Accurate 3D object profiling by FMCW optical ranging system using a VCSEL

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Dissertation Abstract

ACCURATE 3D OBJECT PROFILING BY FREQUENCY MODULATION CONTINOUS WAVE (FMCW) OPTICAL RANGING SYSTEM USING A VCSEL

VCSEL を用いた FMCW 光距離センサによる精密 3D 物体形状計測）

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1. Introduction

The accurate size and the precise shape of the components in electronic and automotive device are the critical aspects to determine the quality of the product. The inaccuracy of the components will influence the performance of the product and even causes an accident. Nowadays, inspection of the size and shape of mechanical electronics components in the automotive and electronic industry are still performed by using human eye and camera. These methods require long measurement time for the inspection and will be affected by human skill and human error. Since the industry needs the sensing system that is capable for inspecting the object and profiling small objects without contacting and harming, a high-speed ranging system with high spatial resolution and high ranging accuracy is required.

Since a few decades, the reflectometric techniques (reflectometry) were established for nondestructively diagnosing fiber-optic devices [1]-[5]. The proposed sensing system will be used for diagnosing and profiling of objects in short and medium range. The Frequency modulated continuous waves (FMCW) reflectometry is one of the reflectometry that is very suitable to be applied in the systems that require the combination between of high speed, sensitivity and high resolution in the medium long-range [3].

The purpose of this study is to configure the optical sensing system that is capable to generate clear object profiling with high spatial resolution and high ranging accuracy at short measurement time.

2. FMCW optical ranging system

2.1. System configuration

Figure 1 shows the basic configuration of FMCW optical ranging system. The system consists of a frequency-swept laser source, a two-beam interferometer and a target located in an arm of the interferometer. The laser beam is divided into two-beam i.e. reference beam and reflected beam. The reference beam is propagated directly to the photodetector. The reflected beam enters to the target, and the reflected light from the target interference with the reference light on the photodetector (PD) [3], [6]. The coherent length of the light source

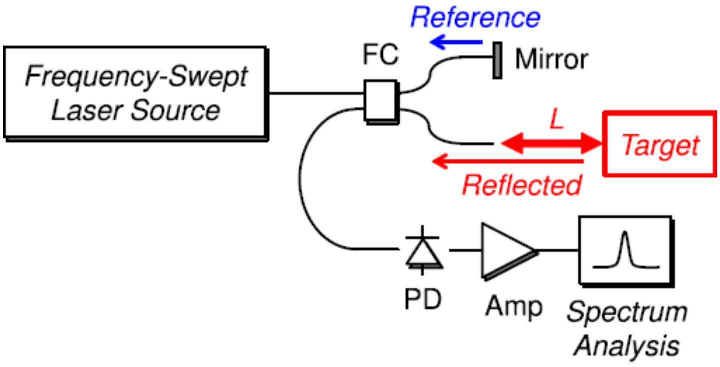


Figure 1 The basic configuration of the FMCW optical ranging system.

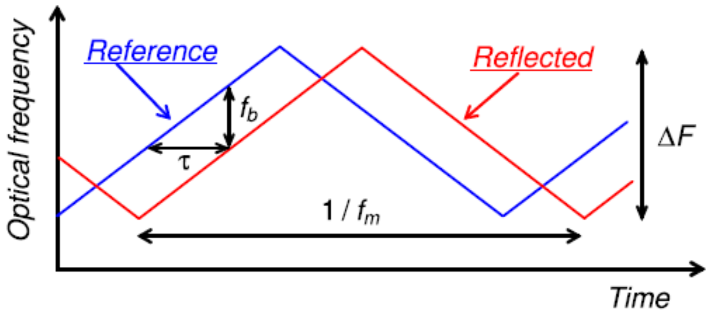


Figure 2 The waveform of the optical frequency change of the reference and the reflected lights.

limits the measurement range of the FMCW optical ranging system. The measurement range can be extended by using a narrow-linewidth laser source.

