Shearing Force Measurement Device Using an Integrated Micro Optical Displacement Sensor

Takuma Iwasaki, Toshihiro Takeshita, Renshi Sawada
Department of Systems Life Sciences
Graduate School of Systems Life Sciences Kyushu University
Fukuoka, Japan
iwasakitakuma@nano-micro.mech.kyushu-u.ac.jp
takeshita@nano-micro.mech.kyushu-u.ac.jp
sawada@mech.kyushu-u.ac.jp

Satoshi Takeuchi, Masutaka Furue
Department of Dermatology
Graduate School of Medical Sciences Kyushu University
Fukuoka, Japan
takeuchs@dermatol.med.kyushu-u.ac.jp
furue@dermatol.med.kyushu-u.ac.jp

***Abstract* — In this paper, the authors propose a novel shearing force measurement device using an integrated micro optical displacement sensor and a frame. The 3 mm x 3 mm square and 0.7 mm thick sensor tip measures the mirror tilt angle on the underside of the frame caused by the shearing force applied to the upper surface of the frame. The authors obtained a linear output change for a single axis shearing force, and expect to be able to detect the magnitude and direction of the shearing force. In addition, it is possible to measure biaxial shearing forces and alter the measurement range and resolution by varying the frame material and shape.**

Keywords — sensor; robot hand; bedsore; tactile sense; shearing force; MEMS;

I. INTRODUCTION

In recent years, developed countries have trended towards super-aging societies, and it is estimated that in 2050 there will be 2 billion people in the world that are 60 years of age or older. The rate of an aging population to productive population will become quarter and younger citizens will have to bear the financial and physical burdens for the aged population. Therefore, in order to alleviate the burden on young people, robots will be needed. Various robots are currently in development and others participate actively in factories, as well as in other areas. These robots are not only necessary in industry, but also for medical welfare, agriculture, and safety system, especially social welfare and livelihood support in the future, as robots can replace humans in various areas of work [1]. However, there are still problems with using robots in human society. The limited tactile sense of robots is one of these problems. Assemblage robots used in factories have been set up to grip specific objects and therefore need only to detect vertical loads applied to their surfaces. However, in general, gripping forces must be determined instantaneously according to the strength of the object to be held. If the robot is unable to detect horizontal forces such as a shearing force, it may drop the object in question. In the field of nursing, it is dangerous to drop human beings after they have been carried to a height. Therefore, emulation of human perception for sophisticated robot manipulation is difficult with only vertical load sensors; a shearing force sensor is also needed.

Certain injuries will also occur more readily in the aged population, one of which is bedsore: a skin lesion that may affect any part of the body after a long time lying in a bed; bony or cartilaginous areas such as elbows, knees, ankles, and the sacrum are the most commonly affected. It is estimated that there are two hundred thousand patients throughout Japan currently, and this number will increase as the population ages. Some causes of bedsores are the local load from the bed, the shearing force between the bed and skin, humidity, and so on [2]. In order to prevent bedsores more reliably, we must detect not only vertical load but also shearing force.

For these reasons, a shearing force sensor is needed. There have been several reports on sensors that can measure both vertical and shearing forces by using electrostatic capacitance change [3-7] or resistance change [8-10], among other techniques. These are soft and thin, which is desirable, but they are not put to practical use as they have problems with hysteresis, drift, creep, and noise. Additionally, the sensors that can measure three axial forces are too large to be embedded in the fingertip of a robot hand.

In this study, we present a new type of shearing force measuring device combining a metallic frame with an integrated micro optical displacement sensor [11] fabricated using micro electro mechanical systems (MEMS) technology. This displacement sensor can measure linear displacement and biaxial tilt angle of an object using one Vertical Cavity Surface Emitting LASER (VCSEL) and four photodiodes (PDs), is downsized drastically compared to the conventional displacement sensor owing to monolithic fabrication and can be utilized for many applications. We believe our sensor will be superior to other shearing force sensors due to its use of optics. In addition, our sensor can be made soft with an elastic frame for embedding in the robot fingertip or a bed.

The purpose of this study is to make sure that we can detect single axis shearing forces using our displacement sensor, and compare experimental results with simulation results using four types of trapezoidal metallic frames.

