High-accuracy endoscopic microscopy using a thin, 1.5 mm diameter probe with optical coherence tomography

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[Translation from *Synthesiology*, Vol.11, No.1, p.23–32 (2018)]

We developed an endoscopic microscopy system with 20 nm accuracy that affords inspection through narrow gaps using a thin, 1.5 mm diameter probe. Accuracy was improved using Optical Coherence Tomography (OCT). The frequency modulated light source is stabilized with closed control from self-interference measurement. The probe is driven by two miniature motors, which allow three-dimensional scanning of an internal surface. Imaging performance is 60 frames per second. The high accuracy with narrow clearance capabilities of this system reduces the need for machine overhauls, which affords trustworthy daily inspections and hence greater machine reliability.

Keywords **:** Endoscope, fiber scope, Optical Coherence Tomography (OCT), super resolution, internal diameter measurement

1 Introduction

How far will machining technology advance? In terms of accuracy, there is a famous roadmap known in the precision machining field as shown in Fig. 1.[1] Since atoms cannot be divided by machining process, 1 nm should be the fundamental limit which is close to the size of an atom, and nanotechnology is the way to approach that limit using various methods. In that sense, atomic manipulation[2] and molecular manipulation[3] using an atomic force microscope (AFM) have been realized, and in theory, further advancement cannot be expected. Yet, does the machining technology end there?

The ultra-high-accuracy machining technologies such as AFM and focusing ion beams are not implemented immediately in personal-use 3D printing or computer numerical control (CNC) mills, and cost and time are not feasible. Recently, 3D printers and CNC mills have been in the spotlight as innovations in production technology, and these may change production technology from the basis. However, in fact, these were invented over 35 years ago. CNC was developed in 1952 as a project of the Massachusetts Institute of Technology,[4] and the 3D printer was invented by Hideo Kodama in 1980.[5][6] Incidentally, when Kodama presented a prototype and printed trial products, the engineers who were so engrossed in submicron level machining precision totally ignored him.[7] Even if technology is of the highest quality, the world will not change if it is useful only to a few. I think

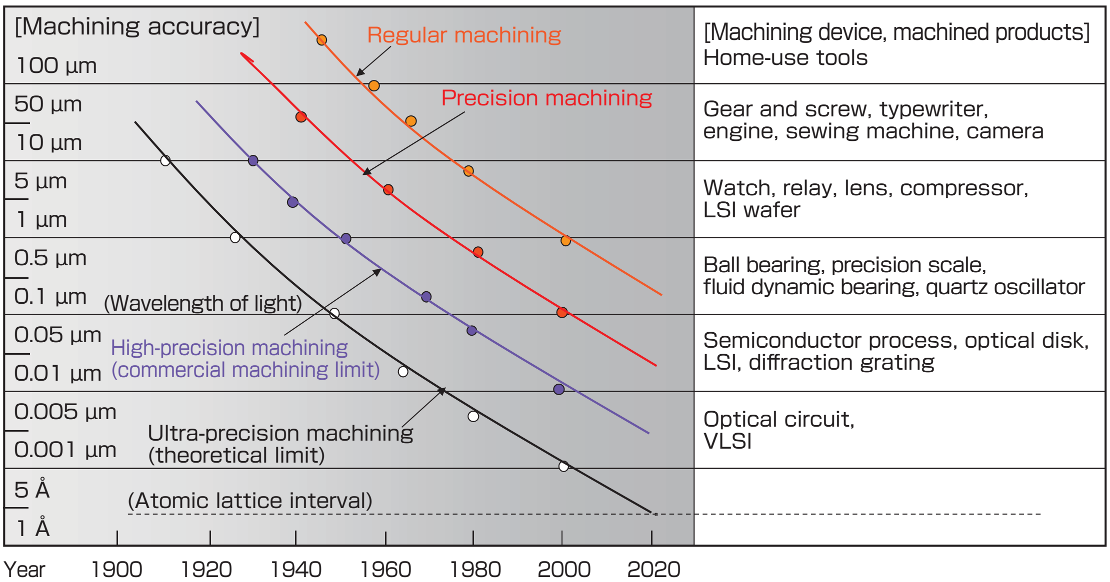

Fig. 1 Trend in machining accuracy

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Original manuscript received November 2, 2017, Revisions received January 19, 2018, Accepted January 19, 2018

evaluation as "innovation" and "novelty" can only be given to the technology that was limited to few researcher becomes widely available for personal use. In this sense, to reform the things that were invented into usable forms and to reduce cost are extremely important form of innovation. Including control technology and measurement technology, the majority of the manufacturing technologies have not reached atomic accuracy, and therefore, there is ample room for advancement.

We are currently looking at the technology for high-accuracy measurement of inner cylinders. Inner cylinders are not only used as combustion baskets of engines or power generator turbines, but are also components whose accuracy affects the energy efficiency of bearings and other parts. Despite this fact, since most of the technologies applicable to high-accuracy measurement have evolved from microscope technology, it is limited mostly for thin, flat samples, and is not suitable for inspection of inner side. For inner cylinder inspection, the current situation is going toward how to achieve high accuracy in conventional roundness measuring instruments. The current highest accuracy is about 0.05 μm, and as long as it is an extension of roundness measuring instruments, expert craftsmanship is required for centering and leveling.