Figure 2 shows the waveform of the reference and the reflected lights. The optical frequency is symmetrically linearly swept in time. The interference signal in the increasing section or the decreasing section of the optical frequency sweep is measured to prevent the phase discontinuity in the interference signal at the turning points of the optical frequency sweep. As is shown in Fig. 2, there is a propagation delay time τ between the reference light and reflected light, and the propagation delay time is given by:

$$\tau = \frac{2nL}{c} \tag{1}$$

where n is the refractive index of the optical fiber, L is the differential distance between the reference and reflected lights, and c is the light velocity in vacuum. If the symmetric triangular waveform is used for sweeping the optical frequency of laser source, the beat frequency of the interference signal, which is the optical frequency difference between the reference light and the reflected light, is given by:

$$f_b = 2f_m \Delta F \times \tau\,. \tag{2}$$

By substituting eq. (1) into eq. (2), the beat frequency is given by:

$$f_b = \frac{4nf_m\Delta F}{c}L = \frac{2n}{c}\gamma L \tag{3}$$

with

$$\gamma = 2f_m\Delta F \tag{4}$$

where f_m is the repetition frequency of the optical frequency sweep, ΔF is the optical frequency sweep range, and γ is the optical frequency chirp rate. The expression in the equation (3) declares that the beat frequency in the interference signal is proportional to the distance L. The distance is obtained by measuring the beat frequency of the interference signal with the Fourier analysis.

As described above, the interference signal in the increasing section or the decreasing section of the optical frequency sweep in measured and the beat spectrum is obtained by FFT analysis for the measured data. Since the measured time is half of the period of the optical frequency sweep, which is given as $1/(2f_m)$, the beat spectrum is given as sinc function. The spatial resolution defined by the Rayleigh resolution of the beat spectrum is given as:

$$\delta L = \frac{c}{2n\Delta F} \; . \tag{5}$$

The spatial resolution can be enhanced by increasing the optical frequency sweep range ΔF. The FMCW reflectometry is very suitable for the applications that require the combination between high speed, high sensitivity, and high resolution in the medium measurement range. Typical application of the FMCW optical ranging system is diagnosis of fiber-optic components, object profiling [7]-[11], and medical application such as optical coherent tomography (OCT) [12].

2.2. Spatial Resolution and Ranging Accuracy

The spatial resolution is the smallest resolvable separation between adjacent two reflecting points in the optical ranging system. The image quality of the object profiling and the detail in the image results can be determined by the spatial resolution. One of the advantages of the FMCW optical ranging system is high spatial resolution, which is determined by the resolution of the beat spectrum. The spatial resolution is evaluated by the full-width at half maximum (FWHM) of the beat spectrum. Figure 3 shows the schematic beat spectrum using the Hanning window (in solid line) in the FFT and without using the window function (in the dashed line). The spatial resolution given in eq. (5) is defined as the differential distance between the peak and the first zero point in the |sinc| function, which is the beat spectrum without using a window function in the FFT. In our experiments, the Hanning window was used. The FWHM of the beat spectrum, δL_{FWHM}, is used as the measure of the spatial resolution.

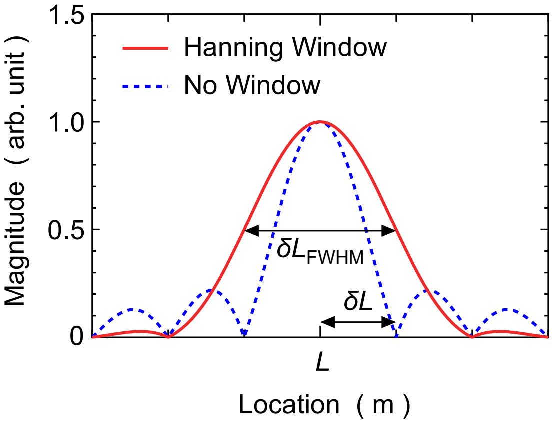


Figure 3 Schematic beat spectrum and definition of the spatial resolution.

