A New Flexible Optical Fiber Goniometer for Dynamic Angular Measurements: Application to Human Joint Movement Monitoring

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Abstract—The electronic measurement of the angle between two planes is generally performed by using the so-called electrogoniometers. The major drawback in using such devices is the presence of a fixed hinge that imposes a fixed center of rotation. This can cause problems when measuring the bending angle in some joints, such as Cardan or human joints, which have a variable rotation center. Based on an optical fiber, a sensor measuring the relative angle in a rotating joint has been developed. This joint makes use of the intensity modulation of a laser beam propagating in a single-mode optical fiber, due to the changes of its polarization status originated by the rotation of contiguous portions of the fiber, where controlled birefringence has been induced by the joint rotation. A prototype of this sensor has been developed with a range of the relative angle of 90°, a resolution of less than 0.01°, and a standard deviation of 0.1°. The main advantages of this innovative sensor are lightness, flexibility, high speed of reaction, and high accuracy. This paper describes the development of the proposed sensor, with particular reference to the applications of human joint movement monitoring. Additionally, the equipment implemented for the test is illustrated, and results from laboratory tests are reported and discussed.

Index Terms—Angular measurements, human joint measurements, human motion tracking, optical fiber sensors, optical goniometer.

I. INTRODUCTION

Fiber optic technology has allowed the development of optical communication systems by providing very large bandwidth, high performance, and reliable links. This flexible and reasonably priced technology can also be used in a wide variety of applications, including noisy and potentially explosive environments. Many of the components used in optical communications have often been employed for optical fiber sensor applications in several measurement fields [1]–[3]. The most important advantages of fiber optic sensors are small size, resistance to electromagnetic interference, high sensitivity, and environmental ruggedness.

In some applications, the measurement of fast variations of the angle between two planes is frequently required. Currently, the devices employed for this purpose are mechanical or electromechanical goniometers, which are implemented using resistive potentiometers or strain gauges. The major drawbacks in using such devices are bulkiness, inaccuracy, and fragility, even if the main limitation is the presence of a fixed hinge that imposes a fixed center of rotation and, hence, an interference with movement. The difficulties in aligning the goniometer with the system under test can introduce a measurement error, particularly when the center of rotation is not a fixed axis. In some applications, this feature of commercially available electrogoniometers makes it hard to supply repeatable measurements when the device is removed and put back on the same joint in a somewhat different position.

Some typical examples are the Cardan joint in mechanical systems and the joints in the human body. All human joints bend around a variable rotation center because the length covered by line AB of the upper limb is different from that covered by line AB of the lower limb, as shown in Fig. 1. A classic hinged goniometer will carry out an incorrect joint angle measurement and will prevent the natural movement of the limb [4], [5].

Proper biomechanics and movement techniques are fundamental to performing well in all sports; most athlete training activities are devoted to mimicking the movement patterns employed in competitions [6]. Some rehabilitation therapies require daily monitoring of patient activities to better identify the disability and to set the relative treatment program [7].

The goal of this paper is to describe the design, implementation, and characterization of a new light, flexible, noninvasive, and accurate optical-fiber-based goniometer. In particular, this system has been designed to measure human joint (anatomical) angle (Fig. 2) for testing, training, and improving athletic performance and, more generally, for physiotherapeutic applications.

Moreover, this system can also operate in the presence of fast angle variations. For his intrinsic flexibility, the proposed goniometer allows hingeless, more accurate, and reproducible measurements of the joint angles with kinesiological advantages for the joint movement itself.

At present, as reported in literature, the goniometers based on light propagating in commercial optical fibers use the transduction principle shown in Fig. 3: A length of optical fiber is connected to the joint; as the joint is rotated, the bending of the fiber changes the attenuation of the transmitted light, and a detector provides a signal correlated to the angular rotation [8], [9].
Unfortunately, these devices present a series of limitations imposed by variable losses in the system that are not related to the angle variation to be measured and that can induce potential errors. In these devices, variable losses are due to connectors and splices, microbending loss, macrobending loss, mechanical creep, and misalignment of light sources and detectors. However, the main limitation of commercial fiber-based goniometers is related to the inaccuracy of the device to exactly follow the joint rotation in the absence of fiber twisting and stretching. In addition, these undesired and unpredictable effects cause attenuation of the light intensity.

In this paper, we present a fiber-based goniometer that makes use of the intensity modulation of a laser beam propagating in a single-mode optical-fiber, due to the changes of its polarization status originated by the rotation of contiguous portions of fiber, where controlled birefringence has been induced by a fixed radius fiber loop [10], [11]. This paper describes the principle and design details of the goniometer, including the results of laboratory test activities.

