Wearable Low-Cost System for Human Joint Movements Monitoring Based on Fiber-Optic Curvature Sensor

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***Abstract*— In this paper, a measurement system for human joint movements monitoring based on a simple and low-cost intensity modulated fiber-optic curvature sensor is presented. The implemented curvature sensor is made up of a plastic optical fiber, which is optimized for small curvature measurements, and has a high sensitivity in a wide measuring range. The sensor sensitivity and resolution, in the measurement range, are 20 mV/° and 1°, respectively. The fabrication process of proposed curvature sensor is also given. The implemented sensor is wearable, noninvasive, nonintrusive, and completely harmless. In this paper, the characteristics of the sensor measured in laboratory conditions as well as measurements of the human knee joint movements are given. Wireless electronics based on ZigBee are also presented. Therefore, the sensor has the possibility of wireless measurement. The main advantages of this sensor are simplicity, lightness, and flexibility. This sensor is also electrically safe and immune to electromagnetic interference. The application, which provides a possibility of remote human joints monitoring over the internet is implemented in the LabVIEW software package.**

***Index Terms*— Curvature sensor, human joint monitoring, optical-fiber sensor, wireless sensor.**

I. Introduction

CURRENTLY, there are increasing market needs for the measurement of fast variations of the human joint movements. The reason for this increased need for monitoring human joint movements is because there are many medical applications which could benefit from it. Medical applications are various and the most common are physical therapy and rehabilitation [1]. Some examples of medical applications are dynamic measuring of lumbar curvature [2], dynamic monitoring of finger joints [3]–[5], monitoring of limbs [6]–[8] and many others. In addition to medicine, monitoring of human joint movements also provides benefits in sports [9], [10].

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For all of these applications, both in medicine and sports, it is necessary to measure the dynamic angle variations. Devices used for this purpose are mechanical or electromechanical goniometers, which are implemented using resistive potentiometers or strain gauges. The most reliable systems for dynamic angular measurements are electrogoniometers. In [11] an electrogoniometer for wearable posture and gesture capture systems which introduces a method for detecting joint angles by using piezoresistive strain sensitive materials is shown. In addition to electrogoniometers, goniometers based on optoelectronics are often used. An optical goniometer for human joint angle measurement which allows continuous and long-term monitoring of human joint motion in everyday setting based on a chip from optical mouse is reported in [12]. Dynamic goniometer with an incremental encoder using a mechanical transmission between a hinge and a pulley connected to an optical disc is reported in [13].

Fiber-optic sensors [14]–[16] are frequently used for human joint angles monitoring. Usually the sensor for this application is based on intensity modulation, and the most common implementations are based on intensity modulation due to bending of optical fiber. The spectral-based fiber-optic sensor implementations with fiber Bragg grating (FBG) sensor have been recently published [5].

The sensors based on the bending of optical fiber have low sensitivity. Therefore, there is a need to increase sensitivity in a certain way. There are several methods to improve the sensitivity of the fiber-optic sensor based on fiber bending such as by using imperfect fiber and by using side polished fibers [17], [18]. The fiber-optic sensors based on the bending of plastic optical fiber with structural imperfections on the outer side of core are reported in [19], [20]. The sensitivity of the sensors [19], [20] was improved even more by increasing the depth of the fiber imperfections.

With the introduction of the fiber-optic curvature sensor with a sensitive zone [21], the sensitivity is not a problem anymore even for the most demanding applications. Analytical optimization of the curvature sensor with a sensitive zone is reported in [22].

An experimental analysis of the static and dynamic characteristics of the curvature sensor, together with a mathematical model, related to the relative output loss, parameters of the sensitive zone configuration (depth, number, height and half angle of tooth), and bending radius based on the geometric

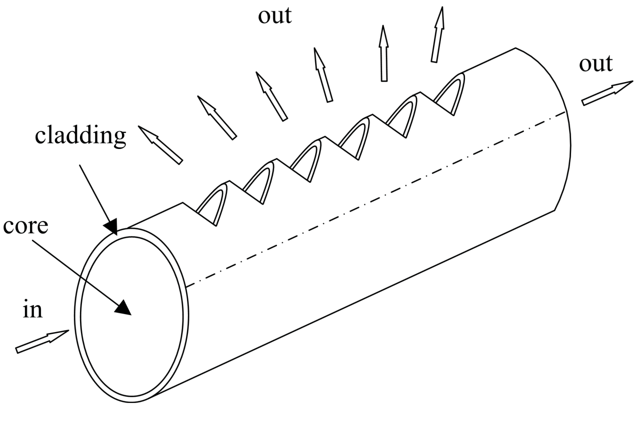

Fig. 1. Principle of the fiber-optic curvature sensor with a sensitive zone.

