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Performance and Sealing Material Evaluation in 6-axis Force-Torque Sensors for Underwater Robotics

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Abstract: In this paper, the effects of two different materials for the sealing on the performance of an innovative optoelectronic force/torque sensor for underwater robotic applications are investigated. The sensor has been designed to exhibit a considerable compliance in comparison with commercial F/T sensors for industrial applications, and optoelectronic components have been used as sensible elements for the development of the sensor, allowing a relatively simple and reliable implementation. These properties allow dealing with uncertain environments and an easy sensor integration in complex robotic systems, such as in robotic grippers for underwater applications.
The paper presents the basic working principle and the design of the sensor together with experimental data to illustrate its main features. Finally, the use of the sensor as an intrinsic tactile sensor is investigated and experimentally validated, and the comparison of different materials for the rubber sealing in terms of their effects on the sensor performance is executed.

Keywords: Force Sensors, Tactile Sensors, Robotic Manipulation, Grasping, Underwater Robots.

1. INTRODUCTION

The development of autonomous robotic systems able to interact with dynamic environments and cooperate with humans is actually one of the most challenging goal in robotics. Either in a domestic or an industrial environment, a robot must be able to sense and recognize what surrounds it in order to operate safely and autonomously. In this scenario, Force/Torque (F/T) sensors allow the implementation of robotic systems designed for interacting with unknown environments and humans, and are also useful for the manipulation of uncertain objects, allowing the online adaptability of the robot to the real object characteristics and conditions.

The large part of commercial F/T sensors are based on strain-gauges. The motivation can be ascribed to the reliability of this solution, to the wide literature about the optimization of this sensing principle Bicchi (1992); Kang et al. (2014), to the relatively simple numerical methods for the estimation of strain in multi-axis F/T sensors Ma and Song (2013) and to the large stiffness of the sensor that does not introduce destabilizing effects when applied on conventional industrial manipulators. This technological solution has been used in a wide number of different robotic applications, e.g. in Kim et al. (2008) where a 6-axis F/T sensor has been embedded in an intelligent robotic foot or in Song et al. (2007) where a 4-axis strain-gauge sensor has been developed for measuring interaction forces in haptic devices.

If grasping and manipulation tasks are taken into account, the sense of touch plays an essential role for manipulating objects properly. In Dahiya et al. (2010) a complete review on tactile sensor technologies and features is reported. Despite the relevance of the application, a limited number of commercial tactile sensors are available on the market due, on one hand, to the high manufacturing complexity and cost and, on the other hand, to the lack of knowledge about the interpretation and the exploitation of tactile sensors data. Despite many different design solutions have been proposed and several physical transduction principles have been exploited, the design of reliable and accurate tactile sensors is still very complex, then the use of simpler F/T sensors as intrinsic tactile sensors has been proposed in literature Bicchi et al. (1990).

While conventional strain-gauge based F/T sensors measure the strain induced on the mechanical structure by the an external force/torque, an alternative solution based on optoelectronic components may introduce several advantages, as shown by the many different implementations of F/T based on this concept proposed in literature. F/T sensors based on optoelectronic components exploit the scattering or the reflection of a light beam emitted by a source and received by suitable detectors to directly measure the deformation of a compliant structure or the relative displacement between elastically coupled elements caused by the external force/torque. Optoelectronic force sensors range from conventional mono-axial measurements, like in Palli and Pirozzi (2011) where discrete optoelectronic components are used to measure the forces in a tendon based transmission system, to 6-axis F/T sensors, as in Lorenz et al. (1999) where the authors adopt optoelectronic devices mounted on a compliant structure to measure human-robot interaction forces. In Hirose and Yoneda (1990) Hirose and Yoneda implemented an optical 6-axis F/T sensor adopting a 2-axis photosensor for measuring the deformation caused by the external load on a compliant structure. In the field of tactile sensors, a quite common optoelectronic technology makes use of Fibre Bragg Gratings (FBG), exploiting the relationship between the variations of the FBG wavelength and the external force applied to the FBG Heo et al. (2006). Other

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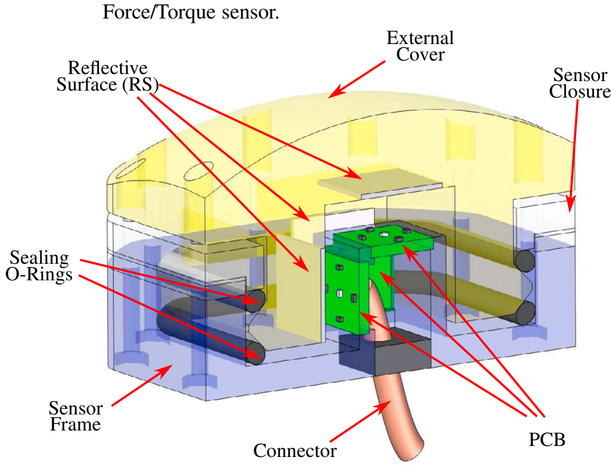
(a) A prototype of the optoelectronic 6-axis Force/Torque sensor.



