The Research Reports under the 7th Micromachine Technology Research Grant

This research grant program started inviting applications in 1993 as a part of the independent activities of MMC. The purpose of the program is to assist college and university staff engaged in basic research on micromachines, as well as to promote further development of micromachine technology and communication between academics and people in the industrial world.

Among the themes selected for the seventh (1999) research grant, one 1-year research project and six 2-year research projects carried over from fiscal 1998 have been completed.

Turn the page for a summary of the research results.

Subjects for the Micromachine Technology Reserch Grant

Research Project Selected for Fiscal 1999

Leader & Co-Worker	Affiliation	Subjects	Period
Assoc. Prof. Takaaki Oiwa	Faculty of Engineerring, Shizuoka University	Coordinate Measuring Machine Using a Parallel Mechanism for Micromachine Parts	1 Year

Carried-Over Projects Selected for Fiscal 1998

Leader & Co-Worker	Affiliation	Subjects	Period
Prof. Masao Washizu	Department of Mechanical Engineering, Kyoto University	Molecular Surgey of DNA based on Microsystems	2 Years
Prof. Kazunori Kataoka Research Assoc. Atsushi Harada	Department of Matenals Science, Graduate School of Engineering, The University of Tokyo Department of Matenals Science, Graduate School of Engineering, The University of Tokyo	Structural Design of a "Chemical Nano-machine" Based on the Self-organization of Polymers and Its Application to Targeting Therapy	2 Years
Research Assistant Prof. Tooru Ooya	School of Materials Science, Japan Advanced Institute of Science and Technorogy	Study on Biomedical Micromachine Using Biodegradable Supramolecular-Assembly	2 Years
Lecturer, Hiroshi Toshiyoshi Prof. Hiroyuki Fujita	3rd Division, Institute of Industrial Seience, The University of Tokyo 3rd Division, Institute of Industrial Seience, The University of Tokyo	Micromachine System for Micro-optical Smart Pixel Application	2 Years
Prof. Shigefumi Nishino Research Assoc. Kiyoshi Takano	2nd Division, Institute of Industrial Science, The University of Tokyo 2nd Division, Institute of Industrial Science, The University of Tokyo	Experimental Study on Fluid Flow and Heat Transfer inside Microchannels Utilizing Micromachining Technology	2 Years
Prof. T. H. Barnes	Physics Department, University of Auckland, New Zealand	Low Noise Feedback Interferometry for Micromachine Servo Actuators	2 Years

Application Guidelines for the 9th (Fiscal 2001) Research Grant Themes on Micromachine Technology

1. Objective of the research grant
Basic research on basic technology, functional element technology, and systematization technology for micromachines

2. Research period
Theme A : April 2002 - March 31, 2003, or
Theme B : April 2002 - March 31, 2004

3. Application period, theme decision, and funding grant date
Application period : July 10 - October 31, 2001
Theme decision : Middle of March 2002
Funding grant date : End of March 2002

4. How to apply
Send a fax requesting the application form to the Micromachine Center. Be sure to include your own fax number or a fax number where we can contact you.
Micromachine Center Fax : +81-3-5294-7137

5. Qualifications
College or university faculties (professors, associate professors, lecturers and research associates) who belong to academic societies affiliated with the Federation of Micromachine Technology

6. Other
(1) Total funding granted : Approximately 10 million yen
(The upper limit for a single research project is 2 million yen for theme A, and 3 million yen for theme B.)
(2) After the grant is decided, we may ask recipients to carry out their research in collaboration with supporting member enterprises of the Micromachine Center, as one of the objectives of this project is to encourage communication between enterprises and academics.
(3) Contact : Research Department, Micromachine Center
Person in charge : Hodono
E-mail : hodono@mmc.or.jp

Coordinate Measuring Machine Using a Parallel Mechanism for Micromachine Parts

Takaaki Oiwa
Associate Professor,
Faculty of Engineering, Shizuoka University

1. Introduction

As the formation of high-precision micro-parts having complex 3D shapes is becoming feasible, there is increasing necessity to perform precise 3D evaluations of such parts. Rather than using mechanisms based on the conventional rectangular coordinate system, we proposed a new 3D coordinate measuring machine (CMM) using a parallel mechanism in which active pairs are set in parallel with an output link. In the present study, we will develop a small parallel μCMM using such a mechanism. This paper will give a brief outline of this device and report on the results of studies on the link layout, as well as the trial-manufactured prismatic links (struts).

2. Outline

Fig. 1 shows a conceptual diagram of the parallel μCMM, the basic design principles of which are described below.

(1) A link mechanism consisting of a parallel mechanism with 3 degrees of freedom (DOF) is used in place of the mutually orthogonal slide mechanisms using the rectangular coordinate system.
(2) While the spherical joints are the basic form of reference for conducting precise measurements, calibration is performed based on displacement sensors built into the strut that measure the rotational error of the joint.
(3) The link layout is designed as a retracting mechanism to improve the measuring resolution in relation to the scale resolution. Therefore, the mechanism is larger in relation to the measuring space.
(4) The link layout is optimized to eliminate the effects of joint rotational error and error in the mechanism's parameters on measurement precision.