 ISBN: 978-1-61208-297-4

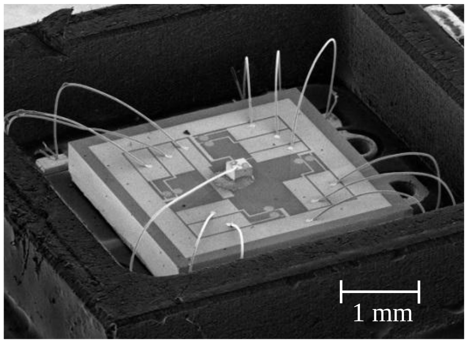

Figure 1. View of displacement sensor

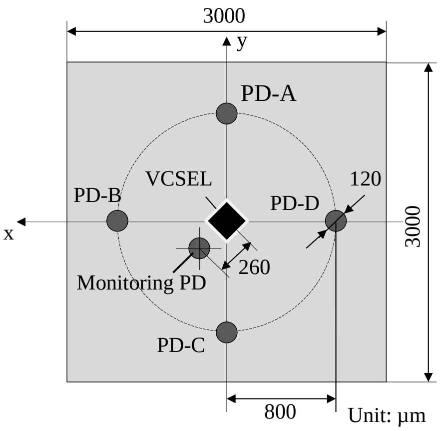

Figure 2. Structure of displacement sensor

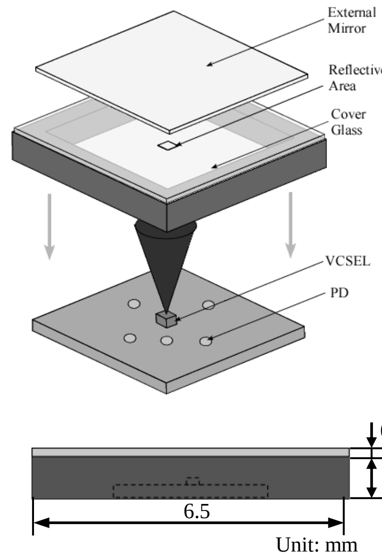

Figure 3. Overall view of the sensor

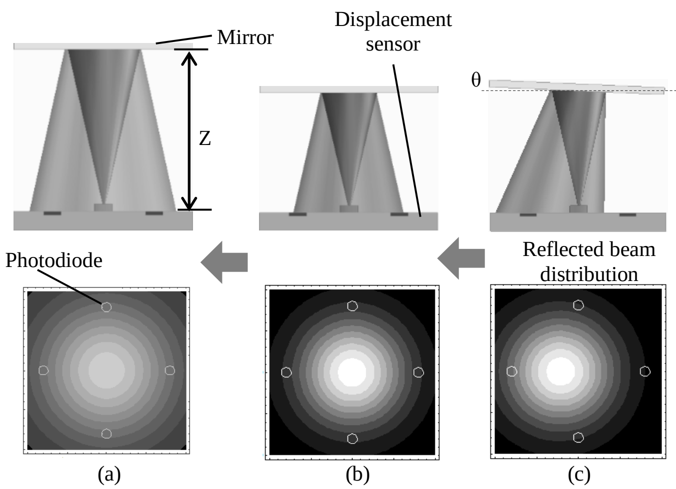

Figure 4. Principle of measurement

II. STRUCTURE AND PRINCIPLE

Our shearing force measurement device applies the integrated micro optical displacement sensor as shown in Fig. 1. The structure of the displacement sensor is described in Section A. The principle of measurement is detailed in Section B.

A. Structure of Displacement Sensor

The sensor has area 3000 µm x 3000 µm and thickness 700 µm. As shown in Fig. 2, a VCSEL in the center of the sensor and four detecting PDs, which apply electrical current according to the intensity received at the PD, are integrated monolithically and arranged in a concentric pattern. The diameter of each PD is 120 µm and the distance of the center from the VCSEL to the center of each outer PD is 800 µm. In addition, a monitoring PD is located near the VCSEL at a distance of 260 µm. This assembly is covered by glass as shown in Fig. 3, and there is a reflective area near the center of the glass. Some of the emitted beam from the VCSEL enters the monitoring PDs after being reflected from the reflective area. In this way, the sensor can obtain feedback for laser output according to temperature change. The VCSEL differs from a normal laser in that the beam is emitted perpendicular to the chip surface; it is superior with respect to production costs, power consumption, and integration capabilities.

