Choosing the optimal parameters of reconstruction for the shape sensor based on multicore spun optical fiber

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Abstract. Multicore optical fibers are widely used for developing compact shape sensors for various applications. The accuracy of such sensors strongly depends on the resolution of the measured data. In this paper, we analyze the influence of the number of sensing points on the error and mean time of reconstruction of the multicore fiber shape. A criterion on the choice of this parameter is given considering the impact on the performance.

1. Introduction

Fiber-optic sensors (FOS) are widely used in various applications, because of their key advantages: lightweight, compact size, immunity to electromagnetic interference, ability to create sensors array in a fiber and simultaneous measurements of several physical parameters [1]. For these reasons, these sensors have found wide applications in the oil industry, aerospace, structural health monitoring and medicine [2,3].

Typically, FOS are based on single-mode fibers, in which one central core is located on the axis of the fiber. With the development of technology for creating multi-core optical fibers (MCF), which in addition to the central core also have several side ones, the possibilities for creating FOS based on MCF have significantly expanded. For example, this type of FOS could be used to create a 3D shape sensor based on strain measurements in each core of MCF along the fiber [4]. These shape sensors can be used in many tasks, for example, in minimally invasive surgery to track the location of a flexible manipulator during surgical operations [5,6].

To increase the accuracy of shape reconstruction at a limited signal processing time, these sensors should have optimal parameters, both in the number of measurement points and in their location. In this paper, we present experimental results on the reconstruction of fiber shapes based on measuring strain along a fiber with twisted side cores and analyze the influence of the number of measurement points (which dictates the distance between them) on the shape reconstruction error and mean computation time.

2. Shape reconstruction and experimental setup

In order to obtain a shape of the fiber, one needs to calculate curvature vectors along the fiber length and use, for example, differential geometry equations to construct a curve in a three-dimensional space, which will be continuous even if the curvature is measured at some discrete points. In this case, the obtained curve is some approximation relative to the original one. Principles of fiber shape sensors imply the calculation of curvature vectors from bending-induced strain (a relative change in length) in
the cores of a multicore fiber (MCF), which, in turn, can be determined either from the analysis of the reflection spectrum of fiber Bragg gratings (FBGs) or from the measured phase shifts when using optical reflectometry with Rayleigh backscatter analysis. The first method allows determining strain values at separate discrete points, where FBGs have been inscribed, providing the resolution limited by the distance between FBGs. The second method results in nearly continuous strain measurement with the best spatial resolution and, therefore, better possible accuracy comparing to an FBG based sensor, however, in the cost of the interrogation rate. The question of the choice of the optimal distance between measurement points is important in some cases a high-speed FBG based interrogation scheme will be suitable despite relatively low accuracy. Alternatively, an optical reflectometer can be used when high resolution is desired and fast measurements are not required.

To reconstruct the shape of the MCF we calculated curvature vectors using an approach suggested in [4], which is to consider partial curvature vectors for each of the side sensing cores and calculate their averaged sum:

$$\mathbf{k} = \frac{2}{Nr} \left( \sum_{i=1}^{N} \varepsilon_i \cos \alpha_i \mathbf{n}_x + \sum_{i=1}^{N} \varepsilon_i \sin \alpha_i \mathbf{n}_y \right),$$

(1)

where $\mathbf{k}$ is the curvature vector at a given point of the MCF, $N$ is the number of sensing cores, $r_i$ is the core-to-core distance, $\varepsilon_i$ is the bending induced strain in $i$-th core, $\alpha_i$ is the angular direction on the $i$-th core in the local coordinate system defined by unit vectors $\mathbf{n}_x$ and $\mathbf{n}_y$ (see figure 1 (a)). Vectors (1) are calculated in each measurement point and then interpolated by a cubic spline to obtain smooth function $\mathbf{k}(s)$, where $s$ is the length parameter.

Strain values $\varepsilon_i$ were determined from the measured phase shifts of the light reflected due to Rayleigh scattering from density fluctuations inside a fiber core as $\varepsilon_i = \lambda_0 \Delta \nu_i / c k_i$ ($i$: 1, …, $N$), where $\lambda_0$ is the central wavelength of the reflectometer laser scanning range, $\Delta \nu_i$ is the phase shift, $c$ is the speed of light and $k_i$ is the sensitivity coefficient. The sensor calibration was done by winding the MCF on metal cylinders with various known radii and calculating sensitivity coefficients $k_i$ for each core. The central core practically does not experience bending-induced strain, so it can be used to exclude the influence of longitudinal strain and temperature effects by subtracting the phase shifts from the respective shifts obtained for side cores at the same point along the MCF. A spatial form of the fiber is then reconstructed using the Frenet-Serret equations in a similar way as described in [4].