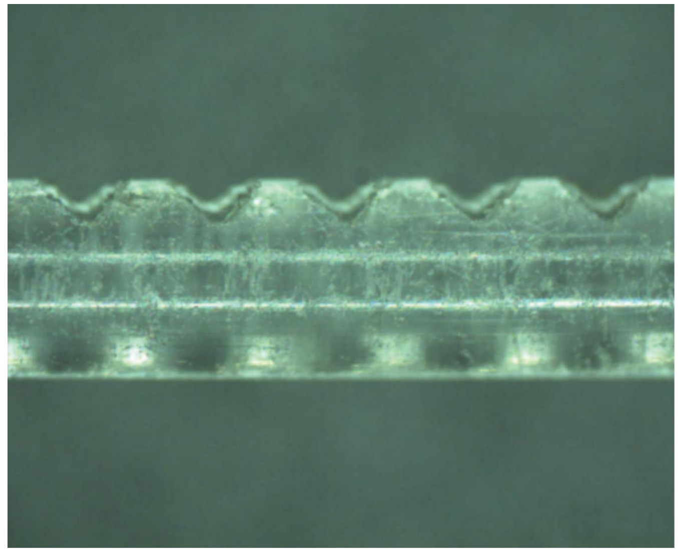

Fig. 2. Photograph of drilled POF taken on Signatone H-100 Probe Station.

optics are analytically described in [23]. The Monte Carlo simulation based on ray tracing and an orthogonal matrix used to optimize the fiber-optic curvature sensor configuration is reported in [24]. With different configurations of the curvature fiber-optic sensor with a sensitive zone, many physical quantities can be easily measured. The results from [24] show that the depth of the sensitive zone and the number of teeth are two main parameters that affect the sensor sensitivity. It is also concluded that the optimum number of teeth is 55.

This paper presents a sensor system for monitoring the movements of human joints based on fiber-optic curvature sensor with a sensitive zone. The resulting curvature sensor is made with a 1.5 mm diameter plastic optical fiber (POF). A ZigBee based wireless communication board, which provides wireless measurement option, is also used. In addition to wireless measurements, client-server applications in LabVIEW software package are implemented, which give possibilities of remote measurements over internet. In [25] a system for dynamic angular movements monitoring based on polarization change due to the joint rotation, is presented. In comparison to sensor from [25], the sensor presented in this paper is more simple and cheaper.

A wearable and wireless system designed to evaluate quantitatively the human gait is presented in [18]. The advantage of produced sensor compared to the previously mentioned system is better sensitivity. In comparison to FBG sensors for joint monitoring the resulting sensor is characterized by low-cost design. The plastic optical fiber is much cheaper than the FBG, and it does not require expensive interrogation system as in the case of the FBG. Also, the resulting human joint movement monitoring system enables sending measured data over the internet, which provides a possibility of continuous and remote monitoring. This important feature makes the proposed sensor system a better solution in comparison to other sensing systems for human joint movements monitoring.

II. Sensor Principle and Fabrication

As mentioned above, in order to increase the sensitivity of the fiber-optic curvature sensor, the optical fiber can be etched, most often in the shape of teeth. As shown in Fig. 1 teeth are formed on the side of the fiber, and cover cladding and part of the core layer of optical fiber. When the fiber bends positively (teeth are on the convex side), the intensity of light that reaches the other end of the fiber decreases. The negative bending (teeth are on the concave side) differs from the positive bending. With the negative bending the light intensity that reaches the other end of the fiber increases.

There are many solutions where the teeth are grouped without spaces between them. In this paper, the teeth are created with space between them.

