## Contents

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### Research Articles

<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
</table>
<pre><code>                                                                   |                                                                                                                                                    |
</code></pre>
| Microelectromechanical System (MEMS) Switches for Radio Frequency     | Ashish Kumar Sharma, Navneet Gupta  
                                                                       | Applications - A Review                                                                                                                                                                                     |
| Measurement of Transient Surface Temperature of Conductive Solid Using | Zhiqiang Sun, Yu Chen, Xing Chen  
                                                                       | Thermocouples with Different Junctions                                                                                                                                                                        |
| Optical Force Sensor for the DEXMART Hand Twisted String Actuation    | Gianluca Palli and Salvatore Pirozzi  
                                                                       | System                                                                                                                                                                                                   |
| Ultrasonic Tomography Imaging for Liquid-Gas Flow Measurement         | Muhammad Jaysuman Puspanathan, Nor Muzakkir Nor Ayob, Fazlul Rahman Yunus, Khairul Hamimah Abas, Herlina Abdul Rahim, Leo Pei Ling, Ruzairi Abdul Rahim, Fatin Aliah Phang, Mohd Hafiz Fazalul Rahiman, Zulkarnay Zakaria  
                                                                       |                                                                                                                                                                                                        |
| Development of Ethernet Based Remote Monitoring and Controlling of MST  | Lakshmi Narayana Roshanna, Nagabhushan Raju Konduru, Rajendra Prasad Thommendru, Chandrasekhar Reddy Devanna, Chaitanya Pavan Kanchisamudram  
                                                                       | Radar Transmitters using ARM Cortex Microcontroller  
                                                                       |                                                                                                                                                                                                        |
| A Portable Spectrophotometer for Water Quality Analysis               | Xiaomin Zhang, Yanjun Fang, Youquan Zhao  
                                                                       |                                                                                                                                                                                                        |
| MATLAB Graphical User Interface based Fuzzy Logic Controllers for Liquid | Immanuel J., Parvathi C. S., L. Shrimanth Sudheer and P. Bhaskar  
                                                                       | Level Control System                                                                                                                                                                                         |
| Method and Device for Image Coding & Transferring Based               | Su Jun, Vasyl Yatskiv  
                                                                       | on Residue Number System                                                                                                                                                                                   |
| Estimation of Emissivity with the Help of an Infrared Camera           | B. Chakraborty and B. K. Sinha  
                                                                       |                                                                                                                                                                                                        |
| Simple and Robust Multipoint Data Acquisition Bus Built on Top of the  | Alexey Pavluchenko, Alexander Kukla, Sergey Lozovoy  
                                                                       | Standard RS 232 Interface                                                                                                                                                                                   |
| Optimizing Micro-scale Thermoelectric Model using Finite Element Method | Divya Jatain, Ajay Agarwal, Manoj Kumar  
                                                                       |                                                                                                                                                                                                        |
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Optical Force Sensor for the DEXMART Hand Twisted String Actuation System

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Abstract: In this paper, the force sensor developed for the twisted string actuation system of the DEXMART Hand is described. The proposed solution makes use of optoelectronic components for measuring the deformation of the properly designed motor module structure caused by the force applied to the tendon transmission system. The paper reports the working principle, the calibration and the characterization of the sensor in terms of sensitivity, repeatability, full-scale and Signal-to-Noise ratio. Copyright © 2013 IFSA.

Keywords: Force sensor, Optoelectronic sensor, Mechatronic design, Tendon transmission, Robotic hand.

1. Introduction

Tendon-based transmission systems represent the most promising solution toward the implementation of dexterous anthropomorphic robotic hands [1-4]. To solve some of the problems that characterize tendon-based transmissions, the so-called ‘twisted string actuation’ has been developed within the DEXMART Project [5]. In [6] and [7] the authors present the mechatronic details of this actuation systems together with its modeling and performance within a force feedback control loop. With respect to conventional solutions, the main advantages of this actuation system consist in the direct connection between the motor and the tendon without intermediate mechanisms (like gearboxes, pulleys or ball screws), in the direct transformation from rotative to linear motion, in the extremely reduced friction (only an axial bearing is needed), in the very high reduction ratio, in its intrinsic compliance and in the possibility of using very small high-speed motors, allowing to obtain a very compact and lightweight actuation module.

In the last years, the interest in lightweight and compliant robotic systems has significantly grown. This new class of robots has not been explicitly conceived 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 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 and or force control, hence force and torque sensors appear mandatory [8, 9].