B. Operation Principle of Displacement Sensor

The displacement sensor can measure linear displacement and tilt of an object by using the VCSEL, four detecting PDs, and an external mirror attached to the object to be measured beforehand. VCSEL emits beams in a direction perpendicular to the sensor surface, with a certain spread angle. Fig. 4 shows side views of the sensor and mirror, and the corresponding reflected beam distributions on the sensor.

1) Linear displacement: As the distance between the mirror and the sensor changes, the size of the reflected beam distribution — that is, the intensity received at PDs — also changes as shown in Figs. 4 (a) and 4 (b). Fig. 5 shows the relationship between the distance Z and the output *S*, which is given by (1):

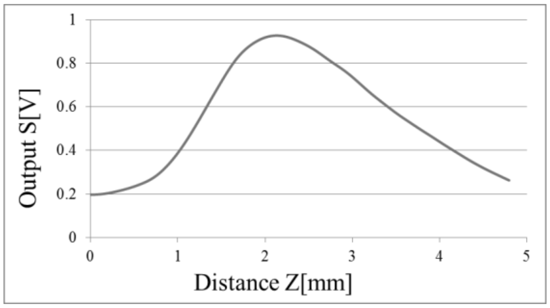

Figure 5. The relationship of output *S* and distance *Z* between mirror and sensor

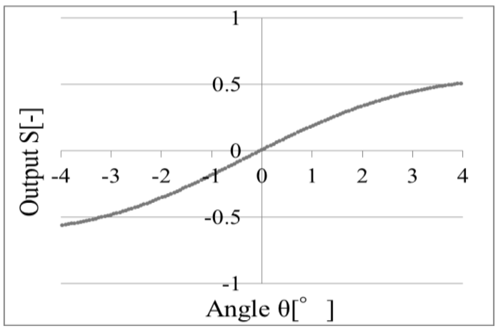

Figure 6. The relationship between output and mirror tilt angle

$$S = P_A + P_B + P_C + P_D \quad (1)$$

where P_A~P_D are the output of PD-A~PD-D, respectively.

When the mirror is close to the sensor, the distribution is small, and only a small amount of the reflected beam enters the PDs. As a result, the output *S* is small. As the mirror moves away from the sensor, the laser beam distribution becomes larger and the PD areas that receive the beam increase proportionately. Therefore, the output *S* increases linearly and peaks when the beam completely enters the PDs. Following this, the output *S* decreases linearly as the intensity weakens with decreasing distance. By using two linear regions on the graph, the sensor can be used to measure linear displacement.

2) Tilt angle: Changes in the tilt angle of the mirror move the reflected beam distribution directionally, as shown in Figs 4 (b) and 4 (c). This causes a difference in the PD intensity. Fig. 6 shows the relationship between tilt angle and the output *S*, which is given by (2)–(3):

$$S_x = \frac{P_A - P_C}{P_A + P_C} \quad (2)$$

$$S_y = \frac{P_B - P_D}{P_B + P_D} \quad (3)$$

In the case of *x*- or *y*-axis rotations, equations (2) or (3) are used, respectively.

For example, when the mirror tilts clockwise as in Fig. 4 (c), the intensity of PD-B increases and that of PD-D decreases. Therefore, the output S_y increases. By using the region where *S* changes linearly, we can determine the tilt angle.