In the realization of the sensor, the POF with 1.5 mm diameter is used. Plastic optical fibers are used for the fabrication of the sensor because they are cheap, robust and easy to handle [26], [27]. Also, POF is very suitable for the realization of the sensor because it has a large core diameter, and the fabrication of teeth is very simple.

To create a sensitive zone, on the one side of the fiber, teeth are created by precision drilling. The teeth were made on a Protomat S100, produced by LPKF Laser & Electronics AG, with micro cutter tool. The teeth creation was performed in two passes of the tool because there was sawdust that remained in the teeth area after the first pass. Fig. 2 shows a photograph of a few teeth of the produced sensor taken with the microscope. This sensor has 50 teeth, and the distance between the centers of the teeth is 1 mm. The length of the sensitive zone is 5 cm. From Fig. 2 it is evident that the teeth have almost an ideal shape, as teeth shown in Fig. 1.

III. Experimental Setup

Fig. 3 shows a block diagram of the laboratory experimental setup for angular movement measurement. For laboratory tests sensor is mounted on an improvised joint, which is attached to a precise manual rotation stage (MRS) produced by Thorlabs, Inc. As a light source and detector, LED and photodarlington are used. High power red LED, IF E97 with the peak wavelength of 660 nm, and photodarlington IF-D93 produced by Industrial Fiber Optic, Inc are used.

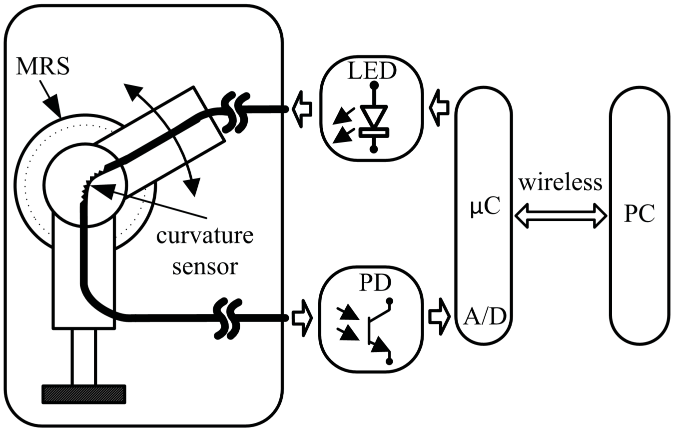

Fig. 3. Block diagram of the laboratory experimental setup for human joint movements monitoring based on the curvature sensor. MRS: manual rotation stage. PD: photodarlington. LED: light-emitting diode. μC: microcontroller. A/D: analog-to-digital converter.

Photodarlington provides a very high optical gain, eliminating the need for the post amplification. The integrated design of the IF-D93 makes it a simple, cost-effective solution in a variety of applications. Optical response of the IF-D93 extends from 400 to 1100 nm, making it compatible with a wide range of visible and near-infrared LEDs and other optical sources.

This includes 650 nm visible red LEDs used for optimum transmission in PMMA [poly(methyl methacrylate)] POF. Both source and detector are housed in a "connector-less" style plastic fiber-optic package, to which POF can be easily connected.

As microcontroller (μC), ATtiny13 from *Atmel* is used. This microcontroller is used because it is appropriate for the desired application tasks, and it is very cheap and small. μC drives LED, measures a signal from photodarlington by using 10 bit A/D converter, and communicates with a PC via ZigBee module. The device is supplied by a 9 V battery. Power supply for whole device is stabilized to 3.3 V with step-down voltage stabilizer.

The battery indicator that measures the level of battery charge and provides graphical information is implemented with one A/D converter channel. The battery level is displayed as a percentage. When the battery discharges to 8 V the user is informed by the computer that there is a need to recharge the battery.

In Fig. 4 a photograph of the produced curvature sensor with an improvised joint mounted on the precise MRS is shown.

Fig. 5 shows a block diagram of the implemented device for dynamic angular movements monitoring in real conditions.

As we can see from the block diagram, the system produced is designed for wireless and long-term remote monitoring. The complete electronics is packaged in a box attached to a belt during the measurements. Measured values can then be displayed, analyzed, recorded on a PC and distributed over internet.

For ZigBee communication XBee-PRO module produced by MaxStream, Inc., is used. The modules were designed to meet ZigBee/IEEE 802.15.4 standards and support the unique needs of low-cost, low-power wireless sensor networks. The modules have indoor range up to 100 m and outdoor range with line-of-sight up to 1500 m.