Different solutions for the measurement of the forces transmitted by tendon-based actuation systems have been proposed in literature. In [10] a tension differential-type torque sensor is presented. It is based on the idea that the torque around a drive pulley is proportional to the tension difference, and as a consequence it can be directly measured without sensing tendon tensions. In [1] the authors present a force sensor based on the use of one strain gauge with a compact mechanical structure. A solution based on the Fiber Bragg Grating, directly bonded to the tendon, has been adopted in [11], with the aim to guarantee, for the proposed sensor, the immunity to electromagnetic disturbances, by exploiting the properties of optical fibers. In [12], the authors present, for the first time, a force sensor based on the use of discrete optoelectronic components, limited to the measurements of the tendon force at actuator side. The solution proposed takes advantage of mechanical properties of a compliant metallic frame specially designed and integrated into the actuator. In [13] and [14] a sensor for the tendon force measurement, that can be positioning at any point along the tendon, is presented. To control the twisted string actuation system with its intrinsic compliance, the measurement of the actuation force is fundamental as described in [7]. Solutions based on strain-gauges has been investigated, but, from the mechanical point of view, these solutions, with the corresponding conditioning electronics, were very cumbersome with respect to the twisted string actuation system, and the conditioning electronics were quite complex due to the low voltage levels typical of the strain-gauges, which need of filtering and amplifying stages. But the major drawback of the strain gauge based solutions was the high sensitivity to electromagnetic disturbances that make it unusable near the motors and in the industrial environments. For these reasons, a suitable force sensor for the actuation module of the DEXMART Hand has been developed, as reported in this paper.

The technology selected for the sensory system of the DEXMART Hand is principally based on the optoelectronics, in order to avoid any problem related to electromagnetic disturbances and to obtain very compact, lightweight and low power consumption sensor solutions. All other optoelectronic based sensors developed for the DEXMART Hand can be found in [12-16]. The proposed innovative force sensor exploits the angle-varying radiation pattern of common Light Emitting Diodes (LEDs) and responsivity pattern of Photo Detectors (PDs) in order to measure the deformation of the motor module structure caused by the tendon force. Optoelectronic components with a very narrow angle of view have been chosen (manufacturing codes SEP8736 for the LED and SDP8436 for the PD), both from Honeywell, with the aim of obtaining a large sensitivity for the sensor (please refer to the components datasheets for details on the radiation and responsivity patterns). The advantages of this type of implementation consist in the very high sensitivity and the simplicity of the conditioning electronics used in this work with respect to strain gauge based load cells, together with the high immunity to electromagnetic disturbances, low weight and low power consumption.

2. Sensor Description

Fig. 1 reports a detailed view of the motor module that drives the twisted string actuation system. This module, manufactured in ABS plastic by rapid prototyping, is characterized by an integrated force sensor composed by a LED and a PD, by a mounting rail for a rapid mechanical connection with the forearm structure that ease the assembly and the repairing of the system, by the integrated motor power electronics, by a flexible connection (realized by a silicon tube) between the motor shaft and the transmission shaft for solving problems of misalignment of their rotational axes and by an integrated combined bearing. This structure has been implemented in such a way that the transmission force is entirely supported by the output shaft, the combined bearing and the flexible beams (which are necessary for force measure as detailed in the following), while the motor is only used to transmit to the output shaft the necessary torque for driving the twisted string actuation.

The structure of the motor module is schematized in Fig. 2. This structure is composed by a couple of compliant beams, that support the motor, and produce a translation $\Delta x$ of the upper part of the structure under the effect of the transmission force $F$. The behavior of the beam with constraints at both its ends, highlighted by the red dashed rectangle in Fig. 2, is a well know topic in the field of compliant structures and as a consequence the relation between the force and the deformation is known in closed form. For the realized structure, within the linear
deformation domain, the relation between the transmission force $F$ and the displacement $\Delta x$ can be represented by the sum of the contribution of the two flexible beams as

$$\Delta x = \frac{F}{2} \left( \frac{L^3}{12EI_s} \right) = \frac{FL^3}{24EI_s}, \quad (1)$$

where $I_s$ is the moment of inertia of the beam sectional area, $L$ is the beam length and $E$ is the Young’s modulus of the material. The displacement $\Delta x$ causes a variation of both the view angle and the distance between the LED and the PD, allowing an indirect measurement of the force $F$ through the change in the PD photocurrent caused by the deformation of the structure.

Fig. 2. Force sensors based on optoelectronic components.

