A simple and easy-to-build optoelectronics force sensor based on light fork: Design comparison and experimental evaluation

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**Abstract**

In this paper, the design and the implementation of a force sensor based on a commercial optoelectronic component called light fork and characterized by the simple construction process is presented. The proposed sensor implementation is designed to measure the force applied by a cable-based actuation by detecting the deformation of a properly designed compliant structure integrated into the actuation module. Despite this, the design method here presented allows to adapt the sensor to a large set of robotic applications, thanks to its simplicity in the construction and low cost. The main advantages of the proposed sensor consist in the use of a very compact commercial optoelectronic component, called light fork, as sensing element. This solution allows a very simple assembly procedure together with a good sensor response in terms of sensitivity, linearity and noise rejection to be achieved using an extremely simple electronics, thereby obtaining in this way a reliable and very cheap sensor that can be easily integrated in actuation modules for robots and can easily adapted to a wide application set.

The paper presents the basic sensor working principle and the compliant frame design. An analytic model of the compliant frame deformation is proposed and verified both by finite element analysis and by experimental measures performed on four different sensor specimens manufactured by 3D printing and CNC milling, and the results have been compared. Moreover, the sensor specimens calibration and the experimental validation have been performed both in static and dynamic conditions.

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1. Introduction

Nowadays, advanced robotic systems are conceived for dealing with unstructured environments, therefore the physical interaction and their coexistence with humans plays a crucial role. With respect to their precursors, these robots are provided with enhanced cognitive capabilities, making them able to adapt to dynamically changing conditions. A number of innovative features are required to achieve this goal, among them the physical interaction with the environment and human–robot interaction are enabled by the availability of the interaction forces measurement. Force and torque sensors are of primary importance also in the developments of wearable and assistive robotic devices, such as servo-actuated prostheses and exoskeletons, in which physical human–robot interaction is of paramount importance, providing proper information for detecting the human intentions. These devices cover a wide application set, ranging from rehabilitation and human assistance to military tasks and haptic operations. In last few years, the applications of exoskeletons to support the hand and lower/upper-limb mobility have significantly grown [1,2].

Several uniaxial force sensor and multi-axis force/torque sensors are available on the market, and almost all of them are based on strain gauges, consisting on both thin-film resistors or semiconductors. Conventional strain-gauge based force sensors measure the strain induced on the mechanical structure by the external force. The main advantage of these sensing elements are mainly the extremely good linearity, at the expense of quite complex electronics for the signal acquisition, sensitivity to electromagnetic noise and temperature variations. Moreover, strain gauges require properly designed supporting structures that can pose some difficulty during their integration into complex mechanical systems like robots. Another critical point with that sensing technology is that the strain gauge assembly procedure is a quite complex and error-prone task, requiring significant experience and careful implementation. This results in significant limitations of the design customization, fact that brings robot designers to rely very often on commercial non-application-optimized products.

Several advantages in the field of force measurement can be introduced by alternative sensing solutions. One alternatives is pro-
vided by force sensors based on piezoelectric sensing elements, as proposed in [3]. Another promising solution relies on the use of optoelectronic components as sensing elements for the implementation of force sensors, as already proposed in literature by several authors [4–7]. These kind of sensors exploit the scattering and/or the reflection of a light beam emitted by a source and received by suitable detectors to detect the deformation of a compliant structure or the relative displacement between elastically coupled elements caused by the external force. In [6], a force sensor based on the use of discrete optoelectronic components for the measurements of the robotic hand tendon force at the actuator side is presented for force control and friction compensation purposes [8]. In [9], an optical microinertial force sensor based on the differential measures of the light intensity is presented, while [10] presents a sensor based on changing coupling of optical power between a photodiode and a vertical-cavity surface-emitting laser facing each other and separated by a deformable transducer layer. In [4] the authors adopt optoelectronic devices mounted on a compliant structure to measure human–robot interaction forces. 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 [11]. Other optoelectronic devices such as fiber Bragg gratings have been exploited for the implementation of force tactile sensors [12]. An optoelectronic force sensor based on CCD or CMOS camera to acquire the deformation of a surface caused by external force is presented in [13]. In [14,15] the light beam of a light emitting diode (LED) is scattered by a silicon dome and a urethane foam cavity respectively: the compression of the dome or the cavity due to applying an external force, causes a scattered energy density variation that is detected by several photodetectors (PDs). In [16] an optical tactile sensors based on a matrix of LED/PD couples covered by a deformable elastic layer is reported. In [17] an example of tactile/force sensor exploiting the reflection of the light cone emitted by an LED on a silicon rubber dome is reported. In [18] another alternative solution has been proposed by a fiber optic force sensor using Fabry–Perot Interferometry that is compatible in the high-field magnetic resonance imaging (MRI). In [19] machine learning techniques are investigated to dynamically compensate for environmental biases affecting multi-axis optoelectronic force sensors, such temperature and ambient light.

This paper reports an innovative solution for the implementation of an optoelectronic force sensors for robotic applications. The basic sensor elements are a compliant frame, manufactured in ABS plastic by 3D printing or in DELRIN by CNC milling, and a commercial optoelectronic component, a light fork embedding in a compact and high-sensitive device both the LED and the PD required for measuring the compliant frame deformation. The same working principle adopted for the implementation of the proposed force sensor has been exploited by the one of the authors in [20] for the implementation of joint position sensors in highly-integrated robotic hands [21]. In the case here reported, an optoelectronic element integrating both the LED and the PD has been exploited for improving the sensitivity, the compactness, the noise rejection and reduce the assembly complexity. Moreover, in this case the working principle is applied to the measurement of a linear force instead of an angular position. The main advantages of the proposed solution consist in the design and assembly simplicity, the low-cost, the sensitivity, the noise rejection and the possibility of an easy integration in the same monolithic structure of an actuation module manufactured by 3D printing. In particular, the proposed sensor structure has been investigated for the integration of an affordable force sensor in a twisted string actuation module [22]. The paper reports the description of the sensor working principle, the design of the compliant frame, its theoretical model and finite element analysis (FEA), the experimental characterization of the light fork used as sensing elements and the mechanical properties validation for four sensor specimens characterized by different physical dimensions, manufacturing modality and materials. The sensor specifications, such as sensitivity, linearity, hysteresis area and bandwidth, have been experimentally verified by means of static calibration procedure and evaluation in dynamic conditions. Finally, the noise attenuation obtained by means of a simple modulation and filtering technique has been evaluated.

The paper is structured as follows. In Section 2, the structure of the proposed device, its working principle and the modeling of the compliant sensor frames are presented. The experimental evaluation and the comparisons of the four different sensor specimens are described in Section 3 together with their static calibration and the dynamic response of the proposed devices. Finally, Section 4 draws some conclusion about the presented research activity.
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