Portable OCT and its Industrial Application
Simple OCT for Industrial Use and Basic Health Care

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Keywords: OCT (Optical Coherence Tomography), Industry, Health Care, Dentistry, Skin.

Abstract: Portable OCT; Optical Coherence Tomography has been developed for industrial use. This portable OCT is time-domain type and it is evolved independently from the medical OCT in terms of product cost, system size, flexibility, and its concept. To realize the unique concept, the new scanning mechanism was devised, which is consisted of a rotating corner-reflector and a fixed mirror. Its scanning rate is not so high (<200scan/s), while its measurement range can be enlarged easily. The Spectra-domain OCTs such as Fourier-domain and Swept-source OCTs needs signal processing to obtain the information in the depth direction. Their resolution depends on the scanning range and the sampling-rate. The time-domain OCT has the feature that the resolution only depends on the spectrum width of the incident beam in isolation from the measurement range. The depth information can be derived from the measured data easily and directly. The system structure of the portable OCT is elastic in viewpoints of design of the optical prove and the measurement range, and it is applied in various fields to date. Industrial use, educational aim, and basic health care are its applications. In this report, the concept and the technical feature of the portable OCT are mentioned. The concrete applications are introduced to represent the flexibility of the portable OCT, too.

1 INTRODUCTION

The optical sensors has been utilized for a long time to measure and to diagnose the condition and the appropriate structures of industrial materials. Here, the optical sensors are interferometer, optical displacement meter, moire inspection, stereoscopy, holography, and so on. Especially, after the innovation of laser, these devices and methods have an advantage of high resolution in comparison with the other sensing methods such as ultrasonic or electrical measuring methods. The interior monitoring of targets or materials is no less important than the external form. The interior structure measurement is fundamental. Clack, bubble and uneven concentration can be visualized by the interior monitoring of the optical sensors.

OCT, optical coherence tomography, is a low coherence interferometer. (Huang 1991; Schmitt, 1999) The principle of measurement is the same with white light interferometer. The white light interferometer, however, mainly measures the external form and displacement of the sample, while OCT obtains the cross-sectional image. OCT progressed in ophthalmology field. Its development is started in the 2000s. Its technology and product's value are sufficiently matured.(Jiao, 2005; Rosa, 2007))

This ophthalmologic OCT, however, cannot dominate to the industrial applications up to now. The industrial OCT has large needs. (Goode, 2009; Merken, 2011; Song, 2012; Wurm, 2007) Though it is too expensive to install into industrial fields, it is not only the reason to prevent its prevalence. The ophthalmologic target, that is human eye, has the typical size and features, and the manufacturer can fix the specification of ophthalmologic OCT. In other words, the system specification of ophthalmologic OCT is optimized due to the human eye. By this consideration, the high speed and the high resolution are current trends of the ophthalmologic OCT development. In the industrial fields, there are various kinds of targets. Its size, material, structure and measurement point are different individually. The optical probe, which throws the incident beam to the target, should be changed due to the target, too. There are many restrictions to adapt the ophthalmologic OCT to the industrial fields. It will be better that the system is simple, compact, robust and low cost. To apply the

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OCT technology to the industrial use, the system should have flexibility to the various kinds of targets. Its approach was started from the different viewpoint with the development of the ophthalmologic OCT.

The authors fixed such a concept of the industrial OCT by 2000, and its portable one was developed in 2009. The system has a unique feature to meet the industrial needs. The targets of an early date of the industrial OCT are interior monitoring of industrial materials, that is, glass, plastic, polymeric films. In a half-decade, the targets spread not only in industrial fields, but also expands to plant/food fields and basic health care fields. In this report, the concept of the portable OCT is explained and its actual applications are introduced.

2 CONCEPT

The current OCT has some variations for the interior diagnosis. Spectral domain OCTs including Fourier domain OCT and swept source OCT is a technical method to abandon the scanning in the depth direction. They become high-speed and high-resolution. These methods, however, fix their measurement range and resolution due to the characteristics of the light source, and it is hard to change them for the targets. The high-resolution needs the optical probe to be solid. The flexibility of the measurement will be lower. The ophthalmologic OCT is specialized for the human eye, while the flexibility of the system configuration and the measurement will be essential for the industrial application, in which the targets will change its size and specification.

