Micro Optical Position Sensor with Vibrating Light Source

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Summary

We propose a novel non-contact distance-sensor. The sensor is composed of a point light source and a photo detector both placed on a micro vibrator. The distance between the sensor and an object is obtained by the ratio of the detected light intensity and the amplitude of the intensity alternation by the vibration. It is applicable to both a scattering surface and a mirror-like one, and it is stable against the dirt and the sensitivity fluctuation of the detector. Its expected applications ranges from medical treatment to new type of computer interface, such as a proximity sensor in minimally invasive surgery, and a tongue motion sensor. The principle and the results of basic experiments to measure up to 3 cm within 1 mm error are shown.

Key words: Position sensor, distance measurement, proximity sensor, micro-sensor.

1 INTRODUCTION

Minimally invasive surgery using a micro actuator is one of key medical technologies drawing recent attentions. However, due to difficulty of the operation using endoscope view, some accidents hurting patients have been reported [1]. One solution for this problem would be a small sensor to measure the exact distance from the end-effecter to the tissue.

Such a small sensor is also required in other fields. A small sensor to detect tongue position, is useful for various applications, i.e. making database of phonetics [2], a silent computer interface using oral motion, supporting a learner to obtain a correct tongue position in foreign language pronunciation, and medical treatment of speech impediment.

Unfortunately, such a sensor has not been realized so far with the following two main restrictions. First, the sensor must be compact within several mm, and secondly, it must obtain the distance to human tissue with various conditions of color, inclination, wetness, and reflection properties, in addition to that, it must stable against dirt of the sensor itself. Traditional methods using trigonometry [3], focometry [4], time-of-flight of optical or acoustic waves [5][6], and optical interferometry are not effective for this sensor.

In this paper we propose a novel small sensor that measures distance to a living tissue using a vibrating light source.

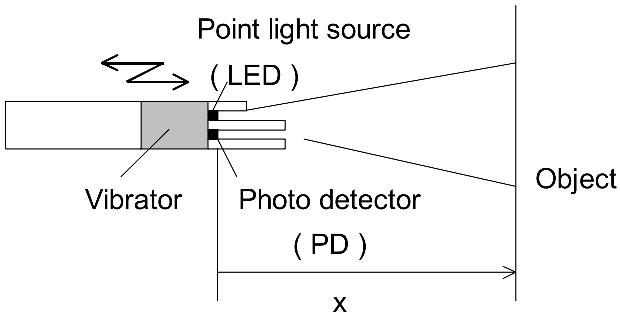

Fig. 1: Structure of the sensor and the sensing principle.

2 PRINCIPLE OF MEASUREMENT

The conditions our optical sensor should satisfy are summarized as follows,

<1> Small in millimeter size

<2> Stable against the dirt and the sensitivity fluctuation of the detector. Accurate with less than 1mm error.

<3> Applicable to a surface with unknown color, inclination, and reflection characteristic (scattering or mirror-like).

Here we propose a method to satisfy these three conditions. As shown in **Fig. 1**, a point light source (LED) and a photo detector (PD) are attached onto a surface which can vibrate in *x* direction. Two cylinders are attached to the LED and the PD, respectively, which give the spatial selectivity instead of lenses.

We move the vibrator with amplitude A. And we observe the reflected light in the vibration. Here we let the average intensity detected by the PD and amplitude of intensity alternation detected by the PD be D and ΔD, respectively. Then $\Delta D/D$ depends only on distance x. We shall show it in each case of scattering and mirror-liked surface.

1] Scattering surface

If the source of light is an incoherent point light source, scattered light intensity is proportional to the incident light intensity I on the surface located at x. Since sensitive area of the PD is proportional to x^2, which cancels the decay of scattered light, the D is written as

$$D(x) = \alpha I(x) = \frac{\beta}{x^2}. \quad (1)$$

The amplitude of intensity alternation by the vibration is given as

$$\Delta D(x) = A\left|\frac{d}{dx}D(x)\right| = \frac{2A\beta}{x^3}. \quad (2)$$

Therefore the distance is obtained by

$$x = 2AD/\Delta D. \quad (3)$$

As this equation shows, if the vibration amplitude is reliable, surface color and sensitivity fluctuation of the PD and the LED do not influence the distance evaluation.

