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Design of a glove-based optical fiber sensor for applications in biomechatronics

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Abstract— **The development of a glove-based sensor using flexible optical fiber microbending transducers for applications in biomechatronics is reported. The devices are attached onto the dorsal surface of monitored joint, resulting in the detection of variations of ~4° in angular displacements. In addition, the sensor system was evaluated for the real-time detection of hand movements, as well as for the assessment of grasping patterns during the manipulation of cylindrical objects. The preliminary experiments indicated that sensor could be suitable for practical applications in robot-assisted rehabilitation and diagnosis of impaired subjects.**

I. INTRODUCTION

The development of instruments for the assessment of human hand movements plays an important role on biomechatronics and medical robot applications, providing methods to monitor the user motions during the accomplishment of different tasks, as well as to proportionate the dexterous teleoperation of medical robotic manipulators. Examples include robot-assisted surgeries [1], medical procedure simulators [2], hand rehabilitation systems [3], and health-monitoring devices [4].

Nowadays, a variety of technologies has been developed for acquiring the hand movements, including optical tracking based on external cameras [5], acoustic and magnetic tracking [6], exoskeletons [7], electromyography [8], and glove-based sensors [9]. In comparison to the other approaches, the wearable device exhibits several advantages since it is not affected by fingers occlusion or latency, and is also compact and can present real-time response [9].

Although the measurement of finger joints angles in glove-based sensors can be carried out by different types of transducers, such as resistive flexsensors [10], printable conductive mixtures [11], carbon nanotubes [12] or graphene [13] strain gauges, and magnetic induction coils [14], the utilization of optical fiber sensors provides attractive characteristics for its implementation in datagloves, including lightweight and small size, multiplexing capability, and immunity to electromagnetic interference [15]. In this sense, examples of glove-based optical fiber sensors have been successfully reported, considering both commercial and experimental approaches. Examples of commercial devices include the Data Glove (MIT, VPL) and the 5DT Glove (Fifth Dimension Technologies), both based on proprietary fiber transducers [9]. Even though such technologies exhibit good response and reliability, they present a relative high cost, which can be a limiting factor for some applications. As to the experimental approaches, different types fiber optic datagloves have been proposed, for example, based on the measurement of fingers joints flexion by fiber Bragg gratings [16] and hetero-core fiber sections [17]. The authors also have been working on the development of fiber transducers for glove-based systems, based on flexible microbending transducers using sliding structures [18], or by fixating the fiber directly to the glove surface by applying adhesive gel on equally spaced points [19].

In this context, the present research reports the development of a low-cost glove-based optical fiber sensor for measuring the finger movements. In contrast to the current fiber-based technologies, the proposed sensor does not demand neither the utilization of structured waveguides or fiber gratings, nor complicated interrogation schemes. The developed transducer also presents notable improvements in comparison to the previous versions [18,19], since it provides higher sensitivity and does not include moving parts. In addition to the characterization of transducers, application examples regarding the monitoring of hand posture and analysis of grasping patterns are also presented, aiming its utilization in rehabilitation and biomechatronics contexts.

II. GLOVE-BASED SENSOR

A. Sensor Design

The instrumented glove is based on flexible optical fiber transducers (Fig. 1) which are directly mounted over the glove surface. The garment is made of stretchable fabric and its dimensions were adjusted in order to properly fit to the user hand. The transducers comprise of a multimode fiber placed between 2 layers of silicone rods (30 mm × 5 mm × 3 mm) arranged in periodical fashion, being the waveguide placed between these structures. Each device is attached over the dorsal side of monitored joint by using an adhesive gel, causing a ~20 mm fiber length to be pressed by the bending rods as the respective degree-of-freedom (DOF) is flexed. The small-radius mechanical disturbances along the waveguide induce optical losses due to microbending effect, causing energy coupling between guided and radiation modes [20], and consequently, the light attenuation can be correlated to the joint angular displacement.