The portable OCT for industrial use should cover the various kinds of targets. It is different viewpoint from the ophthalmologic OCT. The system is desirable to change the following terms due to the target.

- Measurement range
- Working distance of the optical probe
- Scanning speed and repetition rate

Measurement range should be enlarged or be shorten due to the target. The working distance of the optical probe is better to have redundancy to expand or to shorten it owing to the measurement target, too. The scanning speed will be changed by the observation method whether it is fixed-point measurement or cross-sectional imaging. The former gives the information of length (depth), while the latter is an imager. The targets of industrial application are from transparent materials such as glass, plastic and polymeric film to scattering or absorbing materials such as paper, paint, semi-conductor material and biological tissue. The sensitivity of OCT measurement will be sometimes too high, and the strong reflection from the target may lower or influence dynamic range of a detector. The sensitivity should be changed due to the target, too. The background optical noise, which does not contribute to the interference, is also reflected by the target surface. It should be removed.

At the viewpoint of redundancy, compactness and low cost, we have developed the time-domain type OCT (TD-OCT). Its resolution of the measurement is uniquely decided by the spectrum width of the low-coherent light source. The measurement range and the working distance can be fixed without relying on the resolution. As the measurement data directly reflects the interior structure, it makes the ensuring judgment easy.

3 PORTABLE OCT SCANNER

TD-OCT needs the mechanical scanning to move the interference point in the depth direction. Typical TD-OCT utilizes the piezoelectric transducer to generate beat frequency of the interferogram. The scan in the depth direction is conducted by another scanning stage. This method is hard to speed up with stable scanning. The stability of scanning depends on the stage accuracy. In consequence, the long-path scanning stage has the solid platform to keep the accuracy. For the industrial use, the measurement sample is often hard to fix its position precisely. It is also difficult to shorten the distance between the sample and the measurement probe. As a result, the industrial OCT should have the flexibility in the working distance and the measurement range designs. The probe design and the scanning speed should be optimized for each target.

The repetitive scanning motion should be stable, too. In this study, the long optical path scanning mechanism was developed as shown in Fig. 1. It consists of a rotating corner reflector and a fixed mirror. The scanning range depends on the rotation radius of the reflector. The scanning speed (repetition rate) is variable due to the rotation speed of the reflector. The optical path length is derived by the following equations.(Shiina, 2003)

Calculation examples of the optical path change and the beat frequency of the interferogram are shown in Fig. 2. The rotating radius and speed of the reflector are 10mm and 50rps (= 3000rpm),

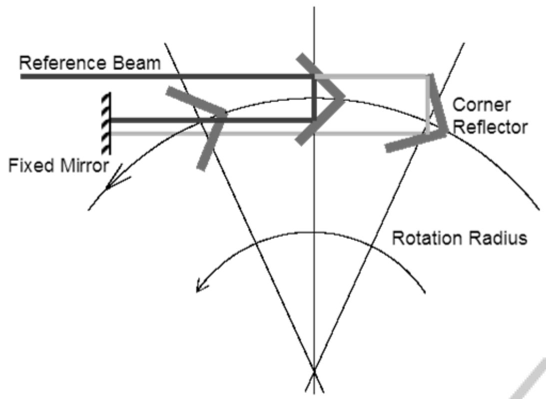
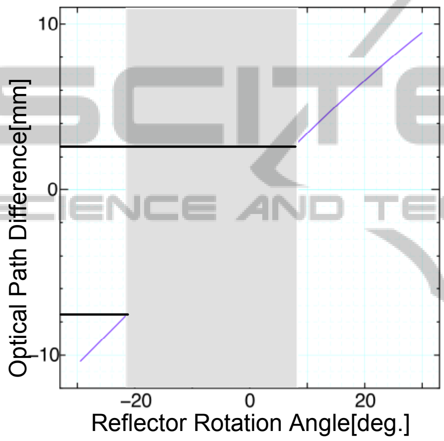
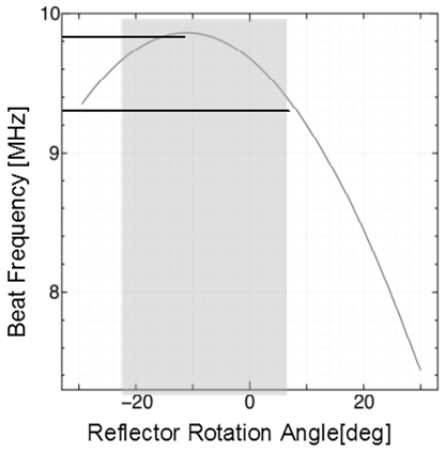


Figure 1: Long path scanning algorism.