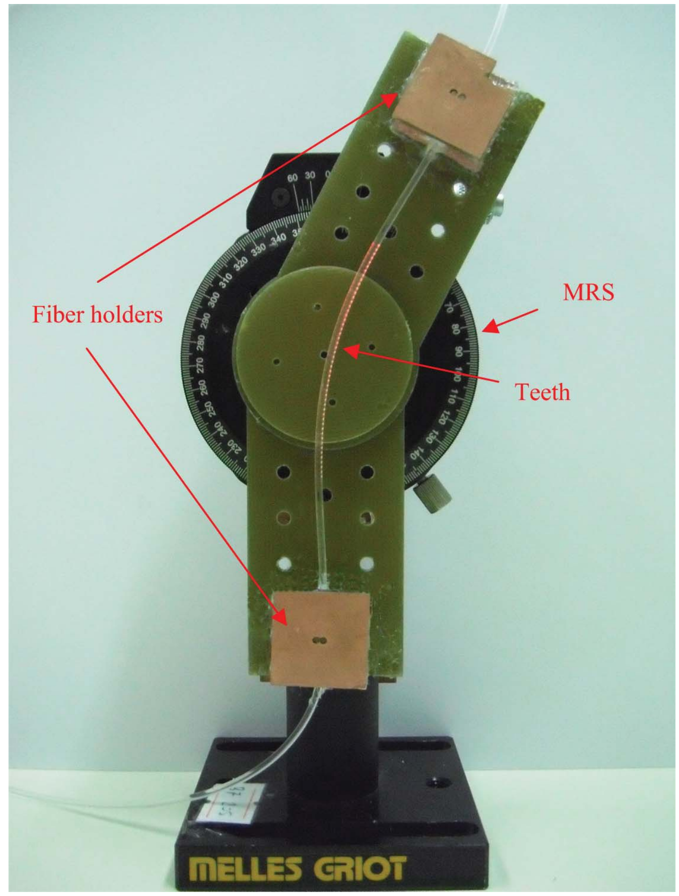

Fig. 4. Photograph of the curvature sensor used in laboratory measurements.

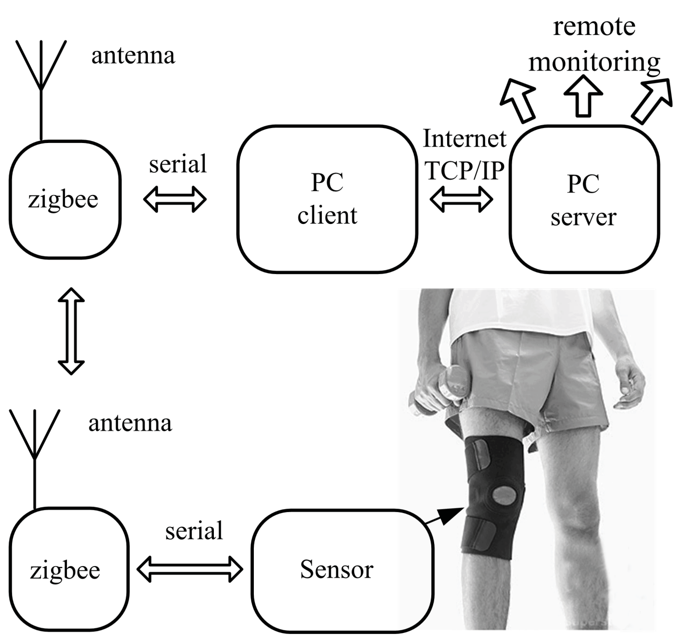

Fig. 5. Block diagram of the hardware and software realization for dynamic angular measurements of human joint movement.

Fig. 6. Photograph of the produced wearable fiber-optic sensor mounted on the knee joint brace. The curvature sensor is sewn on the knee joint brace. The electronics are placed in the box (open in the photograph), which is attached to the belt.