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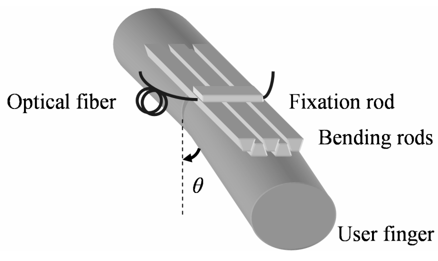

Figure 1. Schematic of optical fiber transducer.

The transducers were positioned to detect the flexion/extension movements of proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joints of the index, ring, middle, and little fingers, as well as the thumb interphalangeal (IP) and metacarpophalangeal (MP) joints, which represents the measurement of 10 DOF. Even though the human hand is usually modeled as a ~21 DOF system comprised by joints and links [9], it is worth to observe that some simplifications can be adopted due to the natural constraints on finger movements [21], which is useful for reducing the amount of necessary transducers and the complexity of system analysis.

B. Experimental Setup

The experimental apparatus is shown in Fig. 2. A continuous white LED source is used to launch light into the sensing fibers (~2.5 m of standard plane-polished silica multimode fiber with polymer coating), which are connected to the respective transducers, being each fiber designated to a single DOF. The modulated optical signals are then acquired by a CCD camera (15 Hz) and subsequently processed in a routine developed under MATLAB (MathWorks) environment for the evaluation of light intensities. Additionally, a reference fiber is used for direct measurement of source intensity in order to compensate eventual power fluctuations. The normalized intensities are evaluated by dividing the optical signals from sensing fibers by the reference one.

C. Characterization

For the evaluation of sensor response, the glove was firstly worn by a single subject, who tightly adjusted the garment to his hand for avoiding most of fabric wrinkles and sliding over the skin surface, which could reduce the sensitivity of microbending device. The experiment was then carried out by requesting the user to flex his fingers according to calibration objects manufactured with predetermined angles (10° to 110°). The results for index PIP and MCP joints and for the thumb IP and MP joints are illustrated in Fig. 3, by considering the mean of 400 points for each angular displacement. Due to the anatomical similarities regarding the fingers movements, the index finger analysis can be extended to the middle, ring, and little fingers, and consequently the related transducers also present equivalent results. In general, the bending devices exhibited a better response for $\Delta\theta \geq 20°$, making possible to detect variations of ~4° on joints positions. The reduction of sensor performance for angles < 20° can be explained by the stretching of glove material during the beginning of flexion event, causing the compensation of the mechanical stresses applied over the optical fiber. As the angular displacement increases, the effect of the bending rods tends to be more significant than the fabric contribution, and consequently the transducer sensitivity to the finger flexion/extension increases. On the other hand, the utilization of less flexible glove material could result in the application of excessive load and restriction of hand movements, which are not desirable for most of the practical applications. Regarding the measurement of thumb MP, the sensor reduced performance was probably caused by the influence of the trapeziometacarpal joint, since part of its movements are connected to the MP displacements because of the hand anatomical constraints.

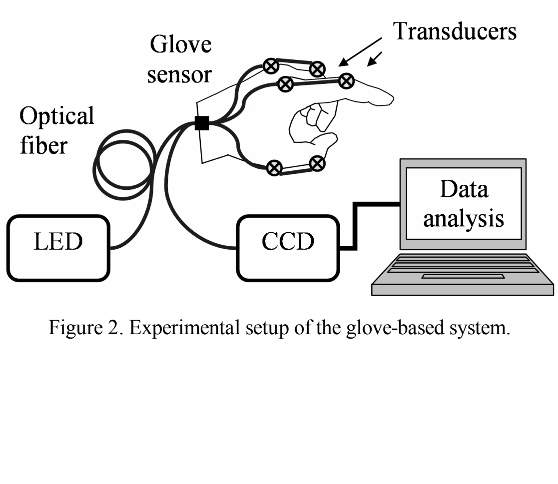

Figure 2. Experimental setup of the glove-based system.

