FBG Sensing Glove for Monitoring Hand Posture

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***Abstract*—A wearable sensing glove for monitoring hand gestures and posture has been developed. The glove sensing capability is based on optical fiber Bragg gratings (FBGs) sensors. These sensors, due to their inherent self-referencing and multiplexing capability, are a value-added choice for this application. A single optical fiber would cross all the hand with Bragg structures in specific spots, as the finger joints. The functionality and performance of the glove was fully evaluated. The sensor response was linear to the hand movements for opening and closing down. Through the sensor response, it was possible to retrieve information about the joint angles from which other set of information like finger force can be estimated. The developed glove was able to provide numerical data about the angles of the hand posture in real time. The simplicity of the system and performance makes it well suitable for physical therapy applications, study of the human kinematics during sport activity, virtual reality or even remote control applications, among others.**

***Index Terms*—Optical fiber sensors, fiber Bragg gratings (FBGs), hand motion monitoring.**

I. Introduction

STROKE is one of the leading causes of long-term disability in adults, with an estimated cost of 73.7 billion dollars for 2010 [1]. A part of this amount is only for rehabilitation programs, which are important for minimizing muscle spasticity or pain and recovering from impair. Hand movement is one of the main disabilities that many times put the subjects in a position where they are not able to perform action on their own. The hand performs two main types of movements: flexion-extension and abduction-adduction. During therapeutic sessions, the patients are stimulated to exercise the hand by performing finger passive range of motion, fist making, object pickup, finger extension, and grip strengthening movements. These exercises fall over the category of flexion-extension movements. It is clear that the majority of movements that one performs daily are based on this group, without neglecting the abduction-adduction. However, the amplitude of the former movements is much lower than the first ones.

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The evaluation of the hand movements requires a set of exams to measure the grip and pinch strength, sensitivity to temperature and vibrations, joint range of motion, and functional abilities [2]. Such exams are an important source of information for diagnosis and rehabilitation planning. Also, during therapy, the exams allow the asses of the health state and treatment progress.

The traditional methods for hand kinematic evaluation are based on measurements of the finger joints range of movements. In general, the measurement uses mechanical goniometers, which are placed on each finger joint to measure flexion and extension angles. Therefore, this method may be affected by human errors due parallax errors or, by other side, may be used inappropriately by using the wrong size device. In addition, the simultaneous motion range measurement of all the joints in the hand is a complex task. Consequently, the therapy is time-demanding, for both therapist and the patient [2].

In addition, the traditional exam is more suited for static measurements than dynamic ones. However, the latter one is the most common kind, concerning the hand movement.

Another methodology is based in the therapist own evaluation. Basically, he opposes the patients' motion and, feels and grades the motion resistance in a 1 to 5 scale, for example, which is a very subjective exam.

Independently the performed test, the full assessment of the subject's effective capacity to perform a functional task is not correctly determined, leading to possible miss diagnoses.

Sensor-based garments are very common nowadays due to the interest in wearable devices, which can be used for monitoring human posture and gesture. The systems have evolved dramatically and the more recent advances in this area can be worn for long time with nondiscomfort [3].

The ability to monitor the human body kinematics, posture, and gesture is one of the focus areas in bioengineering.

A set of sensors integrated in a glove can provide data related to the hand posture, from which directly, or indirectly, depending on the sensor system architecture, other measurand can be also retrieved as pinch strength, motion range, among others [2].

Several glove-based input systems have been developed so far. The main differences between them are the sensing approaches that have been chosen, from electrically conductive elastomer [3]–[6], accelerometers [7], induction coils, [8] to hetero-core fiber optic sensor [9]. However, they present a few concerns. The magnetic induction approach requires the use of the time-division method to scan the generator coils to compensate for the magnetic interference. The electroconductive solution could be integrated directly over the glove's garment, however, its nonlinear response and long relaxation time for steady state are the main issues. The hetero-core fiber approach had a very simple principle. However, a few fragility issues due to