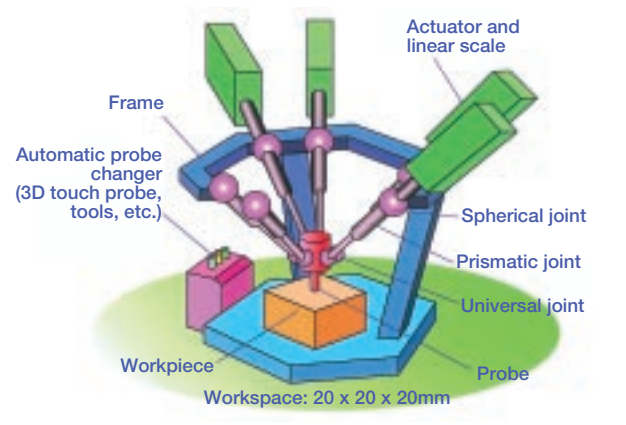

Fig.1 μ-CMM using a parallel mechanism

3. Link Layout Design

The link layout was studied to reduce the effects of errors in parameters and joint rotation on movement of the probe in order to further improve measuring resolution. We used singular values in a Jacobian matrix as a function for expressing the magnitude of the above effect. For purposes of comparison, the radial position of the spherical joint on the base and the size of the measuring space (100 × 100 × 100mm) were set equivalent to the conventional parallel CMM. The stage radius, probe length, and position on the measuring space along the Z-axis were set as design variables. Fig. 2 shows the layout of the links for the parallel μCMM based on this design. The actual size of the parallel μCMM is expected to be about 1/2-1/5 the dimensions given in the diagram.

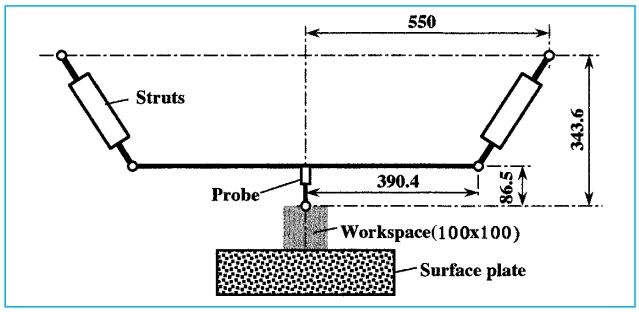

Fig.2 Link configuration after optimal design

4. Prismatic Links

Next, an outline will be given for the trial prismatic links. Fig. 3 shows a photo of the link. An inchworm mechanism having a layered piezoelectric element was used as the actuator. The theoretical drive resolution was set to 2nm or less. An advanced linear measuring unit (scale) having a precision of ±0.1μm and a resolution of 2nm or less is also built into the link. Velocities were measured when applying a load in the form of weights having masses of 10-400g. From these measurements, it is clear that the velocity is nearly proportional to the size of the load, and the links have a thrust of more than 4 N per link. Next, positioning with closed loop controlwas performed using the measuring unit as a feedback sensor. The time required for performing a 10-μm step positioning process was within 0.1sec.

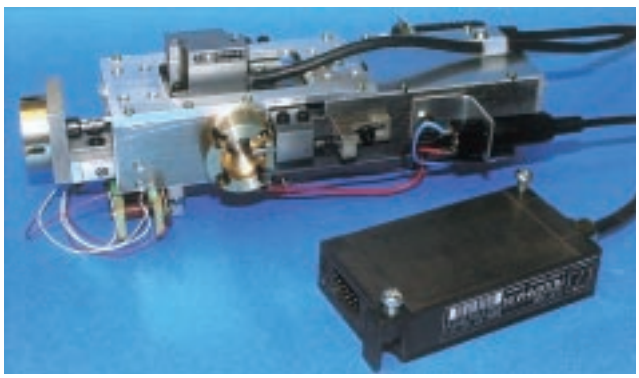

Fig.3 Photo of the trial-manufactured prismatic link

5. Conclusion

As described above, we proposed a small 3D CMM employing a parallel mechanism of 3 DOF with the aim of measuring the dimensions and geometric deviation of 3D parts, such as micromachine parts. The link layout was designed and trial prismatic links were manufactured and evaluated. Future plans call for studying the effects of the elastic deformation and rotational error in the joints unit on thermal deformation of the links.

Molecular Surgery of DNA based on Microsystems

Masao Washizu
Professor,
Department of Mechanical Engineering, Kyoto University

1. Introduction

In recent years, research has intensified on μ-TAS and other such systems that fabricate chemical systems to be integrated on a chip. Although μ-TAS in its present state is not really micro-sized, the samples are provided in an aqueous solution, that is, as a bulk sample. Hence, by further miniaturizing these systems, we should be able to develop an ultimate chemical system capable of treating molecules individually. DNA is thought to be the most suitable target for manipulation on the molecular level, because DNA molecules contain the fundamental blueprints of life and can easily multiply molecules. In the present study, we researched a method of "molecular surgery" for fixing a single DNA molecule to a fixed surface in order to cut or otherwise alter the molecule.

2. Molecular Surgery of DNA

Just as a patient is fixed to an operating table in normal surgery, the DNA molecule, which is the target of our molecular surgery, must also be fixed to a surface. It is also necessary to stretch the DNA molecule in a linear shape in order to access the desired location. The author and others developed a method using the electrostatic field in a micromachined electrode to stretch the DNA and anchor the ends of the molecule. As shown in Fig. 1, enzyme cutting at a specified position is achieved by laser-manipulated micro-particles on which DNA-cutting enzymes are immobilized.

