

# Monitoring of tunnel shape using distributed optical fiber sensing techniques

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**ABSTRACT:** The directly obtained output from Distributed Optical Fiber Sensing (DOFS) system is strain, while control parameters in majority of engineering applications are defined in terms of displacements. This paper introduces general three-dimensional (3D) shape and displacements monitoring method by means of distributed optical fiber sensing combined with appropriate fiber installation scheme. The displacement precision as a function of strain precision, resolution, and sensing fibers configuration are mathematically established in a simple equation. The results of the actual monitoring project are also provided to further illustrate the effects of the proposed approach. Three types of available DOFS systems, namely *Brillouin Optical Time Domain Reflectometry* (BOTDR), *Pulse-Pre-Pump Brillouin Optical Time Domain Analysis* (PPP-BOTDA) and *Tunable-Wavelength Coherent Optical Time Domain Reflectometry* (TW-COTDR), each with precision an order of magnitude better than the other, are compared to highlight their influence on obtained displacement precision. Millimeter-order precision required in tunnel, bridge, or railway tracks monitoring applications, for distance over several kilometers, are possible with TW-COTDR, while BOTDR measurements cannot provide any valuable information.

## 1 INTRODUCTION

The safety of civil infrastructure must be assured at all times as it is almost always linked to human life. Detecting and identifying any structural problems long before they escalate is a challenging task. Many different monitoring techniques can be used. Distributed optical fiber sensing (DOFS) is emerging trend in such applications on the tide of IoT (Internet of Things). It reduces the costs and complexity of such monitoring, allowing one to cover tens of kilometers using just one 'sensor'. DOFS are destined to replace all electrical sensors and thus must meet all the requirements they do. However, many DOFS systems use a simple, if not simplistic, detection scheme in which acquired signal is directly compared with a predefined threshold strain values.

Lopez-Higuera et al. (2011) graded structural health monitoring (SHM) systems using Level I through V. At Level I, SHM system is capable of only detecting the presence of damage without locating it, while at Level V to estimate the remaining service life-time. To reach that level DOFS system should be properly designed and installed as a complete solution, not a complimentary or fashionable component. The acquired data must feed the database-backend software with built-in classification, analysis, prediction, and anomaly detection modules.

This paper describes the design, required hardware, and implementation details of DOFS system for 3D displacement tunnels monitoring, which addresses most of the tunnel safety issues.

## 2 MODEL FOR 3D SHAPE SENSING USING DOFS SYSTEM

This Section describes the fundamentals of the shape sensing using DOFS systems and based on error analysis discusses the required instrument precision.

### 2.1 Smart Rod – continuous displacements measurements using spiral FOs

Structural behavior of many civil structures can be modelled, at least at engineering level, using beam or rod deformation principles. The theory of deformation modes states that only 4 quantities (diameter is omitted here and will be discussed in Section 4) are required to fully describe the rod deformation, that is, axial tension/compression, twist, and bending for two directions. The position of the rod and thus its deformation or shape, can be obtained from its curvature and the ratio of twist angle (rotation rate). The rotation rate corresponds to the specific twist angle,  $\psi$ .

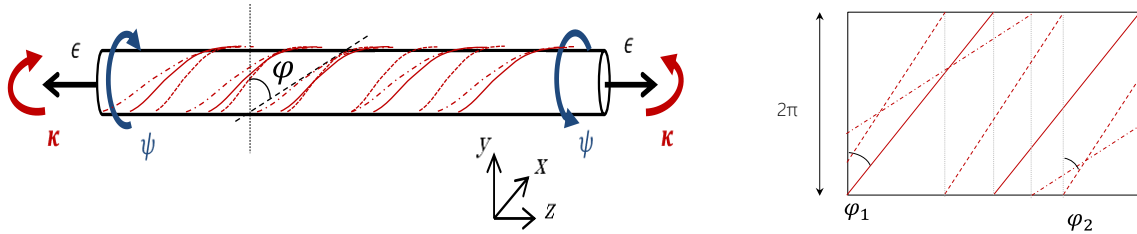


Figure 1. Fiber layout on the rod (left) and unfolded view (right)

