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High speed measurement for object profiling using FMCW optical sensing system

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Abstract. A sensor that is beneficial to inspect small devices has been missing in life science as well as industry. Frequency modulated continuous wave (FMCW) optical sensing system has been successful in profiling the image of a coin and a printed circuit board with the measurement accuracy of $3\sigma = 29 \mu\text{m}$ in 10 minutes by using a DFB laser. Here we propose and demonstrate a faster profiling system using a VCSEL. We applied three conditions for high-speed FMCW optical sensing system, i.e. symmetric method with the different modulation frequency, modulation amplitude, and asymmetric method. The results show that asymmetric method is successful in profiling a coin object with a diameter of 2.25 cm in 23.13 seconds.

1. Introduction

Instruments and sensors in manufacturing equipments and automotives necessitate the accuracy of size and shape of small instruments which configure it. Inaccuracy in manufacturing process will degrade the performance and frequently cause accidents. Hence, it needed a sensor that operates as an inspector for small devices that compiles the instrument. Our purpose is to configure sensing system to capture the profile of an object with high accuracy in short measurement time. Besides, we need a sensor that is capable to inspect the object without contacting and harming it.

The optical sensing have been applied in many field such as weight sensor, water level, and temperature [1, 2] because the sensor based on optic has many advantages i.e. non-contact sensing, high sensitivity, high resolution, immunity from electromagnetic waves and multiplexing [3]. Usually, optical time domain reflectometer (OTDR) is widely used for diagnosing optical fibre, but this system has relatively low spatial resolution [3]; on the other hand, frequency modulated continuous wave (FMCW) optical sensing system is a high resolution ranging system using an optical frequency swept laser source and a two-beam interferometer. In previous research, the FMCW sensing system has been successful in profiling the image of a coin and a printed circuit board with the measurement accuracy of $3\sigma = 29 \mu\text{m}$ [4, 5].

FMCW optical sensing system is composed of a frequency swept laser source and a two-beam interferometer, and the target under test is located in the arm of the interferometer [6] as shown in Figure 1. The optical frequency of the laser source is linearly swept in time without mode hopping [7]. The light from the laser source was split into two beams; one of them as the reference beam and the



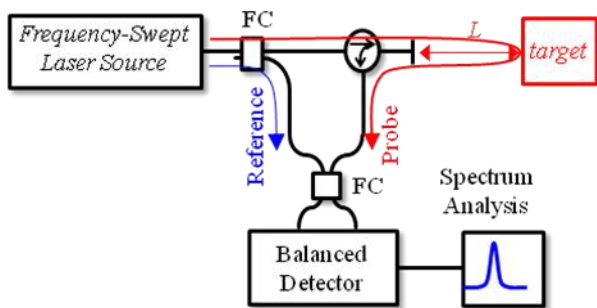


Figure 1. Basic configuration of FMCW optical sensing system.

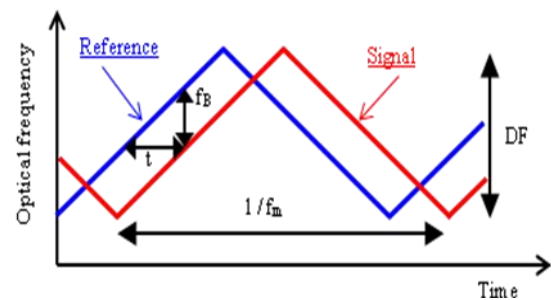


Figure 2. The waveform of the optical Frequency.

other as the probe beam. The reference beam directly arrives at the balanced-detector and the probe beam is directed to the target. The reference beam interferes with the probe beam reflected from the target. The interference signal contains the beat frequency corresponding to the distance to the target, L .

If the optical frequency of the laser source is swept in triangular waveform as illustrated in Figure 2, the beat frequency is given as equation (1) and the spatial resolution δ_z is given as equation (2) [9-10]

$$f_b = 2 f_m \Delta F \times \tau \quad (1)$$

$$\delta_z = \frac{c}{2 n \Delta F} \quad (2)$$

where τ is the differential time delay between the probe and the reference beams, and is given by $\tau = 2 n L/c$. Then the equation (1) can be rewritten as:

$$f_b = \frac{4 n L f_m \Delta F}{c} \quad (3)$$

with f_m as the repetition frequency of the optical frequency sweep, ΔF the tuning range of optical frequency sweep, n the refractive index, c the light velocity in vacuum and L the distance to the target.

