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Fiber Optic Sensing Technologies for Structural Health Monitoring of Underground Infrastructure

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1. ABSTRACT

Monitoring underground infrastructure is crucial to early-stage damage detection and prevention of catastrophic failures. Fiber optic-based monitoring systems provides a promising engineering solution for the timely detection of early damage. Fiber optic-based monitoring systems use quasi-distributed and continuously distributed sensing based on a variety of techniques, including, Fiber Bragg Gratings (FBG), Optical Time-Domain Reflectometer (OTDR), and Optical Frequency Domain Reflectometer (OFDR). In such systems, a standard single-mode optical fiber/cable connected to an interrogation device is deployed. These systems are easy to install, capable of autonomous operation, and designed to measure strains due to mechanical and thermal stresses. The application of this fiber optic–based sensing technology protects structural health by sensing (1) pipeline buckling, damage or leaks caused by construction activities, farming, illegal tapping, or sabotage, and (2) cracks or openings in underground tunnels which may further lead to severe failure. This paper aims to review the current state-of-the-art of fiber optic sensing/monitoring technologies for damage detection of underground infrastructure (pipelines and tunnels), as well as damages that can occur during trenchless installation of new structures. Moreover, the paper will introduce some innovative concepts for employing this sensing technology for continuous inspection of ongoing trenchless work in areas of different pipe rehabilitation techniques.

2. INTRODUCTION

Predicting the long-term behavior of underground infrastructures such as pipelines and tunnels can be very challenging when considering a wide variety of nearby geologic conditions and nonlinear soil/rock properties. Long-term monitoring of these structures is crucial to early-stage damage detection and prevention of catastrophic failures. Field measurements and dynamic modal analyses are more feasible than theoretical models for predicting the condition and performance of these structures. In general, underground or subsurface monitoring can be categorized into two groups; (1) by conducting in-situ tests to determine geotechnical properties such as shear strength, permeability and compressibility; and (2) by monitoring specific parameters including inclination, displacement, and crack of existing underground structure.

Trenchless techniques are widely used in applications such as new installation of pipelines; replacement or rehabilitation of existing underground pipeline infrastructure; and building underground tunnels, with minimal disruption to traffic, business and other activities as opposed to open trenching/excavation. Recent developments in trenchless techniques are proved to be cost-effective alternatives to open trenching (Rabiei et al., 2017; Bascom et al., 2016; Kramer, 2012). The increase in costs is typically due to inadequate monitoring of trenchless construction with elevating risks causing geological and structural failures. Deployment of distributed sensors allows effective monitoring and the potential to reduce the risks associated with such failures.

Recent advancements in fiber optic sensing techniques offer unique advantages for i) long-term monitoring, ii) large distances (in the range of several kilometers), and iii) early detection of risks associated with damage of underground infrastructures (Leung et al., 2013). One of the distinct advantages of fiber optic sensors is their ability to measure physical quantities (such as displacements, inclination and strains) continuously distributed over the full length of the fiber. The geometry and versatility of these sensors allow them to be effectively integrated into structures for monitoring strains that could assist in providing early warning signals related to timely detection of damage to prevent catastrophic failures from happening. In order to measure distributed strains over the full length of a fiber, several techniques have been proposed, including Fiber Bragg Gratings (FBG), Optical Frequency Domain Reflectometry (OFDR), and Stimulated Brillouin Scattering (SBS) (Annamdas, 2011). However, SBS has been widely used for high-resolution strain measurements distributed over long distances (Garus et al., 1997; Bernini et al., 2009). FBG is used for quasi-distributed strain measurement using numerous gratings at discrete locations along the fiber (Ramakrishnan et al., 2016). On the other hand, OFDR is used for strain measurements for short distances with high spatial resolution (Froggatt and Moore, 1998; Lopatin et al., 2000). Applications of fiber optic–based sensing technology allow engineers to monitor structural health by sensing (1) pipeline buckling, damage or leaks caused by construction activities, farming, illegal tapping, or sabotage, and (2) cracks or openings in underground tunnels which may further lead to severe failure. Also, these sensing systems are easy to install, capable of autonomous operation, and are designed to measure strains due to mechanical and thermal stresses.

The objective of this paper is to review the current state-of-the-art of optical fiber sensors for damage detection of existing underground infrastructures (pipelines and tunnels), as well as the damages that can occur during trenchless installation of new structures. Moreover, novel concepts for deploying fiber optic-based sensing technology in continuous monitoring of ongoing trenchless work for pipe rehabilitation are introduced.

3. FIBER OPTIC SENSING TECHNIQUES

An overview is shown in Figure 1 to illustrate the components in fiber optic monitoring systems.