The power supply voltage for these modules can be in the range from 2.8 to 3.4 V. XBee-PRO modules provide a possibility to build an easy to configure network, with a high data rate up to 250 000 Baud/s. For the configuration of the XBee-PRO module, X-CTU software is used. Connection of the XBee-PRO module to the microcontroller is done by using 4 wires: Power-Supply (3.3 V), Ground, TX and RX. XBee-PRO module is configured to operate in Transparent Mode. When operating in this mode, the modules act as a wireless serial communication (UART). In this mode it is necessary that all modules have the same PAN-ID, both a module, which sends data broadcast, and all other modules that receive data.

In this work, communication with two modules is implemented, but in order to obtain a wireless sensor network, communication with more modules can be easily implemented. Client and server applications are implemented in LabVIEW software package. The client application receives measured data from XBee-PRO, and graphically displays and captures measured data. The client sends received data to a server over the internet using TCP/IP protocol. These data from the server are available for remote monitoring.

The potential errors arising from the connector imperfections, misalignment of light sources and detectors and other effects that are not related to the angle variation are reduced by simple calibration. The calibration button is implemented in hardware. When it is pressed and angle is set to zero, the microcontroller sends value of A/D converter to the client application that sends data to the server application, which calculates the calibrated sensor characteristic.

The curvature sensor was mounted on a commercial knee joint brace and the signal was measured, recorded and analyzed. In Fig. 6. a photograph of the resulting measurement system for dynamic angular measurement mounted on a knee joint brace is shown. As can be seen from the photograph, in order to tighten the sensor on the knee brace, the curvature sensor is sewn on the knee joint brace. In the same photograph it is also shown the produced electronics, which can be easily attached to the belt.

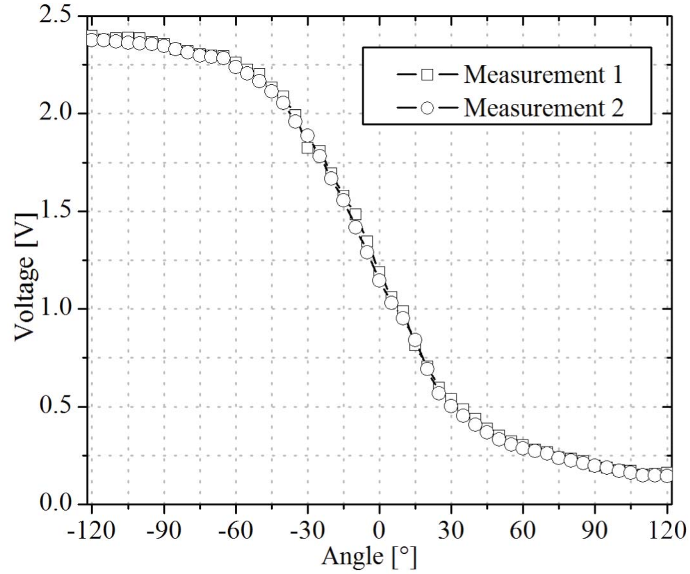

Fig. 7. Measured characteristic of the sensor in range of $-120°$–$120°$.

IV. Results and Discussion

The sensor characteristic is measured in two cases, for positive and negative bending. In both cases the characteristic has exponential dependence of the intensity of light on the angle of curvature (see Fig. 7). The characteristic is measured in the range of $-120°$–$120°$. The sensor stability is measured by capturing the output signal during one hour at the fixed angle value of 0°. The samples are taken every second (sampling rate is 1 Hz) which makes a total of 3600 measured values. The measured 1σ error (obtained as the standard deviation of the measured data) for one hour sensor stability measurement is 0.18°.

The repeatability [28] of the sensor is obtained by measuring the sensor characteristic twice at the same conditions. The same conditions mean that the sensor characteristic is measured at the same temperature, with the same photodarlington gain. Also, optical fibers are placed in the same way to the light source and detector (connection of the optical fiber and the light source/detector is identical in both measurements). The sensor characteristics obtained in two measurements are shown in Fig. 7. It is evident that the high degree of sensor repeatability is achieved.

The sensor has high reliability [28] in the temperature range that satisfies maximum rating for operating temperature of POF (declared by manufacturer). If the sensor is used at the temperatures above 70 °C, the fiber begins to deform and changes its characteristics. In practice this is not a problem because the person, on whose knee the sensor is placed, will never be active at extreme temperatures.