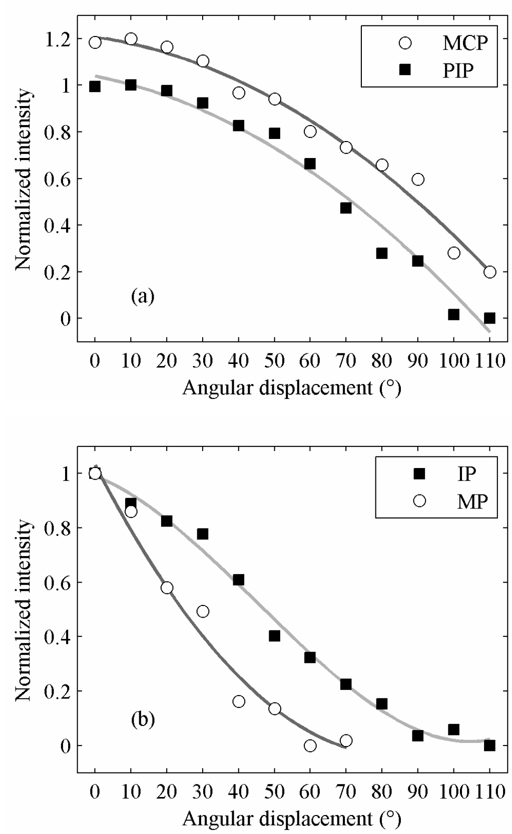

Figure 3. Transducers response on the measurement of angular displacements for (a) index finger MCP and PIP joints and (b) thumb MP and IP joints.

D. Repeatability Analysis

The sensor repeatability was evaluated based on the experiment proposed by [22]. After performing the glove calibration, the subject was requested to place his hand over a flat tabletop with the joints extended and the forearm in pronated configuration. Then, the user grasps a mold for ~5 s, causing his hand joints to be flexed according to constant angular displacements. Subsequently, the object is released and the user hand returns to the initial extended condition. Such procedure was repeated 10 times, and the range (difference of maximum and minimum flexion angles) and standard deviation were calculated considering 4 trials with 10 grasping-releasing events.

The repeatability parameters for the index PIP and MCP joints as well as the thumb IP and MP joints are summarized in Table X, resulting in an average range and standard deviation of 8.06° and 3.45°, respectively. These values are compatible the available literature for other glove-based sensors [22-24]. The eventual differences on repeatability results for each trial can be explained by changes on the glove adjustment to the user hand, which could affect the transducers response, and by variations on grasping posture and applied forces, since it was relatively difficult to maintain exactly the same manipulation pattern during the whole experiment.

III. Applications

A. Measurement of Hand Movements

The measurement of hand movements can be utilized in several activities related to rehabilitation, such as robot-assisted therapy for treatment of partial body paralysis caused by cerebrovascular accident. In this case, the movements of the patient healthy side are acquired by the data glove and then replicated to the impaired hand by means of the robotic device [3]. Another case regards to the treatment of rheumatoid arthritis, in which the instrumented glove can be applied on the assessment of joints angles for a quick diagnosis [25]. In addition, such device could be also useful in therapy for repetitive strain injuries of the upper limb, for example on the real-time monitoring of movements during the performing of stretching exercises [26].

Firstly, a previous system calibration was carried out, in which the user was requested to grasp calibration objects during ~5 s in order to flex the finger joints according to predetermined angles. Subsequently, the measured light intensities were correlated to the angular displacements for the determination of the calibration curves for each joint. Finally, the data were loaded in a software programmed using MATLAB, which was responsible to evaluate the angular positions given the measured optical signals, and then display the respective movements in a simplified virtual anthropomorphic manipulator.

The normalized intensity signals for each monitored joint are shown in Fig. 4, whereas the evaluated hand postures for some situations are displayed in Fig. 5. The finger movements can be retrieved in real-time according to the user input, making the technology feasible for monitoring and rehabilitation purposes. However, it is important to observe that the complete representation of hand posture should consider the detection of the abduction/adduction of metacarpal joints, as well as the DOF of wrist and forearm, which demands additional transducers.

Moreover, some fiber transducers also presented a considerable noise during the experiments (for example, the devices designated to detect the displacements of MCP joints of index and ring fingers), resulting in slight variations on the calculated joint angles. This effect was probably generated due to the formation of wrinkles on the back of fabric glove, caused by the repetitive clinch and open hand movements. Such problem could be ameliorated by reallocating the transducers to positions that are less affected by the garment deformations.