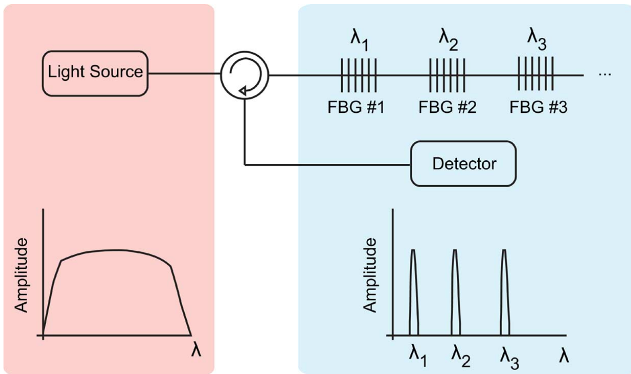

Fig. 1. Basic FBG's multiplex working principle.

the existing splice between the different fiber diameter portions may be a concern for long-term use. Although this last approach presents some fragility worries, optical fiber sensors are one of the sensor technologies with most potential, when seeking performance and long-term stability [10]. They have proved their performance in a set of applications such as the aeronautics [11] or civil [12], but also in physiological measurements [13]–[15].

The proposition explored in this paper is to achieve a sensing glove simpler than the previous competitors without neglecting its performance, via optical fiber sensors. The simplicity that is sought is referred to the sensor system design. The goal was to achieve a glove that can ensure minimum issues when wearing continuously.

II. System Design

The purpose of a sensing glove is the ability to measure the angles between the finger phalanxes. The most common strategy is to measure the elongation of the upper side of the finger joints when stretching out or in the finger. A strain gauge sensor can be applied to each phalanx joint in order to measure the skin stretch as one opens or closes the hand, and consequently translate the strain to the interphalanx angle. The sensor choice and its positioning layout in the glove are essential factors for achieving simplicity and functionality.

A. Sensor

There are several optical fiber sensors configuration and sensor types, from interferometers to scattering/reflection ones, among others [10]. In the wide variety of optical fiber sensors, there is one that has been receiving a lot attention in the last decade, the Fiber Bragg Grating (FBG) sensor.

FBGs are optical fiber-based sensors sensitive intrinsically to strain and temperature. They present the entire set of advantages related to optical fiber sensors. FBGs are a type of sensor useful in a variety of applications and, in particular, in the field of embedded sensing structures, which makes it the right choice for the sensing glove. The working principle of a FBG-based sensor system relies in the reflected Bragg signal, which changes its spectral component as a function of the measurand. The FBGs have an inherent self-referencing capability and can be easily multiplexed in a serial distribution along a single fiber (Fig. 1) [16].

The number of sensors that can be placed in the same fiber depends on the dynamic range that is required. As the number of sensor increases, the spectral range available decreases, as each FBG signature occupies a small bandwidth.

The Bragg wavelength condition is given by the expression

$$\lambda_B = 2 \cdot n_{\text{eff}} \cdot \Lambda_B \tag{1}$$

where Λ_{B} is the grating pitch and n_{eff} is the effective refraction index of the fiber core. By injecting light from a spectrally broadband source into the fiber, a narrow spectral component is reflected back as it reaches the fiber grating, while the remaining components are transmitted. The spectral reflection is defined by the grating period, which is sensitive to strain and temperature. The strain response results from both the physical elongation of the sensor (and corresponding fractional change in grating pitch), and the change in fiber index due to photoelastic effects, whereas the thermal response arises due to the inherent thermal expansion of the fiber material and the temperature dependence of the refractive index [17].

Equation (1) implies that the wavelength component of the reflected signal λ_B varies according to any variation in the physical or mechanical properties of the grating region. As strain is applied, it changes Λ_B and n_{eff}, by the stress-optic effect. Likewise, temperature changes lead to variation in n_{eff} by the thermo-optic effect [18]. In an unconstrained fiber, Λ_B is influenced by thermal expansion or contraction. Equation (2) correlates the FBG behavior. The first equation term provides the strain effect on λ_B while the second describes the temperature effect.

$$\Delta\lambda_B = \lambda(1 - \rho_\alpha)\Delta\varepsilon + \lambda_B(\alpha + \xi)\Delta T \tag{2}$$

where $\Delta\lambda_B$ is the change in Bragg wavelength, $\rho\alpha$, α and ξ are, respectively, the photoelastic, thermal expansion, and thermo-optic coefficients of the fiber, $\Delta\varepsilon$ is the change of strain and ΔT is the temperature change [18]. For a typical grating written in a silica fiber and with $\lambda_B \approx 1550$ nm embedded in a polymeric foil, the sensitivity to strain and temperature is approximately 8 nm per 1% of elongation and 0.1 nm/°C, respectively [19].