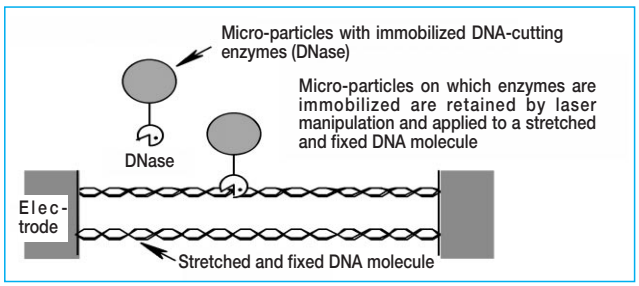

Fig.1 Conceptual drawing of DNA molecular surgery

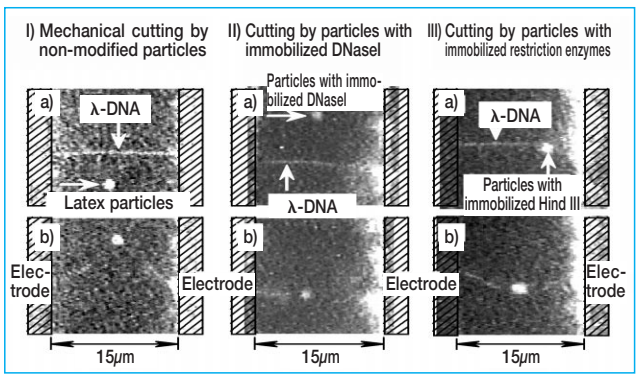

Fig.2 Molecular surgery of DNA

Fig. 2 shows photos of the cutting operations. In Fig. 2 I), latex particles on which enzymes are not immobilized are pressed against the DNA. Mechanical cutting does not occur until the DNA has stretched 1.5 times its natural length. In Fig. 2 II), DNaseI are immobilized on particles that are pressed against the DNA for cutting the DNA without relation to its base sequence. Cutting occurs the moment the particles contact the DNA. In Fig. 2 III), restriction enzymes are immobilized on the particles for recognizing and cutting a specific sequence. In this case, cutting occurs only when the particles contact the sequence to be cut (see Fig.2 III b).

3. Developing Microprobes for Molecular Surgery

In order to perform molecular surgery at a high resolution, we developed a probe for molecular manipulation, as shown in Fig. 3. The probe is formed of a substrate having a sharp point and three or more spherical particles fixed to the top surface of the probe. By retaining the particles on the substrate independently by a laser beam, the probe is designed to push its pointed tip, on which enzymes are immobilized, on a desirable position and at a desirable orientation. The probe is first manufactured as a cantilever structure by performing Si anistropic etching on the substrate. The micro-particles are then fixed to the substrate by a molecular linker, and the structure is broken off at the root.

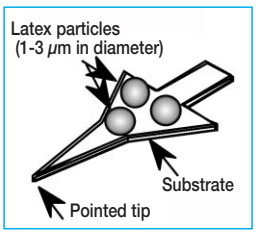

Fig.3 Microprobe for manipulating molecules

Fig. 4 shows an example for controlling the orientation of the probe. By deflecting a single laser beam at a high rate of speed using a galvanometer mirror, each of the three particles are trapped through a time-division method. Translational and rotational movement of the probe is then achieved by moving the micro-particles while maintaining their relative positions to one another.

4. Conclusion

Micromachine technologies, such as micromachined electrodes and micromachined probes, are powerful means for interfacing with the molecular nano-world and macro-world. Based on our current direction, we anticipate breaking away from conventional biochemical methods, in which molecules are collected in a test tube base, and developing new biotechnologies capable of performing deterministic manipulation on specific molecules at specific positions.

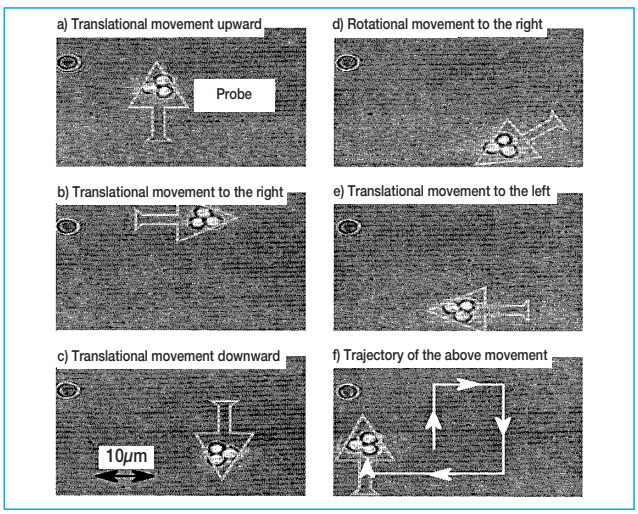

Fig.4 Translational and rotational movement of the probe

Structural Design of a "Chemical Nano-machine" Based on the Self-organization of Polymers and Its Application to Targeting Therapy

Kazunori Kataoka, Professor,
Atsushi Harada, Research Associate,
Department of Materials Science, Graduate School of Engineering, The University of Tokyo

1. Introduction

The capacity to work effectively in microspaces is important in the field of micromachine technology. Focusing from such viewpoint, there are many kinds of available molecules in nature. Enzymes, for example, serve as a biological catalyst that, when catalyzed under mild conditions in an organism, can generate numerous organic reactions with phenomenal speed and selectivity. Hence, enzymes can be considered a type of natural micromachine. However, their use *in vivo* often limited due to their instability and antigenicity. In particular, solving these problems is a major issue in the field of site-specific enzyme delivery. In this study, we prepared core-shell type multimolecular assembly entrapping enzyme molecules in the core (see Fig.1), which were formed from the mixture of charged block copolymer (polyethylene glycol-block-poly α,β-aspartic acid) with an enzyme (egg white lysozyme) driven through electrostatic interaction in an aqueous solution. We studied the utilities of the "chemical nano-machine" to perform appropriate biochemical reactions under various conditions.