B. Grasping Monitoring

The study of grasping is also essential for applications in teleoperation and design of bio-inspired devices. The human hands are used to carry out both exploratory and manipulatory functions. When a subject manipulates an object, it is possible to retrieve information about its physical characteristics [27], and the way of how the object is handled depends on its geometry, weight and texture, for example. Grasping is defined as a sequence of movements that can be divided in planning, reaching and gripping

TABLE I. Repeatability analysis. Range and stantard deviation (S.D.) values in degrees.

Trial	**PIP**		**MCP**		**IP**		**MP**	
	Range	***S.D.***	***Range***	***S.D.***	***Range***	***S.D.***	***Range***	***S.D.***
1	4.49	1.62	6.03	1.86	3.73	1.23	6.93	2.35
2	0.37	0.12	7.91	2.76	1.99	0.78	9.97	3.21
3	5.11	1.71	4.13	1.63	7.72	3.00	10.98	3.80
4	4.43	1.47	13.45	5.47	8.71	3.01	13.02	4.84
Mean	3.60	1.23	7.88	2.93	5.54	2.00	10.22	3.55
Trials 1-4	4.08	1.75	10.73	4.95	10.89	4.63	6.53	2.85

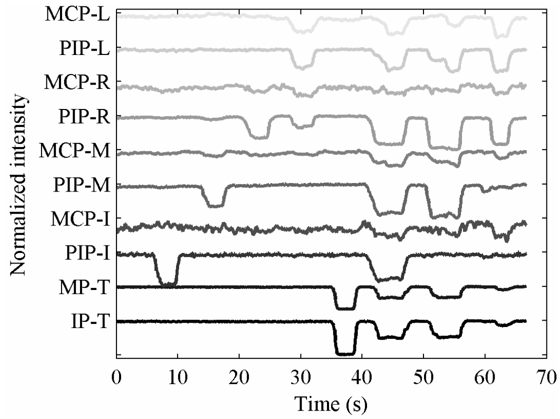

Figure 4. Measurement of light intensities during the monitoring of hand movements: MCP and PIP joints of index (I), medium (M), ring (R), and little (L) fingers, and MP and IP joints of the thumb (T).

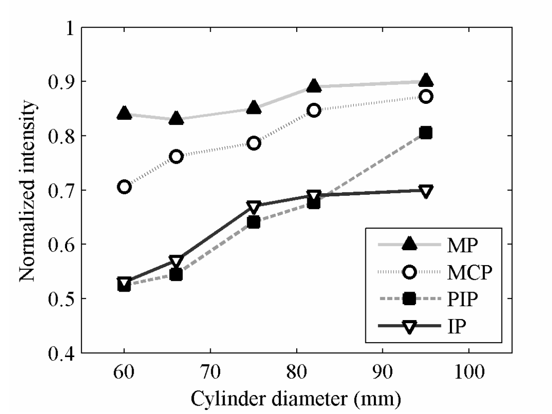

Figure 6. Effect of object diameter on grasping experiment. The intensity values for MCP and PIP correspond to the mean of index, middle, ring and little joints, whereas MP and IP are related to thumb joints.

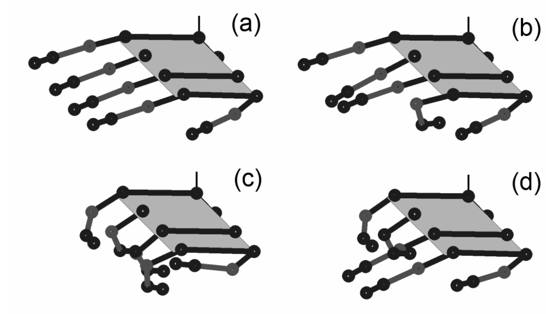

Figure 5. Representation of hand posture by the virtual manipulator at (a) 0.7 s, (b) 8 s, (c) 45 s, and (d) 64 s.

events. The analysis of this action can be performed in terms of the arm and hand movements, as well as the magnitudes and distribution of applied forces [28]. During the manipulation, the grip forces must be induced normal to the object surface in order to compensate the tangential slips introduced by load forces. Therefore, the human brain must adjust the grip by means of sensorimotor control for the sake of prevent application of excessive or insufficient forces, which could result in object damages or drop, respectively [27]. In addition, the form of a grip also varies according to the task, which could be classified into power – which aims stability – and precision grips – that focuses on dexterity [29].