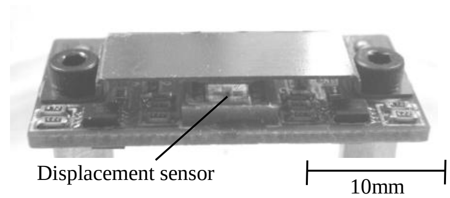

Figure 7. View of shearing force measurement devices

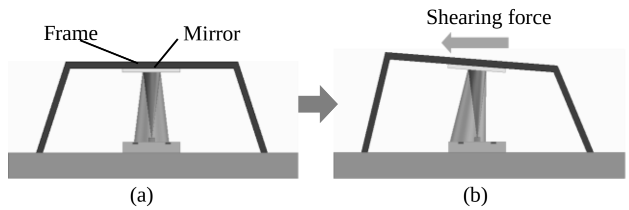

Figure 8. Conceptual diagram of shearing force sensor

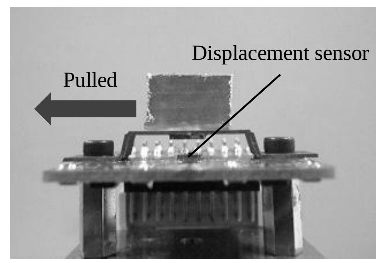

Figure 9. Photograph of the experimental system

C. *Structure and Principle of Shearing Force Sensor*

Our shearing force measurement device uses the above displacement sensor. The displacement sensor is covered by a trapezoidal fame as shown in Fig. 7. The mirror is attached on the underside of the frame. When a shearing force is applied to the upper surface of the frame, the frame is deformed and the mirror tilts as shown in Fig. 8. By measuring the tilt angle of the mirror with the displacement sensor, the shearing force can be detected. We can change the accuracy and resolution by varying the material and shape of the frame. For example, it is better to use a soft sensor can detect a biaxial shearing force, and by using the principle of measurement of linear displacement, it can detect both normal loads and shearing forces simultaneously. This leads to a reduction of the total component count, which cuts costs.

III. EXPERIMENT

In order to ensure that a single axis shearing force can be measured by using the principle mentioned in the previous sections, we conducted an experiment using metallic frames. The experimental system is shown in Fig. 9. The displacement sensor is in the center of a board, covered by the frame. Applying a shearing force to the upper surface of

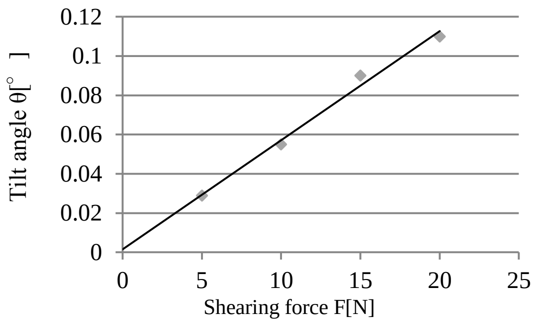

Figure 10. Analysis of the relationship between shearing force and tilt angle with frame (a)

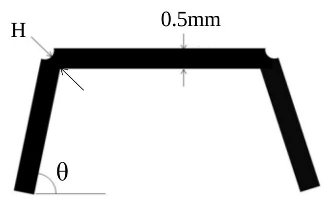

Figure 11. Schematic showing the frame

TABLE I. CHARACTERISTICS OF FRAMES USED IN THE EXPERIMENT

	Material	Young's modulus	Thickness of corners H	Angle of frame sides θ
a	SUS	199 GPa	0.1 mm	70 °
b				90 °
c			0.3 mm	70 °
d	Cu	117 GPa	0.1 mm	70 °
e				90 °
f			0.3 mm	70 °

the frame involved attaching a rectangle object and pulling it side to side with a translation stage; the applied force was measured with a force gauge with 10 mN resolution.

We applied shear loads from 0 N to 20 N to each frame. The loads applied were in the x-axis direction (see Fig. 2); the output S was thus given by (3) and the outputs of PD-A and PD-C were not used. Before the experiment, we analyzed the relationship between shearing force and mirror tilt angle by finite element method. We obtained a linear relationship as shown in Fig. 10. Therefore, it is expected that we obtain a linear relationship between the output and shearing force because estimated mirror tilt angle of 20 N falls within the linear area completely as shown in Fig 6. We prepared six types of metallic frames as shown in Fig. 11 and Table 1. We expected the stainless steel frame to deform more readily than the copper frame because the Young's modulus of stainless steel is larger than that of copper. In addition, we expected the frames with a corner thickness of 0.1 mm to be easier to deform than those with 0.3 mm, and that there would be little change in the frame with 90 degree lower corners.