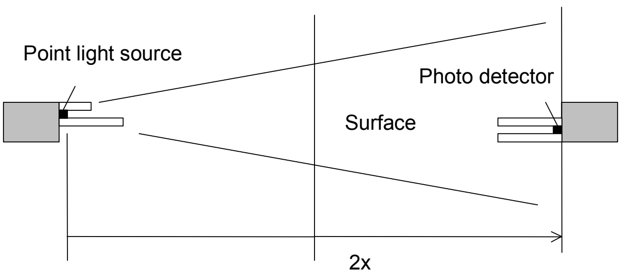

Fig. 2: Case of a mirror-like object.

2] Mirror-like surface

If the point light source is facing to the mirror-like surface perpendicularly (if not, the photo detector cannot observe the reflection light at all), the detected light is equivalent to that detected by the mirrored image of the PD at $2x$ as shown in **Fig. 2**. Therefore

$$D(x) = I(2x) = \frac{\gamma}{x^2} \quad (4)$$

Here we get the same algorithm as Eq. (3) to obtain x.

Thus, we can obtain distance to a surface by a single algorithm, regardless of whether the surface is scattering or mirror-like.

3 PROTOTYPE OF SENSOR

We fabricated a prototype sensor as shown in **Fig. 3** and **Fig. 4**. The displacement of a PD and a LED are regulated mechanically, and moved by a coil.

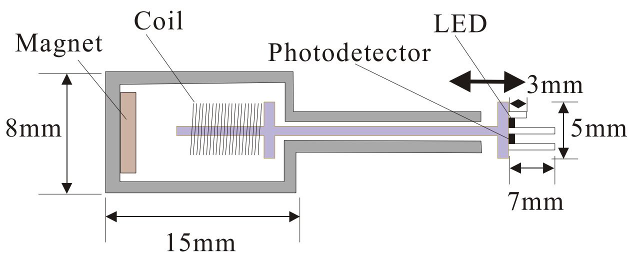

Fig. 3: Prototype of the sensor. A FET is located near the PD.

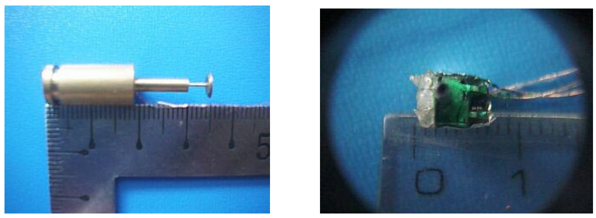

Fig. 4: Photograph of the prototype.

4 EXPERIMENTS

1] Confirmation of basic principle

We put a PD in front of a LED and examined relation of the observed intensity and the distance to confirm the $I(x)$ is proportional to x^{-2}. Next we record again the observed intensity versus the distance in a similar situation, but this time, with a sheet of paper located at the center between the PD and the LED to interrupt and scatter the light.

The results are shown in **Fig. 5**. In both cases, the observed intensity falls proportional to the inverse square of the distance as the theory predicted.

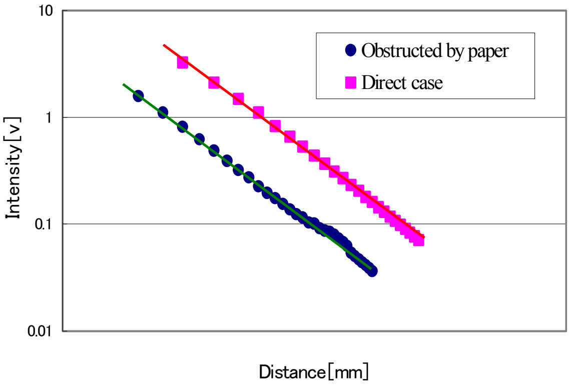

Fig. 5: Measured light intensity versus distances from the light source. Direct case (■), and indirect case (◆) with a sheet of paper located at the center between the PD and the LED, to interrupt and scatter the light.