There are many limitations such as in accuracy, procedures, measurable sizes, and measurable shapes in the technology for measuring the inner diameter. They cause its low usability and application range. These equipment should be used not only for quality control during parts manufacturing, but be also used in routine inspection and load tests to determine the wear/tear and exchange period, and it is necessary that anyone can obtain highly accurate digital data that can be managed on a PC.

The endoscope would be suitable for this purpose. However, it usually provides still or motion images as seen in Fig. 2 left, which did in short-term diagnosis only. The digitized information would be more useful for the comparative analysis, as shown in Fig. 2 right. Since it is difficult to detect minute shape variations of a subject with a photograph, comparison by digitized data is preferable. Regarding this point, rather than a conventional endoscope, we need a digital microscopic endoscope combining the functions of digital microscope and the endoscope-like probe that can enter small spaces.

In our research, the digital microscopic endoscopy has realized to perform high-accuracy measurement based on optical coherence tomography (OCT). Although optical interferometry used in OCT has been common in industrial surface measurement as white-light interferometry, Professor Tanno of Yamagata University and J. Fujimoto *et al.* of MIT almost simultaneously showed that this can be applicable to tomographic measurement of the fundus.[8]–[10] After these research, application to ophthalmology advanced rapidly, and the products with user-friendly interface are available from almost all ophthalmological device companies around the world. Innovative change was made in ophthalmological diagnosis when human retinal tomography became available.

Originally, OCT was configured using optical fibers, and it is suitable for the fabrication of microprobes, but its deployment in endoscopes has been slow. Endoscopes using OCT are used limitedly in the medical field, and vascular OCT with which blood vessels are imaged from inside has been drawing attention. On the other hand, when irradiating a vessel wall with measurement light emitted from a probe that is inserted into a vessel, blood interferes with the OCT optical path. Therefore, it is necessary to stop the blood flow by blocking the vessel for a short time using a balloon catheter, flush the blood by injecting physiological saline, and then observe the blood vessel wall. This requires more skill compared to the conventional intravascular ultrasound (IVUS), and the OCT method has not replaced the conventional method. An innovation that allows easy operation is necessary.

On the other hand, there is hardly any industrial application of OCT. While it will be discussed in the next chapter, the specifications required are different from medical application,

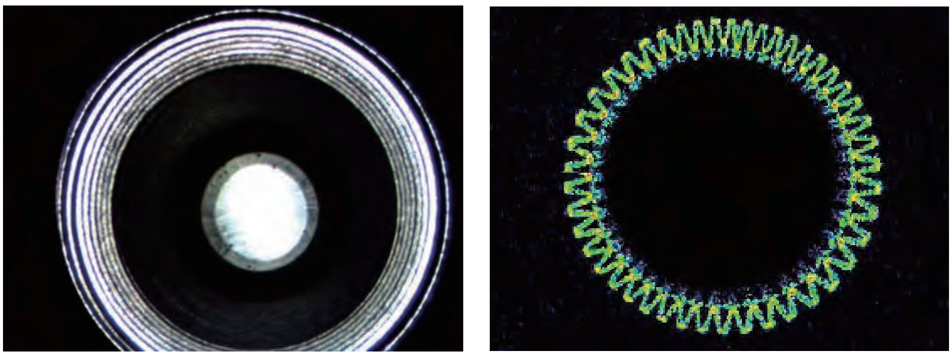

Fig. 2 Examples of analog endoscope and digital endoscope
Although the samples are different, the photographs show an endoscopic photograph (left, conventional) and digitized data (right, our technology) of a tube interior.

and both optical and machine technologies that are different fields are necessary to fill in the gap. We took the approach of advancing the two technologies through collaboration between the Electronics and Photonics Research Institute, AIST (hereinafter, AIST) that specializes in optics, and Adamant Namiki Precision Jewel Co., Ltd. (hereinafter, Namiki) that specializes in precision machine technology. Namiki is number one in the world for the fabrication of micromotors that are key parts of probes. We set an extremely high goal value that was to measure the surface shape at 20 nm accuracy using a 1.5 mm diameter probe. Since such a measuring device did not exist previously, the field of application is yet unknown, but we expect there will be usage for inspection from small gaps and data accumulation, without disassembling machines, for generators, automobiles, aircraft, or any situations where rotation wear in machines must be addressed.

For example, domestic shipment of precision measurement devices was about 110 billion yen/year in 2016, according to data of the Japan Precision Measuring Instruments Manufacturers Association.[11] Considering that this research can be utilized in conventional roundness measurement instruments (16 billion yen/year), surface roughness testers (9 billion yen/year), 3D measuring machines (5 billion yen/year), and measurement of inner diameter of deep holes that cannot be measured by industrial CCD camera endoscopes, and assuming 30 % or more increase in the production of such instruments (about 30 billion yen), it is thought that a new market of about 10 billion yen/year scale will be formed.

2 Methods and Results

2.1 High-accuracy OCT by self-phase detection: 20 nm

Since OCT advanced as medical technology, it has already overcome the period of expensiveness which attends initial diffusion of technology, and currently, parts are available at a relatively reasonable price. Utilizing this merit, diffusion for industrial use is being prepared, but the issue of repeatability is the index that sets apart medical and industrial uses.

The performance required for medical OCT is to obtain a clear image of each layer of the retina, and the indices of a good image are mainly depth resolution and degree of penetration depth of light. One of the endoscope-type OCT used in medicine is vascular OCT.[12] On the other hand, the performance required for industrial OCT is the ability to accurately trace the surface of an object, and distance accuracy and repeatability are the main indices. Particularly, for industrial use, when the object is a metal surface, depth resolution and degree of depth are hardly necessary, and the direction of research is different. To address this issue, we used the following method.