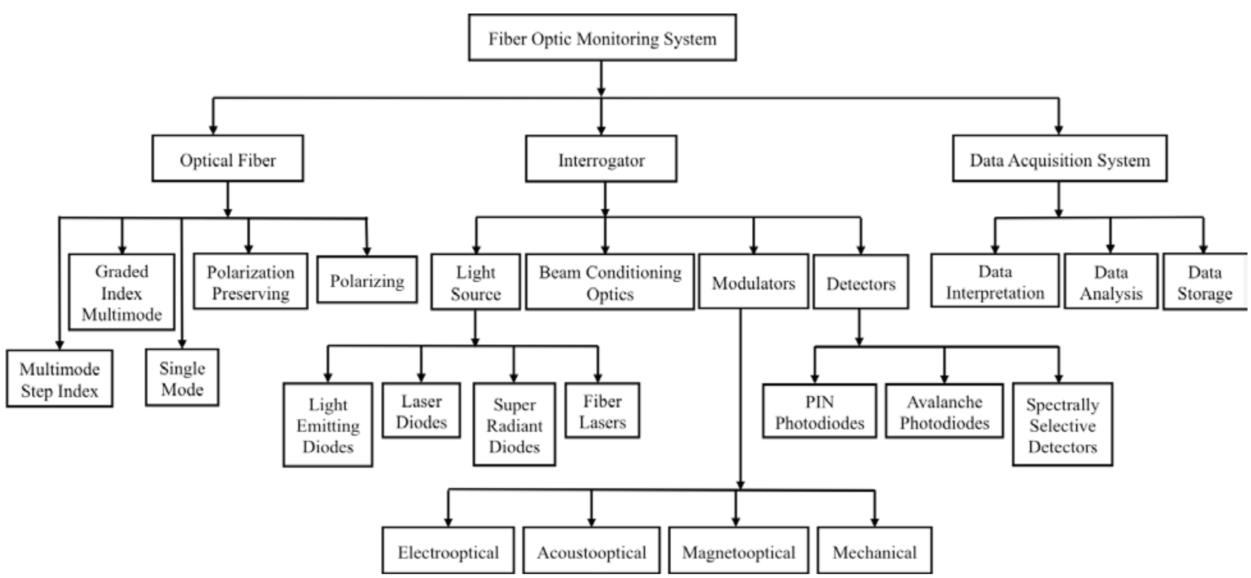


Figure 1. Overview of fiber optic monitoring systems

3.1 Fiber Bragg Grating (FBG)

Fiber Bragg Grating (FBG) is one of the most popular fiber optic sensing (FOS) techniques. FBG is a distributed Bragg reflector fabricated inside the optical fiber with a periodic variation of refractive index highly sensitive to specific wavelengths of light (Kashyap, 1999). Figure 2 shows a typical cross section of the FBG sensor and its working principle. In FBG, the wavelength corresponding to the period of index variation (λ_B) is reflected and recorded differently when a broadband or a tunable signal passes through the optical fiber. The Bragg wavelength λ_B and the periodic spacing of the grating are related by (Hill and Meltz, 1997; Rao, 1997):

$$\lambda_B = 2n_e\Delta \qquad [1]$$

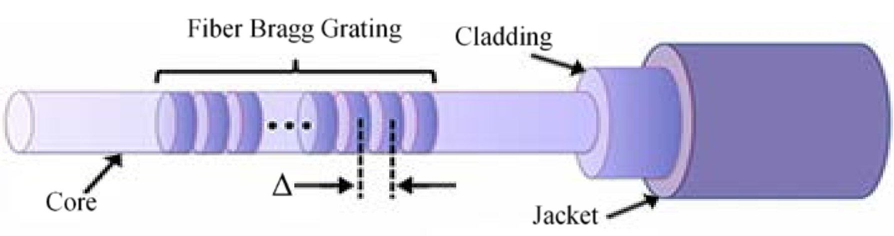
where n_e is the effective refractive index of the core of the grating.

When an optical fiber is subjected to mechanical strain (ε_m) or temperature variation (ΔT), the measured λ_B will change in its frequency domain. This change is associated with a peak shift in the reflected wavelength, which can be distinguished/detected by using a tunable laser, spectrometer, or a wavelength filter. The shift of Bragg wavelength and the total induced axial strain are related by (Kashyap, 1999)

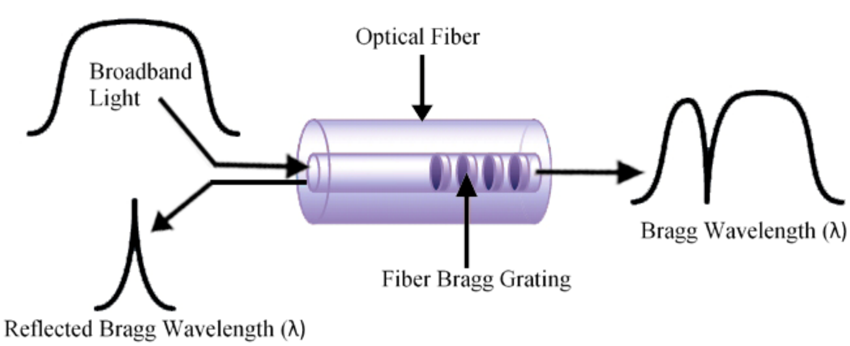
$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon_m + (\alpha + \tau)\Delta T \qquad [2]$$

where p_e, α and τ are strain-optic coefficient, thermal expansion coefficient and thermal-optic coefficient, respectively. For silica fibers, $\tau = 7\text{x}10^{-6}\ ^oC^{-1}$, $\alpha = 5.5\text{x}10^{-7}\ ^oC^{-1}$, and $p_e = 0.252$ (Wang et al., 2013; Bertholds and Dandliker, 1988). Eq. [2] provides the theoretical basis for strain and temperature measurements using FBG.

To obtain strain measurements at more than one point, gratings of different periods are placed at various points along the fiber. The reflected signal will then exhibit a number of peaks corresponding to individual gratings at different locations. In other words, the shift of Bragg wavelength corresponds to the total induced strain at the location of a grating (sensing node). Such a feature qualifies FBG as a point-sensing technique.



(a)



(b)

Figure 2. (a) A typical cross section of FBG sensor and (b) illustration of its working fundamental principle of FBG Sensor (Revised from National Instruments, 2016).