The measurement time for profiling an image of 100 JPY coin in our previous research is 10 minutes by using a DFB laser as the laser source and utilizing averaging to achieve high accuracy and fine image.

2. Experimental Methods

The experiment set-up is shown in Figure 3. The light source used was a vertical cavity surface emitting laser (VCSEL) emitting at 1310 nm and the optical frequency was swept by modulating the injection current with a triangular wave. The VCSEL was selected as a light source because the tuning range, ΔF , is wider than a DFB laser, and then high spatial resolution and high measurement accuracy can be achieved as compared to using DFB laser [6, 11-12].

An auxiliary interferometer was configured in the sensing system to overcome the degradation of the spatial resolution and ranging accuracy due to non-linearity in the optical frequency sweep. This degradation is affected by slow temperature change of the laser cavity as the outcome from the injection current in the VCSEL [11].

The laser light was launched from the circulator and propagated toward the object to be surveyed. The reflected beam from the object interferes with the reference beam coming through the fibre coupler FC1 and FC2. This interference signal was sampled by the TTL-clocked interference signal of the auxiliary interferometer. The interference signal in the increasing section of the modulation signal was analyzed by Fast Fourier Transform (FFT). The exact beat frequency was measured by parabolic approximation around the peak of the beat spectrum. A 100 JPY coin was used as the target.

The focus of this research is high speed measurement for fine profiling of the target. For that achievement, three experimental methods have been performed; the first one is changing the modulation current amplitude between 4–10 mA with the modulation frequency of 500 Hz. The second is changing the modulation frequency in the range of 500 Hz – 2.0 kHz with the modulation current of 6 mA. The third method is asymmetric method, in which the increasing section used for the data acquisition (DAQ) is shorter than the decreasing section used for FFT analysis as illustrated in figure 4.

In our previous study, a symmetric triangular signal was used as the modulation signal as shown in figure 5. The increasing section in the modulation waveform was used for DAQ and the decreasing section was used for FFT. No averaging in the beat spectrum is used in the FFT analysis. The measurement time is decreased by increasing the scanning speed of the galvano mirror. However too fast scanning caused degraded imaging result because of the transient vibration of the galvano mirror for DAQ.

3. Results and Discussion

For the first method, the clear profile is shown in Figure 6 (a) for the modulation of 9 mA and 10 mA, the frequency modulation of 0.5 kHz and the FFT analysis for 8192 points. The measurement time was 41.29 seconds for 201×201 points.

The profile of the object was seen clearly at the second method as shown in Figure 6 (b) and (c). This profile would be found when the light source was modulated with frequency of 1.2 kHz and 1.4 kHz with FFT analysis of 4096 points, and the measurement time was 33.458 and 28.887 seconds, respectively.

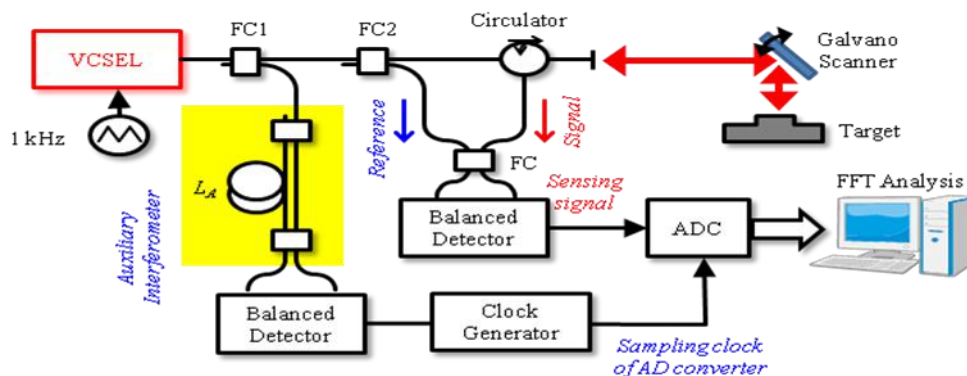


Figure 3. Experiment set-up profiling 100 JPY coin using FMCW optical sensing system.