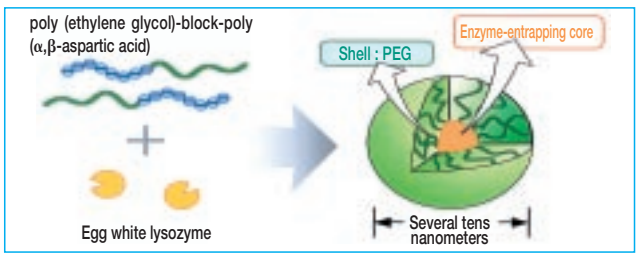

Fig.1 Chemical nano-machine entrapping enzyme in the core

2. Environmental-Responsive Chemical Nano-machines

We confirmed that core-shell type multimolecular assembly entrapping enzyme in the core, as shown in Fig.1, exhibited a reversible formation with the change in the ionic strength (NaCl concentration) in the aqueous solution. Enzyme was entrapped in the core at a low ionic strength, but was released from the assembly when the ionic strength was increased. The enzyme once again returned to the core of the assembly after the ionic strength was lowered. It was applied this behavior as on-off control system of enzymatic reaction. In order to evaluate enzyme activity, a substrate (bacterial cell) with larger size than the assembly was used. There observed no activity, when the enzyme was entrapped in the assembly (low ionic strength), since the enzyme could not interact with the bacterial cells. However, increasing the ionic strength, the enzyme was released from the assembly and could easily interact with the substrate, at which enzyme activity was shown (see Fig.2). It was also confirmed that this process was repeatable, and enzymativactivity could controlled through the reversible formation of core-shell type assembly.

3. Chemical Nano-machine System Using the Core of Assembly as Enzymatic Nanoreactor

As mentioned above, the enzymatic reaction is controlled through the reversible formation of the assembly. Such assembly has another possibility as applied material by using the core of the assembly having the structure shown in Fig.1 as an enzymatic reaction field. Thus, it was evaluated the enzyme activity of lysozyme in the core of the assembly. In this evaluation, the substrate with relatively small size, which could diffuse into the core of

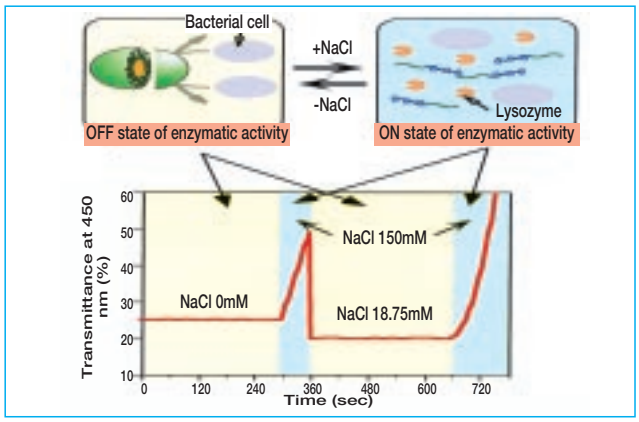

Fig.2 On-off control of enzymatic activity synchronizing with reversible formation by an external stimulus

the assembly, was used, and enzymatic activity was evaluated through the monitoring of the release amount of p-nitrophenol. Fig.3 shows the results of observing the generation of p-nitrophenol directly after combining the enzyme by itself and entrapped in the assembly with the substrate solution. These results showed that an enzyme reaction occurs even when the enzyme is entrapped in the assembly. Interestingly, the reaction rate of enzyme in the core of the assembly was twice as fast with free enzyme. By determining the kinetic constants of enzymatic reaction, it was confirmed that the enhanced effect of enzymatic reaction was induced by the effective condensation of the substrate to shell-layer of the assembly. Hence, the shell-layer might work as a reservoir for the substrate. This suggests the possibility of further encouraging the enzyme reaction without chemically conjugation of the enzyme with polymers, by increasing the affinity of the substrate and the shell-forming segment.

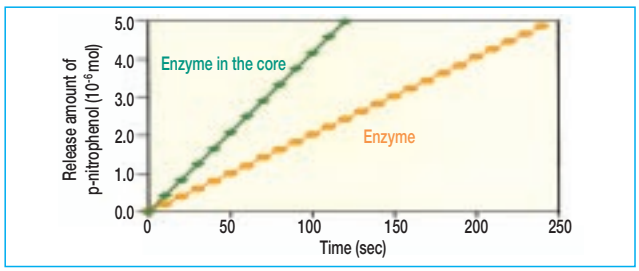

Fig.3 Release profile of p-nitrophenol with enzymatic reaction using the core of the assembly as a reaction field

4. Conclusion

Using self-organization between an enzyme and a synthetic polymer, we prepared multimolecular assembly with an average particle size of 50 nm having a core-shell structure for entrapping the enzyme. The formation of the assembly exhibited a reversible behavior that could be controlled by external stimuli (modifying the ionic strength). It was confirmed that such external stimuli can be used to turn the enzyme activity on and off. We also confirmed that the core of the assembly could be used as a nanoscopic enzymatic reaction field. Based on such interesting behavior, the assembly could be aptly named a "chemical nano-machine." This system shows great promise not only in enzyme targeting, but in various fields as a diagnostic tool.

Study on Biomedical Micromachine Using Biodegradable Supramolecular- Assembly

Tooru Ooya
Research Assistant Professor,
School of Materials Science, Japan Advanced Institute of Science and Technology

1. Introduction

Recently there has been a general trend of growing expectations throughout the world in the fields of nanoscale science and nanotechnology. Strategic approaches are important in the design of biomedical micromachines for controlling molecular forms from nano to micro level. This study focuses on the supramolecular structure and cylindrical shape of polyrotaxanes, in which numerous alpha cyclodextrins (α-CDs) are threaded onto a polyethylene glycol (PEG), to investigate the effects of a particular polyrotaxane structure on the function of molecular recognition.

2. Enhanced Enzymatic Recognition by Supramolecular Structure of Polyrotaxanes

In synthesizing the polyrotaxane, a peptide sequence phenlyalanylglycylglycine (FGG) is introduced at the ends of the polyrotaxane as the oligopeptide group. FGG itself can be completely degraded by an exo-peptidose, such as aminopeptidase M (AP-M). From the result of in vitro experiment, it was found that FGG in FGG-terminated PEG that had not been threaded through the α-CD cavity degraded only 30%. This indicates that increased while molecular weight due to conjugation of FGG and PEG are chemically bonded and interaction between the AP-M and FGG terminals. On the other hand, degradation of FGG-terminated polyrotaxane completely proceeded, indicating that the interaction increases again due to α-CD threading through the PEG (see Fig.1). Since the *Km* value was about 1/22 of the FGG-terminated PEG, it was suggested that the supramolecular structure of the polyrotaxane actually improved the enzymatic recognition.