B. Layout

The sensor disposition in the glove is a crucial step. In order to measure the flexion and extension movements of the finger, a sensor should be placed over each phalanx joint [20].

If a FBG is placed in each joint, starting from the flat hand position, the sensor modifies its Bragg pitch in correspondence of a flexion or extension of the finger or thumb.

A single hand has 14 joints in which a sensor should be positioned. As the FBG has self-referencing and multiplexing capability, it is only required a single fiber (Fig. 2). Besides, the FBG's sensitivity enables the required spatial resolution to monitor the finger's range of movements.

The finger joints, while performing flexion and elongation, stretch around 14%, which is higher than what a silica-based fiber is able to withstand. Thus, it was necessary to overcome this issue without leaving the glove loose. There are at least three feasible approaches. One is to place the sensor not on the top of the joint but in the side face of the joint. There is still

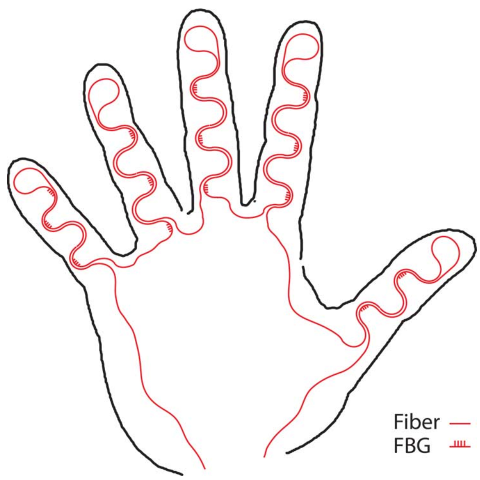

Fig. 2. FBG sensor positioning proposal.

Fig. 3. Upper side of the final sensing prototype.

Fig. 4. Bottom side of the final sensing glove.

elongation, but the sensor is placed closer to the midline, where the elongation is null. So, as the fiber is placed in that range, the measured elongation value will be between the minimum $(=0)$ and the maximum $(\sim 14\%)$ elongation. However, this solution has a drawback, as the wrinkles in the surface of the glove can influence the measurement. Another approach is to coil the fiber around the finger. This would create a spring effect as the finger performs flexion and extension. However, this approach would put the optical fiber under the stress of wrinkles as the fingers close, which would lead to fiber breakage. Consequently, a different method was considered that would enable a wide elongation range and still be compatible with the manufacturing process. So, instead of using it in a straight optical fiber layout, the fiber was placed in a curvilinear layout. This layout simulates the coil's approach, but with the fiber in a two-dimensional structure. Such disposition enables a longer elongation range. A set of tests have been performed to test this configuration [19].

In order to manufacture a sensing glove based in optical fiber sensors, it is necessary to overcome fiber integration challenge. For this case, it was proposed a full integration of the fiber in a flexible structure with the shape of a glove that would work as one of the gloves' faces. This approach ensured the positioning of the sensors in the right place as well as fiber protection. With the full wrap of the sensors, it was guaranteed enough protection enabling reliability during its use, decreasing the risk of wearing out.

One major concern was the possible wrinkles that would appear due to the elasticity of the hand. In order to minimize them, it was chosen to place the sensors in the upper face of the glove. In this face, the sensors are positively stretched, instead of the bottom side where, when closing the hand, the stretch is negative, creating the nondesired wrinkles.

C. Glove Fabrication

A flexible polymeric foil specially designed for embedding optical fiber sensors as FBGs has been previously developed [21], [22]. The main characteristics for this foil are the flexibility, the stretchability and the capability to sustain a good bonding between the optical fiber and the substrate.