The rod, as a curve, in 3D space can be expressed as  $r(s)$ , where  $s$  is the arc-length parameter,  $0 \leq s \leq L$  and  $L$  standing for the rod length. Denoting local coordinate system as  $[e_z(s) \ e_x(s) \ e_y(s)]$ , the rod curvature equation becomes:

$$\frac{d}{ds} \begin{pmatrix} e_z \\ e_x \\ e_y \end{pmatrix} = \mathbf{A} \begin{pmatrix} e_z \\ e_x \\ e_y \end{pmatrix} \quad (1)$$

where the matrix  $\mathbf{A}$  is given by:

$$\mathbf{A} = \begin{pmatrix} 0 & \kappa_x(s) & \kappa_y(s) \\ -\kappa_x(s) & 0 & \psi(s) \\ -\kappa_y(s) & -\psi(s) & 0 \end{pmatrix} \quad (2)$$

The position in 3D space can be obtained from an integral equation:

$$\mathbf{r}(s) = \mathbf{r}(0) + \int_0^s \mathbf{e}_z(u) du \quad (3)$$

where  $u$  is the displacement, which is obtained from strain-displacement relation. Hence, for any section of a rod, if 4 strain components can be measured then the deformation of a rod can be uniquely determined. This can be achieved by installing the fiber spirally, as schematically shown in Figure 1. The measured strain in the fiber can be expressed in terms of fiber layout helical angle,  $\phi$ , as:

$$\begin{aligned} \varepsilon_f = & \epsilon(\sin^2 \varphi - \nu \cos^2 \varphi) + \kappa_x r \sin \theta (\nu \cos^2 \varphi - \sin^2 \varphi) \\ & + \kappa_y r \cos \theta (\nu \cos^2 \varphi - \sin^2 \varphi) + \psi r \sin \varphi \cos \varphi \end{aligned} \quad (5)$$

Thus, distributed optical fiber system is capable of providing at each cross-section of the rod 4 equations required to determine coefficients in matrix  $A$ , and rod displacements. It should be noted here that measurements spatial resolution, sampling interval, and most of all accuracy are of crucial importance in achieving required, from engineering perspective, precision of calculated displacements.

The fiber layout presented in Figure 1 can be considered as piece-wise integration segment. The FO installation pitch is thus spatial resolution of the rod in 3D, denoted as  $\Delta s$ . The minimum value of  $\Delta s$  is the resolution of sensing instrument. If the FO is installed just at spots, then the distance between spots should be used here as  $\Delta s$ .

The maximum error of calculated rod position is at its far end. The standard deviation of this error can be expressed as:

$$\sigma_{xy} = \sqrt{\frac{L_c^3 \Delta s}{6} \frac{\sigma_{\varepsilon_f}}{r_\alpha a_\beta}} \quad (6)$$

where  $\sigma_{xy}$  stands for the standard deviation,  $L_c$  the total length of the fiber while  $r_\alpha$  is the radii of the pipe, and  $a_\beta$  is a parameter determined by the helical angle of optical fiber layout. In the above equation  $\sigma_{\varepsilon_f}$  is the error of strain measurements of the interrogator. Table 1 summarizes the distributed sensing technologies and their achievable precision as well as limiting factors for a typical installations in the tunnels. It is assumed that tunnel is 5 km long and its twist moment is negligible. Thus, the fiber can be installed in axial direction of the tunnel, only. As the tunnel diameter change is 3 orders of magnitude smaller than overall tunnel (centerline) deflection, it also can be safely ignored, as in equation (6).

Table 1. Distributed sensing technology and their precisions

Technology (instrument/model)	Best specifications		Typical specifications for tunnel displacements		
	Spatial resolution (m)	Precision ( $\mu\varepsilon$ )	Spatial resolution (m)	Precision ( $\mu\varepsilon$ )	Displacement uncertainty at 5 km (mm)
BOTDR (NBX-5000 Series)	0.50	50	1.00	100	850.52
PPP-BOTDA (NBX 6000 Series)	0.02	10	0.10	10	147.31
TW-COTDR (NBX 7000 Series)	0.02	0.1	0.10	0.1	1.47

In case of single-end fiber access instruments, such as BOTDR or TW-COTDR, it was assumed that instrument can be located near the center of the tunnel, reducing the length  $L_c$  to 2.5 km. In case of double-end fiber access technologies (PPP-BOTDA and BOTDA), we can still assume the best precision at half of the tunnel length when we measure twice from both end of FO.

