Miniaturized Optical-based Force Sensors for Tendon-driven Robots

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Abstract—In this paper, an innovative sensor based on optoelectronic components and compliant frames for the measurement of the tendon tension is presented. With respect to conventional solutions for force sensing, like strain-gauge or Bragg-grating based force sensors, this sensor presents several advantages, mainly in terms of compactness, simplicity of the implementation and conditioning electronics. The proposed sensor exploits the properties of optoelectronic components with a narrow angle of view to measure the very small deformation of a compliant frame caused by the tendon tension. The sensor can be placed at the tendon ends as well as in any position along the tendon. The paper reports the basic working principle and a simplified procedure for the design of the sensor frame together with the results of an experimental testbench where a couple of the proposed sensors are used for the feedback control of a tendon-driven robotic joint.


I. INTRODUCTION

It is well known that the availability of joint torque sensors improves the dynamic performance of the servomechanisms that are the basic components of any robot, from the industrial manipulators to anthropomorphic robotic hands [1], [2], [3], [4]. This fact can be attributed to the possibility of rejecting disturbance torques acting on the motion transmission chain by means of torque feedback. Precise regulation of the transmission force is a crucial issue in the case of both position, force or, more in general, impedance control [5], [6], and this is especially true when industrial robots are considered.

In the last years the importance of torque/force sensors has significantly grown due to the increasing interest in lightweight robots and robotic hands. This new class of robots has been conceived not only for industrial applications, but to extend the robotic tasks scenario also to common human-like operations and manipulation activities, such as home and entertainment applications, as well as assistance to elder and impaired people. The development of these robotic devices actually represents one of the most challenging aspect in robotics. Besides their importance also for prosthetic applications [7], the introduction of robotic hands and lightweight robots makes possible a new level of interaction with the humans and the environment, in fact such complex systems are specifically designed to allow the robot to interact with completely unstructured environments: a safe interaction in a so generic and critical scenario can be ensured only by introducing in the mechanism a smooth and compliant behavior.

In robotic hands, such a compliant behavior is usually provided by torque control, hence finger joint force/torque sensors appear mandatory [8], [9]. With the aim of providing to these devices an intrinsic compliant behavior, several research activities have been devoted to the development of non-conventional kinematic chains that make use of compliant structures and to the investigation on the properties in terms of compliance given by the introduction of non-rigid transmission systems like tendons [10] or variable stiffness actuation [11].

Nowadays tendon-based transmission systems are widely used for the implementation of several robotic devices, such as end-effectors for surgical robots [12], [13], haptic interfaces [14], robotic hands [15], [3], [8], [16]. The first prototype of the new tendon-driven robotic hand, called UBH-IV [4] (University of Bologna Hand, version IV), developed with the DEXMART project [17] is shown in Fig. 1.

Although tendon-based transmission systems present various advantages mainly from the point of view of the mechanical design especially when the remote placement of the motors is necessary for encumbrance reasons, some intrinsic limitations are introduced mainly due to the unidirectionality

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of the actuation forces and to the limited stiffness of the tendons. Moreover, the measurement of the tendon tension is necessary for the fine regulation of the forces on the transmission system and in particular for the compensation of the friction generated by sheaths and pulleys used to route the tendon along its path [10]. Several solutions for the measurement of the forces transmitted by tendon-based actuation systems have been proposed in the past, as reported in [18], [19], [4].

The force sensor proposed in this paper takes advantage of the angle-varying radiation pattern of common LEDs and responsivity pattern of PhotoDetectors (PDs). This choice is based on interesting properties typical of optoelectronic devices such as immunity to electromagnetic fields, lightness and low power consumption. The paper reports the basic working principle of the sensor, a simplified procedure for the design of the compliant frame that act as support for the optoelectronic components, the realization of a sensor prototype and the calibration and testing of the sensor in a feedback control system.

II. SENSOR DESIGN

Figure 2 reports a scheme of a typical tendon-driven robotic finger with a linear actuation module connected to a tendon. In order to directly measure the force applied by the actuator to the tendon, it is necessary to introduce a force sensor in such a system.

Carrying on the research activity performed for the development of the UBH-IV joint position sensors [20] where the characteristics of optoelectronic components have been exploited to measure relatively large angular displacements, LED and PD couples with a narrow angle of view have been used in the development of the proposed sensor to measure the quite small deformations imposed by the tendon tension on a suitably designed deformable smatricialtructure, also referred as “compliant frame”. A CAD drawing of the sensor is reported in Fig. 3.