The optical system we used was composed mainly of an optical fiber interferometer. It is a type called swept source OCT (SS-OCT) that uses a wavelength scanning light source. Figure 3 shows the schematic diagram. The light source is a swept source (Santec HSL-2100) whose wavelength range is 1240–1400 nm. The light source is divided into two fibers at a ratio of 95:5 at coupler 1, and the each beam was led to the Michelson interferometer to measure the distance and to the auto-interferometer for phase correction, respectively.

In the Michelson interferometer, the introduced light was separated into 95:5 by optical fiber coupler 2, for the reflective surface of the object to be measured and the reference reflective surface. The reflected lights from the object and the reference are coupled together at optical fiber coupler 3, and the interference signal is measured by a detector. Regarding this interferometer, the interference signal strengthens when the difference of the distance to the reflective surface of a sample and the distance to the reference reflective surface from the position where the beam is split at optical fiber

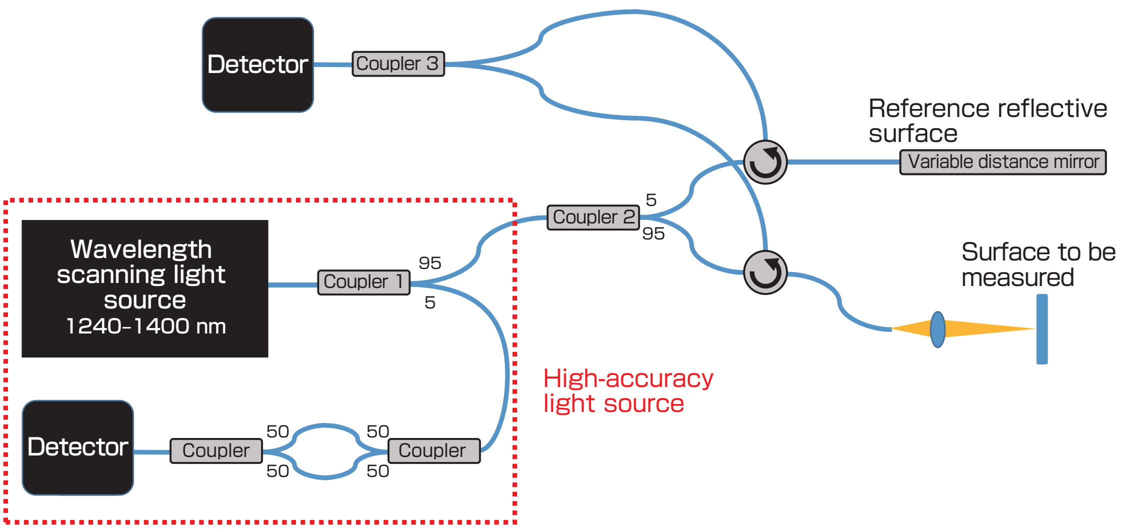

Fig. 3 Schematic diagram of high-accuracy OCT optical system

coupler 2 become the integral multiple of the light source wavelength. Therefore, the difference between each distance (optical-path difference) or each beam can be measured by scanning the light source wavelength. That is, when the sample surface is placed at a zero-path position (the same distance as the reference surface), the interference signal intensifies without dependency on the wavelength. When it departs from the zero-path position, fringes occur in the light source spectrum (spectral interference fringe patterns). The frequency of the spectral interference fringe becomes higher as the distance difference increases, you can calculate distance difference using the Fourier analysis.

Here, the distance difference is determined by the frequency of spectral interference fringes, and it is necessary that the frequency of spectral interference fringes be stable to conduct distance measurement with high accuracy. However, it is difficult to keep a constant speed of wavelength scanning. Although it may depend on the scanning mechanism of laser utilized, in general, the wavenumber variation often slows down at the beginning and end of scanning, and the light source wavenumber against time is nonlinear. This is shown in Fig. 4 left (before improvement). In this demonstration, a mirror is used as the sample, and the spectral interference of even intervals should be seen when the scanning speed is kept constant, but the spectral interference fringes were wide around 1240 nm at the beginning of wavelength scanning and around 1400 nm at the end of scanning, and they are narrow around 1320 nm at the center. In general, light source manufacturers correct this nonlinearity so it will become even with constant scanning speed by linking with detection software. Rough correction can be done using this method, but blurring at each scanning remains, and we conducted improvement of the correction by monitoring the scanning rate in real time by guiding part of the light source to the auto-interferometer. With the auto-interferometer, optical path difference between two divided beams is caused only by the difference of the length of two fibers, and therefore, if wavelength scanning is conducted at constant speed, spectral interference will occur at even intervals. If there is unevenness in wavelength scanning speed, which will be reflected in the fringe intervals of spectral interference, and intervals of sample detection signals can be corrected based on this information. According to this principle, even if there is unevenness in the light source, the constant scanning speed can be reproduced. As a result, as shown in Fig. 4 right (after improvement), constant measurement from start to finish of wavelength scanning has become possible, and stability of measurement positions increased. Figure 5 shows the result of the OCT position measurement before and after improvement. Before improvement, the standard deviation of measurement repeated 500 times was 380 nm, while after

