POLYMERIC OPTICAL FIBER CURVATURE MEASURING TECHNIQUE BASED ON SPECKLE PATTERN IMAGE PROCESSING

Clemens Hägele* Anselmo Frizera Neto* Maria José Pontes*

*Universidade Federal do Espírito Santo
Av. Fernando Ferrari, 514
Goiabeiras Vitória
ES Brazil

Email: clemens.h@mail.com, anselmo@ele.ufes.br, mjpontes@ele.ufes.br

Abstract— A light intensity-modulated curvature measuring principle for gauging bending angles within a range between $-120^\circ$ and $+130^\circ$ based on speckle image processing is presented in this paper. Coherent light with a wavelength of 632.8 nm is propagated through a looped Polymeric Optical Fiber (POF) and received by a Charge-Coupled-Device camera (CCD), positioned on its end face. After applying a chain of image processing techniques the determination of the angle is realized by using the average of the pixel intensity and the amount of speckles within a Region Of Interest (ROI). Practical results revealed the existence of a non-linear dependence in the range of $-120^\circ$ and $+130^\circ$ between the geometrical arrangements of the POF, the average pixel intensity, the amount of speckles and the bent angle.

Keywords— Polymeric optical fiber, POF, Curvature sensor, Bending sensor, Speckle image processing, Light intensity-modulated curvature sensor, Transmission loss sensor.

1 Introduction

In the last decades the demand of POFs increased rapidly with regard to technical improvements in minimizing attenuation and bandwidth (Zubia and Arrue, 2001). Several physical characteristics such as lightweight, electromagnetic interference immunity, chemical resistance, mechanical robustness and flexibility made the POF more attractive for industrial applications in comparison to previously developed polymeric fibers. Sensors based on POF technology are frequently used applications for gauging physical related parameters such as strain, pressure, stress, vibration, current, rotation, displacement and bending. Manufacturing the POF is characterized by low installation and linking effort resulting from a high numerical aperture, low bending radius and large diameter. Comparatively low expenses for material and elementary development equipment make the processing of the POF feasible (Zubia and Arrue, 2001), (Anwar Zawawi et al., 2013).

Important applications for POFs have been developed in the sensing area where the focus on the research topic of human joint movements increased significantly. The analysis of human joint movements with the aid of tri-axial accelerometers was proposed in (Anwar Zawawi et al., 2013). Several inertial sensors have to be fixed next to the target joint before application, resulting in an extensive overall sensor design. A graphical analyzing technique utilizing CCD cameras to detect reflecting markers, attached on the human body for determination of joint position and body parts was proposed by Safaei-Rad and Shwedyk (1990) in (Anwar Zawawi et al., 2013). The accuracy of this technology depends mainly on the distance between the camera and human body, the size and the amount of markers (Anwar Zawawi et al., 2013).

POF based sensors are frequently used to monitor health indicators such as respiration (Babchenko et al., 1999), (Ahmed et al., n.d.), (Lomer et al., 2014), arterial pulse, heart rate (Lomer et al., 2014), joint movement analysis (Louis et al., 1993), curvature of lumbar spine (Williams et al., 2010), trunk motion and upper or lower limb motion analysis (Anwar Zawawi et al., 2013) (Williams et al., 2010). Arterial pulse and chest respiratory were successfully determined by analyzing changing speckle patterns affected by mechanical perturbations caused by the acoustic waves of the pulse and the expansion of the thorax (Lomer et al., 2014).
Most of the aforementioned sensors are based on light intensity modulation, which consists of five different subcategories related to their function: fiber displacement, shutter modulated, reflective, transmission loss and evanescent field. Fortunately the determined loss in light intensity is often proportional to the physical related measured parameter. However secondary losses caused by absorption, scattering and radiation are included in the resulting measured parameter, which presents a negative influence on the accuracy and reliability of the sensor (Anwar Zawawi et al., 2013).

A reliable and high precision curvature sensor based on light intensity-modulation to gauge the dynamic angles of a human knee joint was presented in (Stupar et al., 2012). The measured sensor curve possess an exponential dependence in the range of $-125^\circ$ to $+125^\circ$, where the linearity field is found between $-45^\circ$ to $+25^\circ$. In a reproducible process the POF is finely formed with cavities arranged in a defined pattern. The imperfections provoke a change of the light wavelets incident angle, resulting in a summation of partial internal reflections, reverse reflections and double refractions (Babchenko and Maryles, 2007). These physical facts are utilized in (Stupar et al., 2012) to distinguish the polarity of the bent direction. The effects of the imperfections and its characteristics such as abrasion angle, location angle, displacement and v-groove cavity depth on the output of light intensity is documented in (Babchenko and Maryles, 2007). The aforementioned parameters offer additional degrees of freedom for the individual adjustment of the sensor to its target application (Babchenko and Maryles, 2007). Imperfections on the fiber limit the mechanical flexibility as reported in (Stupar et al., 2012), where the fiber core cracked at a bent angle of $+140^\circ$. In (Efendioglu et al., 2012), (Rodriguez-Cobo et al., 2014) and (Lomer et al., 2014) it was proved that speckles change their intensity and pattern when the light guide is mechanically perturbed where the total intensity of the pattern remains unchanged.