(a) Optical path difference



(b) Beat frequency shift

Figure 2: Optical characteristics of scanning algorism.

respectively. The gray area in each graph indicates the optical path difference of 10mm. The rotating corner reflector generates the quasi-linear motion. The divergence from the linear motion is 1-3% within the rotation angle of +/-20 degrees. The

$$
\begin{aligned}
Path\_Difference &= 2l_1 + l_2(1-\sin 2\theta) \\
l_1 &= (r+s)\sin\theta - \frac{(1+r)(1-\cos\theta)}{\tan(\pi/4+\theta)} \\
l_2 &= \frac{l_3}{\cos(\pi/4+\theta)} \\
l_3 &= \sqrt{2}s + \frac{(1+r)(1-\cos\theta)}{\sin(\pi/4+\theta)}
\end{aligned} \tag{1}
$$

interferogram changes its frequency about 1MHz within the above rotation range.

The portable OCT scanner is composed of SLD light source module, optical fiber unit, motor unit for optical path change and detector circuit as shown in Fig. 3. The SLD light source is with a fiber optical pigtail, witch is specially fabricated by Anristu Co. Ltd. Its power is 3mW [max]. Its wavelength is 0.8µm or 1.3µm and its spectrum width is <60nm. The resolution of TD-OCT is defined with the spectrum width of the light source, and it became 6-8µm for the portable OCT. This SLD light source does not have a cooler. A radiator can be stable when the output of the optical power is refrained. A radiator cooling fun is used for long time operation when the output closes to the maximum (a few milliwatt). The fiber assembly is specially developed, too. It consists of a 2x2 fiber coupler and two collimators, for fundamental structure. Optical probe and reference ports have collimators. The optical probe has the other lens optics due to the target or optical arrangement. The detector circuit catches the interference signal with a detector. It outputs the interferogram signal and its envelope signal through an electrical filter and an amplifier. The digitized signals are gathered in PC via an oscilloscope or an A/D interface card. The example of the concrete setup is summarized in Table 1. The scanning range is about 12mm when a reflector rotates at the radius of 10mm. The scanning speed is 25scan/s. Position accuracy is <1µm. The divergence from the linear motion is able to correct by using the equation (1). Figure 4 shows the snapshot of the portable OCT scanner. Its size is 120mm x 70mm x 160mm. It can drive with a DC power supply or a battery.

The wavelength, measurement range, and scanning speed are fixed due to the target, while the optical probe should be also designed individually. The optical probe arranges the working distance between the probe edge and the target. It receives the backscattering light from the target with the adequate numerical aperture (N.A.). It is designed from 0 (parallel beam) to 0.3 due to the target. The plate-like target is measured with narrow

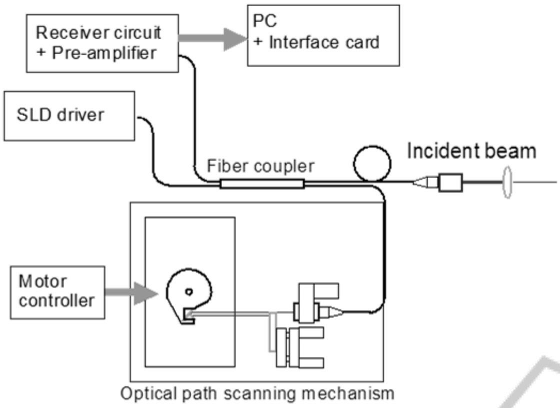


Figure 3: Portable OCT scanner.

Table 1: Portable OCT scanner.