3. Experimental Configuration

Figure 4 shows the experimental setup of the FMCW optical ranging system [7]-[10]. The system consists of a sensing interferometer and an auxiliary interferometer. A laser diode emitting at 1310 nm is used as a light source and the optical frequency is swept by modulating the injection current with a symmetric triangular signal with the repetition frequency 1 kHz. In this experiment, two types of laser diodes used as the laser source, a DFB laser (Furukawa, FOL13F1MWS-A4-SA7) and a single-mode VCSEL (Raycan, RC22xxx1-T). The laser light launched from the Circulator and the lens is focused on the target with a focal length of 20 cm. The Galvano mirror (Thorlabs, GVS002) is used for scanning the laser light over the target. In this experiment, the beam size is not measured, however is estimated from the profiling result to be a few tens µm. The reflected light from the target interferes with the reference light passed through the fiber couplers FC2 and FC3. The beat spectrum will be overspread and the spatial resolution is degraded if the optical frequency chirp rate, γ, varies in time, which is caused by the nonlinear optical frequency sweep. The nonlinear optical frequency sweep is an impact of slow temperature change in the laser cavity. The optical frequency change of the DFB laser and VCSEL lags behind the injection current [3]. As a result, the optical frequency sweep due to the injection current change is nonlinearly swept.

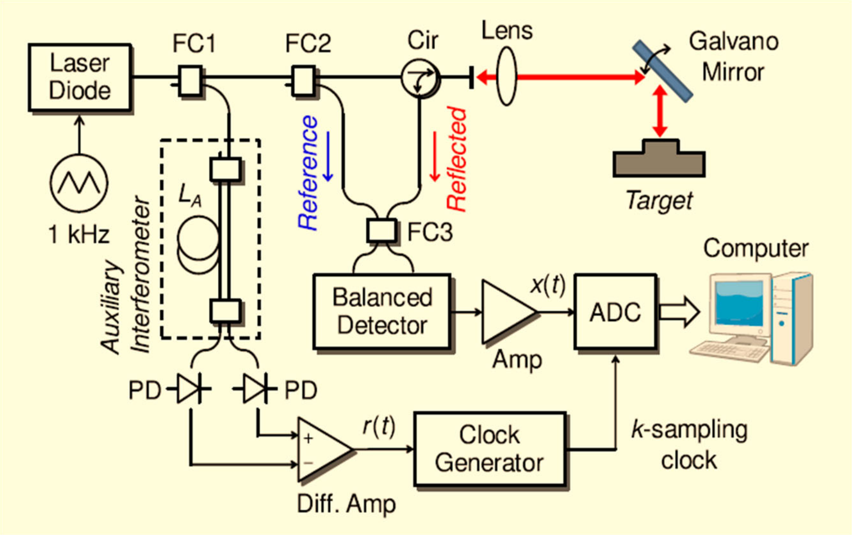


Figure 4 The experimental setup of FMCW optical ranging system for object profiling. (FC1, FC2, FC3: Fiber couplers, Cir: Circulator, PD: Photodiode)

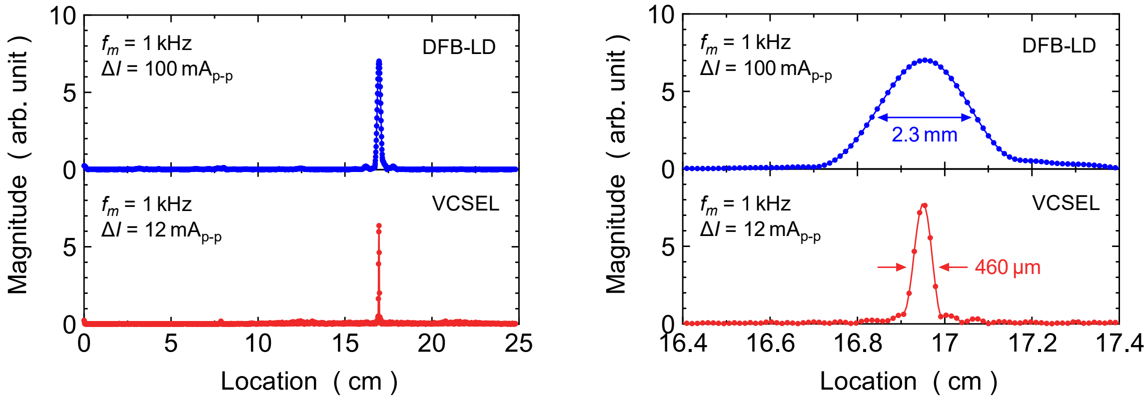
4. Result and Analysis

4.1. Spatial Resolution and Ranging Accuracy

When the VCSEL is used as the frequency-swept laser source at the modulation frequency is 1 kHz, the FM efficiency is 60 GHz/mA. By using the same the modulation frequency, the FM efficiency of the DFB laser is 1.6 GHz/mA. The FM efficiency of the VCSEL is 38 times higher than the DFB laser.