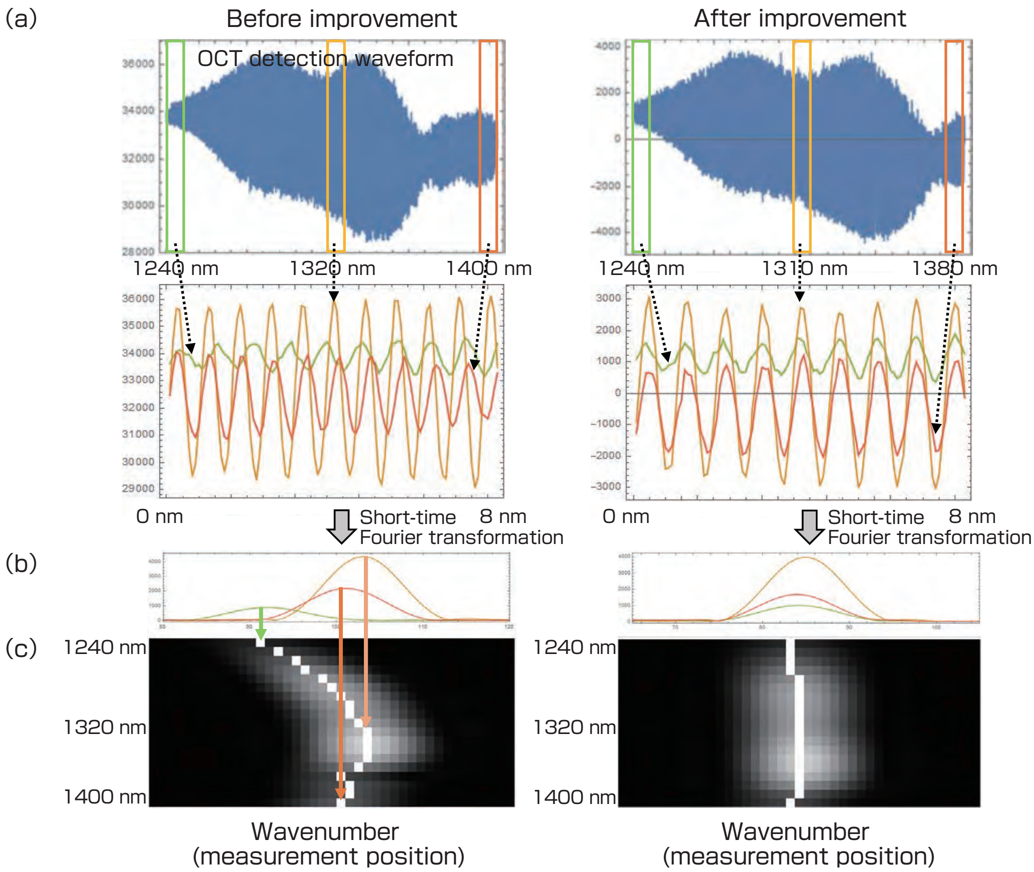

Fig. 4 Comparison of nonlinearity of interfering waveforms seen in a current light source (left), and the one after correction using auto-interferometer (right)

improvement, it was 22 nm, and improvement of about 17 times was obtained.

Applying this high-accuracy position measurement technology, shape measurement of a ten-yen coin was demonstrated as shown in Fig. 6 left. Roughness of the ten-yen coin was about 100 μm, which was too large for verification, so the flat part of surface without unevenness was tested for the performance demonstration. Figure 6 right shows the result, whose height is magnified 100 times. Surface roughness was calculated as Ra = 0.31 μm from the measured data. Since detailed surface shape measurement can be conducted, surface processing accuracy Ra, important in industrial measurement, can be calculated.

2.2 Rotating probe of 1.5 mm diameter [13]

Namiki developed a micromotor of 1.5 mm diameter for the first time in the world in 2005, and has succeeded in developing motors of 0.9–2.0 mm diameters, aiming for further miniaturization.

In this system, to compose a 3D scanning OCT probe of 1.5 mm diameter, we employed the micromotor of 1.5 mm and 0.9mm diameters for the two axes; tangential and axial scanning. As shown in Fig. 7a, the first micromotor installed at the tip of an OCT probe rotates the mirror using a motor of 1.5 mm diameter. The beam from the optical fiber becomes a side-illuminating beam that is bent 90 degrees, and this allows rotating scanning of 360 degrees. The second motor of 0.9 mm diameter has the role of changing the angle of the side-illuminating beam, and conducts scanning in the axial direction from front to rear. Specifically, the second motor rotates the optical fiber with a tip cut at a certain angle, and the direction of beams irradiated from the optical fiber is off-centered. By doing this, the beam position can be controlled to the upper or lower part of the mirror that is rotated by the first micromotor, and the angle of side-illuminating beams can be varied. The two motors can be synchronously rotated. For example, the first motor can be set to 3600 rpm and the second motor to 3540 rpm, and rotational phase is produced by giving slight rotational difference, and this enables helical scanning where the optical beam rotates at 3600 times per minute and engages in reciprocating motion of 60 times in the axial direction.