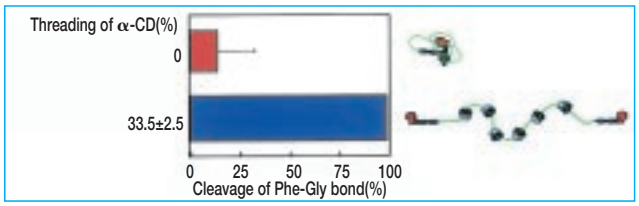

Fig.1 The effects of α-CD threading on the terminal tripetide degradation by aminopeptidose M

3. Recognition of polyrotaxane-Biotin Conjugates

Approximately 300-400 hydroxyl groups exist along the cylindrical structure in one molecule of polyrotaxane. If numerous water-soluble ligands are introduced, it is expected that the ligands become oriented along the cylindrical structure of the polyrotaxane. Based on the hypothesis biotin was introduced into the polyrotaxane and its interaction with streptavidin (SA) precoated on the surface of a sensor was analyzed using a surface plasmon resonance (SPR) appratus. From the SA binding curve during the coating process, the surface density of the SA was estimated at 2.5×10^{-5} nmol/mm^2. Based on a theoretical length estimated on the presumption that the polyrotaxane-biotin conjugate is cylindrically shaped, a polyvalent interaction such as that shown in Fig.2 is considerable. The biotin introduced into the polyrotaxane was recognized by SA which was confirmed from the binding curve when adding the solution containing the polyrotaxane-biotin conjugate. This demonstrates that molecular designs introducing ligands in cylindrical structures of polyrotaxane can be used as probes for recognizing specific receptors.

4. Inhibiting Peptide Transporter (PepT1) function by Dipetide-Polyrotaxane conjugates

This work was carried out collaboration with Professors Akira Tsuji and Dr Ikumi Tamai of Kanazawa University, Department of Pharmaceutical Sciences. A dispeptide of varyl-lysine (Val-Lys) that is transportable via peptide transporter (PepT1) was introduced into numerous hydroxyl groups of polyrotaxane. PepT1 is well known to be expressed in the small intestine on the brush border membrane of intestinal epithelial cells. In the in vitro experiment, we studied the capacity of the polyrotaxane cylindrical structure of the synthesized Val-Lys-polyrotaxane conjugates to inhibit transporting (uptake) of a dipeptide derivative (glycylsarosine; GlySar), which is specifically recognized by the PepT1. It was confirmed that the conjugate included about 46 molecules of Val-Lys in one molecule of polyrotaxane. The uptake of GlySar was decreased by adding this conjugate to a Hela cell culture medium in which PepT1 was stably expressed. When converting the concentration of Val-Lys to the same concentration of Val-Lys-introduced dextran or Val-Lys-introduced α-CD, the inhibition is weaker than when using Val-Lys-introduced polyrotaxane. This suggests that the cylindrical structure of the polyrotaxane is effective in the interaction between Val-Lys and PepT1. Therefore, it is suggested that Val-Lys in the conjugate polyvalently interacts with PepT1 (see Fig.3).

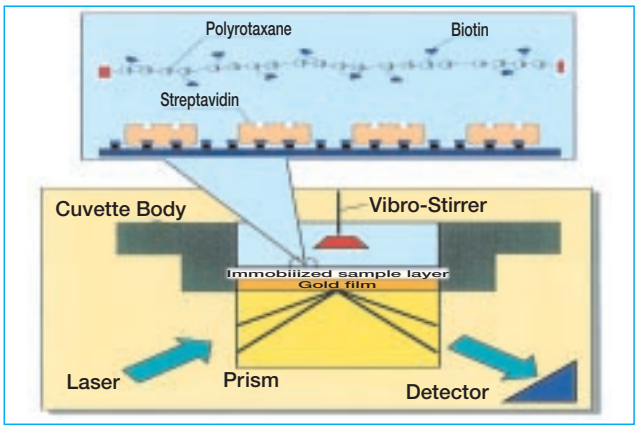

Fig.2 Image of polyvalent interaction between a polyrotaxane-biotin conjugate and streptavidin in a surface plasmon resonance (IAsys, Affinity Sensors)

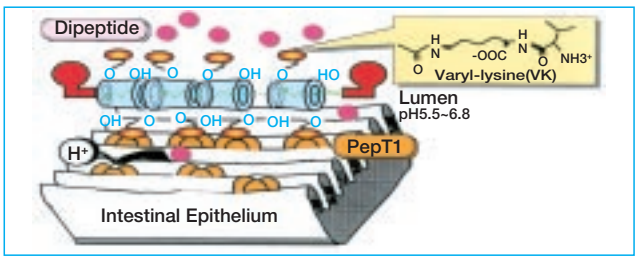

Fig.3 Illustration of Inhibiting transport of dipeptide is inhibited by polyvalent interaction between a polyrotaxane-VK conjugate and PepT1

5. Conclusion

The above results indicate that the supramolecular structure and cylindrical shape of the polyrotaxane is useful for (1) forming an enzyme-substrate complex and (2) controlling receptor recognition.

Micromachine System for Micro-optical Smart Pixel Application

Hiroshi Toshiyoshi, Lecturer,
Hiroyuki Fujita, Professor,
3rd Division, Institute of Industrial Science, The University of Tokyo

1. Introduction

We designed and manufactured two-dimensional micro-mechanical optical scanners and evaluated their properties with the aim of applying smart pixels in optical communication switching. Smart pixels are used to integrate mechanical, electrical, and optical devices in a micro three-dimensional space.

