Fiberoptic 6-DOF Force-Torque-Sensing for Haptic Feedback in Minimally Invasive Robotic Surgery

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Abstract

In minimally invasive robotic surgery long and slender instruments are introduced into the body of the patient through small incisions or natural orifices. Robotics technology is applied in order to comply with the kinematic constraints of the fulcrum point, to increase the immersion for the surgeon by sensors and to increase dexterity by supplemental motion capabilities.

Haptic feedback for the surgeon can be realized in such a robotic system (MIRS, minimally invasive robotic surgery) through measurement of interaction forces at the instruments tip and a high bandwidth haptic user interface for the surgeon. Contact forces should be measured as close as possible to the distal tip of the instrument (i.e. tips of forceps, scalpel) to reduce impact of parasitic forces like friction and moments in the fulcrum point or actuation forces of distal joints.
Forces are commonly measured by applying strain gauge sensors to a suitable sensor structure allowing a decoupled measurement of forces and torques in several degrees of freedom. She response is very small and has to be amplified and processed in close proximity to the sensors, thus inside the patient.

A six degrees of freedom sensor based on a Stewart platform and strain gauge sensors integrated into a MIRS system (see figure 1 left) was presented in [1]. However, the constraints shown above lead to suboptimal designs. This is reflected by multiple approaches to this problem in research [1-5].

In the presented work a novel approach to this problem based on fiberoptic sensing is demonstrated. The sensing of strains in difficult environmental conditions by fiberoptic sensors based on fiber-bragg-gratings (FBGs) is a well known technique for health monitoring in large structures like bridges and dams.
An optical single-mode fiber can transmit a certain range of wavelengths with low damping over very long distances. If a short region of this fiber contains a periodic modulation of its refractive index, this region represents a very narrow bandwidth reflector for a characteristic wavelength. When strain is applied to this modified region or its temperature is changed, the reflected wavelength changes. Although the required sampling rate and precision of the spectroscopic interrogation is very high, the technique has interesting advantages:

- raw sensor signals can be transmitted almost lossless over long distances.
- the surgical instrument can be built without integrated or near-by sensor conditioning electronics.
- the sensor signals are immune to, and do not create EMI.
- the FBG material itself is biocompatible and robust against high temperatures.
- raw sensor signals of several FBGs can be transmitted in one fiber.
- the FBG does not have to be applied to the sensor structure surface.

Figure 1 (right) shows the 6 DoF sensor prototype based on fiber-bragg-gratings with mounted optical fibers. Each fiber-bragg-grating has a length of only 1 mm and is

embedded into the leg of the sensor. The fibers are connected via a 2x8 coupler to the light source and the spectrum analyzer. The sensor diameter could be reduced from 10 mm to 6.4 mm. As the FBGs are embedded into the six legs of the sensor they are completely shielded from any environmental influence other than strain and temperature. Technical data are as follows:

- characteristic FBG wavelengths: 1540.0 nm – 1557.5 nm.
- full-width-half-maximum of peak: 0.4-0.6 nm.
- force range 10 N; moment range 150 Nmm.
- size: 6.4 mm diameter x 6.3 mm length.

The achievable sensor resolution depends mainly on the quality of temperature compensation and wavelength measurement. The spectrum can be measured in several different ways:

- commercial optical spectrum analyzer.
- spectral scanning using either a swept light source or tuneable filter.
- application specific spectrometric measurement based on diffraction gratings.

In the presented system an Erbium-ASE (amplified spontaneous emission) source is used as broadband light source, covering the complete wavelength range of all FBGs. The spectral signal reflected by the sensor is depicted in figure 2 (top: light source, bottom: reflected sensor signal).

Since the sensor signal can be transmitted almost lossless over long distances the size of the spectroscopic signal processing system is initially irrelevant, although some analysis concepts can be miniaturized. Sampling rate should be in the range of 1-3 kHz to guarantee high performance of the haptic feedback in the presence of hard contacts. Spectrometric measurement based on diffractive elements shows large potential due to high speed synchronous sampling of the entire spectrum. Future work focuses on the development and integration of an application specific high speed spectrum analyzer with high dynamic range.

References

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Web Links

DLR German Aerospace Center, Institute of Robotics and Mechatronics
MIRO Homepage. http://www.dlr.de/rm-neu/en/desktopdefault.aspx/tabid-3828/

DLR German Aerospace Center, Institute of Robotics and Mechatronics
MICA Homepage. http://www.dlr.de/rm-neu/en/desktopdefault.aspx/tabid-3829/

Figures

Figure 1: Comparison of 10 mm diameter prototypic MIRS instrument with strain gauge based force torque sensor [1] (left) and new fiber-bragg-grating based 6 DoF sensor (right).

Figure 2: Spectral power distribution of light source (top) and reflected signal by the sensor (bottom). The individual peaks of the reflected spectrum shift with temperature and strain.