3.2 Optical Time Domain Reflectometry (OTDR)

Optical Time Domain Reflectometers (OTDR) have been the preferred choice for distributed sensing techniques. In this technique, an optical pulse is injected into the fiber and the amount of light that is backscattered or reflected is measured by a photo detector as the pulse propagates through the fiber. The reflected signal is referred as Rayleigh signature which depicts an exponential decay with time that is directly correlated to the linear attenuation of the fiber (Barnoski et al., 1977). Raman and Brillouin scattering phenomena (as shown in Figure 3) (Culverhouse et al., 1989; Horiguchi et al., 1989; Horiguchi et al., 1992; Tateda et al., 1990) have been used for distributed sensing where Brillouin has enhanced range of OTDR compared to Raman for strain and temperature monitoring applications. Brillouin scattering occurs due to the interaction of the propagating optical signal with the material waves (GHz range) present in a medium which in this case is silica fiber. The optical signal undergoes diffraction on a dynamic grating which is generated by the material wave. This diffracted signal experiences a Doppler shift as the grating propagates at the acoustic velocity in the fiber. The acoustic velocity is directly associated to the density of the medium that is temperature and strain dependent. As a result, the so-called Brillouin frequency shift carries the information about the local temperature and strain of the fiber (Figure 3).

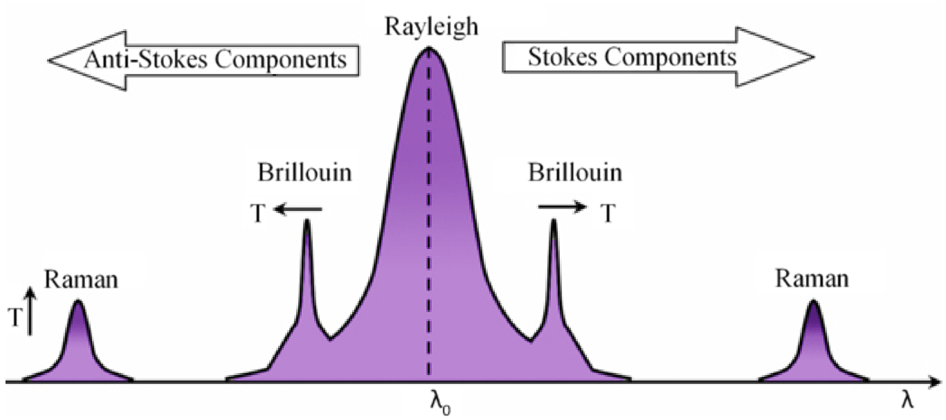


Figure 3. Optical scattering components in optical fibers. (Revised from Zhou et al., 2012)

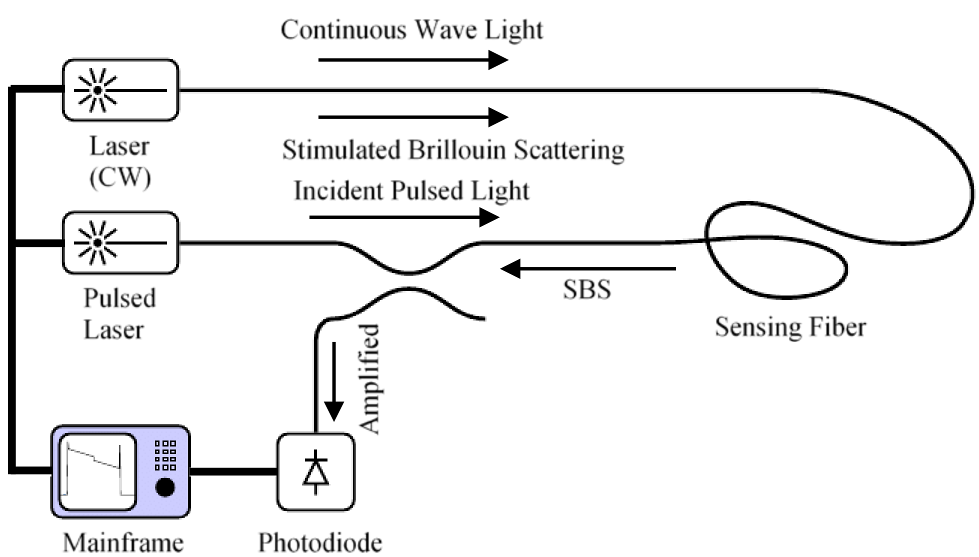


Figure 4. Working principle of OTDR (Revised from Schenato, 2017).

In Figure 3, it can be seen that the backscattered light is divided into Stokes (*S*) and anti-Stokes (S_A) components. Upon photoexcitation, the Stokes and anti-Stokes components of a mechanically stressed and thermally disturbed optical fiber are shifted in a Raman spectrum (Gorshkov et al., 2017). As a result, strain is linearly dependent on the intensity change of each of the Stokes and anti-Stokes components. Temperature, on the other hand, is nonlinearly dependent on these components. Therefore, a linear approximation is considered with relative changes of the Stokes (δS) and anti-Stokes (δS_A) components to calculate strains and temperature. These approximations are given by (Lu et al., 2017)

$$\begin{bmatrix} \delta S \\ \delta S_A \end{bmatrix} = \begin{bmatrix} a_1 & a_2 \\ b_1 & b_2 \end{bmatrix} \begin{bmatrix} \Delta T \\ \varepsilon \end{bmatrix} \quad [3]$$

$$\begin{bmatrix} \Delta T \\ \varepsilon \end{bmatrix} = \begin{bmatrix} a_1 & a_2 \\ b_1 & b_2 \end{bmatrix}^{-1} \begin{bmatrix} \delta S \\ \delta S_A \end{bmatrix} \quad [4]$$

where ΔT and ε are temperature change and strain respectively; a_1, a_2, b_1 and b_2 are sensitivity coefficients. Note that δS and δS_A are products of normalization by the Stokes and anti-Stokes signals taken under initial conditions. Table 1 provides specifications of a commercial OTDR system as an example (Leung et al., 2013). Eq. [3] and [4] provide the theoretical basis for strain and temperature measurement using OTDR. Furthermore, it is also popular to use the Stokes/anti-Stokes component ratio for temperature measurement.