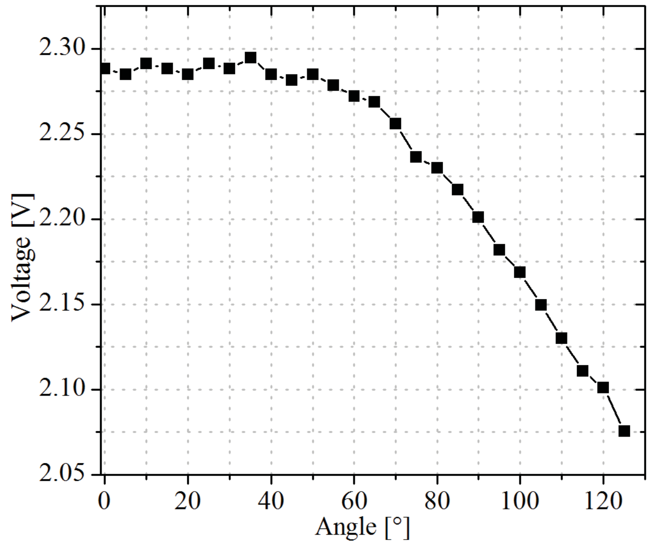

Fig. 8. POF bending characteristic. POF is bent in the range of 0°–125°.

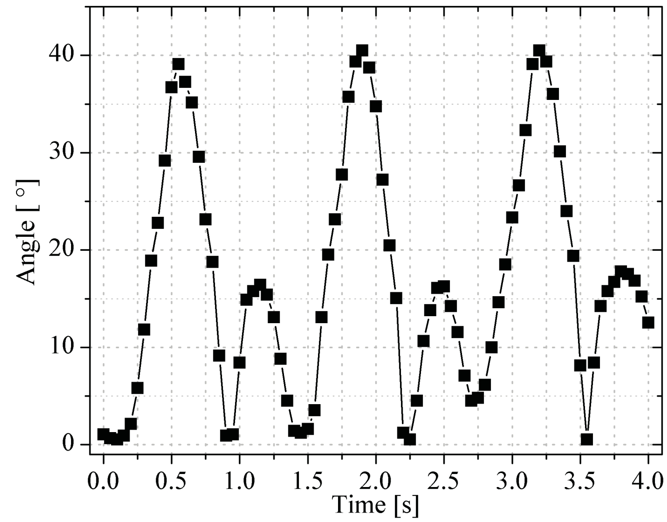

Fig. 9. Knee flexion angles measured during a walking session for one subject. The samples are taken every 50 ms.

The measurement had demonstrated that the sensor has a linear characteristic in the range of −45°–25°. In this region the achieved sensitivity is 20 mV/°, where for angles over 25° it decreases significantly.

The positive bending part of the characteristic (0°–25°) is not suitable for this application because of its narrow range, but it can be used for other applications.

In contrast to the positive bending, the negative bending measured characteristic has approximately linear region along 45°. In the negative bending region (−45°–0°) a good linear response is achieved. In this region the sensor resolution is better than 1°. The sensor resolution depends on the signal/noise ratio, resolution of A/D converter and sensitivity. For the measurement of joint movements the negative bending sensor characteristic is used. This range is used because the aforementioned linear range is suitable for monitoring human knee joint angle.

It is worth to mention that the lead-in and lead-out sections of the curvature sensor can disturb the performance of the intensity based fiber-optic curvature sensor. Therefore, for the proposed measurement system it must be ensured that the lead-in and lead-out sections of the fiber do not strongly bend. In this implementation the lead-in and lead-out sections of the fiber are guided via the thigh (in order not to bend) to the box with electronics which is placed on the waist. By connecting the sensor and the electronics box in this way, the lead-in and lead-out sections of the fiber are maintained fixed in order not to affect significantly the measurement results. The effect of the errors due to bending of the lead-in and lead-out sections of the optical fiber is shown by measuring the attenuation produced by the bending of the lead-in and lead-out fiber sections. The attenuation is measured on the same experimental setup as by measuring the curvature sensor characteristic. The obtained measurement results in the range of 0°–125° are shown in Fig. 8. The radius of the curvature which corresponds to 125° on the MRS is a slightly less than 2 cm. The measured results are well matched with data