2. Micro-mechanical Smart Pixels

Fig.1 shows a conceptual view of a micromachine system, the objective of the present study, employing smart pixels to integrate micro-mechanical (MEMS) elements. This system includes an array of optical input fibers and optical beam steering elements (scanners) using micromachines. The optical switching function is achieved by projecting an optical beam onto corresponding output ports. As shown in the diagram, a lens, diffraction grating for wavelength selection, and filter are inserted between the input and output fibers to magnify the beam scanning angle.

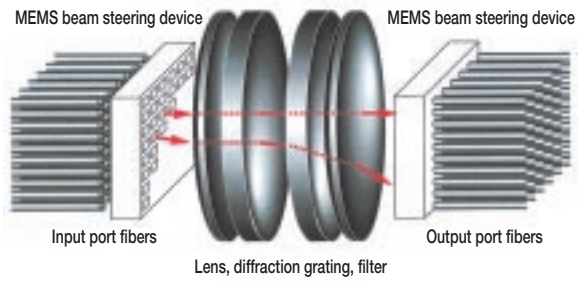

Fig.1 Concept of micro-mechanical smart pixels

3. Two-Dimensional Torsion Mirror Laser Scanner with Electrostatic Actuators

Fig.2 shows an electrostatic torsion mirror device serving as a two-dimensional optical scanner, using a micro mirror to reflect light. The transter function of this device has large nonlinearity and crosstalk. Hence, complex feedback control would be needed to achieve precise positioning control in a device for modifying the optical path of smart pixels, for example. In order to simplify transient control for switching, we developed a reliable open-loop control method and an analytical model. The drive voltages are determined based on this model. Fig.3 shows the reflected beams projected on a grid pattern grating. With this

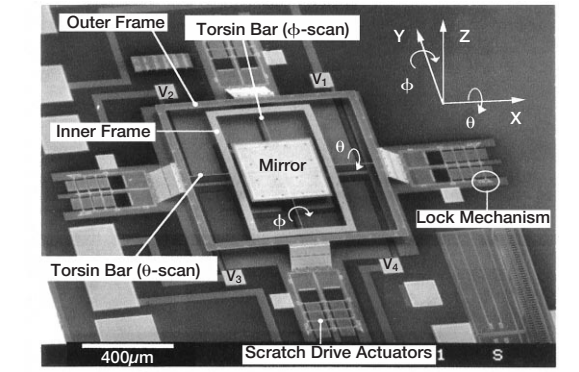

Fig.2 Two-dimensional torsion mirror laser scanner

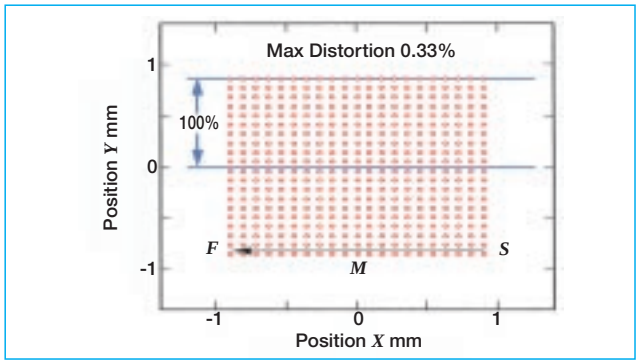

Fig.3 Results of scanning with the mirror scanner

construction, it was possible to prevent beam aberration and to shorten the switching time. The construction can also contribute to lowering signal leakage if the switching paths are arranged skillfully.

4. Micro-lens Two-Dimensional Laser Scanner

Fig.4 shows an optical transmission scanner employing the XY movement of a micro lens. Unlike the mirror type scanner, the lens movement and scanning angle of the light are linear. Further, the lens can be maintained at a desirable position. Four polysilicon scratch drive actuators are employed to drive the lens. The lens position (scanning angle) is controlled through the counting of voltage pulses.

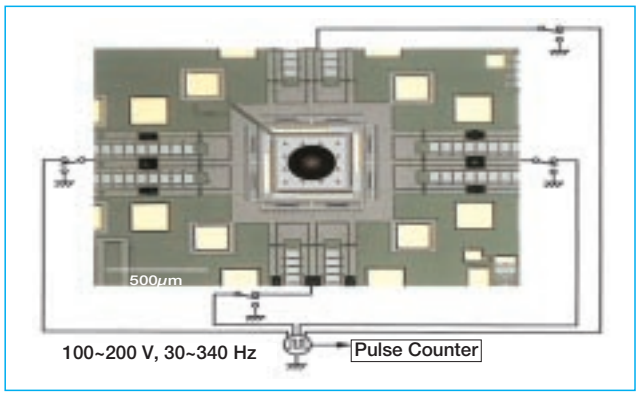

Fig.4 Two-Dimensional micro-lens laser scanner

5. Conclusion

As described above, we developed two types of trial optical scanners: a reflection type and transmission type, evaluated their performances, and built an analytical model. We were able to gather much data on process yields inherent in surface machined devices, failure modes during operations, and analytical methods. We would like to further reduce the size of these devices and attempt to integrate them with an actual control drive circuit.

Acknowledgments

The results of this study were obtained through joint research conducted during FY 1999 and 2000 in the laboratory of Prof. Ming C. Wu of UCLA's Electrical Engineering Department.