A single-channel optical backscatter reflectometer OBR 4600 (Luna Technologies, USA) was used to interrogate a 7-core spun fiber Fibercore SSM-7C1500(6.1/125) with a straight central core and 6 twisted hexagonally positioned side cores. The pitch of side cores twist is $l_p = 15.4$ mm and the core-to-core distance is $35 \mu$m. The cores operate in a single-mode regime with a mode field diameter of $6.3 \mu$m @ 1550 nm. The outer coating diameter is $185.7 \mu$m. A special Fibercore FAN-7C fan-out was used to select a separate core for measurement. The reflectometer operated in a sensing mode when the time domain reflectogram is processed to obtain a phase shift at discrete points along the MCF with an interval of 1 mm.

3. Results and discussion

Two shapes were chosen to analyze the dependence of accuracy on the distance between points: an s-shaped and loop-like forms. First, reference reflectograms of the straight unstressed fiber were taken. After that, the fiber was taped to a sheet of graph paper in a selected shape, then photographed, and the frequency shifts were measured in all cores. The length of the sensing part of the fiber amounted to $L = 300$ mm. During the shape reconstruction calculations, some points were dropped to create the situation of lower resolution with the overall length $L$ remaining the same. As an example, two reconstructed curves with a different number of points superimposed on the respective photograph of the s-shape are shown in figure 1 (b). Although here we opted for 2D shapes since it is more difficult to have a reliable reference for a 3D measurement, the reconstruction procedure remains the same and the analysis results, in general, are applicable for arbitrary shape. In the case of complex 3D shapes,
external twist may increase the absolute error, however, the measurement resolution will affect the accuracy and computation time in the same manner.

The reconstruction error $\delta_{\text{err}}$ was determined as the maximum deviation of the calculated curve from the original one in the $xy$ plane of picture and along the $z$-axis. The relative reconstruction error was defined as $\delta_{\text{rel}} = \delta_{\text{err}}/L$. Both error values are provided in table 1. In figure 2 (a) the relative error depending on the interval between measurement points is shown for both shapes.

![Figure 1](image)

**Figure 1.** (a) Scheme for curvature vector calculation, (b) photo of a part of the MCF with the length $L = 300$ mm and calculated curves with two measurement point interval $d_{\text{point}}$: 1 mm and 100 mm (dashes do not represent actual measurement points).

| Interval (mm) | $\delta_{\text{err}}$ (mm) | $\delta_{\text{rel}}$ (%) | $\delta_{\text{err}}$ (mm) | $\delta_{\text{rel}}$ (%) |
|--------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 1            | 6.1                      | 2.03                     | 1.8                      | 0.6                      |
| 5            | 8.2                      | 2.73                     | 2.2                      | 0.73                     |
| 10           | 9.8                      | 3.27                     | 4.8                      | 1.6                      |
| 20           | 13.7                     | 4.57                     | 13                       | 4.33                     |
| 30           | 16                       | 5.33                     | 13.6                     | 4.53                     |
| 50           | 14.6                     | 4.87                     | 15.8                     | 5.27                     |
| 75           | 39.2                     | 13.07                    | 18                       | 6                        |
| 100          | 39.6                     | 13.2                     | 28.8                     | 9.6                      |

The impact, which the point interval will make on the reconstruction accuracy, is dependent on the shape itself. In the case of a loop-like shape, the bending direction remains the same relative to the local coordinates of the MCF, while in the case of an s-shape, the curvature vector changes its direction by 180 degrees closer to the end of the sensor. If this change in direction is not properly resolved the divergence greatly increases. This can explain the observable difference in relative error between two shapes (figure 2 (a)). The remained deviation of several millimeters present for small point interval values can be further reduced by measuring the distributed sensitivity for each core in order to address the imperfections of core-to-core distance, twist pitch and centricity.
Figure 2. (a) Relative reconstruction error versus distance between measurement points for the fiber shape sensor bent in different forms (circles and squares) together with the mean computation time of shape reconstruction (crosses), (b) curvature $|\kappa|$ versus the length along the fiber.

The general consideration is that the interval between points should be less than the value of minimum curvature radius $R$ to be measured by the sensor. In our experiment, the minimal values of curvature radius were 30–40 mm as can be seen from the measured dependence of curvature ($|\kappa| = 1/R$) on the length along the MCF (see figure 2 (b)). So, lowering the interval by an order of magnitude smaller than the minimum curvature radius should provide the best accuracy in this situation. However, increasing the number of points will lead to the increased complexity of computations when reconstructing the shape of the sensor. To find the optimal point separation interval we also monitored the time needed to process the measured phase shifts data and draw the curve on a display, which is shown in figure 2 (a) as a mean for two shapes. It is clear from the graph that the computation time dramatically reduces when changing the point interval from 1 mm to 5 mm (300 and 60 points in the dataset, respectively). To clarify, the computation time depends linearly on the total number of points $N = L/d_{\text{points}}$, but nonlinearly on the point interval $d_{\text{point}}$ that is plotted in figure 2 (a). In contrast to the computation time, the relative error does not change significantly, which indicates the optimal distance between measurement points of 5–10 mm. This value is also suitable for FBG based sensors where typical grating length is about 1-2 mm, which ensures a fairly narrow resonance peak in the reflectance spectrum.

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