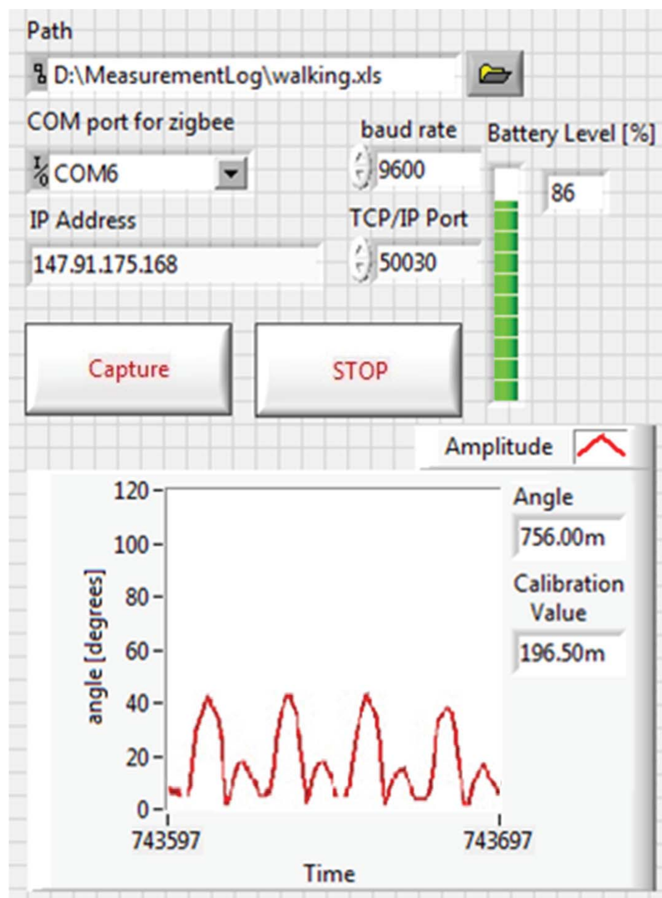

Fig. 10. Implemented client application with the measured results.

provided by the POF manufacturer (Industrial Fiber Optic C-60 Eska 1.5 mm High-Performance Plastic Optical Fiber). The manufacturer proposed a minimum bend radius of 3 cm, and guarantees that the attenuation for the 3 cm bending radius is less than 0.5 dB. The measured attenuation for the bending radius of less than 2 cm is about 0.8 dB. It is important

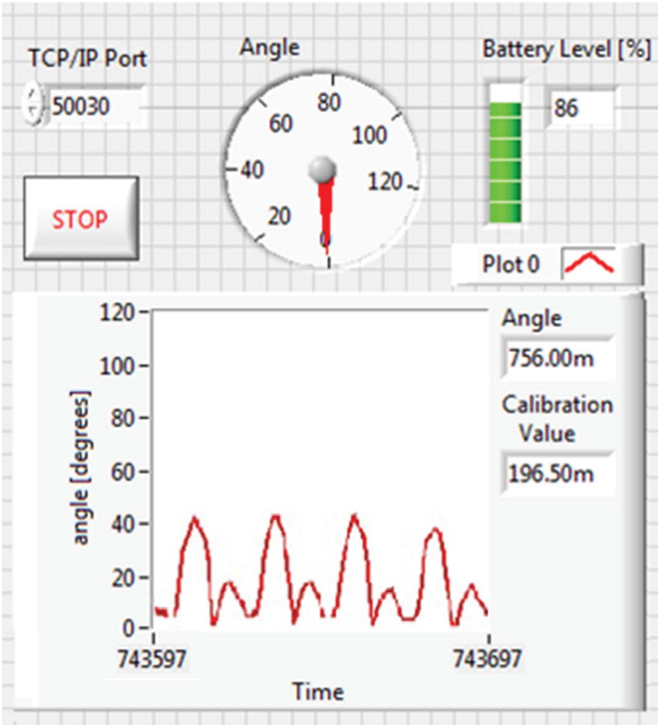

Fig. 11. Implemented server application with the measured results.

to note that the POF begins to deform when crossing the bending limit (bending radius of less than 3 cm) specified by the manufacturer. The reliability of curvature sensor is also disturbed when fiber bends in radius less than 2 cm. When the 1.5 mm POF with etched teeth bends with radius less than 1.5 cm (this corresponds to angles above 140°), curvature gauge cracks because in this area the fiber is weakened.