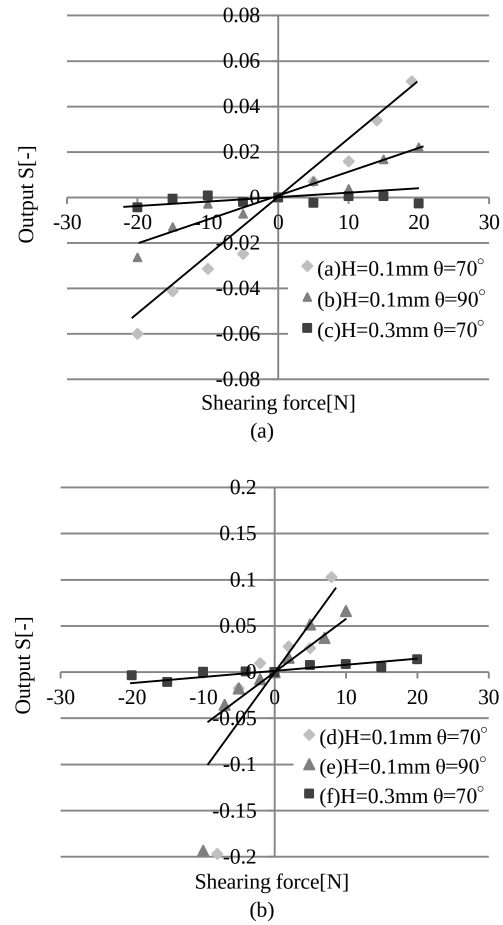

Figure 12. Variations in the output S for (a) stainless steel, and (b) copper

As shown in Fig. 12, we obtained a linear increase in S for a single axis shearing force as we had expected. As a result, we can determine the magnitude and direction of the single axis shearing force. In addition, we found that the output changes were dependent largely upon the material and shape of the frame. Therefore, smaller shearing forces are likely measurable if a softer material is used for the frame. In the experiment, copper frames with corner thickness 0.1 mm were more likely to collapse, so we did not apply up to the maximum 20 N. As expected, the gradient of the frames with corner thickness 0.1 mm (shown by the light gray points) is much steeper than that of the frames with corner thickness 0.3 mm (black points). When the frame is deformed by applied shearing force, it is essentially identical that the sides and corners of the frame are bended by reaction force as shown in Fig. 13. Therefore, it is thought that the thickness of the corner affects the ease of deformation largely and the gradient of the frames with corner thickness 0.1 mm is much steeper than that of the frames with corner thickness 0.3 mm. Additionally, the gradient of the frame with 70 degree bottom corner angles (light gray points) is steeper than that of the frames with 90 degree bottom corner angles (dark gray points).

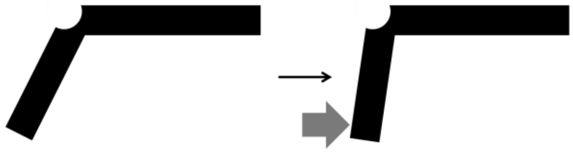

Figure 13. Schematic diagram of deformation

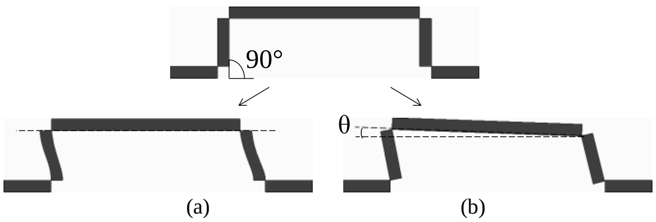

Figure 14. Schematic diagram of frame deformation at (a) the sides, and (b) the corners