This paper presents a technique based on the determination of amount of speckles for determination of curvature angles. It was possible to extract the amount of speckle contours within a ROI for the identification of the bent angle applying image processing techniques. The amount of speckles and their intensity vary within a ROI due to a varying bending angle. The fiber is looped for several times to achieve a higher transmission loss during the bending process. In Section 2 the necessary theoretical considerations for the realization of this work are described.

The image processing techniques are addressed in Section 3 followed by Section 4 describing the experimental setup. Test procedures are explained in Section 5 where the analysis of the main findings are presented in Section 6. A final conclusions and prospects are presented in Section 7.

2 Theoretical Considerations

2.1 Curvature of Fiber and Resulting Effects

A coherent light source emitting light waves of different constant phases, same frequency and amplitudes through a multicore POF is assumed. Abstracted to a geometrical plane, each light wave has a different angle with respect to the angle of the light guide. Therefore the modes differ in traveled distance and phase delays. The light at many points of the fibers exit face consists of a summation of several individual coherent wavelets which interfere constructively, in antiphase, or destructively, in equiphase, resulting in a statistically intensity distributed granular spatial speckle pattern (Varyshchuk et al., 2014). Considering each mode as a vector, the final output vector is a summation of different vectors with random angles and amplitudes. Speckle patterns vary in dimension and brightness when mechanical perturbations are applied on the light guiding part of the POF. The coherence of light and the characteristics of the light source have influence on the contrast of the speckles and its amount within a ROI defined by the number of modes and the average size of speckles (Rodriguez-Cobo et al., 2014).

2.2 Light Distribution in Light-guiding Core of POF

The distribution of light intensity in a bent fiber is concentrated at one side at the end face of the fiber as reported in (Ying et al., 2013). In a straight fiber the incident ray crosses the whole section of the POF whereas in a bent fiber it crosses only half of the cross section as shown in figure 1.

Figure 1: Energy distribution at end face of bent fiber, adapted from (Ying et al., 2013)
3 Image Processing

Figure 2 illustrates the image processing after acquisition by CCD camera. Several steps are applied in order to obtain the angle values.

3.1 The Region of Interest

As previously discussed, the intensity of light is concentrated on one side of the end face of the POF (Ying et al., 2013). Utilizing this fact, the determination of the amount of speckles is realized by using a ROI of size 500 x 270 pixels positioned on a defined point of the image. All following described image processing tasks are applied to the cropped image.

3.2 The Gaussian Low-Pass Filter

A Gaussian low pass filter is applied to the ROI for reducing noise and distorted edges in order to improve the posterior edge detection process (Gonzalez and Woods, 2002).

3.3 The Bilateral Filter

In order to detect the influence of the image filter on the measurement of the amount of speckles, a non-linear bilateral image filter was applied. This type of filter reduces noise regardless preserves edges and blurs textured areas (Tomasi and Manduchi, 1998).

3.4 Calculation of Mean Value

The mean value of the applied ROI of the image is calculated by summing up all pixel intensities and dividing it by the total amount of pixel. The mean value represents the light intensity of the measured signal.

3.5 The Canny-Edge Detector

The canny edge detector applies Sobel-operators to turn the firstly invisible edges of the recorded image into visible ones. In practice, a pair of convolution masks is applied to amplify the edges in horizontal and vertical direction. The first derivatives of the image are calculated with the magnitude of the gradient values. The gradient of the function \( f \) at coordinates \((x, y)\) is defined as the two-dimensional column vector. A technique called non-maximum suppression is applied to assure that the edge contour is not thicker than one pixel. The neighbor pixels of the pixel with the highest magnitude are evaluated and separated within a defined hysteresis of lower and upper threshold values. By marking closed contours where each contour represents a speckle it is possible to determine the amount of speckles of the cropped image (Gonzalez and Woods, 2002).

4 Experimental Setup

To avoid mechanical disturbances caused by loose parts of the POF, it is bonded on a fixing plate and mounted on a self-created mechanical acrylic goniometer (figure 3). The fiber is bent in a defined direction where the positive angle represents the anti-clockwise rotation and the negative one the clockwise rotation. (figure 3). A Multimode-Step-Index POF, Model Eska Premier, fabricated by Mitsubishi Rayon Co. LTD serves as a medium for propagation of light and as sensing element. A He-Ne Laser provides coherent light with a wavelength of 632.8 \( \mu m \). The POF core with a typical diameter of 980 \( \mu m \) consists of Polymethyl-Methacrylate Resin, a core refractive index of 1.49 and a numerical aperture of 0.5. A video stream with a frame rate of 40 frames per second (FPS) and a resolution of 1296 x 972 is generated by the RaspiCam, controlled by the embedded system Raspbery Pi Model B+. The RaspiCam consists of an individually configurable five Megapixel CMOS Image sensor Omnivision OV5647. A desktop computer realizes the image processing with the
aid of the open source computer vision library OpenCV 2.4.9.

