Sensors and Actuators A 221 (2015) 1–8

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Shearing force measurement device with a built-in integrated micro displacement sensor

Takuma Iwasaki[a,*], Toshihiro Takeshita[a], Yuji Arinaga[b], Satoshi Takeuchi[c], Masutaka Furue[c], Eiji Higurashi[d], Renshi Sawada[a], Koji Uemura[b], Hideyuki Ando[e]

[a] *Graduate School of Systems Life Sciences, Kyushu University, 744 Motooka, Nishi-Ku, Fukuoka 819-0395, Japan*
[b] *Corporate R & D Center, YASKAWA ELECTRIC CORPORATION, 12-1, Otemachi, Kokurakita-ku, Kitakyushu 803-8530, Japan*
[c] *Department of Dermatology, Graduate School of Medical Sciences, Kyushu University, 3-1-1 Maidashi, Higashi-Ku, Fukuoka 812-0054, Japan*
[d] *Research Center for Advanced Science and Technology, University of Tokyo, 4-6-1 Komaba, Meguro, Tokyo 153-8904, Japan*
[e] *Fuzzy Logic Systems Institute, 1-5, Hibikino, Wakamatsu-ku, Kitakyushu 808-0135, Japan*

ARTICLE INFO

Article history:
Received 30 June 2013
Received in revised form
25 September 2014
Accepted 28 September 2014
Available online 18 October 2014

Keywords:
Bedsore
Displacement sensor
Friction
Robot hand
Optical MEMS
Shearing force

ABSTRACT

The measurement of shearing force is increasingly important in the detection of slipping and the measurement of friction. In this paper, we propose a promising shearing force measurement device that is 16.3 mm × 2.9 mm × 6.0 mm, using an integrated micro displacement sensor and a trapezoidal external metallic frame. The optoelectronic subsection of the sensor is 6.5 mm × 6.5 mm, and is 1.6 mm thick. This subsection is used to measure the tilt angle of a mirror on the ceiling of the frame caused by the shearing force applied to the upper surface of the frame. We have been able to successfully obtain a linear output change for a single axis shearing force, and determined that the measurement sensitivity differs largely due to the material and shape of the frame. Therefore, if these factors are known this device can be embedded in various applications.

1. Introduction

The accurate measurement of shearing force is effective to capture the slip phenomenon. In addition, shearing force is related to friction and varies with slipping. The friction also changes before, during, and after slipping. A relatively fine time resolution of the order of milliseconds is required to measure changes in friction force [1]. Therefore, the shearing force must be obtained by rapid sensing. The post processing of the sensing output is a simple calculation which does not require a computer. Currently, optics-based shearing sensors are not sufficient [2] from a speed of response viewpoint. It is expected that slip can be detected and the optimum grip force of a robot gripper can be determined by exploiting this phenomenon. In addition, it has been reported that friction between a bed and human skin is one of the primary causes of bedsores, which leads to ischemia [3]. By embedding a sensor that can measure shearing force in a bed, it is possible to prevent bedsores and design a bed shape that is optimized to minimize damage to the user's skin. The measurement of shearing force allows the gripping of an object with minimal grasping power in order to avoid slipping while minimizing undesirable shearing forces that cause skin to stretch and compress.

There have been several reports of sensors that can measure shearing forces using MEMS (Micro Electro Mechanical Systems) that use piezoresistors, capacitors, or strain gauges [4–7], optical elements [2,8–10], or piezoelectric devices [11]. MEMS shearing force sensors benefit since computational requirements on the central workstation can be decreased due to the integration of electronic circuits within the sensor chip itself [7]. However, these sensors have the disadvantages of being fragile and inflexible. For example, the measurement range of a tactile sensor pixel using a capacitance change is only 0.01 N [6]. The sensor surface must be soft in order to allow human contact when embedded in robot hands and beds. Optical shearing force sensors, especially CCD-based sensors [8], are bulky and complicated systems [12], while piezoelectric based devices tend to experience response hysteresis and are affected by temperature and process variations [13].

In this study, we present a novel shearing force measurement device combining a trapezoidal external metallic frame with an integrated micro optical displacement sensor [14–16] fabricated

---

* Corresponding author.
E-mail address: 3sl13019y@sls.kyushu-u.ac.jp (T. Iwasaki).