In order to evaluate the sensor response during grasping events, a healthy subject was requested to manipulate cylindrical objects with different diameters and approximately the same weight (~0.56 kg). Initially, the user hand is kept open with all joints in fully extended position. After receiving a command, the subject grasps the object by performing a cylindrical grip (power-type grip in which the object is wrapped by all fingers) for 10 s, without lifting the tested sample. Finally, the object is released, the user hand is returned to the initial condition, and the procedure is repeated for the next cylinder. The measured intensity signals are shown in Fig. 6, considering the average value for the flexion of PIP and MCP joints of index, middle, ring, and little fingers, as well as the intensity values for thumb IP and MP joints. As corroborated by previous studies [30], the angular displacements increase with the reduction of cylinder diameter, since in these cases a more acute clinch is necessary to involve the object completely.

Subsequently, the experiment was repeated concerning cylinders with the same diameter (95 mm) but different masses. In this sense, after grasping the object, the subject was requested to lift the cylinder ~50 mm by maintaining this condition for 10 s. Afterwards, the object is lowered and released, and the user hand returns to the initial condition. The calculated mean of intensity values concerning all tests are presented in Fig. 7. The angular displacements of PIP and MCP joints did not varied significantly with the increase of object weight, indicating that the posture of index, middle, ring, and little fingers is more significantly affected by shape characteristics. On the other hand, the analysis of thumb IP joint yielded to an increase on light attenuation for heavier objects, even though the diameter was the same for all trials. This result can be explained considering that higher grip forces must be applied to compensate the slips on object surface. In this context, during the grasping the subject tends to hold the cylinder by supporting it with the index to little fingers, whereas the thumb presses the object to apply grip forces. Such observation is valid once the tested objects presented relatively large dimensions when compared to the user hand, characterizing the manipulation as a case of a "large diameter wrap" [29]. In this case, the changes on thumb posture are caused mostly to generate grip forces in order to maintain the object lifted. Moreover, it is worth noticing that the study was conducted only concerning rigid objects, avoiding eventual effects of shape deformation.

IV. CONCLUSION

The optical fiber transducer was successfully implemented on the measurement of hand movements. In addition to the real-time monitoring of hand posture, which

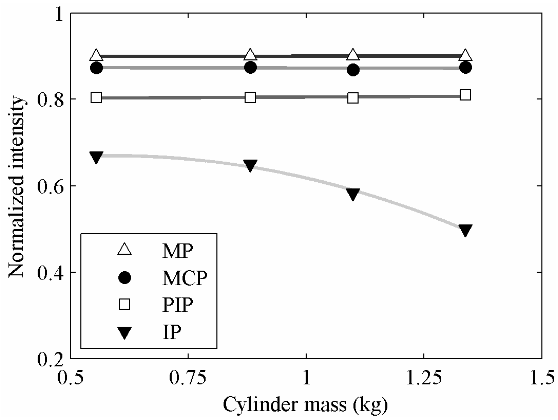

Figure 7. Effect of object mass on grasping experiment. The intensity values for MCP and PIP joints correspond to the mean of index, middle, ring and little joints, whereas the values for MP and IP are related to the thumb.

is suitable to robot-assisted rehabilitation tasks, the developed glove-based device was also experimented on the preliminary assessment of grasping events, considering the manipulation of cylindrical objects. Such study could be conducted in terms of diagnosis, on the comparison of grasping patterns developed by healthy and impaired subjects, for example.

Further developments will focus on the improvement of the glove-sensor sensibility as well as on practical applications in hand rehabilitation-oriented studies.

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