II. Working Principle of the Implemented Goniometer

A prototype of the goniometer was realized at the University laboratories in all of its mechanical and electrical components. A schematic of the goniometer working principle is reported in Fig. 4.

The fiber sensor is composed of a semiconductor laser, a single-mode optical-fiber Ferrule Connector with a Physical Contact polish (FC/PC) patch cable, an Si p-i-n photodiode, and two polarizers (plastic Polaroid sheets) that are used, first, to polarize the laser output and, second, to analyze the polarization status of the light exiting the stress-induced birefringence fiber polarization controller (SIBPC). All these elements are coupled with mechanical ad hoc components to form a single compact part, as shown in the overall block diagram reported in Fig. 5.

The Hitachi HL7851 GaAlAs laser ($\lambda = 785$ nm) was powered by a small printed circuit board supply circuit that assures a constant optical power of 50 mW [12]. The Hamamatsu S2386-44K Si PIN photodiode has a spectral sensitivity ranging from 300 to 1100 nm and was reverse biased by the conditioning circuit [13].

The core of the fiber-based sensor is the SIBPC, which is composed of three independent spools or paddles around which the fiber is looped. Depending on the fiber-cladding diameter, spool diameter, number of fiber loops per spool, and laser wavelength, the three paddles operate as fractional wave-plates that are able to vary the polarization status of the light over the full Poincare sphere. The SIBPC is created by making three fixed radius loops (with a radius of 8 mm) with the optical fiber patch cable; each loop is made of two turns spaced 4 cm apart. A change in the polarization of the light propagating in the fiber is achieved when a relative rotation of the planes of the three paddles occurs. The presence of the two polarizers allows the determination of the initial polarization status, whereas the final polarization status is related to the SIBPC paddle mutual rotation angle.
The fiber single-mode FC/PC patch cable is firmly connected to the laser and to the photodiode by two mechanical components, each of which includes the plastic linear polarizer.

The joint rotation is detected by positioning two of the SIBPC paddles on one side of the “articulation” and the third one on the other side. This way, only one paddle plane is rotated with respect to the others, and the light polarization status is related to this rotation. The Si photodiode converts light intensity at the fiber optic output and allows the rotation angle of one SIBPC fiber loop to be obtained by applying the Malus’ law: The detected intensity attenuation is a function of the square sinus of the rotation angle referred to the initial angle taken as zero.

The photodiode output signal is conditioned by a precision transimpedance amplifier, which gives the maximum sensitivity while maintaining a wide gain bandwidth, and acquired and processed by a sample-and-hold circuit, an acquisition board, and a personal computer running the calibration/measurement software.

**III. Prototype Characterization**

As part of the development phase, the implemented prototype has been tested in the laboratory, using a test-and-calibration system, whose block diagram is reported in Fig. 6 and realization is presented in Fig. 7.

To reproduce the working conditions, a human articulation simulator (HAS) has been implemented. It is composed of a simple artificial joint, a stepper motor supplied by a power driver and controlled by a microcontroller board that is programmed to drive the motor with a given rotation function, and a reference rotary potentiometer that measures the joint rotation angle. We used a Microkinetics four-phase microstepper, with a 1.8° step angle. The motor controller is an ST microelectronics L297 configured in a two-phase bipolar mode. This IC drives a dual full-bridge driver implemented using four BD139 n-p-n transistors that drive four BUX98AP high-voltage n-p-n power transistors. The final power section, which is implemented using two KBPC3508 bridge rectifiers, can supply 30 A for each phase. The microcontroller board, which is built using a Microchip PIC16F877A µC, runs the motor control program. The motor control board is able to communicate with the

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**Fig. 4.** Working principle of the proposed optical fiber goniometer.

**Fig. 5.** Block diagram of the optical fiber sensor.

**Fig. 6.** Block diagram of the test setup.

**Fig. 7.** Test setup.
acquisition software to perform an automatic calibration process. The system acquires both the fiber-sensor output and the reference angle.

The reference sensor is a precision potentiometer—a Novotechnik AW 360ZE-11—that provides absolute 360° angle encoding with a repeatability of 0.007°.
Fig. 10. History tab of the measurement software.

The sensor and reference signals were acquired with NI PXI-6052E, i.e., a data acquisition board with a 16-bit digital-to-analog converter operating up to 333 kS/s that is hosted on a PXI mainframe.

