyo
11:05 ~ 11:25	Market Study on Multimedia and Peripherals (tentative)	Dr. Franz van de WEIJER, NEXUS
Exploiting Applications		
11:25 ~ 11:45	Micromachines for Wearable Information Systems	Prof. Kiyoshi ITAO, The University of Tokyo
11:45 ~ 12:05	Pet Robot and Micromachine	Prof. Tomomasa SATO, The University of Tokyo
Standardization		
12:05 ~ 12:25	Trend on Standard	Prof. Hisayoshi SATO, Chuo University
12:25 ~ 13:30	========== Lunch ==========	
Session 3: Overseas Activities		**Chairman: Prof. H. FUJITA**
13:30 ~ 13:50	Recent MEMS Advances in USA	Ms. Karen W. MARKUS/Cronos Integrated Microsystems, Inc.
13:50 ~ 14:10	Nordic Collaboration in Micromachine Technologies	Dr. Francois GREY, Technical University of Denmark
14:10 ~ 14:30	Recent Developments in Collaborative Micromachine Research in Australia	Dr. Ronald B. ZMOOD, Royal Melbourne Institute of Technology
14:30 ~ 14:50	Recent Activities on Micromachine Technologies in Switzerland	Prof. Nico F. de ROOIJ, University of Neuchatel
14:50 ~ 15:10	========== Break ==========	
Session 4: Innovative R&D		**Chairman: Prof. K. IKUTA**
15:10 ~ 15:30	Recent Research Trends in Biochips	Prof. Eiichi TAMIYA, JAPAN ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY
15:30 ~ 15:50	Micromachine for Medical Therapy	Prof. Tsuneo CHINZEI, The University of Tokyo
15:50 ~ 16:10	Nano-Technologies in Magnetic Disk Drives	Prof. Yasunaga MITSUYA, Nagoya University
16:10 ~ 16:30	MEMS Transducers for Fluidic Control	Dr. Chih-Ming HO, University of California, Los Angeles
Session 5: Thinking of Micromachines –Message to Young Generation–		**Chairman: Prof. T. SATO**
16:30 ~ 16:50	Trends of Value-orientation of Young Generation	Prof. Atsushi KADOWAKI, University of Tsukuba
16:50 ~ 17:10	Science Museum: MM for Use of an Educational Exhibition	Mr. Tatsuo HAYASHI, Japan Science Foundation
17:10 ~ 17:30	MEMS Education Program at UCLA	Prof.Chang-Jin"CJ"KIM, University of California, Los Angeles
18:00 ~ 20:00	Reception Party at Josui Kaikan	

October 29, 1999

9:00 ~	Registration	
Session 6: Current Status of Micromachine Technology Project in ISTF Program		**Chairman: Dr. Y. ISHIKAWA**
9:30 ~ 9:40	Overview of ISTF Program	Mr. Yoshikazu YAMAGUCHI, Director for Machinery and Aerospace R&D, AIST, MITI
Researches and Future Prospects on Micromachine Technology in National Research Laboratories		**Chairman: Dr. Y. ISHIKAWA**
9:40 ~ 9:55	Research and Development on Micromachines at Mechanical Engineering Laboratory	Dr. Shigeru KOKAJI, Mechanical Engineering Laboratory, AIST, MITI
9:55 ~ 10:10	Research on Micromachine Technology at Electrotechnical Laboratory	Dr. Shigeoki HIRAI, Electrotechnical Laboratory, AIST, MITI
10:10 ~ 10:25	Research on Micromachine Technology at National Research Laboratory of Metrology	Dr. Toshio SAKURAI, National Research Laboratory of Metrology, AIST, MITI
10:10 ~ 10:40	========== Break ==========	
R&D in Micromachine Center		**Chairman: Dr. Y. ISHIKAWA**
10:40 ~ 10:55	The outline of the micromachine project	Mr. Tatsuaki ATAKA, Research Committee, Micromachine Center
	● Systems	
10:55 ~ 11:25	Experimental Wireless Micromachine for Inspection on Inner Surface of Tubes	Dr. Nobuaki KAWAHARA, Micromachine Center
11:25 ~ 11:55	Experimental Chain-type Micromachine for Inspection on Outer Surface of Tubes	Mr. Hiromu NARUMIYA, Micromachine Center
11:55 ~ 13:00	========== Lunch ==========	
13:00 ~ 13:30	Experimental Catheter-type Micromachine for Repair in Narrow Complex Areas	Mr. Ryo OHTA, Micromachine Center
13:30 ~ 14:00	Experimental Processing and Assembling System (Microfactory)	Mr. Kazuyoshi FURUTA, Micromachine Center
	● Elements	
14:00 ~ 14:20	Advanced three-dimensional assembly technology for high density CCD micro camera system module	Mr. Hiroshi YAMADA, TOSHIBA Corp.
14:20 ~ 14:40	Development of Flexible Shaped Battery	Mr. Kensuke MURAISHI, Mitsubishi Materials Corp.
14:40 ~ 14:55	========== Break ==========	
14:55 ~ 15:15	Recent Progress in Artificial Muscle Micro Actuators	Dr. Ron PELRINE, SRI International
15:15 ~ 15:35	PZT Thin-Film Actuator Driven Two Dimensional Micro Optical Scanning Sensor	Mr. Hiromi TOTANI,OMRON Corp.
15:35 ~ 15:55	Microgyroscope for Experimental Catheter-type Micromachine	Mr. Kouji TAKEMURA, Murata Manufacturing Co.,Ltd.
15:55 ~ 16:15	Environmental Recognition Devices using Fiberscopes	Mr. Osamu TOHYAMA, Mitsubishi Cable Industries, Ltd.
16:15 ~ 16:35	Development of Micro Servo Actuators for Microfactories	Dr. Hiroshi NAKAMURA, Yaskawa Electric Corp.
Session 7: Closing		**Chairman: Mr. T. HIRANO**
16:35 ~ 16:40	Closing Address	Mr. Hikaru HAYASHI, Managing Executive Director, Japan Industrial Technology Association

Pictures on the cover: Winning artworks in the Micromachine Drawing Contests
Micromachine making micromachine, Good-to-have-it, Letter-enlarging machine and Micro-soccer tournament (from top to bottom)

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