A. Working principle

The working principle of the proposed sensor takes advantage of the angle-varying radiation pattern of common LEDs and responsivity pattern of PDs. The advantages of this type of implementation consist in the very high sensitivity and the simplicity of the conditioning electronics with respect to strain gauge based load cells, as can be seen looking at the scheme depicted in Fig. 6, together with the high immunity to electromagnetic disturbances. The drawbacks of this solution may be the thermal drift, as in the case of strain gauges, and the cross coupling due to other similar sensors mounted in the neighborhood. This latter effect can be annihilated by means of a suitable design of the sensor cover or by modulating/demodulating the LED supply and the output signals, with an additional conditioning electronics.

Figure 4 shows an LED and a PD positioned with an initial relative angle between their mechanical axes $\theta = \beta_1 + \beta_2$. In this figure, $\beta_1$ represents the angle between the LED mechanical axis and the segment that indicates the distance $d$ from the tip of the PD to the tip of the LED, and $\beta_2$ representing the angle between the PD mechanical axis and the same segment. In this state a certain amount of light
emitted by the LED reaches the PD and it is proportionally converted into an electrical current, $I_\theta$.

When the angle $\theta$ between the mechanical axes of the emitter and of the receiver experiences a variation with respect to its initial value a different amount of light will be sensed by the PD and converted into a current different from $I_\theta$. This happens because the radiation pattern of the LED varies with the angle $\beta_1$, so that the receiver detects different values of radiant flux for different values of $\beta_1$. At the same time also the way the PD weighs received light varies, according to the variations of its responsivity pattern with $\beta_2$. The combination of these two effects leads to the observed variations of the photocurrent. Recalling the theory on LED radiation patterns [21], it is possible to model the system in order to optimize the design of the sensor, selecting initial relative angle $\theta$ between the mechanical axis of the two devices. In particular, if the distance $d$ is large enough to render the far-field approximation valid, the LED could be regarded as a point source. In this case the photocurrent $I_\theta$ (and thus the received radiant flux by the PD) will be proportional to the product between the radiant intensity pattern of the LED, evaluated in $\beta_1$ (denoted as $I(\beta_1)$) and the responsivity pattern of the PD, evaluated in $\beta_2$ (denoted as $R(\beta_2)$), and inversely proportional to the square distance $d$

$$I(\theta) = K \frac{I(\beta_1)R(\beta_2)}{d^2(\theta)}$$  

where $K$ is a dimensional multiplicative constant.

For the specific sensor presented in this paper optoelectronic components with a very narrow angle of view have been chosen with the aim of obtaining a large sensitivity of the sensor with a very limited angular variations. In Fig. 5(a) and 5(b) the characteristics of the LED and of the PD are reported. In these figures the large variation of radiant intensity pattern and responsivity pattern of the selected optoelectronic components over a very limited variation of the angular displacement in a suitably selected region has been highlighted. This characteristic has been exploited to implement the force sensor based on these optoelectronic components. As shown in Fig. 7, the LED and the PD has been mounted with an initial relative angular displacement $\theta = 15$, such that the no-load working point ($I(\beta_1)$ and $R(\beta_2)$ for the LED and the PD respectively) is located in the lower part of the response characteristic indicated by the blue stars Fig. 5(a) and 5(b). By rotating the axes of the optoelectronic components of an angle $\Delta \theta$, the relative response of the LED and of the PD changes by $\Delta I$ and $\Delta R$ respectively. This change can be detected by measuring the output voltage $V_{out}$ of the simple circuit shown in Fig. 6.
B. Compliant Frame Design

The compliant frame is a monolithic element suitably designed to obtain an angular displacement of the optical axes of the optoelectronic components linearly proportional to the tension force applied to the tendon. Compliant mechanisms are often used also for the implementation of linear actuators using smart materials [22], for the development of compliant transmission system [23] or as displacement/force magnifiers [24], [25]. With respect to previous solutions, a particular characteristic of the designed sensor is that it can be mounted in any position along the tendon and it don’t need to be designed as a structural element i.e. it can be design a part as a stand alone component of the robot. As can be seen in more detail in Fig. 7, this result has been achieved by means of a V-shaped canal that traverse longitudinally the compliant frame. The tendon pass through this canal: the surface friction ensure that a minimal very small tendon tension prevent the slip of the frame along the tendon, while the shape of the canal allows the frame to be inflected because of the reaction forces exerted by the tendon on the canal caused by the tension itself.

In Fig. 8 a simplified schematic view of the effects of the tendon tension $F_T$ on the compliant frame is reported: the shape of the canal allows to consider the tendon through three pivot points that slightly deviates the tendon path inside the compliant frame in such a way that a normal resultant force $F_d$ is applied at the center of the flexible beam used to resemble the compliant frame, while the canal entry and the exit points together with the tendon act as beam constraints. The force $F_d$ can be then simply determined form the tendon tension $F_T$ as

$$F_d = 2 F_T \sin \alpha$$

where the angle $\alpha$ depends also on the tendon diameter with respect to the canal ones. By keeping the canal diameter as close as possible to the tendon’s one, the angle $\alpha$ becomes similar to the canal slope, but this may generate problems during the insertion of the tendon into the canal.