The manufactured structure is arranged in a three layer structure with a final thickness of 900 μm, in which the fiber (250 μm of diameter) is embedded in the middle one. The host material is PVC with a custom formulation to assure the bonding and the stimulus transfer. The strain transfer through the PVC matrix has been analyzed in previous publications [19].

As the structure is fully customizable, a prototype with a shape of a hand was manufactured. The shape was retrieved from a standard textile glove. A letter sized foil was the base foil shape in which a hand shape was drawn and the fibers were positioned. The foil was then cut in the shape of the glove and sewed to the top face of a standard fabric glove. The final glove prototype can be seen in Figs. 3 and 4.

A detail that was considered relevant was the fact that the hand performs flexion-extension and abduction-adduction movements. It was defined initially that the object of study was the flexion-extension movement and, consequently, it was crucial to minimize the effect of the other movement. This was achieved by the fabrication layout. Although the PVC layer had flexibility, in the defined arrangement with it sewed to the glove's upper face, it constrained this specific

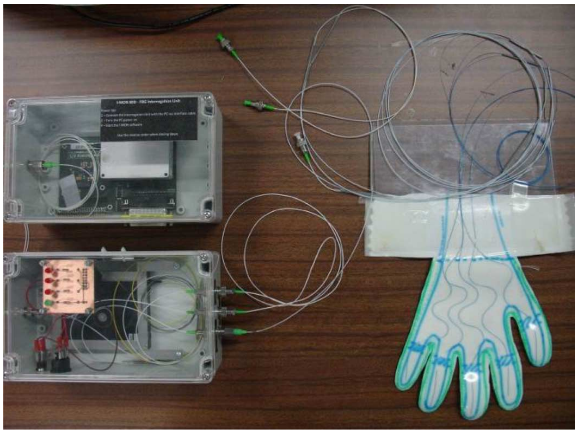

Fig. 5. Glove's optical setup.

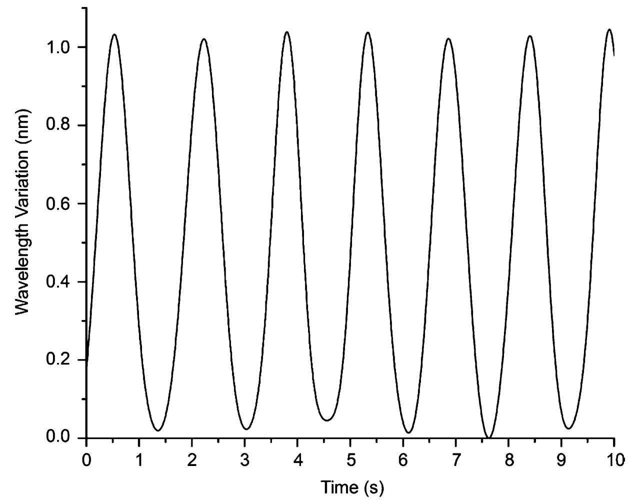

Fig. 6. Ring finger FBG sensor response for opening and closing hand movements.

movement. Nonetheless, if necessary, the PVC layer can enable the abduction-adduction movement, by cutting the PVC at the carpo-metacarpal joint, leaving intact the fiber connection. In this situation, the glove becomes composed by six independent PVC layers (five digits plus the hands back) all connected by a single optical fiber.

Although the fabricated glove is a prototype, it can be customized as a conventional glove, since it can be easily sewed to different materials, including the ones already allowed in healthcare environment, and even the PVC itself can have different finishing styles (from color to patterns).

The optical fiber used in the experiments contains gratings that were written by *FiberSensing* in hydrogen loaded standard telecommunication fiber (SMF28) by way of a phase mask technique [23] with a pulsed Excimer LASER. The length of the gratings was 8 mm, and the resonance wavelength in the optical range communication C-band (around 1550 nm), which corresponds to a refraction index modulation period of the core in the half-micrometer range.