Table 1. Specifications of a commercial OTDR system (Leung et al., 2013)

Spatial Resolution	1 m
Strain Resolution	30 microstrains
Temperature Resolution	0.2ºC
Measurement Range	30 km

Three derivative methods have been developed from OTDR. They are Brillouin Optical Time Domain Reflectometer (BOTDR), Brillouin Optical Time Domain Analysis (BOTDA), and Brillouin Optical Correlation Domain Analysis (BOCDA). BOTDR is based on the spontaneous Brillouin scattering and was initially introduced as a way to enhance the range of OTDR and with the advantage of monitoring the system from one end of the sensing fiber (Shimizu et al., 1994). On the other hand, BOTDA is based on stimulated Brillouin scattering. BOTDR is normally capable of long-distance distributed sensing with a sensitivity of 5 με, which is suited for large-scale applications of subsurface monitoring (Uchida et al., 2015). However, both BOTDR and BOTDA are limited to a spatial resolution (sampling rate in space) of roughly 1 m in current systems. Therefore, they are not suitable for large area monitoring applications requiring high spatial resolution (mush less than 1 m). Moreover, the measurement time required by a traditional BOTDR or BOTDA system is on the order of minutes (Bao and Chen, 2012), also depending on the total fiber length. This measurement time (sampling rate in time) constraint (Nyquist sampling theorem) becomes a serious drawback for dynamic measurement and monitoring for structural health, preventing the system from detecting smaller defects (higher frequencies). Different techniques have been studied with the intention to overcome these limitations (Feng et al., 2013), such as the Brillouin optical correlation domain analysis (BOCDA) that improves its resolution to the cm level (Hotate and Tanake, 2000; Imai et al., 2010; Belal and Newson, 2011).

3.3 Optical Frequency Domain Reflectometry (OFDR)

Compared to OTDR, a cost effective distributed sensor with millimeter scale spatial resolution was developed based on the Optical Frequency Domain Reflectometry (OFDR) of Rayleigh scattering (Froggatt and Moore, 1998; Froggatt et al., 2004; Kingsley and Davies, 1985; Soller et al., 2005).

While OTDR measures the intensity of Rayleigh backscattered signal, OFDR measures the interference fringes of the Rayleigh scattered light from a tunable laser source and a static reference fiber in frequency domain. The amplitude and phase in the frequency domain is converted into time or spatial domain by using inverse Fourier transform. The spatial resolution of OFDR (Δ_z) is determined by using the optical frequency sweep range of the tunable laser source (ΔF). Eq. [5] shows the relationship between Δ_z and ΔF (Eickhoff and Ulrich, 1981).

$$\Delta_z = \frac{c}{2 n_g \Delta F} \quad [5]$$

where c and n_g are the speed of light in vacuum and the group refractive index, respectively. In OFDR, the offset from the desired frequency (i.e., frequency shifts, ΔF_T and ΔF_ε) induced by temperature and strain changes (ΔT and Δε) can be described by the following equation (Li et al., 2013):

$$\begin{bmatrix} \Delta F_T \\ \Delta F_\varepsilon \end{bmatrix} = \begin{bmatrix} \chi_{TA(x)} & \chi_{\varepsilon A(x)} \\ \chi_{TB(x)} & \chi_{\varepsilon B(x)} \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta \varepsilon \end{bmatrix} \quad [6]$$

The elements $\chi_{TA(x)}$, $\chi_{TB(x)}$, $\chi_{\varepsilon A(x)}$ and $\chi_{\varepsilon B(x)}$ are coefficients of frequency shift with respect to temperature and strain, and x denotes segment cell at the particular position along the optical fiber. Equivalently, Eq. [6] can be written as

$$\begin{bmatrix} \Delta T \\ \Delta \varepsilon \end{bmatrix} = \begin{bmatrix} \chi_{TA(x)} & \chi_{\varepsilon A(x)} \\ \chi_{TB(x)} & \chi_{\varepsilon B(x)} \end{bmatrix}^{-1} \begin{bmatrix} \Delta F_T \\ \Delta F_\varepsilon \end{bmatrix} \quad [7]$$

To overcome the limitations of BOTDR, Brillouin Optical Frequency Domain Analysis (BOFDA) was developed, consisting of a light source, light detection components and data acquisition units (Gogolla and Krebber, 1997; Nöther et al., 2008). Figure 5 shows a schematic diagram of a typical BOFDA system. In BOFDA, the Stokes beam emitted from laser is amplified by stimulated Brillouin scattering, and the excited, modulated beam is compared with transmitted beam in amplitude and phase (as a complex transfer function) by a vector network analyzer. The pulse response in time domain is obtained by inverse Fourier transform of the complex transfer function. A photodiode (PD) is used in light detection component to detect the beats of a laser. A digital spectrum analyzer measures the beat frequency (Eickhoff and Ulrich, 1981) and the results are sent to a frequency controller. The frequency controller calculates the offset from the desired frequency for strain and temperature information. Table 2 provides specifications of a commercial BOFDA monitoring system (Leung et al., 2013).

Table 2. Specifications of a commercial BOFDA monitoring and data acquisition system (Leung et al., 2013)

Spatial Resolution	1 m
Strain Resolution	2 microstrains
Temperature Resolution	0.1°C
Measurement Range	12 km
Data Acquisition Duration	30 sec (200m) 300sec (12 km)