Experimental Study on Fluid Flow and Heat Transfer inside Microchannels Utilizing Micromachining Technology

Shigefumi Nishio, Professor,
Kiyoshi Takano, Research Associate,
2nd Division, Institute of Industrial Science, The University of Tokyo

1. Introduction

As channels are being manufactured with increasingly smaller inner diameters, we are beginning to see the emergence of a peculiar thermohydrodynamic effect. This suggests that estimations on the normal scale can produce major errors, making it impossible to estimate the flow and heat transfer characteristics of a fluid with precision. The present study is aimed at determining the channel diameters at which specific thermal and flow phenomena occur and clarifying the characteristics of such phenomena. In general, heat transfer increases with decreases in the equivalent diameter. However, we hypothesized that heat transfer may reach a maximum value at a certain diameter. It is conceivable that the results of this study will provide valuable information for many fields with broad applications.

2. Experiment Methods and Equipment

Fig.1 shows an overall view of the equipment used in the experiment. The equipment comprises a (1) fluid supply system (micro-pump, buffer tank, filter, pressure gauge of diaphragm type, and flowmeter), a (2) fluid heating and vacuum insulation system (constant temperature bath and vacuum pump), and a (3) cooling-fluid supply system (constant temperature bath, pump or air blower, and magnetic flowmeter).

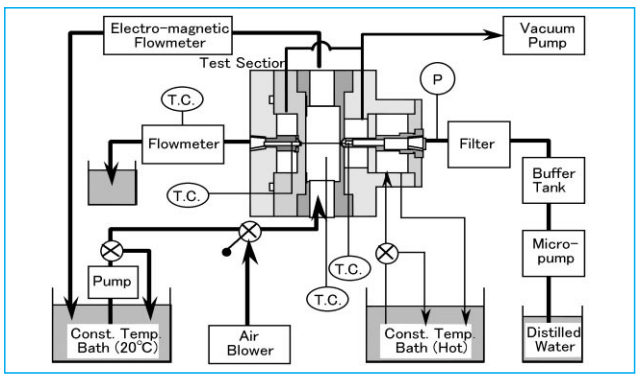

Fig.1 Overview of equipment used in the experiment

Fig.2 shows a detailed construction of the test section in the experimental equipment. Since the test section should be designed to drastically reduce heat loss around the microchannel, all parts except the fluid heating unit at the inlet are made of an acrylic resin. Fluid is introduced through the test liquid inlet (1), where it is heated to a prescribed temperature (50°C) by circulated hot water (2). Subsequently, the fluid passes through a vacuum chamber (3) and is introduced into the microchannel (6). During the experiment, measurements are taken of the fluid temperature at the inlet and outlet of the microchannel, flow rate of the fluid, temperature and flow rate of the cooling water, and pressure of the fluid at the inlet to the microchannel.

3. Results

As for the friction factor on the normal scale, f, the f-Re value is fixed at 64. In the present experiment, however, the f-Re value was approximately twice that on the normal scale. While this is considerably higher than results of microchannel measurements reported thus far, the reason for this high value has not been identified at this stage. Fig.3 shows the measurements taken of the average Nusselt number Nu_i in the channel.

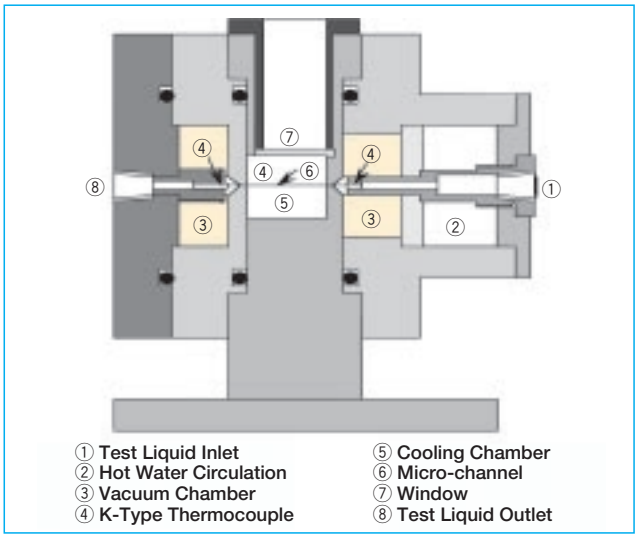

Fig.2 Detailed construction of the test section

The Nusselt number Nu_i in the present experiment was within a range of about 0.7-1.0. This value is clearly smaller than the fixed value 4.36 for laminar flow at a constant heat flux on the normal scale and is 1.7-3 times higher than the results of Choi, et al. Further, the Nusselt number Nui was clearly shown to be dependent on the Reynolds number Re, as the Nusselt number Nui decreased along with decreases in the Reynolds number.

4. Conclusion

The following conclusions were made after analyzing measurements of the coefficient of friction and the average Nusselt number Nu_i in a microchannel having an inner diameter of 52.9μm and a length of 30mm.

(1) The average Nusselt number exhibited heat transfer characteristics thought to be inherent in microchannels, including a value lower than the normal scale and decreases dependent on the Reynolds number.

(2) From the above results, a diameter near the lower limit that exhibits heat transfer characteristics on the normal scale is optimal for the design of heat exchange devices. However, this issue needs to be examined further in the future.

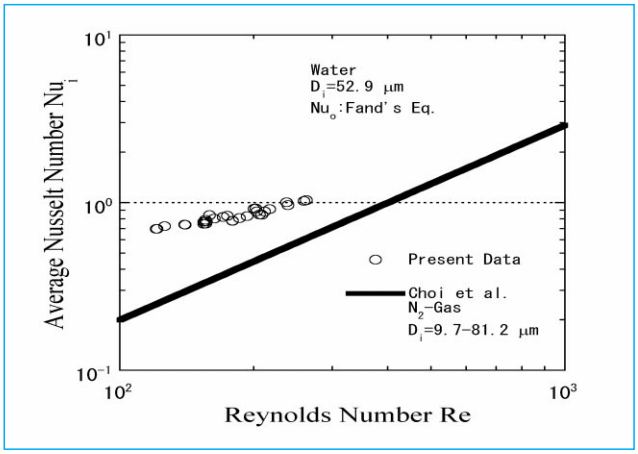

Fig.3 Measurements of the average Nusselt number

Low Noise Feedback Interferometry for Micromachine Servo Actuators

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1. Introduction

In this project we have developed the new technique of feedback interferometry for micro machine applications where displacement measurements to an accuracy of a few nm are desirable. Feedback interferometry has the potential to measure phase rapidly, with high accuracy, using simple optical systems, but its performance limits have not been know until now.