III. Results and Discussion

In order to know how the fabric sensor responds to external mechanical stimuli, a set of tests were performed. The first set of tests was performed to evaluate the pitch variation of the FBG, according to the flexion finger movements. This allows the determination of the required dynamic range for placing all the sensors in a unique fiber.

As the hand performs the abduction and adduction movement, it was necessary to evaluate if it was constrained or not by the built glove. With the hand fully extended over a flat surface, the subject wearing the glove was not able to execute the concerning movements, as they were successfully restrained by the PVC layer.

A. Measurement Setup

The setup used for monitoring the glove was composed by an ASE broadband light source from *Luxpert* in the C-band range (1530 to 1565 nm), an optical circulator from Oplink Communications, Inc., and a FBG interrogator *I-MON 80D* from *Ibsen Photonics* (Fig. 5).

A wide optical spectrum is injected into the glove's optical fibers. As the light reaches the FBG, a spectral component of the injected light is reflected back, entering into an optical circulator that drives the reflected component into the FBG interrogator unit. A computer connected to the interrogator unit performs a full monitoring of the FBG response and enables the virtualization of the hand.

B. Sensor Characterization

In the first test, the FBG responses of Proximal Interphalangeal joints were monitored. Fig. 6 shows the raw signal obtained from the glove, regarding the ring finger movement of flexion and extension. From this raw data, it is possible to retrieve information about the range of motion, strength and how fast the closing and opening movements are performed.

As the subject closes the hand, the upper skin of the hand is stretched, especially at the interphalanx sites. As the glove's sensing elements are placed over the interpahlanxes, the stretch is sensed by the FBG, leading to a positive wavelength deviation.

The opening and closing action of the hand in a continuous manner is translated by the sensor as a positive and negative shift of the pitch wavelength. As the movements are repeated, the signal shape becomes a sinusoid. The minimum and maximum represent the limits of fully open and close hand, respectively.

The strength can be estimated from previous studies [19] from which the 1 nm deviation results from an applied load of 7.8 N.

Fig. 6 is based on a temporal scale and consequently, the speed at which the subject closes and opened the hand is directly retrieved. For this specific case, the subject performed the hand movements at a speed of 103°/s. This value can take different units, more interesting for the therapist, as 0.6 closing and opening movements per second.

A crucial characteristic is the accuracy of the system. In order to evaluate this factor, the measured angle values were compared with reference values obtained from a calibrated device. The reference device was sliding T bevel type of device, used for setting and transferring angles. Fig. 7 compares the real angle from

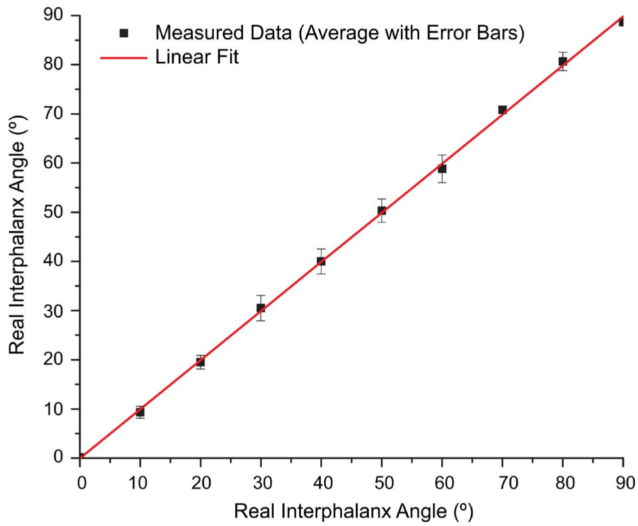

Fig. 7. System accuracy based on the comparison between real and measured angles.

Fig. 8. Example of the real-time monitor of the hand posture.

a reference device with the measured values from the glove's sensors. The determined linear fit was characterized, based on the average of the recorded data, with an adjusted R-square of 0.99929 and a slope of 0.99869. This is representative of the accuracy of the proposed system. The maximum error obtained from all the performed measurements was 2° in a range between 0°–90°.