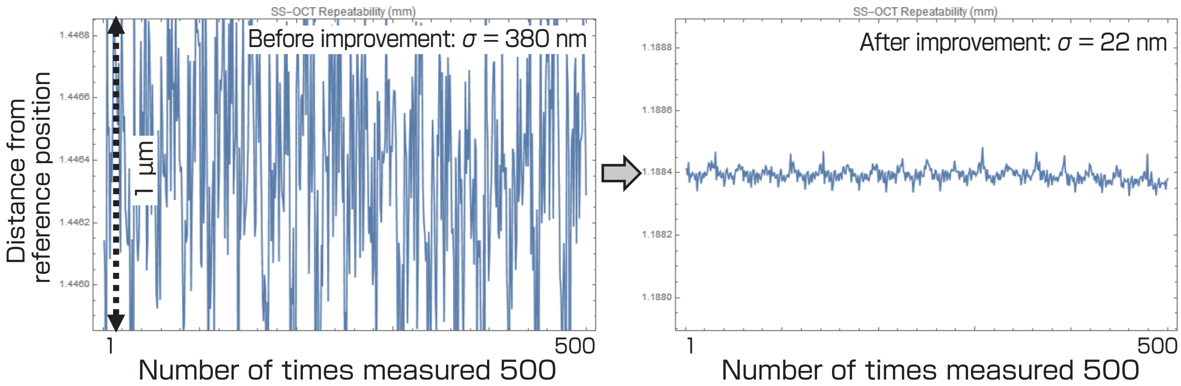

Fig. 5 Comparison of distance measurement accuracy before and after improvement
The vertical axis shows the position of the surface of the measured sample, and the horizontal axis shows the number of times measured. In measurement repeated 500 times, standard deviation improved from σ = 380 nm to 22 nm.

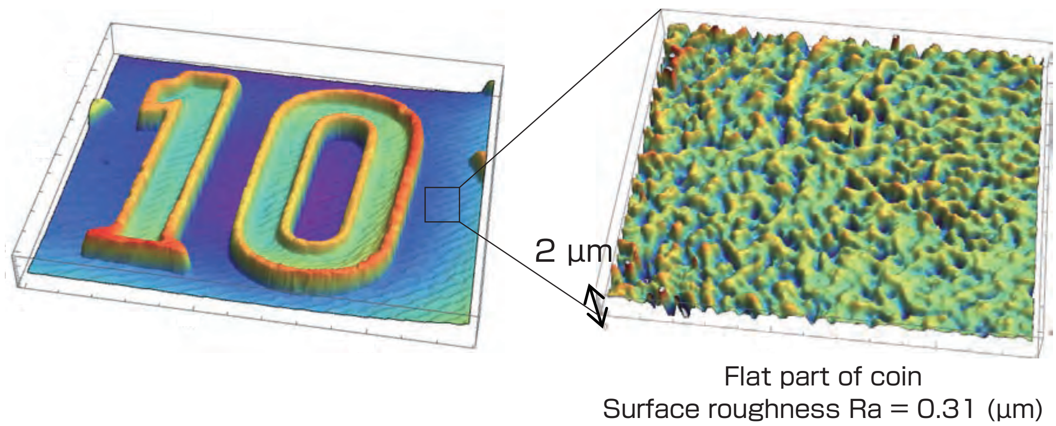

Fig. 6 Measurement of height of a ten-yen coin by high-accuracy OCT (left: 10 mm square), and result of height measurement for the flat surface of a ten-yen coin (right: 1 mm square)

Since the second motor shown in Fig. 7a is extremely thin with 0.9 mm diameter, the brushless-coreless method was used. The parts used in this motor such as the rotating shaft, bearing, coil, and magnet are extremely fine as shown in Fig. 7b. The diameter of the rotating shaft is 0.2 mm, and the optical fiber passes through the center, requiring a hole of 0.125 mm diameter. For the coil, wire of 0.024 mm diameter is coiled at high density using a special winding machine, to maintain rotational torque. The bearing has internal diameter of 0.2 mm, and as shown in Fig. 7c, the herringbone dynamic pressure grooves are etched by lasers in the inner circumferential surface. When rotation starts, oil flows into the bearing along the groove, and the rotating shaft lifts off the bearing as it is supported by oil pressure. This is called dynamic pressure bearing, where the rotation center stabilizes through noncontact rotation using the oil dynamic pressure that occurs by rotation, and accuracy in increased. Such extremely fine and almost artistic manufacturing technology increases the property of micromotors.

As shown in Fig. 8, this high-accuracy 1.5 mm endoscope was used for interior measurement of a hexagonal screw. The result is shown in Fig. 9. Stable digitization at 60 frames per sec was achieved.