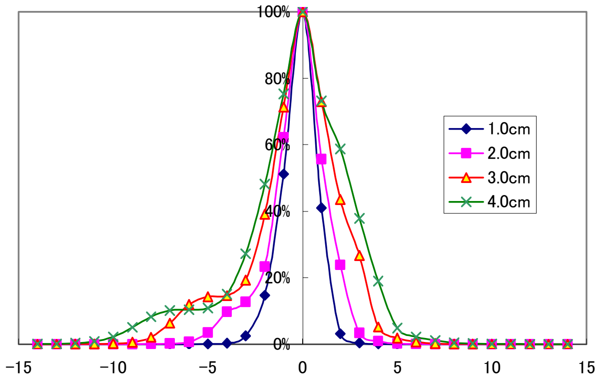

Fig. 6: Selectivity of detector.

2] Spatial selectivity of PD

We attach cylinders to the photo detector with 1 mm inside-diameter and 7mm height. To examine the spatial selectivity, we measure the PD output when we move a point light source on a vertical plane to the cylinder, located at 1, 2, 3, and 4 cm from the PD. The results are shown in **Fig. 6**. For example, when the distance was 3 cm, the radius of the sensitive area was less than 5mm.

3] Scattering surface and mirror

We confirm Eq. (3) for both a scattering surface and a mirror. The ratio of observed intensity D and ΔD for a white paper surface and a mirror are plotted with ◆ and ■, respectively, in **Fig. 7**. The D is obtained with LED modulation at 200 Hz, and the ΔD is obtained by vibrating the sensor head at 5 Hz rectangularly.

Since $D(x)$ is proportional to x^{-2}, the ratio of $D(x)$ to $\Delta D(x)$ is almost in proportion to distance x. The reason why the relation is not completely proportional to x and that the two curves do not overlap, is the PD and LED are not on the same axis. The difference corresponds to the error of about 2 mm. However, it will not be a serious problem because living tissue does not have such an extreme property like an actual mirror.

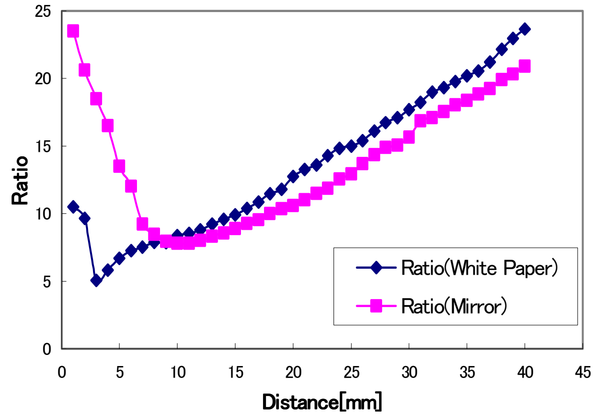

Fig. 7: Measured $D/\Delta D$'s for mirror and white paper surface.

4] Influence of surface color

Living tissue has variation of color. To examine the influence of color on the measurement, we plotted $D(x)/\Delta D(x)$ for various color of paper in **Fig. 8**. The plots overlapped each other.

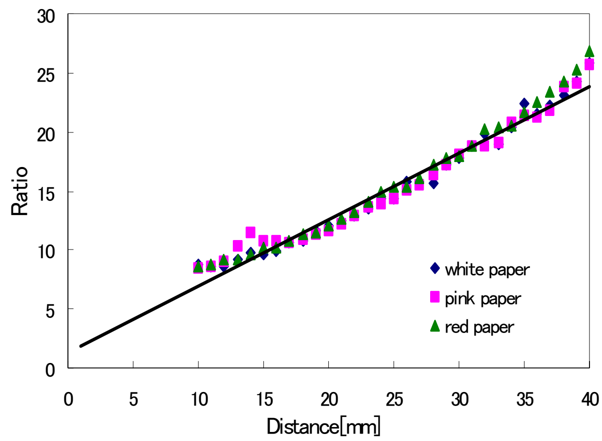

Fig. 8: Experimental results of $D/\Delta D$ for different colors.

5] Influence of surface inclination

We measured $D(x)/\Delta D(x)$ for 10, 20, and 30 degree inclination of an object surface. The results are shown in **Fig. 9**. The errors by inclination were within 1 mm in measurement of up to 3 cm distance. The large errors of the 30 degree data at $x > 3$ cm is caused by the low SN ratio on $\Delta D(x)$ measurement.