SLD light module	Anritsu Co. LTD
Power	3mW [max]
Wavelength	1.3μm
Spectral width	61.2nm
Fiber module	Tatsuta Electric wire & cable Co., LTD
Scanning Mechanism	Maxon DC Servo motor
Rotation	25 scan/s (1500rpm)
Rotation Radius	10mm
Resolution	7μm
Position accuracy	<1μm
Scanning Range	12mm

N.A., while the high-scattered target such as a biological tissue is observed with wide N.A. The spot size of the incident beam becomes 0.5mmϕ (N.A.=0) and 5μmϕ (N.A.=0.3). The measurement data will be obtained by the combination between the measurement range due to the reflector and the depth of field on the optical probe. The design of the optical probe has several assemblies of lenses as shown in Fig.5. The differences among them comes from ease of optical arraignment, simpleness, and probe size.

4 APPLICATIONS

4.1 Industrial Use

The portable OCT can be installed into a factory as an embedded equipment of production line. The targets are the interior monitoring such as clack or air bubble detection of plastic products, uneven fluctuation of material or paint, and precision evaluation of casting. For the industrial use, the cross-sectional image is not always essential. The

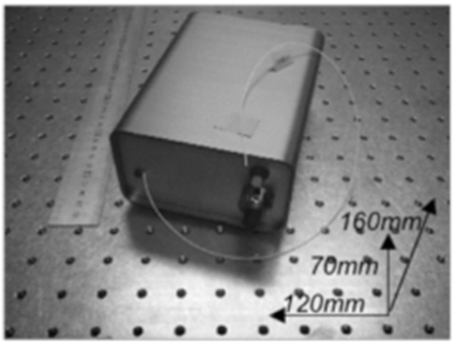


Figure 4: Portable OCT scanner.

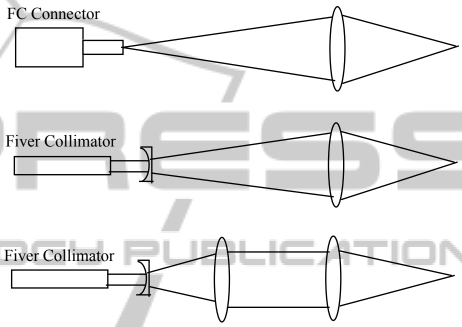


Figure 5: Optical probe assembly.

fixed-point measurement and its multi-channel measurement will accommodate the demands of industrial use.

Figure 6 shows one of the measurement result, which is the evaluation of laser fusion on the plastic plates. (Shiina 2009) The cross sectional image is obtained by moving the probe in perpendicular direction against the optical axis (depth direction). When the laser fusion is conducted perfectly, the boundary surface between the upper and bottom plastic plates is disappeared (left image). Then the scanner does not receive any signal from the fusion part. The gradations of the reflected interferogram intensities are observed in the edges of the fusion part (circle mark in left image). It is dependent on the spot profile of the laser fusion. On the other hand, when the fusion is incomplete, the scanner receives the reflected interferogram signals from the boundary surface (right image). The obtained OCT image clearly shows the difference.

Figure 7 shows the measurement result of a transparent laminated tube (mayonnaise tube). 6-7 layers thin films are layered. Because the differences between the refractive indices are small, the interference intensities inside the tube were small. The layer structure is clearly distinguished. The thickness of each layer is different from point to

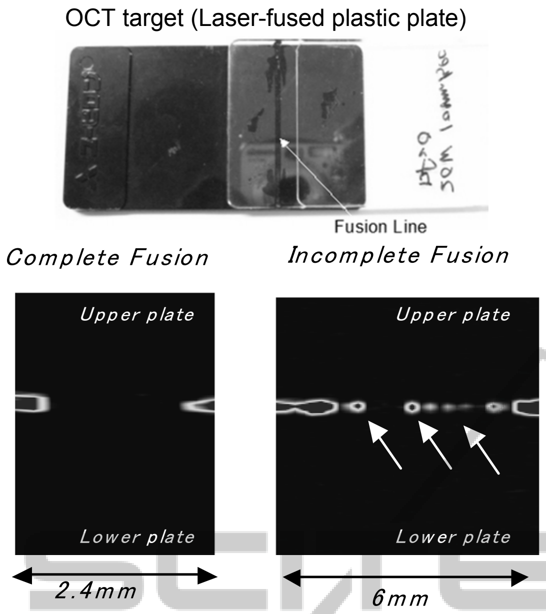


Figure 6: Evaluation of laser fusion on plastic plates.

point of the laminate tube. The individual difference among products can become a target of portable OCT, too.

