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Tactile sensor arrays using fiber Bragg grating sensors

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Abstract

This paper describes two kinds of 3 × 3 force sensor arrays using fiber Bragg gratings (FBG) and transducers for tactile sensation to detect a distributed normal force. One array is developed for a large area tactile sensor that has good sensitivity but low spatial resolution, similar to human body skin. The other is for a small area tactile sensor that has good sensitivity and spatial resolution, similar to human finger skin. The transducer is designed such that it is not affected by chirping and light loss. We also present the fabrication process and experimental verification of the prototype sensors. Experimental tests show that the newly designed sensors have good performance: good sensitivity, repeatability, and no-hysteresis. The load calibration is accomplished by a verified uniaxial load cell. In order to provide a more precise measurement, temperature compensation is applied to all taxels. These force sensor arrays are flexible enough to be attached to a curved surface and they also have simple wiring compared with other types of small force sensors for tactile sensation.

Keywords: Fiber Bragg grating sensor; Tactile sensor; Taxel

1. Introduction

Sensory information of human skin for feeling materials and determining many of their physical properties is provided by sensors in the skin. This tactile information is related to the sense of touch, one of the five senses including sight, hearing, smell, and taste. Presently, many researchers are attempting to apply the five senses to intelligent robot systems. In particular, many kinds of tactile sensors combining small force sensors have been introduced for intelligent robots, teleoperational manipulators, and haptic interfaces. These tactile sensors, which are capable of detecting contact force, vibration, texture, and temperature, can be recognized as the next generation information collection system. Future applications of engineered tactile sensors include robotics in medicine for minimally invasive and microsurgeries, military uses for dangerous and delicate tasks, and automation of industry.

Some tactile sensors and small force sensors using microelectromechanical systems (MEMS) technology have been introduced. MEMS tactile sensing work has mainly focused on silicon-based sensors that use piezoresistive [1,2] or capacitive sensing [3,4]. These sensors have been realized with bulk and surface micromachining methods. Polymer-based devices that use piezoelectric polymer films [5,6] such as polyvinylidene fluoride (PVDF) for sensing have also been demonstrated.

Although these sensors offer good spatial resolution owing to the use of MEMS techniques, there remain some problems with respect to application to practical systems. In particular, devices that incorporate brittle sensing elements such as silicone based diaphragms or piezoresistors, including even those embedded in protective polymers, have not proven to be a reliable interface between a robotic manipulator and the manipulated object. Previous efforts have been hindered by rigid substrates, fragile sensing elements, and complex wiring. These drawbacks can be compensated for by utilizing flexible optical fiber sensors and transducers. In addition, optical fiber sensors have immunity to electromagnetic fields and can be easily multiplexed. Therefore, in this paper, we present a newly designed optical fiber force sensor and 3 × 3 sensor arrays, which are the first step toward realizing a tactile sensor using optical fiber sensors (FBG), as well as two kinds of transducers. The two types of transducers have different size and structure. One is applied to a large size force sensor and the other is applied to a small size force sensor.

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2. Design of flexible force sensor

2.1. Principle of FBG

FBG sensors based on wavelength division multiplexing (WDM) technology are ideally suited for distributed strain monitoring. FBG sensors are easily multiplexed and offer many advantages such as linear response and relative measurement. The basic principle of an FBG-based sensor system lies in the monitoring of the wavelength shift of the returned Bragg-signal, as a function of the measurand (e.g. strain, temperature, and force).

The Bragg wavelength is related to the refractive index of the material and the grating pitch. Sensor systems involving such gratings typically work by injecting light from a spectrally broadband source into the fiber, with the result that the grating reflects a narrow spectral component at the Bragg wavelength, or in transmission this component is missing from the observed spectrum. Fig. 1 illustrates this process simply and schematically.