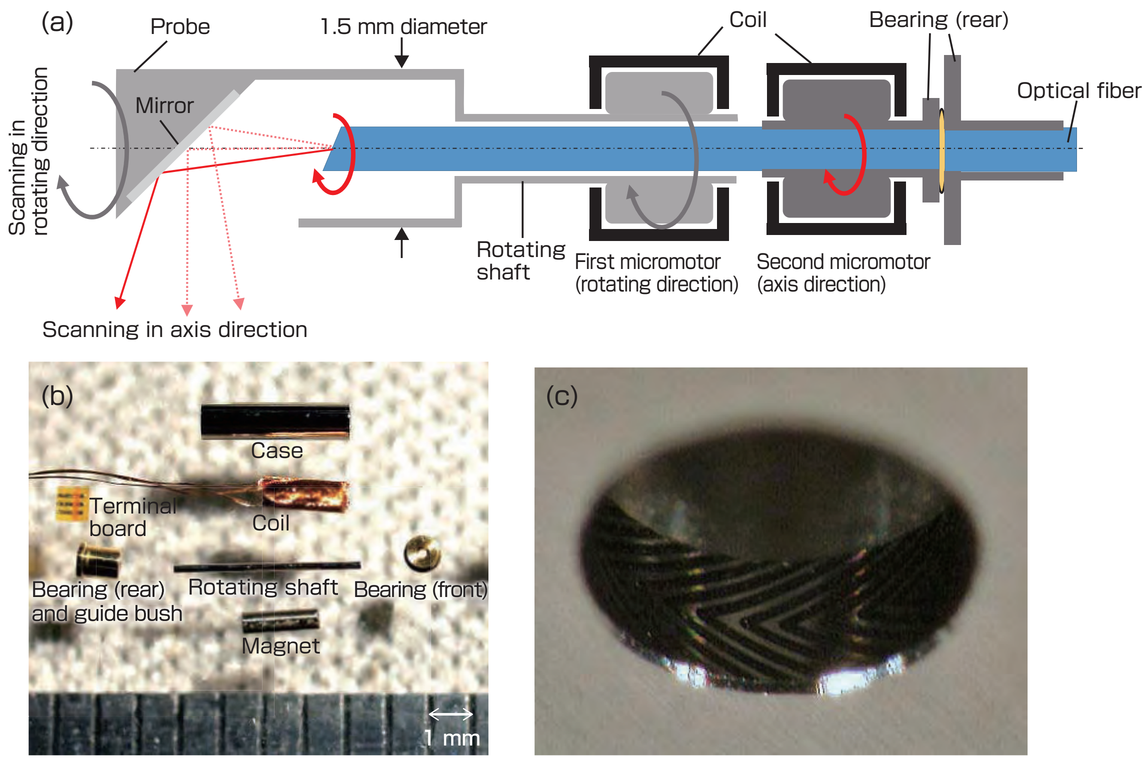

Fig. 7 Control mechanism at the tip of a micro-diameter probe

(a) Cross-sectional structure of rotating probe, (b) parts of second micromotor, and (c) herringbone dynamic pressure groove in the dynamic bearing

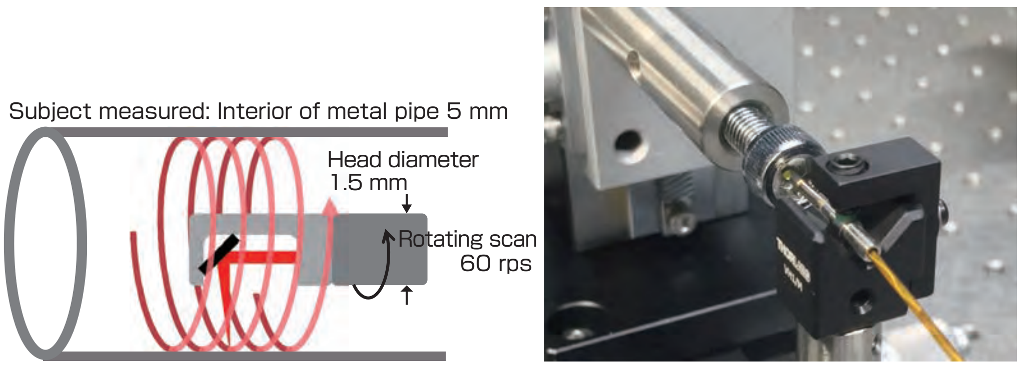

Fig. 8 Appearance of a rotating probe of 1.5 mm diameter (left), and measurement of a sample (head part of M6 screw) (right)

3 Discussion (breakthrough and impact)

With this device, a new endoscope is realized through the fusion of technology for noncontact shape measurement with 20 nm accuracy and technology for a full rotation probe of 1.5 mm diameter. Digitization of the interior at high accuracy through gaps may literally be a "gap" or niche industry, but if this becomes possible, daily inspections can be done without overhauls as shown in Fig. 10, and this may lead to the reduction of down time and daily management cost.

(a) Nanometer level shape measurement using optical (noncontact) technology
(b) Realization of a rotating probe that allows measurement from gaps (digitization, not just photographing)

By integrating the above two technologies, the inspection from gaps can be done easily and overhauls will not be necessary. An assumed target for this device is application to rotary driving devices such as, for example, jet engines that tend to wear quickly, routine management of generator turbines, and inner cylinder tests for small engines of automobiles. In rotary driving devices such as engines, shapes of inner cylinders and polishing accuracy highly affects fuel consumption. While there are many devices that can measure the exterior, there are hardly any devices that can measure the inner cylinders. By managing the wear state and accretion through high-accuracy digitization, high-accuracy quality control can be conducted in a short time. We believe this is useful technology in R&D and production lines as well as routine management.