From Table 1 and equation (6) it is clear that millimeter-order precision required in tunnel, bridge, or railway tracks monitoring applications, for distance over several kilometers, are possible with TW-COTDR, while BOTDR measurements cannot provide any valuable information.

### 3 SENSING SYSTEM

Monitoring of tunnel displacements using DOFS always requires data with cm-order spatial resolution and few micro-strain accuracy. The latter additionally must be purely mechanical, that is, without thermal component, which in turn requires temperature to be fully compensated and sensing fiber properly calibrated, Yamauchi (2010).

Temperature influences frequency shifts of both Brillouin and Rayleigh scatterings. Thus, if temperature is not clearly separated, the strain value cannot be determined. The experience gained by Neubrex in numerous monitoring projects, leads to conclusion that strain free-fiber cannot successfully work in industrial applications. This is due the fact that free-fiber is not actually free from strain induced by friction with its supporter (required in any harsh environment). The value of that strain is usually above 10  $\mu\epsilon$ , cancelling out the accuracy of instrument due to undetermined temperature influence, and leading to overall errors in measured strain higher than 20  $\mu\epsilon$ . In many projects and publications the error introduced by omitting the influence of temperature changes on measured strain is unfoundedly neglected. The main reason is that there is no practical method of performing temperature compensation. The temperature compensation using information obtained from DTS (Raman) will not work either, since the distance compensation cannot be assured, especially, if different (separate) fiber is used. In that case, compensation is performed based on assumption that the temperature is same for both fibers. This would be true only in extremely rare cases of highly uniform temperature (gradient-free) in monitored object.

#### 3.1 Hybrid Brillouin-Rayleigh instrument

The hybrid system, Kishida et al. (2013), combines the advantages of both Brillouin and Rayleigh scattering technologies. It consists of high-precision Pulse-Pre-Pump (PPP)-BOTDA, high-resolution tunable wavelength Rayleigh sub-systems, and two optical switches (OS1 and OS2). The system provides, for the same, single SM fiber, the simultaneously measured shifts for Brillouin and Rayleigh scattering, denoted by  $\Delta\nu_B$  and  $\Delta\nu_R$ , respectively. These values are used to separate strain and temperature by means of the set of equations (7) and (8). The strain separation is performed using following set of equations:

$$\Delta\nu_B = C_{11} \Delta \epsilon + C_{12} \Delta T \quad (7)$$

$$\Delta\nu_R = C_{21} \Delta \epsilon + C_{22} \Delta T \quad (8)$$

where the coefficients are known for a specific sensing cable or obtained using calibration, see Yamauchi (2010).

Equations (7) and (8) can be transformed to a more practical form by introducing coefficients:

$$S = \frac{C_{21}}{C_{11}} \quad (9)$$

$$R = C_{22} - SC_{12} \quad (10)$$

The coefficient  $S$  is constant for almost all types of the fibers and equals to  $-3091$ . System (7) and (8) can be expressed by using introduced coefficients  $S$  and  $R$  to give the equation independent of the strain:

$$R\Delta T = \Delta\nu_R - S\Delta\nu_B \quad (11)$$

Hybrid technology, via equation (11), allows one to directly obtain temperature distribution. Strain distribution can be subsequently obtained using either equation (7) or (8).

### 3.2 Sensing optical fiber cable

Sensing fiber selection, layout design, and installation are by all means the most important issues in any DOFS monitoring projects. While interrogators, software, computers and other elements can be easily replaced, upgraded, and improved over the course of the project, once the fiber is installed (usually embedded) replacing it is almost never a feasible solution.