Fig. 3 reports a scheme of the interaction between the LED and the PD. The two optoelectronic components are mounted facing each other, with an alignment offset $x$ and a distance between the component bases equal to $L$. Subtracting from $L$ the component sizes, is obtained $L_0$. Recalling the theory on LED radiation patterns reported in [16], it is possible to model the system in order to select the positioning of the optoelectronic components. In particular, if the distance

$$d_0 = \sqrt{L_0^2 + x^2}, \quad (2)$$

between the component tips, is large enough to render the far-field approximation valid, the LED and the PD can be regarded as a point source and a point receiver, respectively. With this hypothesis, when the structure is in the rest position (no force applied), the photocurrent $P_0$, measured by the PD, is proportional to the product between the radiant intensity pattern of the LED, evaluated in $\beta_0$ (denoted as $I(\beta_0)$), and the responsivity pattern of the PD, evaluated in $\beta_0$ (denoted as $R(\beta_0)$), and inversely proportional to the square distance $d_0$, i.e.,

$$P_0 = K \frac{I(\beta_0)R(\beta_0)}{d_0^2}, \quad (4)$$

where $K$ is a dimensional multiplicative constant and the symmetrical positioning of the components has been exploited. Note that the dependence on the spherical coordinate $\varphi$ of the radiation and responsivity patterns is here omitted since the devices only move within a plane at constant $\varphi$. When a force $F$ is applied to the structure, the relative position of the optoelectronic components experiences a variation equal to the compliant frame deformation $\Delta x$ with respect to its initial value, according to (1). The variation $\Delta x$ of the alignment offset between the components produces the variations of the distance and the angle $\beta$. As a consequence, a different amount of light will be sensed by the PD and converted into a different photocurrent $P(\Delta x)$, that for a generic deformation $\Delta x$ (proportional to a generic force $F$) can be written as

$$P(\Delta x) = K \frac{I(\beta(\Delta x))R(\beta(\Delta x))}{(d(\Delta x))^2}, \quad (5)$$

This happens because both the radiation pattern of the LED, the responsivity pattern of the PD and the distance $d$ between the two components vary with the relative position. In particular, the LED emits different values of light intensity for different values of the angle $\beta$ and at the same time the PD detects the intensity of incident light with different weights depending on the angle $\beta$. The combination of these two effects leads to the observed variations of the photocurrent.

Fig. 3. Working principle of the proposed force sensor.

This model explains that the sensor characteristics, in terms of sensitivity, full-scale and SNR, depend on how the responsivity and radiation patterns of the optoelectronic components are sensitive with respect to $\beta$ variations. A proper design of compliant structure that supports the motor allows to achieve a quasi-linear response of the sensor, as reported in the next section.

2. Sensor Characterization

The conditioning electronics used to complete the sensor implementation is very simple and the scheme is reported in Fig. 4. There are only two resistors in
addition to the optoelectronic components, a first one used to drive the LED by fixing the forward current and a second one used to transduce the photocurrent measured by the PD into the sensor output voltage. Since the variations of the output voltage are characterized by a high Signal-to-Noise ratio, any additional filtering and/or amplification stages are not needed and the sensor, together its conditioning electronics, are completely integrable in the motor module. The characterization of the sensor has been carried out by using a strain-gauge load cell as reference sensor and by applying a continuous varying load up to the maximum desired value (80 N) to the motor module, reported in Fig. 1, by means of a commercial linear motor (manufacturing code LinMot-37×160). The resulting calibration curve is reported in Fig. 5, where the relationship 'Output Voltage' vs. 'Force' shows the high linearity obtained for the presented sensor. The maximum linearity error is below 1.5 % and the resulting calibration constant is 15 mV/N. Different experiments have been compared in order to test the measurement repeatability.

The figure demonstrates that the noise level is below the signal level for more than 50 dB, since the signal bandwidth is limited to a few Hz.

The results for three experiments are reported in Fig. 6, where the sensor shows a very high repeatability. Finally, Fig. 7 shows a typical voltage signal of the proposed sensor (top) and the Power Spectral Density (PSD) of the same signal (bottom).

6. Conclusions

The very compact force sensor integrated into the DEXMART Hand actuation system is described in this paper. The basic working principle and experimental results are reported, showing that the proposed solution based on optoelectronic components allows the adoption of a very simple conditioning electronics, obtaining a very compact and easy to integrate solution. The resulting sensor presents a full scale of 80N, a sensitivity of 15 mV/N, a maximum linearity error of 1.5 % and an high repeatability.

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References


Jacob Y. Wong, Roy L. Anderson

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