http://dx.doi.org/10.1016/j.sna.2014.09.029

using MEMS technology. In our previous work, we developed the micro displacement sensor using one vertical cavity surface emitting laser (VCSEL) and various photodiodes (PDs) integrated monolithically. This sensor could measure the linear displacement and biaxial tilt angle of an object, and was ideal for downsizing in comparison to previously reported laser displacement sensors. The VCSEL differs from a normal laser in that the beam is emitted perpendicular to the chip surface. In addition, it offers lower production costs and power consumption, with superior integration capabilities [17]. A combination of a laser displacement sensor and an external deformable frame enables a wide range of shearing force measurement since the external frame can be selected from materials with varying stiffnesses. Furthermore, the friction coefficient between the objects to be caught and the shearing force sensor can be changed according to the desired application. Our proposed shearing force measurement device has many features. Firstly, the displacement sensor benefits from a very simple structure and is relatively small (6.5 mm × 6.5 mm) with the wire being carried to one side of the sensor unlike other optical shearing sensors [10]. This allows simple embedding in grippers and other applications. Secondly, the sensor relies only on changes in optical intensity; therefore it is not susceptible to electromagnetic interference from noise compared with the sensors which use electrical change [10] and has a number of advantages such as high sensitivity and a wide dynamic range [10]. Thirdly, we can overcome sensor fragility – one of the shortcomings of MEMS devices – by protecting the sensor chip with the external frame. When measuring the friction applied to human skin, the sensors must have a soft surface in order to prevent harm to the skin [18]. Therefore, our device will be embedded in a soft material. We can expect to alter the measurement range and sensitivity of our device by only modifying the shape of the external frame. Finally, it may also be possible to develop a sensor that can measure both shearing force and normal load together by using the similar measurement principle. It is usually difficult to simultaneously measure shearing force and normal load because the output characteristics for the shearing force change when a normal load is applied, and vice versa. While several other shearing force devices can measure shearing force only when a normal load is applied, our device can also measure shearing force when a normal load is not applied. It is expected that our device is more suitable for applications in a larger field. The purpose of this study is to demonstrate the measurement of single axis shearing forces using our displacement sensor, and compare experimental results with simulation results using four types of trapezoidal shaped external frames.

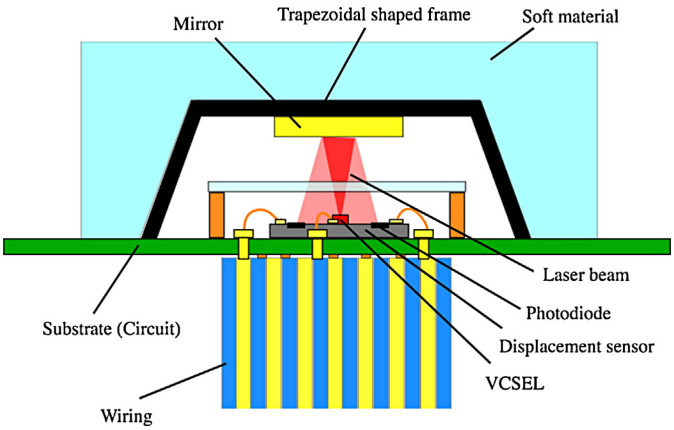

Fig. 1. The complete schematic for the shearing force measurement device that consists of a displacement sensor and a trapezoidal frame.

2. Sensor principle

Our shearing force measurement device is realized by combining a laser displacement sensor with a trapezoidal external frame. The schematic of the shearing force sensor is shown in Fig. 1. The displacement sensor is covered by the frame and embedded in a soft material.

The laser displacement sensor consists of four photodiodes monolithically integrated on the silicon chip with an area of 3000 μm × 3000 μm and 700 μm in thickness. The VCSEL chip is bonded on the center of the silicon chip as shown in Fig. 2. The monolithically integrated PN junction PDs are concentrically formed. The diameter of each PD is 120 μm and the distance from the center of the VCSEL to the center of each outer PD is 800 μm. The wavelength, beam power, and mode of the VCSEL are 850 nm, 2.2 mW, and single mode, respectively. The power consumption of the VCSEL and the amplifier are 20 and 10 mW, respectively. The silicon chip is covered by a plastic case with a covering glass. The total area is 6.5 mm × 6.5 mm and is 1.6 mm thick, as shown in Fig. 3. The diverging light emitted from the center of the VCSEL is incident on the PDs after being reflected from the mirror chip attached to the ceiling of the trapezoidal external frame, as shown in Fig. 1. The individual concentrically formed photodiodes generate electrical current according to the intensity of the received beam. The electrical current from each PD is amplified and converted into a voltage by a circuit on the board shown in Fig. 4. The block diagram of the circuit of each PD is shown in Fig. 5.

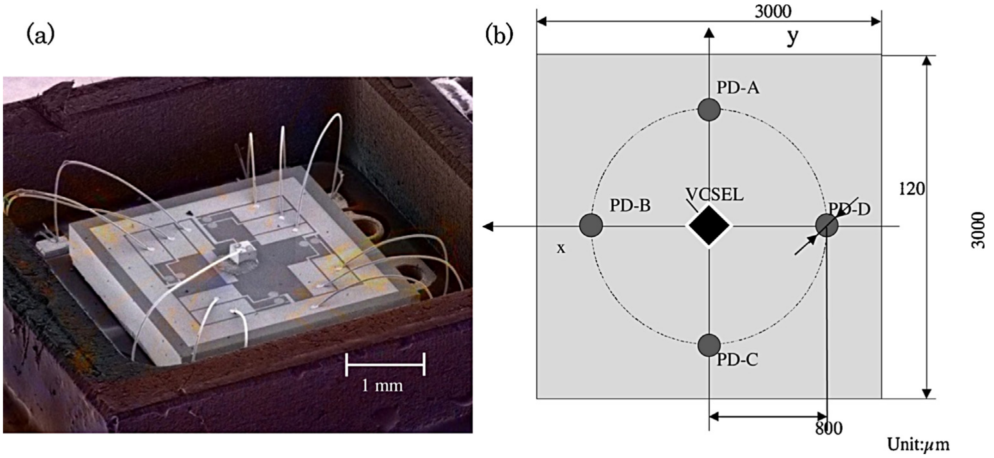

Fig. 2. View of the integrated micro displacement sensor (3 mm × 3 mm, and 0.7 mm thick). (a) Photograph of the sensor tip, and (b) schematic view of the sensor structure.