Neubrex developed special sensing fiber for monitoring civil infrastructure. The FN-SILL-3 is designed for strain and temperature measurements. It consists of 2 optical fibers (in the cable center) and 2 reinforcing bars, which allow cable to sustain up to 25 kg force. The embossed grid makes it easy to embed the cable or attach it to the measured object/structure. The outer sheath is made from olefin-type elastomer, which exhibits superior characteristics regarding long-term heat resistance, and UV-resistance. It also ensures there is no elastic hysteresis effect.

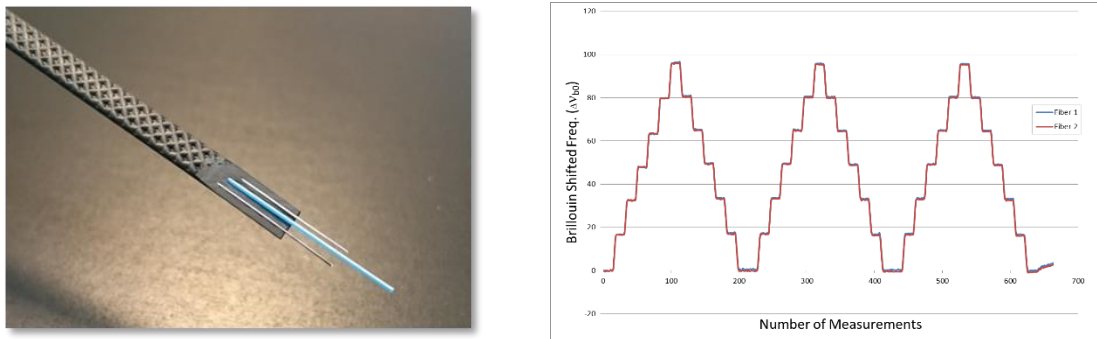


Figure 2. FN-SILL-3 sensing fiber structure (left) and hysteresis test results (right)

### 3.3 Data processing and management system

SHM system to be graded Level V compliant, requires data processing and management system supporting analysis, classification, prediction, and anomaly detection modules. It also is the first line of defense against unauthorized access. Thus, strict control and log of user activities and privileges must be enforced by the application. The longer the time-span of the monitoring project, the more important the data management becomes as it is not unusual to acquire terabytes of data per year.

Neubrex developed dedicated database back-end application (NeubreGate) to integrate and analyze data collected by monitoring system. It also offers a wide range of tools for data storing, analyzing, incident reporting, and many others. The application consists of 5 main components, namely, Data Management, Advisory, Dynamic Monitor, Data Viewer, and Control Center. Application also enables SCADA system integration, as SHM is sometimes a part of a larger control system. As mentioned earlier the user privileges control is also enforced.

## 4 FIBER LAYOUT AND INSTALLATION FOR TUNNELS

The general deformation model of the rod described in Section 2, requires 4 quantities to uniquely determine displacements. It also assumes that diameter of the rod is constant. In many engineering applications out of 4 variables twist usually can be ignored ( $\varphi = 0$ ), reducing number of required fiber lines. However, introducing into model varying radius is an essential problem which needs to be addressed. For monitoring displacements in the tunnel three fiber layouts are proposed.

The fiber can be optionally embedded in the walls while tunnel is constructed. The disadvantage of this approach is that fiber cannot be easily repaired if gets broken due to, for instance, cracks in the walls. Embedding cables in the tunnel walls during construction is usually opposed by the field engineers, due to lack of any previous experience and widely accepted installation techniques or standards. Thus first and the simplest proposed layout is to install FO along the external surface of tunnel walls, presented schematically in Figure 3. The ‘S-Block’, a plastic block with S-shape sleeves are used for hosting the fiber and are to be installed after construction works in the tunnel. S-block installation need a proper pre-tension but this is already proved as an easy task. The layout allows one to measure tension and compression in axial direction, bending in both horizontal and vertical and thus obtain tunnel shape.

In order to detect the radius/tunnel cross-section deformation, the following arc-like structures are proposed. The scheme shown in Figure 4 left, uses elastic rods, which can be made from steel or plastic, anchored at points of interest. The rods act like truss elements and are subjected to compression or tension forces, only. Thus induced strain is uniform, which allows fiber to be attached to the portion of the rods, bypassing the complex shape of the joints. The layout presented in Figure 4, right, employs the arch-like shape sensor with the optical fiber glued to both top and bottom surfaces. The arc sensor can be fixed (anchored) at just a few points on its circumference. The measured bending strain is then used to detect shape changes.