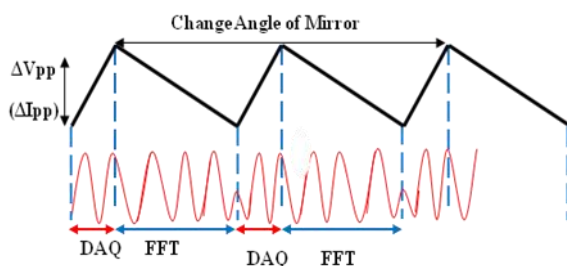


Figure 4. Analysis data signal with asymmetric method.

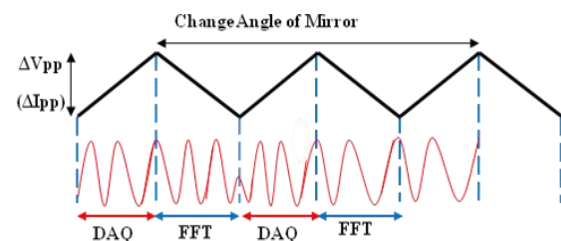


Figure 5. Analysis data signal with symmetric method.

For faster modulation frequency, the measured image was seriously degraded due to transient behaviour of the galvano mirror. Therefore we applied the third method, asymmetric modulation waveform; shown in Figure 4. In this method, the angle of galvano mirror was immediately changed just after the DAQ, and then the acquired data were FFT analyzed. The comparison of the measurement time for the image profile of the 100 JPY coin for symmetric and asymmetric methods are shown in Figure 7. This figure explains that the measurement time for asymmetric method is faster than the symmetric method. The asymmetric method with 28% of increasing section and 4096 points FFT analysis is the fastest measurement time with clear imaging as shown with blue diamonds in Figure 7.

Figure 8 shows examples of the imaging results with 28% asymmetry and different modulation frequency. The modulation current amplitude was 4 mA, which was limited by the response time of the clock generator shown in Figure 3. The opaque profile in Figures 8 (a) and (c) are the results of profiling an object with the modulation frequency of 2.1 kHz and 2.5 kHz, respectively. The clear profile of 100 JPY coin is illustrated in Figure 8 (b). The measurement time was 23.13 seconds for the modulation frequency of 1.8 kHz and the DAQ period is 15.556 μ s.

This proposed system has a performance of observing an object 2.25 cm square with 23 seconds. This research will be beneficial for high accuracy and shorter measurement time for profiling.

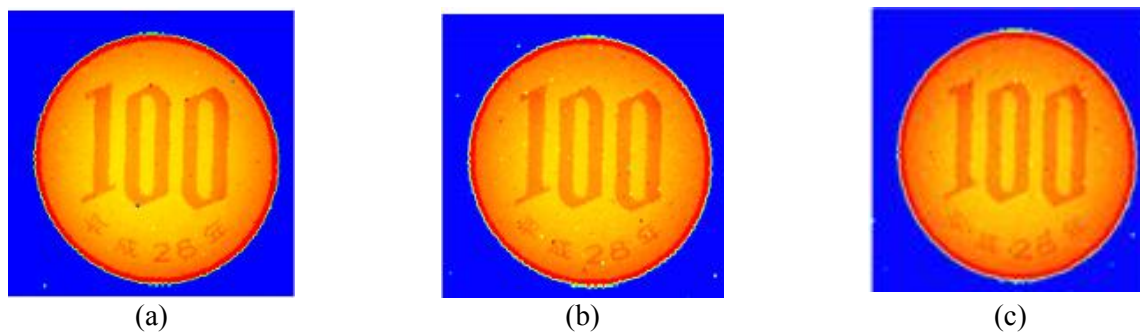


Figure 6. The image profile of 100 JPY coin using symmetric method with the frequency modulation (a) 0.5 kHz FFT 8192 (b) 1.2 kHz FFT 4096 (c) 1.4 kHz FFT 4096.