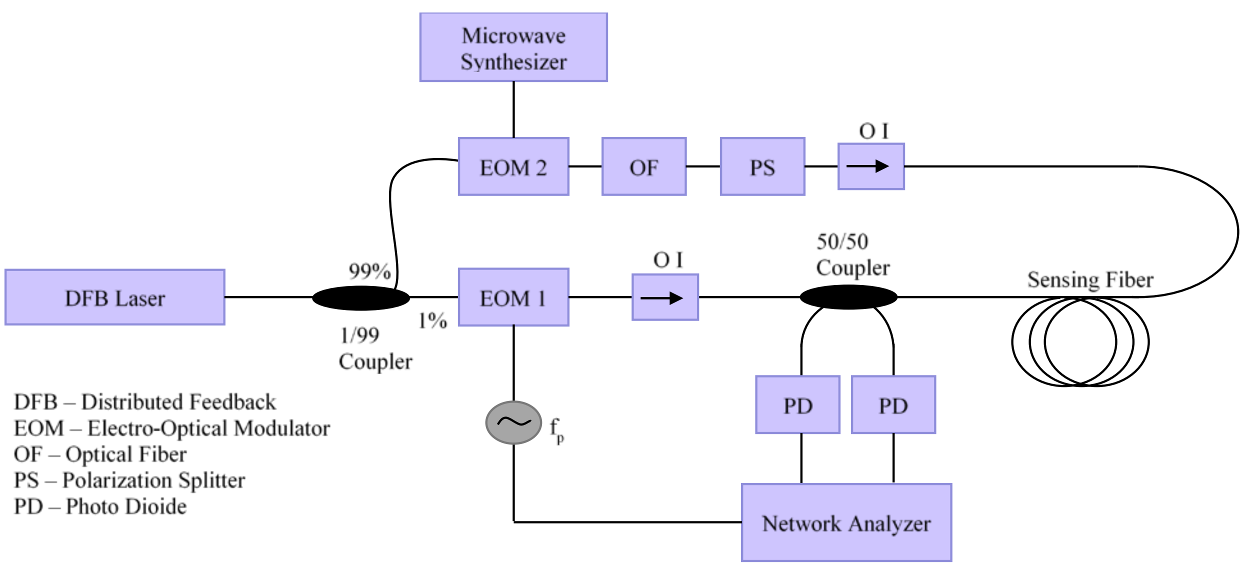


Figure 5. Working principle of BOFDA (Revised from Bernini et al., 2005)

4. APPLICATIONS OF FIBER OPTIC SENSORS (FOS) IN UNDERGROUND INFRASTRUCTURE

An overview flowchart is provided in figure 6 to illustrate the monitoring applications of underground infrastructure using fiber optic sensing technologies.

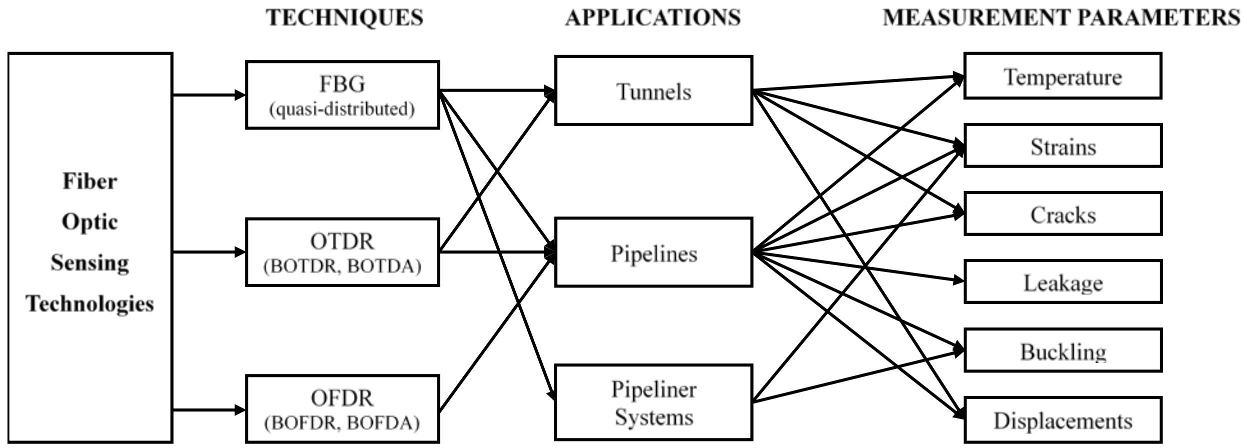


Figure 6. Overview of monitoring applications of underground infrastructure using fiber optic sensing technologies

4.1 Tunnels

Compared to conventional methods, fiber optic sensors (FOS) provide accurate and efficient means to monitor the structural health of the concrete lining in tunnels. Figure 7 shows the application of single mode telecommunication optical fibers by using epoxy adhesive on the surface of a concrete tunnel lining. In such applications, the strain along the optical fiber can be measured by using Brillouin Optical Correlation Domain Analysis (BOCDA) (Imai et al., 2005; Imai et al., 2010; Song and Hotate, 2007). However, the spatial resolution of strain distribution in such a scenario is reported to be less than 100 mm (Leung et al., 2013). Accuracy of the strain measurement deteriorates with measuring distance and hence, the consideration of temperature and optical polarization issues becomes important. This approach is also suitable for dynamic strain monitoring at any arbitrary location, due to faster sampling rates.

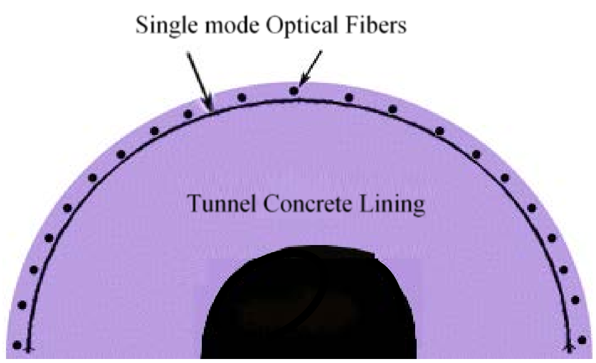


Figure 7. Application of FOS for monitoring a tunnel concrete lining (Revised from Leung, et al., 2013)

The fiber optic distributed sensing approach can also be applied to monitor multiple processes associated with tunneling. One of the monitoring processes in existing tunnels is to evaluate induced stresses and the displacement (vertical and horizontal) caused by disturbances or activities associated close to the underground tunnel (figure 8) (Vorster et al., 2006; Mohamad et al., 2010; Mohamad et al., 2011). The measured induced stresses and the displacement changes can be used to calculate greenfield parameters such as the volume loss and the inflection point (associated with the settlement trough). Other applications of distributed fiber optic sensor include detection and characterization of cross-border smuggling tunnels (figure 9) have been reported by Klar and Linker (2010) and Linker and Klar (2013). Advanced signal processing techniques such as wavelet transforms can also be used in such applications.