The compliant frame can be then modeled as a flexible beam with concentrated load at its middle point and constrained at its ends. The behavior of such mechanical structure is a well known and deeply investigated topic: under the hypothesis of small deformations, the displacement of the beam middle point $\delta$ can be expressed as

$$\delta = \frac{F_d L^3}{48 EI}$$

while the angular displacement $\gamma$ of the beam ends is

$$\gamma = \frac{F_d L^2}{16 EI}$$

where

$$I = \frac{h^3 b}{12}$$

is the moment of inertia of the beam sectional area, $L$ is the beam length, $E$ is the Young’s modulus of the material, $h$ and $b$ are the height and the thickness of the beam respectively. The compliant frame has been designed as reported in Fig. 7 to obtain the desired moment of inertia maintaining the pass-through canal inside the frame structure and to ease the initial alignment of the LED-PD couple. Since the optoelectronic components are fixed at the ends of the compliant frame, the overall displacement $\Delta \theta$ of the LED-PD optical axes can be expressed as

$$\Delta \theta = 2 \gamma = \frac{F_d L^2}{8 EI}$$

This simplified but effective procedure allows to design the compliant frame starting from the maximum tendon tension and the corresponding desired optical axes displacement of the optoelectronic components. The unique design constraints are given by the tendon diameter, by the physical dimensions of the LED-PD couple and by the minimum distance between the two components (2 mm in our implementation). Assuming that the radiation/responsivity characteristics of the optoelectronic components is linear within the working region $\Delta \theta$, see Fig. 5, and that the small
deformation condition is satisfied within this region, it is possible to obtain a quasi-linear force/voltage characteristic of the sensor, as will be shown in Sec. III.

III. SENSOR IMPLEMENTATION, CALIBRATION AND TESTING

Figure 9(a) shows a prototype of the proposed sensor. In this implementation, the compliant frame is manufactured by means of rapid prototyping in ABS plastic: this material has been selected also because, differently from others plastic materials used for rapid prototyping like FullCure, it shows satisfactory elastic properties. The details about the design of the compliant frame are reported in Fig. 7 where also its sections are shown to highlight both the canal and the frame shape.

The sensor has been calibrated by means of a comparison between the tendon force measured by a strain gauge based load cell attached at one tendon end and the output voltage of the proposed sensor. From the sensor calibration curve reported in Fig. 9(b) it is possible to see the quasi-linear response of the sensor together with its high sensitivity that allows to avoid to use of any external amplification circuit. Anyway, Fig. 9(b) shows also how a polynomial interpolation of the sensor data allows a better evaluation of the tendon force, in particular a 3rd-order polynomial represents a good trade-off between simplicity and accuracy in the sensor data interpolation.

With the aim of verifying the effectiveness of the proposed sensor in a real application, a feedback controller for the regulation of the position of a robotic joint that exploit the force measurement coming from a couple of optoelectronic load cell such as the one described in this paper has been implemented. In Fig. 10(a) the experimental setup used for the robotic joint control in shown: the system is composed by two linear motors that drives the robotic joint by means of a couple of tendons connected to the joint itself in antagonistic configuration. The tendons have been equipped with an optoelectronic load cell each, while the strain gauge load cell mounted on the linear motors are used for data verification but not for the system control. The robotic joint is equipped with an angular position sensor also based on optoelectronic components and purposely designed for the integration into the UBH-IV [20]. Figure 10(b) reports a scheme of the robotic joint control system: each linear motor is driven by a low-level force control loop that makes use of the force information coming from the optoelectronic load cell while the joint controller gives to the motor the force setpoint for the regulation of the joint position. The response of a simple joint proportional position controller is reported in Fig. 11: it is possible to note that, besides the significant dry friction acting in the joint, the proposed sensor allows satisfactory performance in the control of the joint position.
This paper reports the development of an innovative force sensor based on optoelectronic components and compliant frames. The basic working principle has been presented together with a simplified design procedure for the definition of the compliant frame geometry.

A prototype of the proposed sensor has been realized and the calibration of the sensor has been performed. The force information has been reconstructed from the sensor output by means of a 3-rd order interpolation.

As a demonstration testbench, a simple force feedback control algorithm has been implemented using the information gathered by the proposed sensor. The experimental results show that the sensor is suitable for the replacement of traditional strain gauge-based load cell for the measurement of tendon forces. In addition, the very limited requirements in terms of conditioning electronics make this solution more feasible for the implementation of highly integrated devices like robotic hands.

**REFERENCES**