Assume that the fiber bends with a bending radius of 3 cm in lead-in and 3 cm in lead-out fiber sections. A bending of 3 cm will cause bending losses of less than 0.5 dB, which results in approximately 2.5° of angular error at the most sensitive part of the characteristic. If the lead-in and lead-out fiber sections bend simultaneously with bending radius of 3 cm, angular error will be maximum 5°. This error will never appear in practice, and it represents the maximum error value for POF bending when it begins to deform. It is important to mention that this attenuation results in an error which demonstrates itself in the indication of the larger angle value than the real angle value is. When the angle at the knee joint is measured in practice, it is ensured that the lead-in and lead-out fiber sections are held fixed (led to the box with the electronics via the thigh).

Although it is ensured that the lead-in and lead-out fiber sections are maintained fixed, it is possible that the sections accidentally bend. Maximum accidental angular bending value of these sections will not exceed 60° (this is achieved by careful fiber guiding to the electronics box). For these practically possible values of the accidental bending of the lead-in and lead-out fiber sections the measurement error is less than 1°. In practice, by guiding fibers via the thigh it is ensured that this error is always below the value of 1°.

The measured knee flexion angles for a walking session for one subject are shown in Fig. 9. This characteristic is obtained by logging the measured angle in the spreadsheet file (.xls), and data is captured every 50 ms.

Client and server applications together with the measured results are shown in Fig. 10 and Fig. 11, respectively. The client sends the measured data to the server and the measured results are available for the distributed and remote measurements. The most important thing for the client is to make the successful connection to the server and to set the adequate port and server IP address. Access to data from server should not be public, but allowed only to certain persons that have permission. These data can be easily password protected if the system is planned to be commercially exploited.

All measured data are collected on the server. These data can be further processed, analyzed, and distributed by anyone who has an internet connection.

V. Conclusion

A simple and low-cost fiber-optic curvature sensor based on intensity modulation together with its application in the human joint angle monitoring is presented. The sensor has an approximately linear characteristic for the measurement range of −45°–25°. The resulting sensor sensitivity and resolution in the corresponding measurement range are 20 mV/° and 1°, respectively.

The proposed sensor is suitable for the medical and sports applications, and it is wearable, non-invasive, nonintrusive and completely harmless. Wireless communication electronics based on ZigBee standard, by which the sensing part of the system communicates with a PC, is developed for this sensor.

By carefully guiding the lead-in and lead-out fiber sections to the box with the electronics we have avoided the errors that can cause losses in the light transmission.

Another way to further minimize these losses is to use the optical fibers with smaller core diameter which are more resistant to the bending. As a logical extension of this work we propose the minimization of the complete angular joint monitoring system to be integrated on the knee brace. In this way, the lead-in and lead-out fiber sections lengths will be minimized which would result in smaller error due to the lead-in and lead-out fiber sections bending. The curvature sensor should be placed as close as possible to the light source and photodetector pair in order to improve the sensor performance.

The advantages of the sensor described here over the conventional sensors are its robustness, simplicity, low-cost and resistance to the electromagnetic interference.

The resulting fiber-optic sensing system compared to the fiber-optic implementations mentioned in the introductory part of this paper has the advantages of higher sensitivity and very simple and low-cost design. Although the measurement system presented here uses very cheap digital microcontroller, it works reliably and with a small measurement error. By adjusting the depth and number of teeth on the curvature sensor the desired sensor sensitivity and width of the linear range can be easily adjusted. Also, from all reported fiber-optic implementations for the joint angle measurements only the curvature gauge provides possibility of distinguishing positive from negative bendings, which is important in some medical applications.

Nowadays, the remote and wireless measurements are very important and the sensor described here has options of wireless (via ZigBee communication) and remote measurements (via internet).

Client and server applications are designed on a PC. These applications display, record and distribute the measured signal over the internet. This option is suitable for the continuous monitoring of simple daily, sports and rehabilitation activities. The implemented sensor is mounted on a commercial knee joint brace and its signal is measured.

The developed measurement system is cheap, simple, and with some modifications, such as miniaturization, can be produced for commercial purposes.

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