(b) Conceptual design of the sensor prototype.

Fig. 1. A prototype of the optoelectronic 6-axis Force/Torque sensor and internal design of the sensor.

optoelectronic sensors are based on CCD or CMOS camera to acquire the deformation of a surface caused by external force Kamiyama et al. (2005). The light beam of a Light Emitting Diode (LED) scattered by a silicon dome and a urethane foam cavity is exploited in E. Torres-Jara (2006); Tar and Cserey (2011) and G. Hellard (2002) respectively. In De Maria et al. (2012) an optical tactile sensor based on a matrix of LED and PhotoDetectors (PD) couples covered by a deformable elastic layer is described.

This paper reports the development of a 6-axis F/T sensor based on optical reflection. The work here reported is based on a previous investigation of the basic concepts and implementation tests for an optical 6-axis F/T sensor Palli et al. (2014). In particular, due to the use of the proposed sensor in the underwater environment, the problem of sealing of the internal components is taken into account in this paper. Due to the advantages of optoelectronic-based solutions, an easily scalable and low-cost F/T sensor is obtained, suitable to be used as an intrinsic tactile sensor. Moreover, the proposed sensor requires an extremely simple conditioning electronics. Finally, the sensor design has been conceived in such a way that all the electronic components are allocated in a single Printed Circuit Board (PCB), making it easier the sensor integration into complex mechanical structures such as grippers for underwater robots.

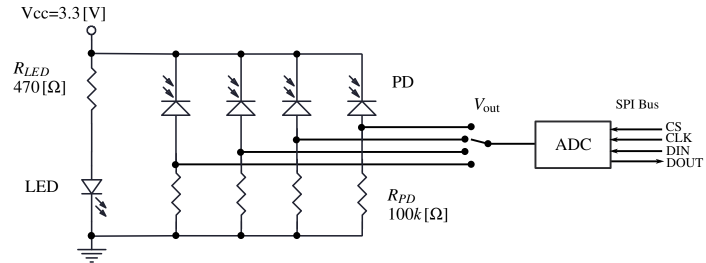


Fig. 2. Simplified measuring circuit of the PCB with one LED and four PDs.

2. SENSOR PROTOTYPE

A PCB with a LED mounted in its center and four PDs symmetrically arranged around it on a circle of radius 3 mm is the basic element for building up the proposed 6-axis F/T sensor. The PCB is a 10×10 mm electronic board (1 cm^2). Moreover, with the aim of measuring forces and torques along the three axes with a proper redundancy, 3 of these basic elements have been placed on three faces of a cube. A prototype of the sensor is shown in Fig. 1(a). Note that the geometry of the sensor and the placement of the PCB may vary depending on the specific application for which the sensor is designed. A compliant frame connecting the internal part of the sensor (where the PCBs are fixed) to the external contact surface, the cover (where the RSs are attached), allows the relative motion of the RS with respect to the PCBs, see Fig. 1(b). The compliant frame deforms in an elastic way when a contact force is applied to the external contact surface. Note that the sensor working range can be freely adjusted according to the application requirements by a suitable design of these elastic frame.

The simple conditioning electronics is shown in Fig. 2. It is worth noticing that the whole circuit in Fig. 2 is implemented in the same PCB where the LED and the PDs are hosted, and the three PCB shown in Fig. 1(b) are then connected through the SPI digital bus to a microcontroller board located into the sensor base that elaborates the PDs output signals to perform noise filtering and providing the force estimation on the base of the calibration data, see Sec. 3. Then the microcontroller can transmit the estimated forces and torques via digital bus using different protocol and bus types: the CAN bus and CanOpen protocol have been adopted for the developed sensor prototype for compatibility reasons with the other parts of the robots (mainly the arm). In the developed prototype, the external surface of the sensor is a spherical cap with radius $R = 44$ mm. This particular design has been developed since the sensor is placed on the fingertips of an underwater three-fingered robot gripper Bemfica et al. (2013) and the sensor dimensions derive from this specific application.

3. CALIBRATION AND CHARACTERIZATION

An ATI Gamma SI-130-10 F/T sensor has been used as reference sensor for the calibration of the sensor prototype. Apart from a suitable changes in the reference frame and in the point where the force is applied, the two sensors are mechanically connected in such a way that they are subject to the same forces and torques. Then a variable load in terms of both forces and torques has been applied to the sensor prototype and the data from both sensors have been collected. Being the compliant