4 Future issues and prospects

In this paper, investigation was conducted using circular scanning in which the same track of the sample is repeatedly measured for accuracy assessment. As mentioned in the part about probe structure, this probe can conduct helical scan by combining axial direction scanning using the second motor, and therefore, measurement of 3D shapes can be done easily. However, to reconstruct 3D digital data, it is necessary to correct axial direction scanning by nanometer accuracy as shown in Fig. 11. We are considering working on this issue in the future. Using only rotational scanning, correct

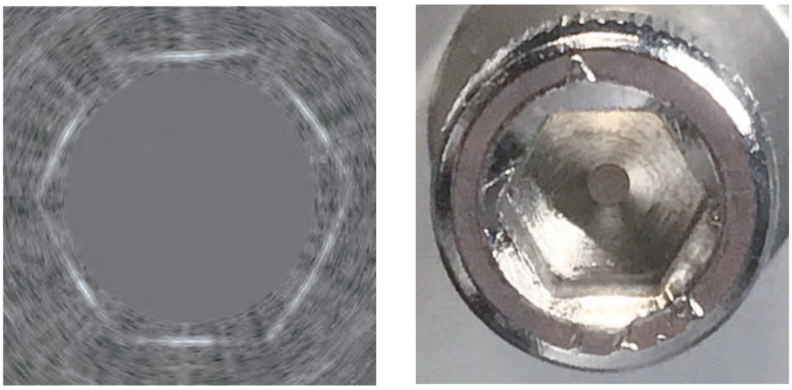

Fig. 9 Measurement of the interior diameter of a sample using a rotating probe of 1.5 mm diameter

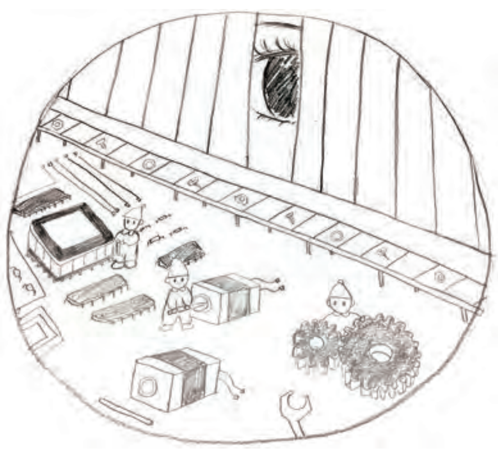

Fig. 10 Image of gap measurement

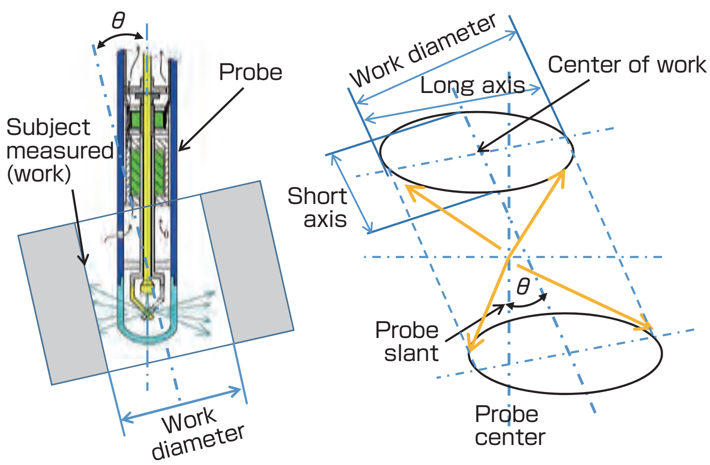

Fig. 11 Algorithm for tilt auto-correction

measurement cannot be taken since the image will be elliptic if the probe is tilted against the cylindrical axis when the probe is inserted in a cylindrical sample. If it is 3D shape, correct measurement can be taken no matter what the angle of insertion, and the usability will increase dramatically.

5 Conclusion

Part of this research was done with the grant from the Strategic Foundational Technology Improvement Support Operation. The screening interview at the start of a project is normally very strict, but in our project, the judges were impressed. Actually they were worried that our goal was set too high. They said, "Even if you are not able to achieve measurement accuracy of 20 nm, and the performance falls short by one digit, it is still sufficiently useful." I was quite grateful when the judges proposed how to lower the goal we should achieve. This was an understandable comment, and in fact, we debated over this, and the majority of the opinions of other optical measurement specialists was also that our goal setting was too strict.

There were three reasons for setting a high goal despite the concerns. First was the low accuracy of the existing devices for measuring the interior diameter of cylinders that was the main theme of this research, and as the judges said, this research would reach to top in the world even if we were one digit short of our goal. Second was that the machining technology level of Namiki and their desire to realize this technology were high, and improvement in optical technology in a short period was also expected. When we discussed how AIST could cooperate, Namiki already had a certain level of OCT-based technology that was totally self-made. Yet they were willing to take advice from us, and that eagerness seemed fresh to us. AIST has been conducting joint research with various companies, but Namiki's enthusiasm for realizing the technology was particularly outstanding, and that was impressive. We were even more surprised when we visited their Aomori plant. We met other members of the development group, and the cliché phrase "we work on development as one team" was truly put into practice. Starting with Plant Director Shibuya, all the staff had high degree of specialty, all the way to the people who were manufacturing the parts. They were truly professional. They correctly received instructions from others, but would not rely entirely on the given, and would work to realize something on their own. We were impressed. Third, there was consideration for the difference between research and manufacturing. In most cases in research, only one prototype device would be made, and accuracy meant "repeatability," or we had a feeling that accuracy was equal to the standard deviation of measurement values. However, since manufacturers suppose mass production, they emphasize standard errors, and this is important for quality control. If standard errors are considered, we can be less stringent.

Thus, research was started with a high goal, a strong will, and a little bit of leeway. As shown in this paper, the goal was achieved even when evaluation was done by repeatability without running away from our original goal. We are conducting technological development to enhance usability to create true innovation in the way we mentioned at the beginning of this paper.