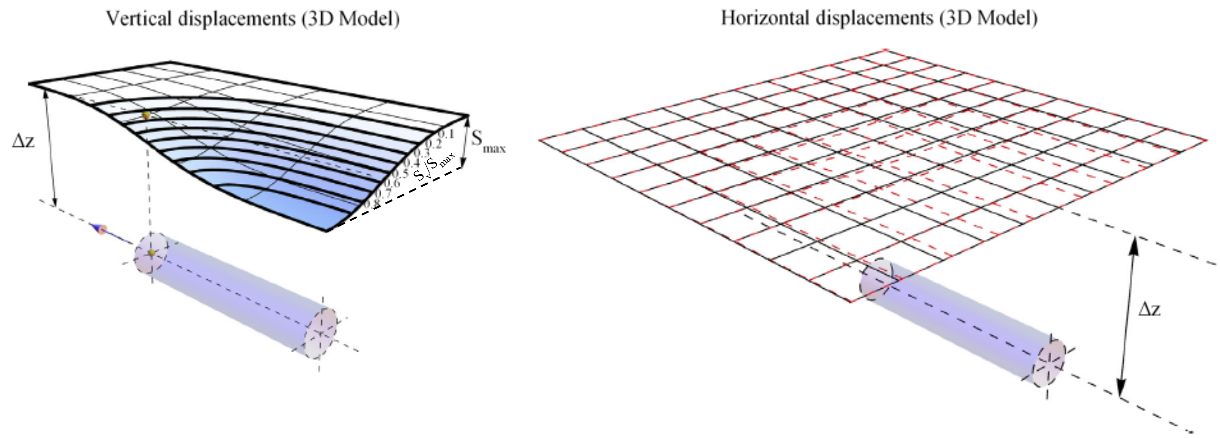


Figure 8. Illustration of vertical and horizontal ground displacements (Revised from Klar et al., 2014)

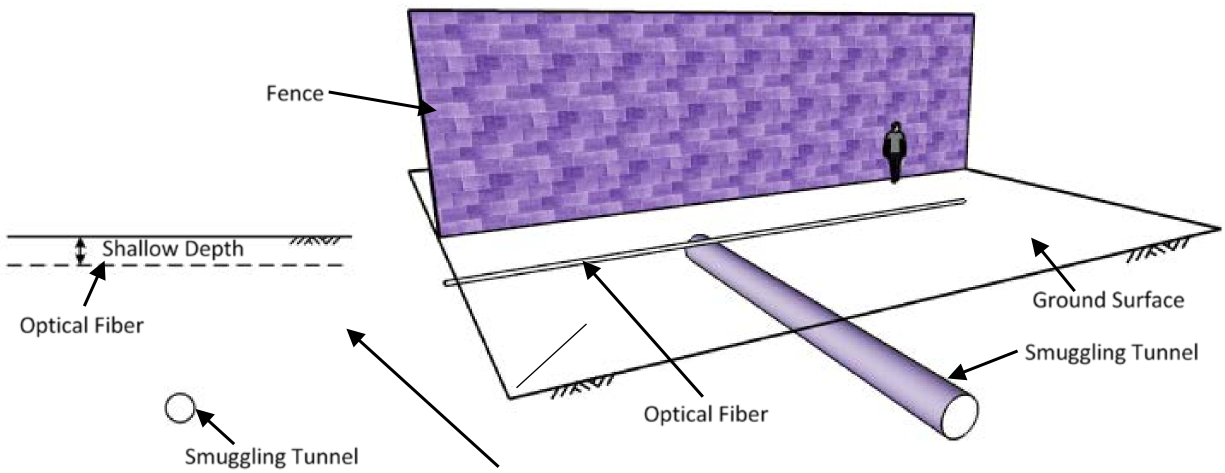


Figure 9. Detection of smuggling tunnel using FOS (Revised from Linker and Klar, 2013)

Additionally, fire hazard also represents a safety concern for tunnels. It is necessary to detect and determine the exact location of a fire in a timely fashion for emergency response. The use of point sensors can be expensive and impractical for fire detection. A distributed temperature sensing system based on Raman optical time domain reflectometry has been used in Xuanwu Lake tunnel located in China (Sensornet: Case studies, 2013). A single optical fiber link was attached along the crown (expected to be the hottest location as fire causes hot air to rise up) of the tunnel, using fixtures with design life of 30 years. The sensing system was tested in a simulated fire with ignition of a 50 cm diameter basin of diesel and the fire location was exactly identified in 80 s (Sensornet: Case studies, 2013).