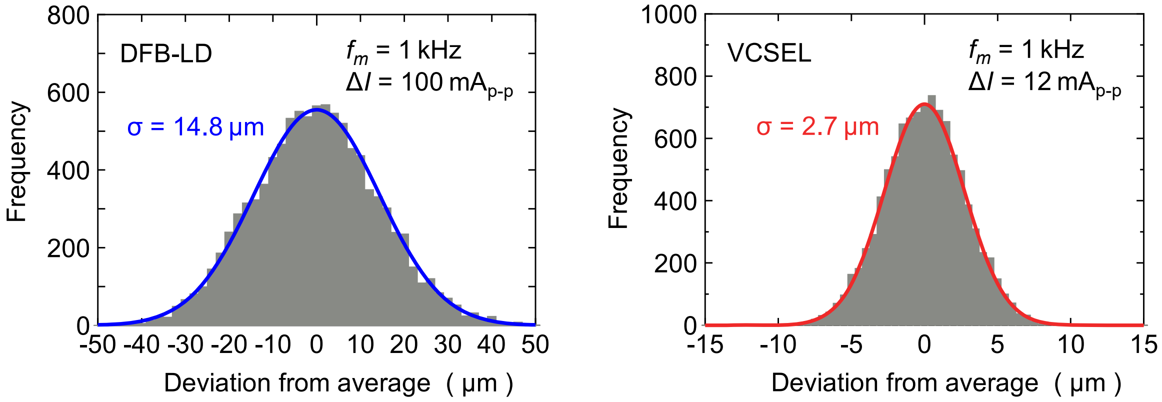
Figure 5 shows the measured beat spectrum for a mirror located at 17 cm when the VCSEL and the DFB laser are used as the laser source. The optical frequency sweep range ΔF is 710 GHz and 136 GHz for the VCSEL and the DFB laser, respectively. Fine beat spectra are observed for both the laser source. By enlarge the beat spectrum, the FWHM can be measured to be 460 μm when the VCSEL is used as the laser source and 2.3 mm when the DFB laser is used as the laser source. The high spatial resolution when using the VCSEL as the laser source is due to the wider optical frequency sweep range, ΔF.

Figure 6 shows the measurement error for 10000 times measurement at the measurement distance of 17 cm. The measurement error is well described by the normal distribution, and the standard deviation σ = 14.8 μm when the DFB laser is used as the laser source and σ = 2.7 μm when the VCSEL is used as the laser source. The smaller standard deviation is achieved when the VCSEL is used as the frequency swept laser source, which is due to high spatial resolution. Then accurate 3D object profiling is expected by using the VCSEL as the frequency-swept laser source.



(a) Whole beat spectrum (b) Enlarge beat spectrum

Figure 5 Measured beat spectrum for a mirror.

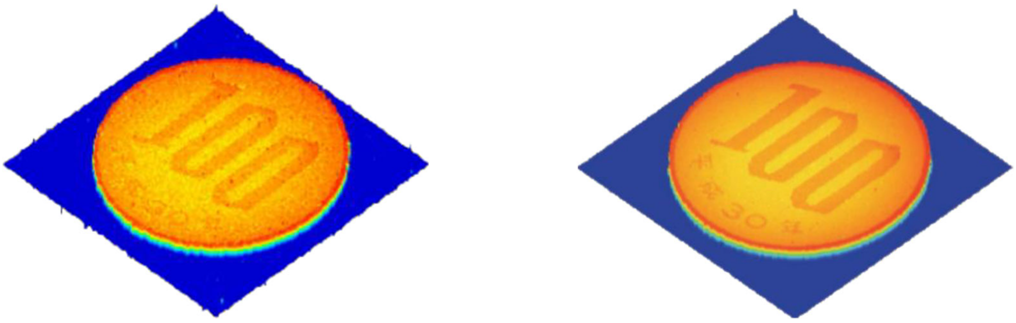


(a) The DFB laser is used as the laser source (b) The VCSEL is used as the laser source.