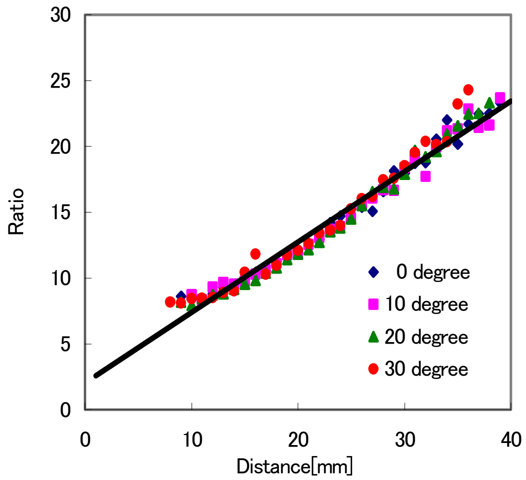

Fig. 9: Experimental results of $D/\Delta D$ for inclined paper surfaces.

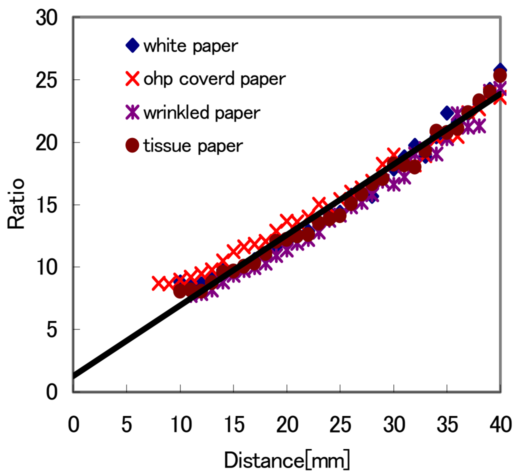

Fig. 10: Experimental results of $D/\Delta D$ for various materials and textures.

6] Influence of surface property

We measured three kinds of surfaces which have different properties from a flat paper surface. One is a paper surface covered by a transparent sheet (a OHP sheet with thickness 0.1 mm) as simulation of living tissue covered by mucus. Since not only scattered light but also coherently reflected light reaches to the PD, some errors are seen from the "white paper" data as shown in **Fig. 10**. The reason is that the PD and LED are not on the same axis as we discussed about the results of Fig. 7. The standard deviation of the error was 1 mm.

Next is a rough surface made of randomly winkled paper. The width and height of each convexity of the roughness are 0.3～2 mm and 0.1～0.5 mm, respectively. The data almost overlapped with that of a flat sheet of white paper. The slight difference reflects the average of the height of the rough surface.

The third is a tissue paper surface as simulation of a surface with reflection from the inside. In this case, significant difference from a white paper was not seen.

5 DISCUSSIONS

Reasons of measurement errors are summarized as follows.

1) Reflection from the back of the surface:
   The measurement gives a larger distance. However, practical error is not large. The penetration depth of human blood for 0.65～0.70 μm light is 10^{-2}～10^{-1} mm [7].
2) Curve of the surface:
   For a curved surface, Eq. (3) does not hold, especially for a mirror-like object.
3) Lack of texture uniformity:
   A radial pattern around the measurement point affects the $D \propto x^2$ property.
4) Difference of the PD and the LED positions:
   As we discussed in section 4.

We are evaluating the practical error in human tissue measurement caused by these reasons.

Acknowledgment

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References

[1] Y.Oikawa, The operation using endoscope and the care, Japan, Syogakukan,pp.7-8, pp.20-21, pp.32-35, 1995. (In Japanese)

[2] G.J.Borden and K.S.Harris, translated by H. Hirose, "A scientific guide to Speech", Medical Research Center, pp.88-120, 1994. (In Japanese)

[3] The society of Speech and Langue of Japan, "Examination of speech－Basis," I-HA-KUSURI Inc., pp. 427–429, 1986. (In Japanese)

[4] Sensor Handbook, Japan, Baifukan, pp.413-432, 1986. (In Japanese)

[5] Handbook of medical ultrasonic machine, Japan, Korona, pp.114-116, 1997. (In Japanese)

[6] M. Rioux: Laser Range Finder Based on Synchronized Scanners," Applied Optics, 23-21, pp.3837-3844, 1984.

[7] U. Kubo: Guide to medical Laser, Ohmu, pp. 70-72, 1985. (In Japanese)