There is a great demand for thickness measurements of glass, polymeric film, plastic, and so on. Thickness fluctuation, precision and layer structures are targets of industrial OCT measurement. Tablet coating (wafer) of medicine was observed as shown in Fig.8. The merit of portable OCT is not only direct measurement of the tablet on a factory line, but also follow-up measurement through a package because the measurement range is enough wide. There is no need of the precise positioning of the target. The wavelength of portable OCT is near infrared light (0.8 – 1.6 μm), and the influence of color is little. The industrial materials have wide variety of size (thickness). The portable OCT can adjust its measurement range to the target size easily. The flexibility of the portable OCT is suitable for the industrial use.

The portable OCT is expanded to add the new function for the industrial demands. In a factory, a certain procedure will separate on plural lines with the same routine. In such case, the portable OCT can separate the optical probe up to the number of the lines. To make it realize, the optical switch is installed into a portable OCT. The optical switch produced by LEONI Co Ltd. was so small that it could be installed into the case of a portable OCT. The optical switch changes its channel at every reflector rotation. When all of the plural probes have the optical fibers with same lengths, each channel will conduct the same measurement on plural lines. When the probes have the different lengths, each probe has a different task in a line.

The large targets such as combination lens, crystal block, and liquid tank needs long measurement range, while the traditional optical sensor uses a long linear stage to scan the long range. Such a sensor becomes large, heavy and high cost. The portable OCT can expand the measurement range by enlarging the radius of the rotating reflector. The radius of 60mm, which is the same size with a compact disc, has the measurement range of more than 100mm. When the 3 x 3 fiber coupler can add the reference port and these two reference ports have different lengths, the measurement range can enlarge twice as long as a single reference port.(PCT 2010)

4.2 Basic Health Care

Medical OCTs including ophthalmology, internal medicine, dentistry and dermatology are productive applications.(Colston 1998, Leung 2011, Shimada 2012, Todea 2010) The ophthalmologic OCT is success case to install it into a hospital. On contrary, the other medical fields are in study phase. The main impediment is a cost. The introduction of such a OCT system needs space, cost and a specialist. The portable OCT started to apply such fields, while it is not the same direction as medical OCTs. The basic health care is our purpose.

The portable OCT for dentistry is specialized its optical probe, which is a stick-like body of the diameter of 10mmϕ with one-directional auto-stage. N.A. was controlled to 0.14. The depth of field becomes 5mm. The caries check is demonstrated with this portable OCT as shown in Fig.11. The caries occurs just under the surface of teeth. The caries of CO could be easily monitored its depth and area, while the optical probe does not reach to the intricate position of a teeth at the adequate angle. Another measurement of dentistry is the boundary layer detection. The boundary layer between enamel and dentin is called EDJ (Enamel-Dentin Junction) and its recognition is important for artificial tooth and implant placement. The depth of EDJ is about 2 – 3 mm. The portable OCT can visualize it with a long measurement range as shown in Fig.12.

The human tissue such as skin is a scattering material for the visible to infrared light. The propagation depth to obtain the interference signal is about 0.7 mm for medical OCT. The cross-sectional image is often reported by medical OCT in

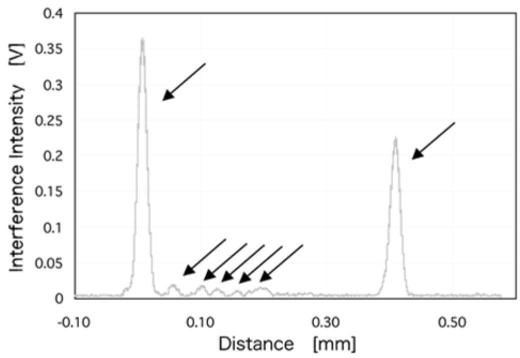


Figure 7: Transparent laminated tube (Mayonnaise tube).