Figure 6 Histogram of the measurement error for 10000-times measurements.

4.2. Object Profiling

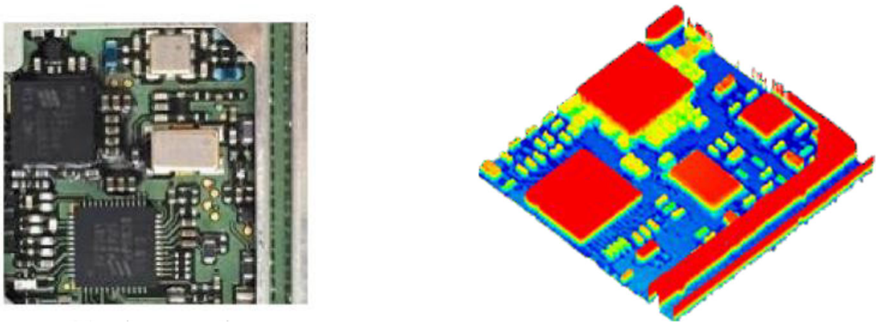
For 3D object profiling, the laser light is scanned from -2.5° to $+2.5^{\circ}$ in 0.025° increment by using the two-dimensional Galvano mirror, and the resultant scanning area is 26.5 x 26.5 mm^2. The number of the acquired data is 450 points when the DFB laser is used and is 2350 points when the VCSEL is used. The number of the FFT analysis is 4096 points by using the zero-padding method. Figure 7 shows the results of the object profiling of 100 Japanese 100YEN coin (a) when the DFB laser is used as the laser source and (b) when the VCSEL is used as the laser source. Clearer object profiling is achieved when the VCSEL is used as the frequency-swept laser source, and the incuse on the surface of the coin (labels "100" and Japanese traditional era name) is successfully profiled by using the VCSEL as the frequency swept laser source. This is due to small measurement error for ranging when the VCSEL is used as the frequency-swept laser source as shown in Fig. 6.



(a) when the DFB laser is used (b) when the VCSEL laser

Figure 7 Three-dimensional profiling result of Japanese 100YEN coin.

The developed sensing system is also capable of profiling the object with low-surface reflectivity such as a glass, a plastic, and a printed circuit board. The profiling result of a printed circuit board when using the VCSEL as the laser source is shown in Fig. 8. The plastic-packaged ICs and chip components are profiled, and narrow wirings (80 μm in width) between ICs and chip components are also profiled.



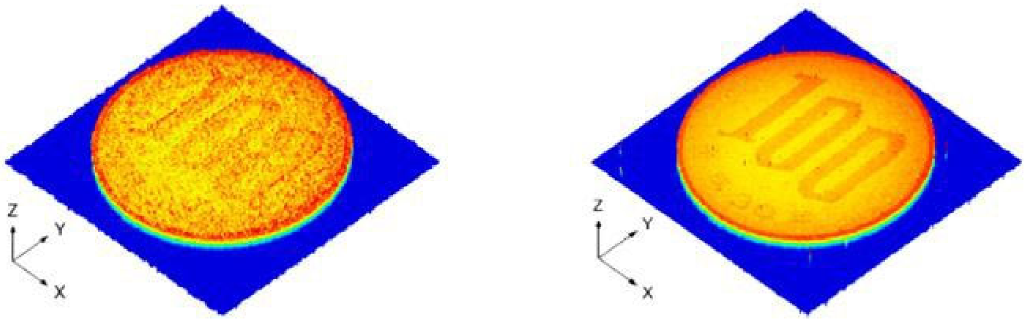
(a) Photograph (b) Profiled Result

Figure 8 Photograph and 3D profiling result of a printed circuit board.

4.3. Short Measurement Time Object Profiling

For high-speed measurement, the repetition frequency of the injection current modulation f_m should be increased. However, the scanning speed of the Galvano mirror limits the measurement speed in this case because of transient response time of about 360 μs of the Galvano mirror. To realize fast and clear profiling, the number of acquired data should be decreased to stabilize transient response of the Galvano mirror.