The intensity of the reflected optical signal is a function of the Bragg grating wavelength, which is related to the applied strain on the FBG. Therefore, the dynamic strain can be derived from the intensity change measurement as a function of the wavelength of the reflected optical signal. The operation of an FBG is based on a periodic, refractive index change that is produced in the core of an optical fiber by exposure to an intense UV interference pattern. This grating structure results in the reflection of the light at a specific narrow band wavelength, called the Bragg wavelength. The Bragg condition is given by

$$\lambda_B = 2n_e\Lambda \tag{1}$$

where λ_B is the Bragg wavelength of the FBG, n_e the effective index of the fiber core, and Λ is the grating period. The Bragg wavelength shift due to strain and temperature can be expressed as

$$\Delta\lambda_B = \lambda_B \lfloor(\alpha_f + \xi_f)\Delta T + (1 - p_e)\Delta\varepsilon\rfloor \tag{2}$$

$$p_e = \left(\frac{n^2}{2}\right)[p_{12} - \nu(p_{11} - p_{12})] \tag{3}$$

where α_f is the coefficient of the thermal expansion (CTE), ξ_f the thermo-optical coefficient, and p_e is the strain-optical coefficient of the optical fiber. The value of $p_e = 0.227$ [7] was measured experimentally and used for this study. If there is no temperature change, we can measure the strain from the wavelength shift as

$$\varepsilon = \frac{1}{1 - p_e}\frac{\Delta\lambda_B}{\lambda_B} \tag{4}$$

2.2. Design of flexible transducer using FEM

First, there are two major factors that must be considered upon designing the transducer of FBG force sensors. The first is light loss by microbending, as shown in Fig. 2. If microbending occurs in the optical fiber, the intensity of the reflected light is remarkably decreased, and as a result the proper Bragg wavelength cannot be measured. As microbending often occurs in a

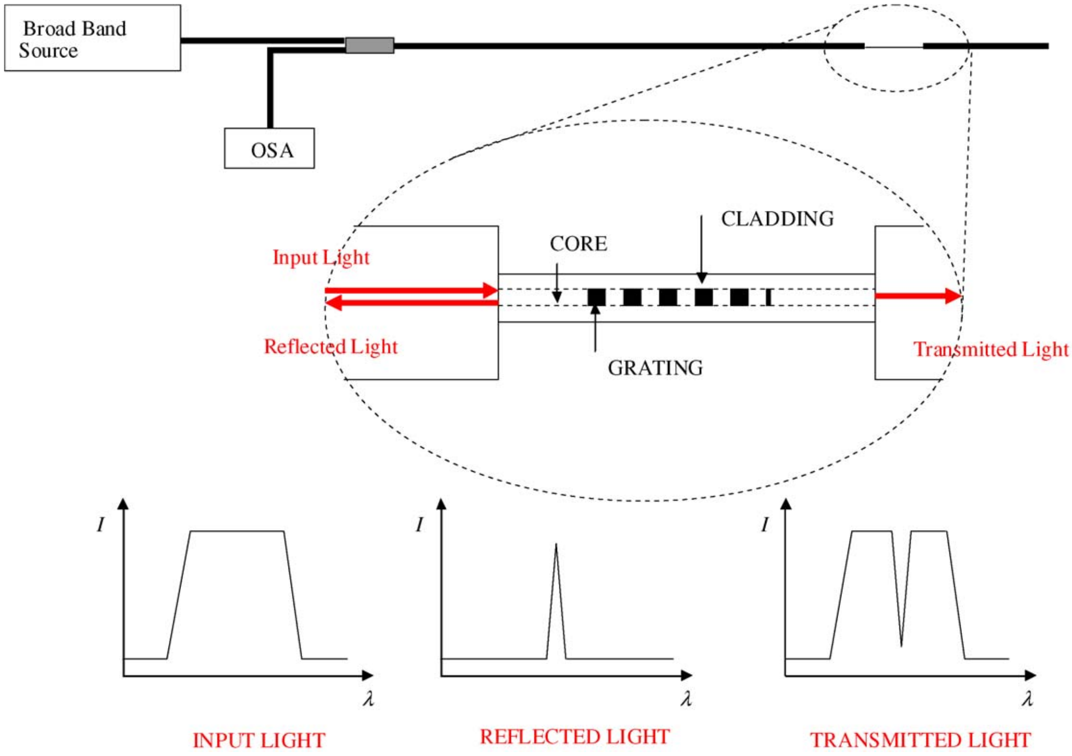

Fig. 1. Fiber Bragg Grating sensor encoding operation.