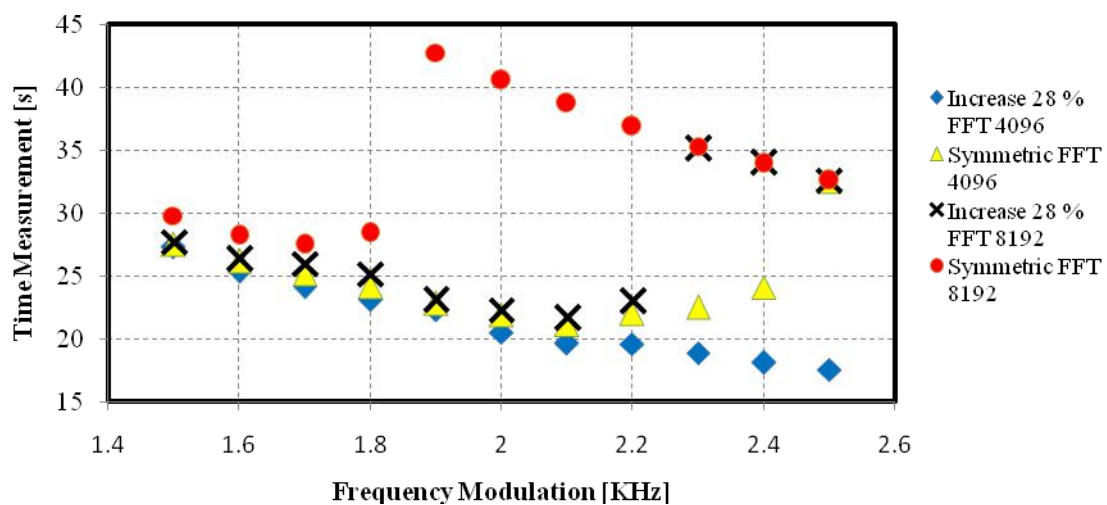


Figure 7. Comparison graphic between measurement time for profiling the image of coin 100 JPY using symmetric and asymmetric methods.

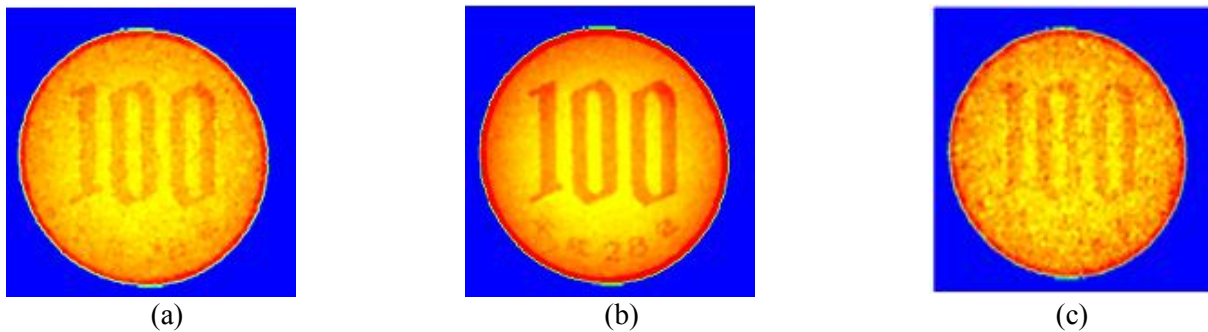


Figure 8. The image profile of 100 JPY coin using asymmetric method with the frequency modulation (a) 2.1 kHz; FFT 8192 in 21.769 s (b) 1.8 kHz; FFT 4096 in 23.134 s (c) 2.5 kHz; FFT 4096 in 17.551 s.

4. Conclusions

We have applied four conditions in FMCW optical sensing system for high speed measurement in profiling a 100 JPY coin. The asymmetric method with 28% for DAQ analysis and 72% for FFT analysis is successful to generate a clear profile of 100 JPY coin image in 23.13 s.

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