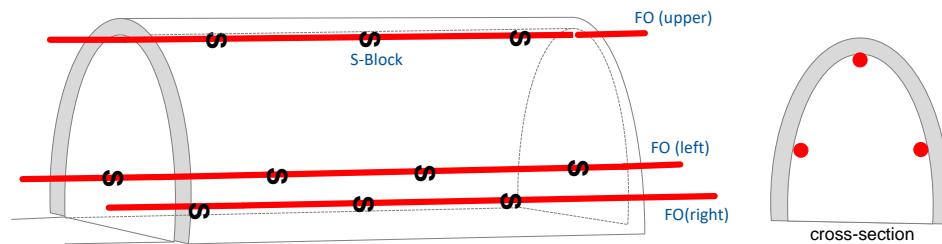


Figure 3. Displacement sensing fiber layout: axial direction layout

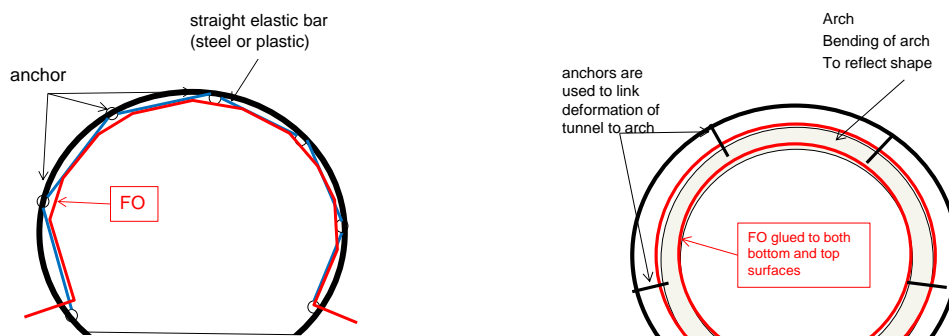


Figure 4. Displacement sensing fiber layout: elastic bars (left) and anchors (right)

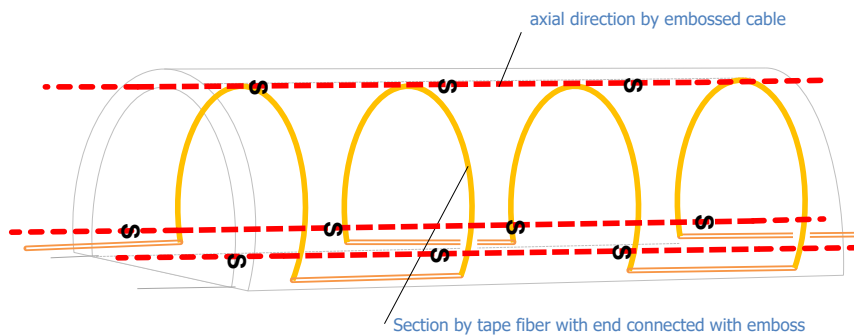


Figure 5. Displacement sensing fiber layout: axial direction layout with independent arches

In Figure 5 this design is enhanced by adding independent fiber lines providing measurements from a number of arch sections. This not only improves the quality of data but also improves considerably installation safety factor. Even if one of the fibers is broken it does not influence the overall system performance.

## 5 APPLICATION EXAMPLES

The axial direction fiber layout (Figure 4) is also the most suitable in excavation safety monitoring projects. The tunnel excavation is typically performed in two steps. First, the upper portion of the tunnel is removed, and then subsequently lower (bottom) one. The ground movement creates risk of tunnel collapse, posing an extreme danger for workers and equipment. In such cases the Extremely Long Pre-Supporting (ELPS) excavation technique can be used. In this method a number of steel pipes, prior to excavation, is inserted directly above the planned tunnel exits. As the length and diameter of the ELPS is only estimated it is crucially important to provide real-time measurements of the wall deflection.