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Technical Advisor, Aomori Plant, Adamant Namiki Precision Jewel Co., Ltd. Doctor of Engineering (Dynamic Bearing). Born in Kyoto. Completed the courses at the National Institute of Technology, Maizuru College in 1973; completed the courses at the Open University of Japan in 2004; and completed the doctor's course at the Graduate School of Natural Science and Technology, Kanazawa University in 2010. Joined Matsushita Electric Industrial Co., Ltd. (current Panasonic Corporation) in 1973; joined the Nidec Corporation in 2010; and in current position since 2012 Worked consistently on design of precision dynamic bearing, development of machining process, and mass production of various products utilizing bearings from 1973 to 2012. From 2012, started working on the development of optical precision measurement device. Received the 25th Ichimura Prize in Industry for Distinguished Achievement in 1993; Okochi Memorial Production Prize in 2002; and Most Interesting Read Award, Japan Mechanical Design Industries Association in 2010.

Hiroshi YAMAZAKI

Section Chief, Motor Development Section, R&D department, Adamant Namiki Precision Jewel Co., Ltd. Completed the courses at the National Institute of Technology, Hachinohe College in 1999, and joined Namiki Precision Jewel Co., Ltd. in 1999. Worked consistently on the development and design of optical parts and micromotors. From 2012, started working on the development of precision measurement instrument that applies fine diameter OCT probe through integration and application of optical parts machining and technologies of micromotor machining and assembly that are unique technologies of the company.

Discussions with Reviewers

1 Overall

Comment (Motoyuki Akamatsu and Ken'ichi Fujii, AIST)

This paper is about an innovative development where Optical Coherence Tomography (OCT) and very small motors were combined, thus allowing the insertion of a microscopic endoscope into narrow gaps of 1.5 mm diameter, and making possible the assessment of the interior of a cylinder at 20 mm precision. The OCT started as a technology using optical fibers, and since it is highly compatible with optical fiber endoscope devices, an endoscopic microscope with the world's highest precision was realized by achieving high-accuracy for OCT by developing auto-phase detection technology, and building this into a probe driven by the world's top class micromotor. In addition to shortening the time required for quality control inspection, routine inspection of the interior of devices becomes possible without overhauls. Medical applications such as vascular OCT to check the interior wall of blood vessels is also considered, and it is a measurement assessment technology with future expandability.

2 R&D of core technology

Question (Ken'ichi Fujii)

As a factor that allowed successful and dramatic increase in accuracy of interior distance (unevenness) measurement to 22 nm, which was conventionally about 380 nm, you mention that part of the light source was guided to the auto-interferometer and this allowed real time monitoring of the wavelength scanning speed. You also mention that this led to the stability of the frequency of spectral interference fringes and increased the stability of distance measurement. Specifically, did you conduct distance measurement using the phase-shifting method? I think the readers will deepen their understanding if you provide more details on the optical phase measurement methods and also explain the principles of surface shape measurement.

Answer (Hiromitsu Furukawa)

Specifically, the wavelength scanning speed of a light source was monitored using an auto-interferometer, and the detected light was corrected as if the scanning speed was kept constant. I made changes to Fig. 4 so the readers could understand easily, and I added a text to explain the technology based on this figure.

3 Application of the endoscopic digital microscope

Comment (Ken'ichi Fujii)

You give application such as to routine inspections of jet engines and turbines utilizing the advantage of a probe being able to be inserted into gaps of 1.5 mm. I think with further downsizing, you can apply this technology to the observation of internal walls of blood vessels and living tissues. If you are considering application to uses other than machine inspection, please elaborate.

Answer (Hiromitsu Furukawa)

As you indicated, medical application was realized earlier, and I described vascular OCT as an example of such application. As you commented, we can also apply this technology to observation of living tissues. Namiki's motor has been cited in the papers of vascular OCT, and I think we must be prepared for progress in that field.

However, although industrial application is also important, it is not done as much. That is because industrial application requires higher specs than for medical, yet the cost must be kept low. Therefore, in this research, we worked on increasing the performance that differ from that of vascular OCT, to create an OCT endoscope suitable for industrial application.

4 Control mechanism of the micro-diameter probe tip

Question (Ken'ichi Fujii)

Figure 7 explains the micro-diameter probe using motors of 0.9 mm and 1.5 mm diameters that were developed by Namiki. I think you should provide explanation of the principles and mechanisms of such micromotors, to promote application of the motor itself.

Answer (Hiromitsu Furukawa)

I added the structure photo of the micromotor (Figs. 7b and 7c) to Fig. 7, and added a text to explain the mechanisms of motors and dynamic bearings.

5 Integration of technology

Question (Motoyuki Akamatsu)

I can see that you realized high-accuracy internal diameter measurement by combining OCT and micromotor-driven probe technologies, but why did you start working on this technology in the first place? Were you planning to use OCT technology from the beginning? Were you looking for application of the OCT technology? There might have been several factors, but what was the actual story? I think such a story will be beneficial for the readers.

Answer (Hiromitsu Furukawa)

When Namiki visited AIST, they already had the basic technology for OCT and I think they had enough technology to complete the device on their own. Normally, a company will think about completing the product on its own, but they consulted AIST, and while I felt honored to be consulted, I also wondered why they consulted us. But when I visited the Aomori Plant, my query faded, and I added some description of this process in "Chapter 5 Conclusion." Although it is not exactly an encounter, I hope it will be useful to the readers to see a corporate culture that truly promotes new ideas in manufacturing.