4.2 Pipelines

The main characteristic of pipelines is the longitudinal length. Conventionally, leak detection in pipelines is based on point sensors or the measurement of mass flow rate at certain points. However, these methods cannot be applied directly to detect exact location of leaks in the pipeline. Methods such as visual inspection of pipelines can help in investigating the location of leaks but may not be cost-effective. In such applications, the use of distributed fiber optic sensors (based on BOTDR) can provide an advantage over aforementioned techniques. The fiber optic sensors can be installed with the thermoplastic tape to monitor deflections, strains and temperature changes that could assist in the detection of leakages in pipelines. Figure 10 shows a cross-section of fiber optic sensors installed within the thermoplastic tape and bonded to the whole length of the pipeline (Inaudi and Glisic, 2005; Inaudi and Glisic, 2006). The strain and temperature resolutions in such applications is reported to be in the range of 20 microstrains and 1^{o}C, respectively, with spatial resolution up to 1.5 m (Inaudi and Glisic, 2006). The strain values influenced by changes in temperature along the pipeline can be calibrated by continuously measuring temperature along the length of the pipeline. A significant variation of temperature along the pipeline helps in detecting the location of the leakage. In gas pipelines, a local drop in temperature along the pipeline can be observed. For example, the leakage of ethylene may reduce the temperature along the pipeline locally to -110ºC when it is depressurized to its natural gaseous state. By using Raman optical time domain reflectometer, the precise location of temperature drop can be identified in real time. In the case of buried liquid pipelines, single mode telecommunication silica optical fiber is installed along the pipeline. The placement of fiber optic sensors in gas pipelines and liquid pipelines can be seen in figure 11. For best results, the temperature sensing cable is placed in direct contact with the surface of the gas pipeline and installed below the pipeline for liquid pipelines (Inaudi and Glisic, 2005; Inaudi et al., 2008; Sensornet: Case studies, 2013).

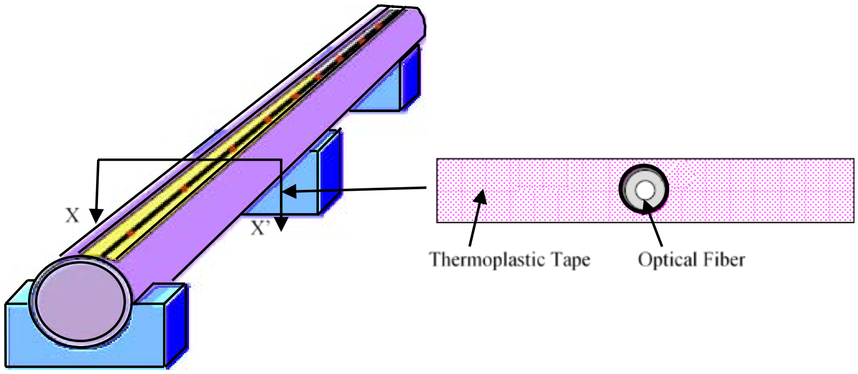


Figure 10. Cross- section and application of sensing tape (Revised from Inaudi and Glisic, 2007)

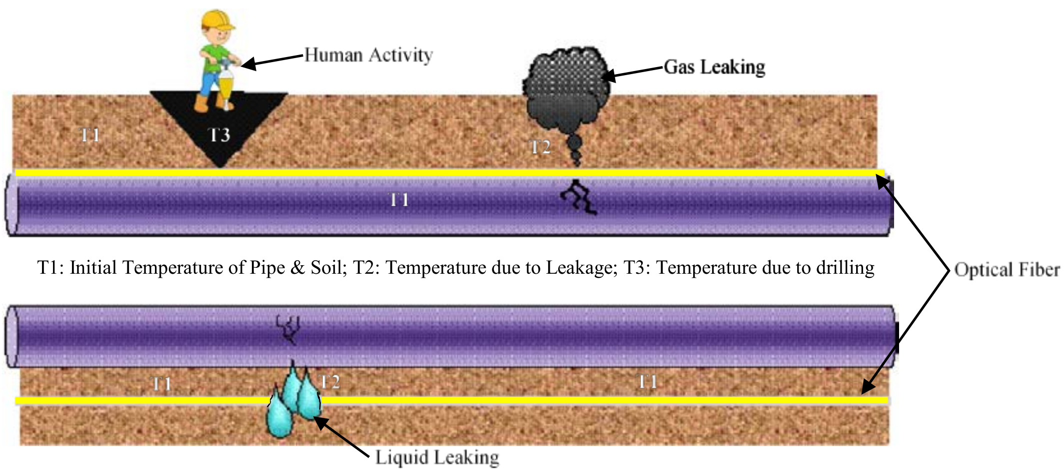


Figure 11. Detection of gas/liquid leak through a cable placed on/under the pipeline (Revised from Inaudi and Glisic, 2007)

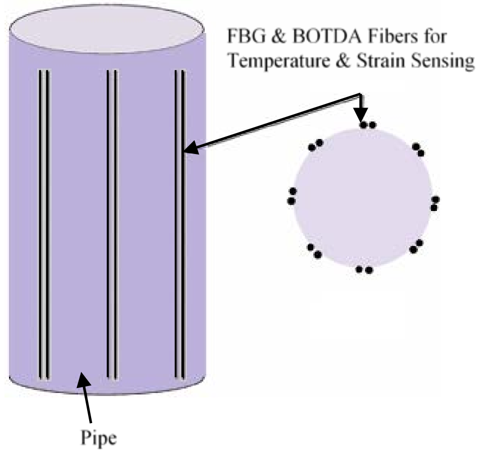


Figure 12. FBG and BOTDA fiber sensors attached along the longitudinal direction of the pipe for temperature and buckling detection (Revised from Leung et al., 2013)

In the case of oil pipelines, the fiber optic sensors (such as distributed Brillouin sensor) can also be used in the investigation of pipeline buckling where the use of point sensors and visual inspection is not feasible (Ravet et al., 2006; Ravet et al., 2007; Zou et al., 2006). In a case study reported in Daqing Oilfield, single mode optical fiber was embedded in Fiber Reinforced Plastic (FRP) to monitor strain variation during grouting of the downhole and well perforation (Zhou et al., 2010; Leung et al., 2013). The FRP along with fiber optic sensor was clamped on the surface of the vertical well pipe and cemented. Moreover, the FBG strain sensors were installed at critical locations such as the welded joints. In such applications, when pipelines are subjected to sudden temperature change, the large thermal induced compressive stress may cause buckling of pipe. Several silica optical fibers were installed on the circumference of pipeline along the longitudinal direction as shown in figure 12 (Leung et al., 2013). A spatial resolution in the range up to few centimeters and a strain accuracy of 15 microstrains was achieved along the whole length of the pipeline that extended over tens of kilometers. The buckling locations could be identified by the ripples of the strain distribution before the pipeline rupture. The hoop strains can be calculated based on measured strains at different angular positions along the pipeline.