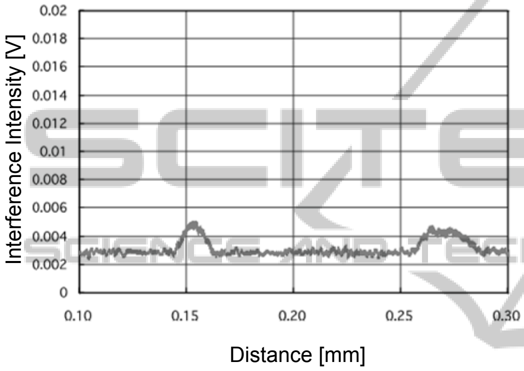


Figure 8: Tablet coating (Thickness measurement).

viewpoint of dermatology.(Koenig 2012, Korde 2007, Mogensen 2009) On another front, the application for skin measurement is unique for the portable OCT. The basic health care and cosmetic perspective are main targets for the portable OCT. As the portable OCT can be compact and low cost, it is easy to install it into a cosmetics counter and a medical interview scene. To adapt the portable OCT to the skin measurement, the optical probe had high N.A. of 0.3. The depth of the field becomes about 1mm. The accumulation of about 1,000 times was conducted for the stable evaluation. The measurement depth became about 0.5 – 0.6 mm.

Figure 13 shows that the effect of cosmetics for skin care is visualized by the portable OCT. The interference intensity was corrected by multiplying the square of distance. The vertical axis was represented by log-scale. The normal skin of arm has two peaks, of which the first is epidermal layer and the second is dermal layer. The normal thickness of the epidermal layer is about 0.2 mm. The patient of Fig.13 had a dry skin. The second layer was not clear. After the cosmetic care by applying a foundation and a lotion to the skin, the second peak from the dermal layer becomes clear. The water retentivity of the lotion is more effective than that of

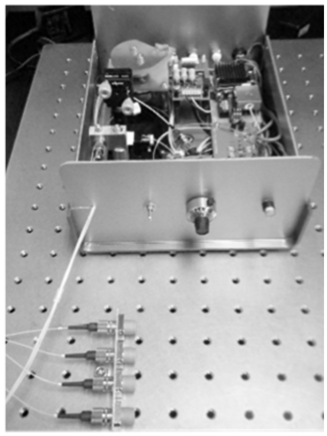


Figure 9: Multi-channel probes on a portable OCT.

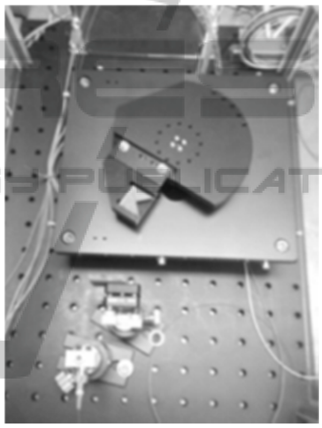


Figure 10: Long-path scanning reflector on a portable OCT.

the foundation.

The atopic dermatitis causes the severe damage on the skin structure. Its damage is not only exclusive to the epidermal layer, but it also rumbles into the dermal layer. Figure 14 represents such damage of the atomic dermatitis. The second peak of the dermal layer was spoiled. It is clear as compared with the normal skin. The epidermal layer was subject to influence, too. It may be no need to be visualized such skin conditions with a cross-sectional image. The fixed-point observation such a stethoscope is useful for a medical interview scene.

The other application is in ophthalmologic field. Here, the direction of the portable OCT is the basic health care, too. The fitting of the contact lens and the combination of the optical power between the naked eye and the contact lens are the targets for the portable OCT. Off course, the traditional ophthalmologic OCT is possible to evaluate such targets. The current sophisticated OCT, however, has a firm and big optical probe. To measure the

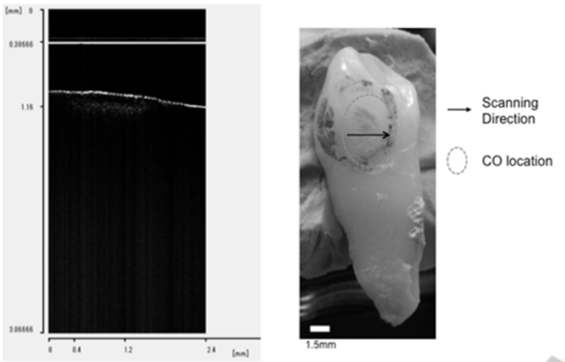


Figure 11: Caries monitoring.