We believe there are two reasons for this. The first is that the angle of the side of the frame may not have been exactly 90 degrees, which would cause the mirror to tilt slightly when the frame is deformed. The second is that the corners of the frame were deformed by the shearing force much more than the sides of the frame; this is shown in Fig. 14. When the sides of the frame deform, the upper part of the frame — that is, the mirror — moves in the horizontal direction and the mirror does not tilt. On the other hand, when the corners of the frame deform, the upper part of the frame tilts geometrically, which in turn means that the mirror is tilted. In the case of the frame used in this experiment, the corners are easier to deform than the sides because the sides of the frame are short. Overall, the output gradient of stainless steel frames is steeper than that of copper frames. As shown in Table 1, the Young's modulus of stainless steel is almost twice that of copper; correspondingly, the results show that the S values for the copper frame are approximately twice that of those for the stainless steel frame. The outputs of (c) and (f) (black points) were mostly unchanged. This is because the shearing force of 20 N was insufficient for deforming the frame. The outputs of (d) and (e) (light gray and dark gray points) in the results of copper were in part non-linear. This can be explained by the yielding of the frames at a shearing force of about 10 N. The thickness of the corners affects the outputs more than both the tilt angle of the side part of the frame and the frame material. Consequently, we need to set the measurement range according to the strength of the frame.

IV. Conclusion and Future Work

In this work, we have successfully obtained a linear dependence on a single axis shearing force by combining an integrated micro optical displacement sensor with a metallic frame. The gradient of the linear change primarily depended on the material and shape of the frame. We therefore expect this sensor to be able to detect the magnitude and direction of a single axis shearing force. We also expect to be able to change its resolution and measurement range. It is possible that this sensor can measure biaxial and smaller shearing forces by using the same principle; it could then be embedded in robot fingertips or consumer beds.

References

[1] D. Sasaki, T. Noritsugu, and M. Takaiwa: "Development of Pressure Measurement Type Tactile Soft Sensor for Life Assist Robot", Transactions of the Japan Society of Mechanical Engineers, vol.70, no.689, 2004, pp.77-82.

[2] http://www.mayoclinic.com/health-information (2013/04/03)

[3] F. Zhu and J. W. Spronck, "A capacitive tactile sensor for shear and normal force measurements", Sensors and Actuators A, Volume 31, Issues 1–3, Mar. 1992, pp. 115–120.

[4] H. K. Lee, S. I. Chang, and E. Yoon, "A flexible polymer tactile sensor: Fabrication and modular expandability for large area deployment," J. Microelectromech. Syst., vol. 15, no. 6, Dec. 2006, pp. 1681–1686.

[5] H. K. Lee, J. Chung, S. I. Chang, and E. Yoon, "Normal and Shear Force Measurement Using a Flexible Polymer Tactile Sensor With Embedded Multiple Capacitors", J. Microelectromech. Syst., vol. 17, no. 4, Aug. 2008, pp. 934-942.

[6] H. K. Lee, J. Chung, S. I. Chang, and E. Yoon, "Polymer tactile sensing array with a unit cell of multiple capacitors for three-axis contact force image construction," in Proc. 20th IEEE Int. MEMS Conf., Kobe, Japan, Jan. 21–25, 2006, pp. 623–626.

[7] Z. Chu, P. M. Sarro, and S. Middlehoek, "Silicon three-axial tactile sensor," Sens. Actuators A, Phys., vol. 54, no. 1–3, Jun. 1996, pp. 505–510.

[8] A. Ito, N. Tsujiuchi, T. Koizumi and H. Oshima: "Tactile Information Processing by Distributed-Type Tri-axial Force Sensor for Robot Finger'', The Science and Engineering Review of Doshisha University, vol. 48, no. 3 Oct. 2007, pp. 86-94.

[9] E. S. Hwang, J. H. Seo, and Y. J. Kim, "A Polymer-Based Flexible Tactile Sensor for Normal and Shear Load Detection," Proc. of IEEE International MEMS Conference 2006, Istanbul, Turkey, Jan. 22-26, 2006, pp. 714-717.

[10] K. Kim et al., "3-Axes Flexible Tactile Sensor Fabricated by Si Micromachining and Packaging Technology," Proc. of IEEE International MEMS Conference 2006, Istanbul, Turkey, Jan. 22-26, 2006, pp. 678-681.

[11] T. Takeshita et al., "Characteristics and application of a monoli- thically integrated micro-displacement sensor" ,Joint International IMEKO Symposium, Germany, 2011.