The measurement software has been implemented in LabView for controlling the test system and storing and processing the acquired data. It consists of three functional blocks. The Main tab, as shown in Fig. 8, displays the instantaneous angle measured by both the fiber sensor and the reference goniometer.

The Calibration tab, as shown in Fig. 9, performs an automatic calibration cycle of the fiber sensor through the microcontroller board: The HAS is automatically rotated in the range of $0^\circ - 90^\circ$; at each sampling point (25 in Fig. 9), both the measured and reference angles are measured several times (17 in Fig. 9) and averaged. The acquired data are processed using the Levenberg–Marquardt algorithm to calculate the best fit to the photodiode’s voltage curve and estimate the Malus’ law parameters, which are stored in a file and used to correct the measured data.

The History tab, as shown in Fig. 10, displays data logged by the recording function on the Main tab and allows for the measurement analysis.

Several tests of the proposed fiber optic goniometer have been implemented to simulate static and dynamic conditions, and the recorded data have been compared with the reference data.

To analyze the measurement repeatability and accuracy in static conditions, we compared the angle, which was measured by the proposed sensor, with that supplied by the reference goniometer, repeating the test starting from the same initial conditions. We obtained a standard deviation of $0.1^\circ$ with respect to the reference angle—a result that shows the good repeatability and stability of the proposed fiber-based sensor.

Successively, we performed dynamic measurements, moving the artificial limb by using the stepper motor. During this test, we repeatedly bended (for 5 s) and stretched (for 5 s) the artificial limb, imposing a rotation angle of $90^\circ$, corresponding to cyclic rotations at a constant angular velocity of $0.6 \text{ rad/s}$ (0.1 Hz). The acquisition sampling frequency for this test was set at 1 kHz. The measured angle was affected by an average root mean square (RMS) error of $1.36^\circ$, which was in some way due to a superimposed noise induced by the motor vibrations. To reduce this noise, we filtered the sensor output with a finite-impulse response low-pass filter with a cutoff frequency of 20 Hz, reducing the average RMS error by about 12%; an example of the results is reported in Fig. 11. Fig. 12 shows a graph of the measured sensor output driving the stepper motor at 1.25 Hz.

Other dynamic measurements were carried out by manually driving the HAS to reproduce the natural movement of a human joint without affecting the signal with the noise generated by the motor fluctuations. The diagrams of Fig. 13 reports the measurements performed at the angular, velocity of 31.4 rad/s (5 Hz). These results show the ability of the sensor to track the angle, also at a more elevated speed of variation. As a comparison to the measurement results obtained by driving the HAS with the stepper motor, these measurements were affected by an average RMS error of $0.59^\circ$.

For a qualitative analysis of the sensor sensitivity and response time, we analyzed the signal produced during the motor rotation steps. An example is reported in the zoomed graph in Fig. 14, where the vibrations and dumped oscillations of the HAS—a mechanical system with large inertia—are quite
visible. The sensor has a faster response, with a settling time that is much lower than that of the HAS, even if it cannot be measured with the implemented test setup, which was conceived to test a different (human) application.

Other tests were performed to verify the independence of the sensor output from the position on the body limb where it will be fixed by translating the paddle along two different directions: The first was a translation in line with the rotation axis (Fig. 15), and the other was perpendicular to the rotation axis. We executed a set of translations that are 2 cm on the right and 2 cm on the left of the initial position, obtaining a realistic insensitivity to the translations: a very low output variation that can mainly be ascribed to the deformation of the fiber segment between the paddle and the photodiode.

Successively, we incorporated the goniometer in the fabric surrounding the joint of a wearable system used to measure the knee flexion angle, as shown in Fig. 16, also ensuring better comfort for long-term registrations. The sensor was linked to the instruments for the testing activities. The obtained results have proven that the system is extremely effective and useful for this kind of application.

IV. CONCLUSION

In this paper, a flexible, compact, and accurate fiber-optic-based sensor for angular measurements between two planes has been proposed, discussing the activities carried out from the initial idea to the implementation of a working prototype.

A series of tests have been performed under several working conditions to evaluate the accuracy and response time of the implemented sensor prototype. The experimental results show the advantages of the proposed sensor.

Based on the described sensor prototype, it is possible to realize flexible sensors for human joint angle measurements.
The applications can refer to an athlete’s performance by testing and training their exercises, with the aim of improving competitiveness, or to physiotherapeutic applications, with the aim of performing correct rehabilitation therapies.

Future developments will be concentrated on reducing the dimension by miniaturizing the whole system.

REFERENCES


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