4.3 Pipe Liner Systems

The use of pipe liners in the rehabilitation of sewer and water mains has increased significantly due to recent advancements in trenchless technologies. Pipeline rehabilitation techniques such as Cured-in-Place Pipe (CIPP), Deform-Reform Pipe (DRP) and Fold-and-Form Pipe (FFP) are used to restore long-term service to a defective pipeline. The use of these techniques offers many advantages including elimination or reduction of the inflow of storm water, exfiltration of pollutants, and infiltration of groundwater. A pipe liner is designed to withstand the hydrostatic pressure caused by groundwater that may infiltrate through the cracks in the host pipe. The physical properties of a pipe liner can be affected by soil consolidation. The maximum strain in a pipe liner around the circumference can be determined by superimposing the flexural and compressive stress components. Fiber optic sensors have the potential to provide reliable performance on rehabilitated pipelines under extreme conditions, improving the design guidelines and the reliability of the pipe liners. Also, fiber optic sensors can be used in by reducing the repair cost of pipelines as well.

In a case study (Saber and Sterling, 2005), optical sensors based on Fiber Bragg Grating (FBG) were embedded in a pipe liner system (Figure 13) to monitor the strains in the repaired pipe liner. The location and orientation of the FBG sensors were determined based on finite element analysis. Experimental results showed that the buckling loads and strain distribution provided by the FBG sensors do not correlate with theoretical values, suggesting the challenges of theoretical calculation and the importance of in-situ monitoring systems.

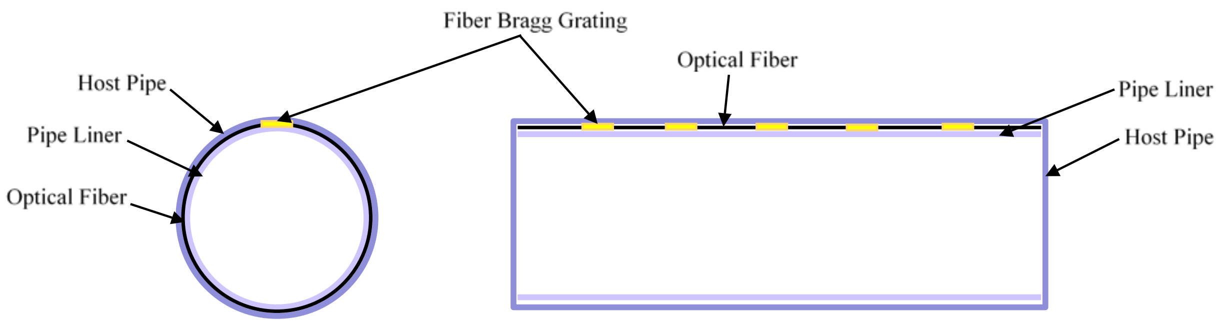


Figure 13. Schematics of FBG Sensors installed in pipe liner (Revised from Saber and Sterling, 2005)

5. SUMMARY AND CONCLUSIONS

Monitoring the long-term behavior of civil infrastructure such as pipelines and tunnels can be challenging, considering the nearby geologic conditions and non-linear soil and rock properties. This paper reviews current state-of-the-art monitoring technologies for early-stage damage detection of underground infrastructures and for preventing catastrophic failures from happening. Several novel trenchless techniques have been proposed to monitor and repair underground infrastructure in the trenchless technology industry. Currently, trenchless techniques are widely used in applications such as new installation of pipelines, replacement or rehabilitation of existing underground pipeline infrastructure, and building underground tunnels, with minimal disruption to traffic, business and other activities as opposed to open trenching. However, the use of fiber optic-based sensing systems is still in its infancy in the industry. This paper provides a critical literature review of different fiber optic sensing (FOS) technologies that are suitable for monitoring of tunnels, pipelines, and pipe liners. Moreover, innovative ideas for employing FOS sensors for continuous inspection of ongoing trenchless work in areas of different pipe rehabilitation techniques are presented in this paper.

Fiber optic sensors offer unique advantages over other conventional techniques in the long-term monitoring of underground infrastructures over large distances (in the range of several kilometers), and could help in early-stage detection of risks associated with the damage or failure of these structures. One of the distinct advantages of fiber optic sensors is their ability to measure physical quantities (such as displacements, inclination and strains) continuously distributed over the full length of the fiber. The geometry and versatility of these sensors allow them to be effectively integrated into structures for monitoring strains that could assist in providing early warning signals related to timely detection of damage to prevent catastrophic failures. Several FOS techniques such as FBG, OTDR and OFDR followed by their applications have been reviewed. While it was difficult to include all the examples, a few case studies were considered to validate the use of FOS on-site or in the final stage of laboratory prototyping. Sensor design, implementation and its performance specific to underground applications have been discussed. These case studies clearly prove that the deployment of FOS sensors monitors structural health by sensing (1) pipeline buckling, damage or leaks caused by construction activities, farming, illegal tapping, or sabotage, and (2) cracks or openings in underground tunnels which may further lead to severe failure. The simplicity, cost-effectiveness, and robust performance of this technology enable it to be employed as an effective monitoring approach. In conclusion, fiber optic sensors have shown a potential over other conventional methods in the monitoring of underground infrastructure.

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