One main advantage of this system is the measurements made on the wavelength instead of optical power. This enables a system that is not sensitive to external factors as fluctuations of the optical source. Plus, the long-term stability of this system is another of the main advantages of this system as the polymer foil adds resistance to the sensing elements without neglecting the sensing performance. The stability is also extended to the bond between the polymer matrix and the optical fiber in which it is wrapped.

From the wavelength variation, the FBG pitch shifts a 1 nm. As stated before, 14 FBG sensors are required in each hand. As the C-band ranges between 1530–1560 nm and the FBG spectral signature width is about 0.3 nm, one single fiber is able to accommodate all the required sensors. They should be inscribed in steps of 1.84 nm, ensuring this way enough dynamic range for hand motion sensing.

C. Virtual Hand Movement

In the second set of tests, a hand motion capture system based in a 3-D virtual model of the hand was built. This virtual reality system may be of great help in therapy sessions, especially, by stimulating the patient to exercise, as the standard therapy session are time-demanding and tedious for most patients. A virtual reality environment not only allows the visualization of the hand but it also enables game-like exercises, for example, providing personalized paced exercises to promote finger strength while keeping motivation.

In the developed environment (Fig. 8), it is possible to see the hand movement in real-time on a computer which can also provide information about the hand posture in terms of angles, strength, and movement range. The model has been built to monitor the flexion and extension movements (the close and opening of the hand). The 3-D monitorization system of the glove was developed in a LabView environment, enabling the full control of the system. The virtual hand software allows the span and rotation of the hand in the computer screen, while it follows the real hand movements. Furthermore, it executes the calculations and presents data about current angle at each joint, range of motion, speed at which one executes movements and the strength. Additionally, the sensors' response graphs are accessible, if desired.

The first time a subject wears the glove, it requires a calibration step in order to define the baseline position. This step is based on the measurement of the sensor response for two distinct hand positions, e.g., one close and one open. From these two points, it is establish the sensor response for the glove movement. Its accuracy is accomplished by choosing two measurements with very distinct hand postures.

The movements of the hand did not felt constrained by the PVC layer with the optical fibers. This results from the custom PVC formulation that provides not only a very flexible structure but also a very stretchable one. The glove was easily worn and felt comfortable without restraining the hand movements. The monitoring hardware enables the hand's movements monitoring at frequencies from 32 Hz up to 2 kHz. The range of movements and angles are not restrained by the software. This ensures that the movements of the hand are directly translated from the optical sensor response. The computer characteristics, where this virtual reality program was developed, were an Intel Pentium IV processor with 512 MB of RAM.

The glove was successfully developed taking into account the need for a straight forward and simple system architecture without neglecting the results accuracy, making it well suited for practical use.

IV. Conclusion

In the present work, a sensorized glove by optical fiber Bragg grating sensors has been introduced. In this paper, it has been explored a different approach in which FBGs are the chosen sensor. Due to their multiplexing and self-referencing characteristics, it makes them the right choice. For manufacturing a glove it was necessary to overcome the optical fiber integration issue in the glove. The solution was to manufacture first a flexible structure made of PVC with the sensor embedded in it. This host structure worked as upper face of a standard fabric glove.

As the base structure is a standard glove, there are no major issues concerning wearability. Plus, based on the strategy to apply the sensing structure, different gloves can be easily produced with different sizes, materials and styles. The selection of FBG sensors embedded in the polymer matrix performs a wavelength deviation of 1 nm for a complete flexion movement, which provides enough dynamic range to use 14 sensors in a single optical fiber. Additionally, as the FBG only requires a single optical fiber end to access the sensor response, the overall system becomes very simple in respect to construction and maneuverability, which are crucial requirements for the possible applications.

The manufactured glove was characterized in respect to the finger movements, from which it was obtained a linear response while the hand was opening and closing. The linear performance facilitates the retrieve information about the movement range and hand posture.

A program in LabView was developed to monitor the hand in real time. Not only did it provide information about the angle of the joints where the sensors were placed, but it also provided a virtual hand model in 3D for visualization.

The presented system has an enormous potential in physical therapy applications, especially designed for hand-impaired people. The system was planned to be safe and personal, with a valuable output not only for the physician with accurate results but, also for the patient with motivating exercises.

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