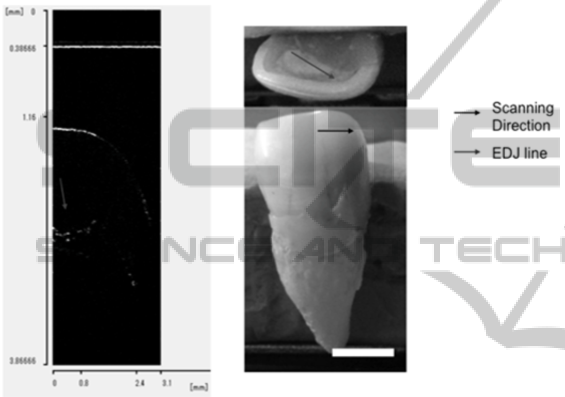


Figure 12: EDJ monitoring.

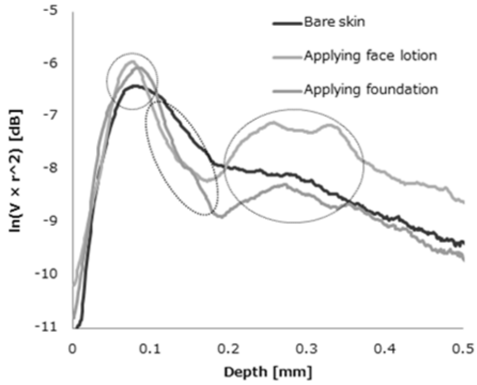


Figure 13: Skin measurement through cosmetics.

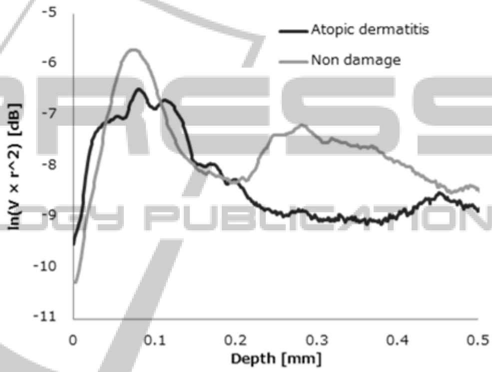


Figure 14: Atopic dermatitis measurement.

optical power, the eye should be unblocked to focus an image. The portable OCT has the flexibility to design the optical probe because the design of the optical probe is separated from the resolution factor and it is designed to unblock the eye.

The some applications mentioned above are now in clinical practice. To install the portable OCT into the clinical use as basic health care or cosmetics, the usability will be pursued. It is because the users will be not professionals. From this perspective, the simple structure of the device and the direct manifestation of the observed information are important on medical care, especially basic health care. The portable OCT can be operated with a buttery. It is useful on rural clinics and developing countries.

5 CONCLUSIONS

The portable OCT is time-domain type OCT. It is not latest technology in comparison with the ophthalmologic OCT. Especially its scanning speed is much slower than the current ophthalmologic OCT. The high scanning speed of the ophthalmologic OCT, however, is for the real time observation of the three-dimension or four-dimension. The high speed signal processing is also needed to calculate the huge memorized data. The portable OCT is simple to analyze the obtained data because the obtained interferogram directly represents the condition of the interior structure of the target. The scanning speed is not so high, but it is enough for most of the industrial applications. Instead the portable OCT has a feature of wide flexibility for the designs of the optical probe and the measurement range. It is adequate for the variety of the industrial targets.

The applications of the portable OCT for medical use are the direction to the basic health care and cosmetics. At viewpoint of the simple operation, small apparatus and low cost, the portable OCT will be easily installed into such fields. The cross-sectional image of teeth is useful to check the caries and EDJ, while the skin condition can be evaluated by the fixed-point observations. Easy to use approach and direct representation of the desired information are important for the medical interview scene and formulation of cosmetics.

Up to now, the wide variety of targets were evaluated by the portable OCT. Their directions are summarized in Table 2. It shows the targets' directions with some categories. Now plural Japanese companies produce the commercial products of the portable OCT. They are evolved as built-in system, stand-alone apparatus, and custom-made device.

Table 2: OCT applications of industrial use.

Industrial use
Displacement, Thickness, Reflective index, Solution concentration, Crack check, Volume change, Time response, Vibration, …
Plant and Food processing
Plant Factory, Growth monitoring, Food processing, Freshness check, Seal check, …
Basic health care and Cosmetics
Ophthalmology, Internal medicine, Visceral Examination, Dentistry, Dermatology, Cosmetics, …

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