In this installation the smart rod was used and inserted into ELPS pipes. The tunnel and smart rod dimensions are shown in Figure 6. Figure 7 presents installation process.

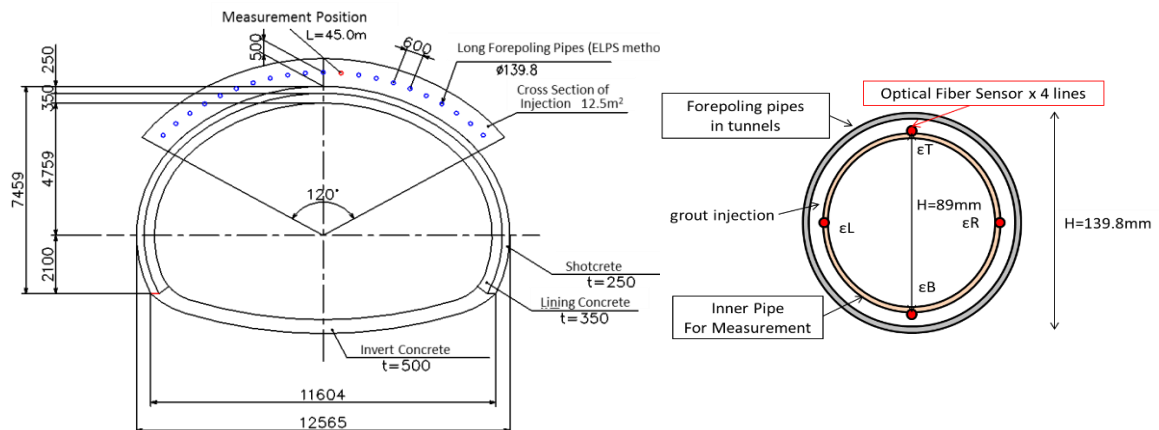


Figure 6. Tunnel (left) and smart rod (right) dimensions

The displacements were obtained using the integration method (Eq. 3) and displayed in real-time by NeugreGate system. This provided an engineering team valuable information and helped to control the speed of the excavation process and ensure its safety. Other application examples will be presented at the conference.



Figure 7. Smart rod installation process (left) and ELSP (right)

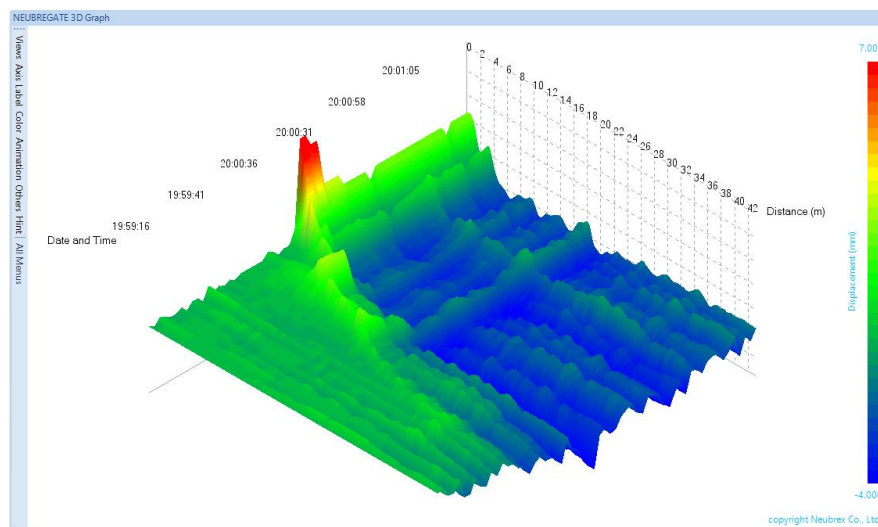


Figure 8. Tunnel deflection as a function of time in NeubreGate results viewer module

## 6 CONCLUSIONS

This paper discussed the requirements of the tunnel displacements monitoring system. It outlined the design of several fiber layouts, presented the required interrogators capabilities and parameters. Finally, an example application using the smart rod to provide real-time deflection values during tunnel excavation process was presented.

## 7 REFERENCES

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