4.1 Geometrical Arrangements of the Sensing Fiber

The signal loss increases with the amount of loops owing to the increasing amount of bending points of the fiber, as shown in figure 4. This fact can be considered as an adjustable sensibility parameter of the measuring technique. The influence of amount of loops to the signal response is analyzed by applying following arrangements for the practical tests.

![Figure 4: Different arrangements of fiber](image)

5 Test Procedures

In this specific sub-section, for convenience, the term signal substitutes the definition of the mean pixel intensity and amount of speckles e.g. contours. Both values are recorded and evaluated during all measuring procedures.

5.1 Measuring Range

The amount of contours and the average value of the light intensity for different bent angles geometrical arrangements of the the POF are recorded in a range of $-120\,^\circ$ to $+130\,^\circ$. In intervals of $5\,^\circ$ one leg of the goniometer is moved. After each step the movement is maintained at the angle of destination for three seconds to stabilize the signal. The procedure was realized for an fivefold-, threefold- and a single-looped fiber. The 500 x 500 pixel array ROI is located over the whole illuminated circle. For subsequent tests the ROI is reduced to 500 x 270 pixel array and located ones at the lateral side and secondly at the upper part of the light circle, according to figure 2. A polarizer added to the lens of the CCD camera leads to an absorption or reflection of light waves which are not perpendicularly-orientated to the polarizer. The influence of the image filters on the signal response was evaluated by switching between bilateral- and Gaussian-Low-Pass Filter. The measurement procedure was repeated for ten times to determine the accuracy of the sensor. Figures 5,7 and 9 present the amount of contours $n$ in relation to the bending angle. Figures 6,8 and 10 present the dimensionless intensity over the bending angle.

6 Results and Discussion

The way of fixing the fiber on the goniometer causes a different bending behavior for both bending directions. The fiber is bent over the edges of the fixing plates which causes a lower bending radius for the clockwise rotation leading to a higher signal loss as can be seen for all measurement setups. The single-looped fiber setup is affected most by this fact as can be seen on its signal responses. The shape of the measuring curve is significantly changed and the total amount of speckles and intensity reduced by the polarizer for all measurement setups. The signal responses of the bilateral filter prove that that the information of the amount of edge is preserved where the Gaussian-Low-Pass Filter diminishes the measured amount of speckles about 25 % significantly. The intensity is not influenced by both filters. Different ROI positions on the image do not affect the shape of the measuring curve where the absolute value of the amount of speckles is less. The rise of the intensity can be ascribed by a rise of the mean value of the ROI pixel intensity. Less pixels with low intensity are present in the calculated ROI. The average standard deviation for the light intensity is 0.22 and 155 for the contours.

The evaluation of different POF arrangements proved that the signal loss rises strongly with the increment of loops. The values for the amount of speckles and intensity of the fivefold- and threefold-looped fiber setups converge to zero from a bending angle of $-90\,^\circ$. The fivefold- and threefold-looped fiber setups depict a linear behavior in the range of $-90\,^\circ$ to $-40\,^\circ$ and the single fiber setup in the range of $-130\,^\circ$ to $-40\,^\circ$. It can be observed that the signal response for the amount of speckles is more distorted than of the intensity. It is noted that the computational effort for the usage of the bilateral filter is 20 % higher in comparison to the Gaussian-Low-Pass Filter. Applying a ROI results in about 40 % less computational effort in comparison to the ROI over the whole circle. The tests revealed that the determination of values is only possible in static operation. Distorted images and oscillating
Figure 5: Amount of contours of fivefold-looped fiber

Figure 6: Intensity of fivefold-looped fiber

Figure 7: Amount of contours of threefold-looped fiber

Figure 8: Intensity of threefold-looped fiber

Figure 9: Amount of contours of single fiber

Figure 10: Intensity value of single fiber
values for the amount of speckles and intensity are detected during dynamic operation and shortly after caused by the elasticity of the fiber. Low energy vibrations and mechanical transients applied on the measuring table cause a distortion.

7 Conclusion

In the present paper, a elementary measuring technique with low cost-components and low computing effort for the analysis of speckle images is described. Geometrical arrangement, physical characteristics of the fiber, mechanical and temperature disturbances affect the reliability of the signal response decisively. Further studies will focus on the improvement of the measuring setup and the robustness. The motive is to generate a symmetrical measuring curve for both bending directions. Additional image processing techniques and methodologies will be taken into account to compensate disturbances and signal fluctuations for edge detection. The influence of the CCD camera parameters can be inquired in depth to achieve higher accuracy.

8 Acknowledgments

In thanks to Laboratório de Telecomunicações (LABTEL) from Universidade Federal do Espírito Santo (UFES) for the opportunity. Gratitude to Fundação de Amparo à Pesquisa do Espírito Santo (FAPES), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and Petrobras for the financial support of the project.

References