We have for the first time determined feedback interferometer accuracy, the conditions under which they are stable, and their noise performance. We tested our theory in the laboratory using a prototype high-precision feedback interferometer. It was capable of measuring movements with a repeatability of λ/80, and linearity better than λ/100.

2. Principles

Fig.1 shows a generic feedback interferometer. The output intensity of the interferometer is used to control the phase in one arm of a two beam interferometer. The instrument measures the interferometer phase ϕ_i which in a micromachine system might - for example - arise from movement of the other interferometer mirror. By solving the feedback interferometer equation:

$Io/B=1+\cos(\phi_i+GIo/B)$ ·····(1)

we find that the interferometer output intensity Io varies linearly with phase. Interferometer phase can then be determined directly from the output intensity (Fig.2). The system can track accurately over several wavelengths.

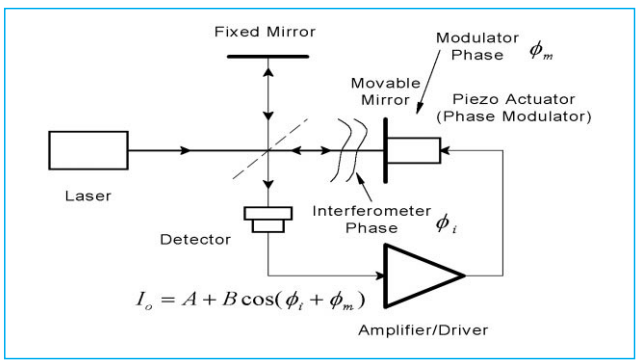

Fig.1 Feedback Interferometer

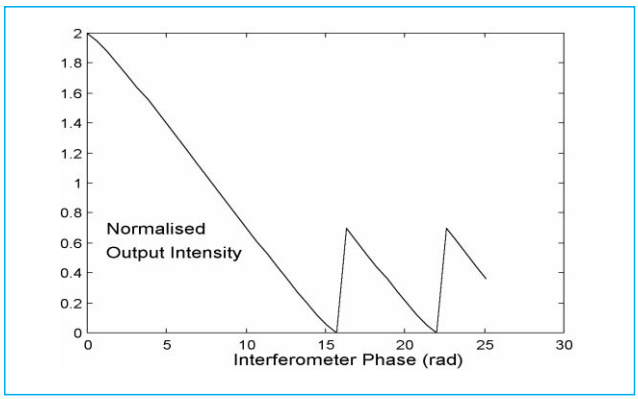

Fig.2 Feedback Fringe Profile

3. Experiments and Results

Fig.3 shows our prototype interferometer to compare the accuracy of feedback interferometry with conventional phase-stepping and heterodyne techniques.

Feedback is applied via mirror M2, with mirror M1 moved by piezo actuator to vary interferometer phase.

Fig.4 shows the interferometer accuracy. The phase from feedback interferometery is linearly related to that phase stepping with repeatability of λ/80.

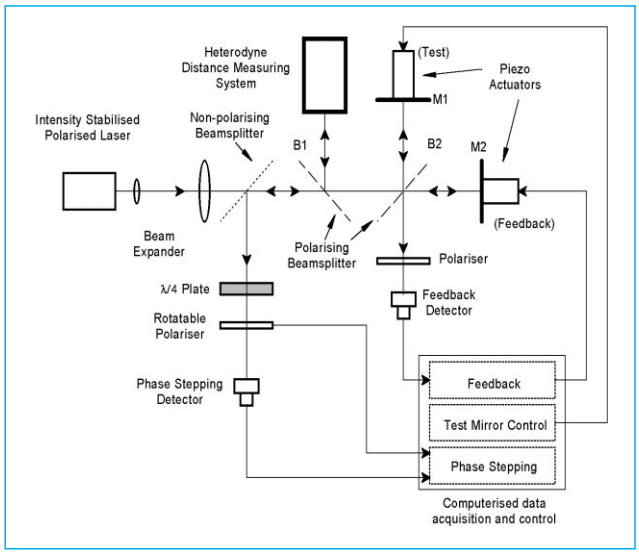

Fig.3 Experimental Interferometer System

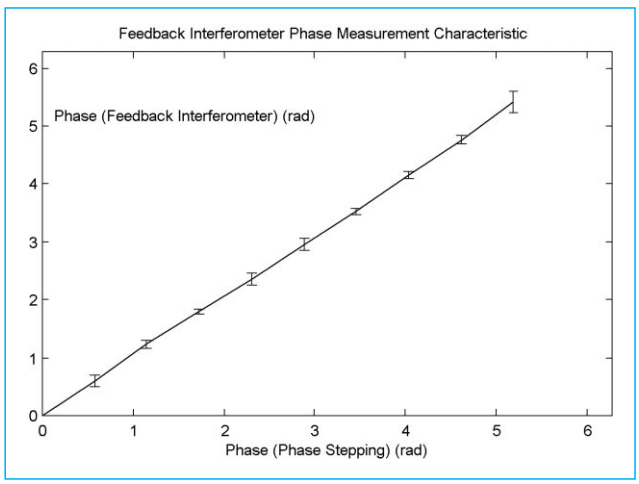

Fig.4 Phase Measurement Characteristic

4. Conclusion

We have shown that feedback interferometry is a promising candidate for application to micromachines. It is capable of high accuracy and linearity with a simple opto-electronic system that can be made to operate at high speed.