Figure 9 shows the profiling results of a Japanese 100YEN coin for f_m = 1.8 kHz, (a) and (b) are the results for the number of the acquired data of 1450 points and 600 points, respectively. Clear profiling is obtained by decreasing the number of the acquired data because the Galvano mirror is stabilized. The measurement time is 22.6 sec for 201 x 201 points measurement.



(a) 1450 points (b) 600 points

Figure 9 Three-dimensional profiling result of Japanese 100YEN coin with different number of acquired data for f_m = 1.8 kHz.

Although clear profiling is achieved by decreasing the number of the acquired data, there are some spike noise in the profiling result. The spike noise can be effectively eliminating by applying a median filter without blurring the profiled result. Figure 10 shows the improved profiling results by applying 3-points median filter for x-direction. More clear profiling without spike noise can be achieved.

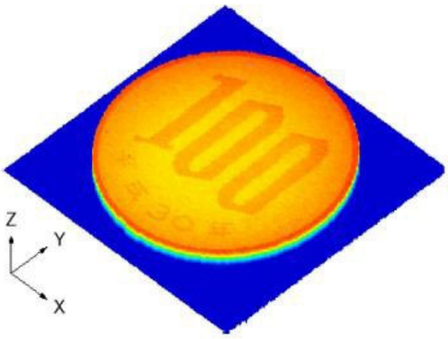


Figure 10 Three-dimensional profiling result of Japanese 100YEN coin after 3-points median filter for x-direction with f_m = 1.8 kHz

5. Conclusions

We have developed the three-dimensional object profiling system using the FMCW optical ranging system. High spatial resolution of 460 μm and small measurement error of 2.7 μm are achieved by using a VCSEL as the frequency-swept laser source, and clear object profiling of a Japanese 100YEN coin and a printed circuit board is realized. High-speed measurement is also realized by optimizing timing of the data acquisition, the scan of the Galvano mirror and the FFT analysis by taking account of the transient response of the Galvano mirror. As a result, the fastest measurement time of 22.6 sec is realized for 201 x 201 measurement points. The developed system is very useful for industrial application such as diagnosing the shape of components in automotive and electronic industries, and profiling mechanical workpieces and inspection in mechanical and electrical assembly process.

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令和 2 年 2 月 5 日

学位論文審査報告書（甲）

1．学位論文題目（外国語の場合は和訳を付けること。）

Accurate 3D object profiling by FMCW optical ranging system using a VCSEL

（VCSEL を用いた FMCW 光距離センサによる精密 3D 物体形状計測）

2．論文提出者　(1) 所　属　電子情報科学　専攻

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(2) 氏　名　RINI KHAMIMATUL ULA

3．審査結果の要旨（600～650 字）

令和 2 年 2 月 5 日に第 1 回論文審査会を開催し、同日に口頭発表を実施し、その後に第 2 回審査委員会を開催した。慎重審議の結果、以下のとおり判定した。なお、口頭発表に対する質疑を最終試験に代えるものとした。

光周波数が線形に掃引されたレーザ光源と光の干渉を利用した FMCW 光距離センサは、数 cm から数 10 m の距離を高い距離分解能・測定精度で測定できることから、光ファイバ部品の診断や測量などに利用されている。本研究は、FMCW 光距離センサを用いた精密な 3 次元物体形状計測に関する研究である。高分解能化・高精度化のためには大きな光周波数掃引幅が不可欠であるため、大きな光周波数掃引幅が得られる面発光レーザ (VCSEL) を用いることで、17 cm の距離において 460 μm の距離分解能と 2.7 μm の測定精度を得た。また、レーザ光をガルバノスキャナにより 2 次元スキャンすることにより物体形状計測を行い、100 円硬貨やプリント基板の精密な形状計測を実現した。また、ガルバノスキャナの過渡応答を考慮してデータ取得やレーザ光スキャンのタイミングを最適化することにより、201×201 点での測定時間を 84 秒から 22 秒に短縮した。

以上の研究結果は、FMCW 光距離センサにより精密 3 次元物体形状計測を実現しており、工業製品の精密検査などへの応用が期待でき、博士（学術）に値すると判断した。

4．審査結果　(1) 判　定（いずれかに○印）[✓ 合　格]・　不合格

(2) 授与学位　博　士（　学術　）