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Temperature Sensing in Underground Facilities by Raman-OFDR Using Fiber-Optic Communication Cables

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Abstract

Gaining information on climatic conditions in subway tunnels is the key to predicting the propagation of smoke or toxic gases in these infrastructures in the case of a fire or a terrorist attack. As anemometer measurements are not suitable, the employment of alternative monitoring methods is necessary. High-resolution temperature sensing with Raman-OFDR using optical communication fiber cables shows great potential as it allows the surveillance of several kilometers of underground transport facilities without the need for installing sensing equipment in the tunnels. This paper presents first results of a study using this approach for monitoring subway tunnels. In the Berlin subway, temperature data gathered from newly-installed as well as pre-existing communication cables were evaluated and compared to reference data from temperature loggers. Results are very promising as high correlations between all data can be achieved showing the potential of this approach.

Key words: distributed temperature sensing, Raman-OFDR, underground transport facilities, temperature monitoring

Introduction and Motivation

Correct climatic boundary conditions are fundamental for achieving relevant results from computational fluid dynamic (CFD) simulations. This is of particular importance for predicting the propagation of fire-induced smoke in underground transport facilities. For instance, the velocity and direction of air flow in tunnels of a subway system are quite complex. During operation, running trains push air forward, described as the well-known piston effect [1]. In case of a subway fire, train traffic is stopped immediately, and the background airflow re-establishes within a few minutes [2]. Knowledge on the flow velocity in the adjacent tunnels is required to set up valid CFD simulations for predicting the propagation of smoke and for identifying safe evacuation routes.

Gaining the airflow information from anemometer readings is not suitable. Monitoring each tunnel mouth of each station in a subway system would lead to a massive application of anemometers which will cause tremendous costs due to the high numbers of devices and especially the required wiring and installation work. Airflow, however, can be derived from temperature information along the tunnels by using the distributed temperature sensing (DTS) method, based on the Raman scattering-effect [3]. Subway systems already have a wide network of optical fiber cables installed, so it is a promising idea to use those for temperature sensing. This study focusses on stepping forward to gaining airflow information of subway systems for reasonable costs.

Temperature Sensing Method

The techniques used in this study are based on the method of distributed temperature sensing (DTS). DTS systems are based the fact that an optical fiber can function as a linear sensor as well as a transmission medium. Thus, DTS devices are an interesting alternative to multiplexed point measurement since one fiber-optic cable can replace thousands of single sensors and therefore reduce the costs for installation, maintenance and readout while simplifying the whole process of data acquisition [4].

DTS devices can measure temperatures of the surrounding environment along the full length of the sensor up to several tens of kilometers range. Physical effects change the scattering of light in the fiber in a way that allows a highly accurate determination of the location and size of external effects like changes of air temperature [5].

The optical frequency domain reflectometry (OFDR) is characterized by both a high sensitivity and a large dynamic measurement range. First OFDR systems used Rayleigh scattering for sensitive measurement of fiber attenuation. The techniques used in this study use OFDR measurements of Raman scattering for temperature monitoring. OFDR devices operate lasers in a quasi-continuous wave mode and use narrow-band heterodyne detection of backscattered photons. This results in a waer-free laser operation and in high signal amplitudes of the measured signals [5, 6].

The LIOS controller employed in this study uses a three-channel design with an additional reference channel besides the two channels for measuring the Raman Stokes and anti-Stokes bands [7].

Set up of Measurements

Inside the Berlin subway system, a Raman-OFDR-DTS measured temperature profiles along a 1-km and a 2-km tunnel route including two subway stations using a dedicated fiber-optic sensor cable with two optical fibers connected to the OFDR controller device. In addition four fibers of a pre-existing communication cable with up to 144 fibers where also used for temperature sensing. Channel 2 (new sensor cable) and Channel 3 (pre-installed communication cable) connect the subway stations Osloer Straße (Olu) and Residenzstraße (RE), crossing the station Franz-Neumann-Platz (FN), while Channel 1 (new sensor cable) and Channel 5 (pre-installed communication cable) head south to the station Pankstraße (Pk).

Several stand-alone temperature loggers were also installed along the cable to validate the temperature data (see Fig. 1). The optic fiber links are patched at every station, which leads to extra losses. This introduces higher demands for the temperature calibration on each segment. Temperature data was logged at the beginning, termination and patch link of the cables.

Recorded Temperatures in the Tunnels

Figure 1 also shows the temperatures from June 2016 to February 2017. At a glance, great similarities between the new sensor cable and the pre-installed communication cable become apparent. Although the data range does not cover a full year, shifted annual variations could be observed. The temperature maxima were recorded in October while the minimum occurs in March. This shifting effect is due to the depth of the tunnels.

On a closer look cold spots were observed at several distances from the OFDR controller, which correspond quite well to the locations of emergency exits and other openings to the above ground. The sidings north of Osloer Straße are used to park non-operating trains during the night break causing the hot area observable around 100 - 200 m in channel 2 and 3.

Sensor Calibration and Localization of Control Loggers

In addition to pre-calibration done by LIOS software, data were calibrated by the authors using data loggers at positions near the ending points of the fiber-optic cables. With these reference temperatures, we could eliminate the effect of differential attenuation between Stokes and anti-Stokes signals increasing with increasing distance from the controller module.

To assess the measurement quality of the fiber optic cables, the exact position in terms of cable meter at the location of the stand-alone loggers must be known. This was achieved by cooling the fiber-optic cables using freezing spray (See Fig. 2).

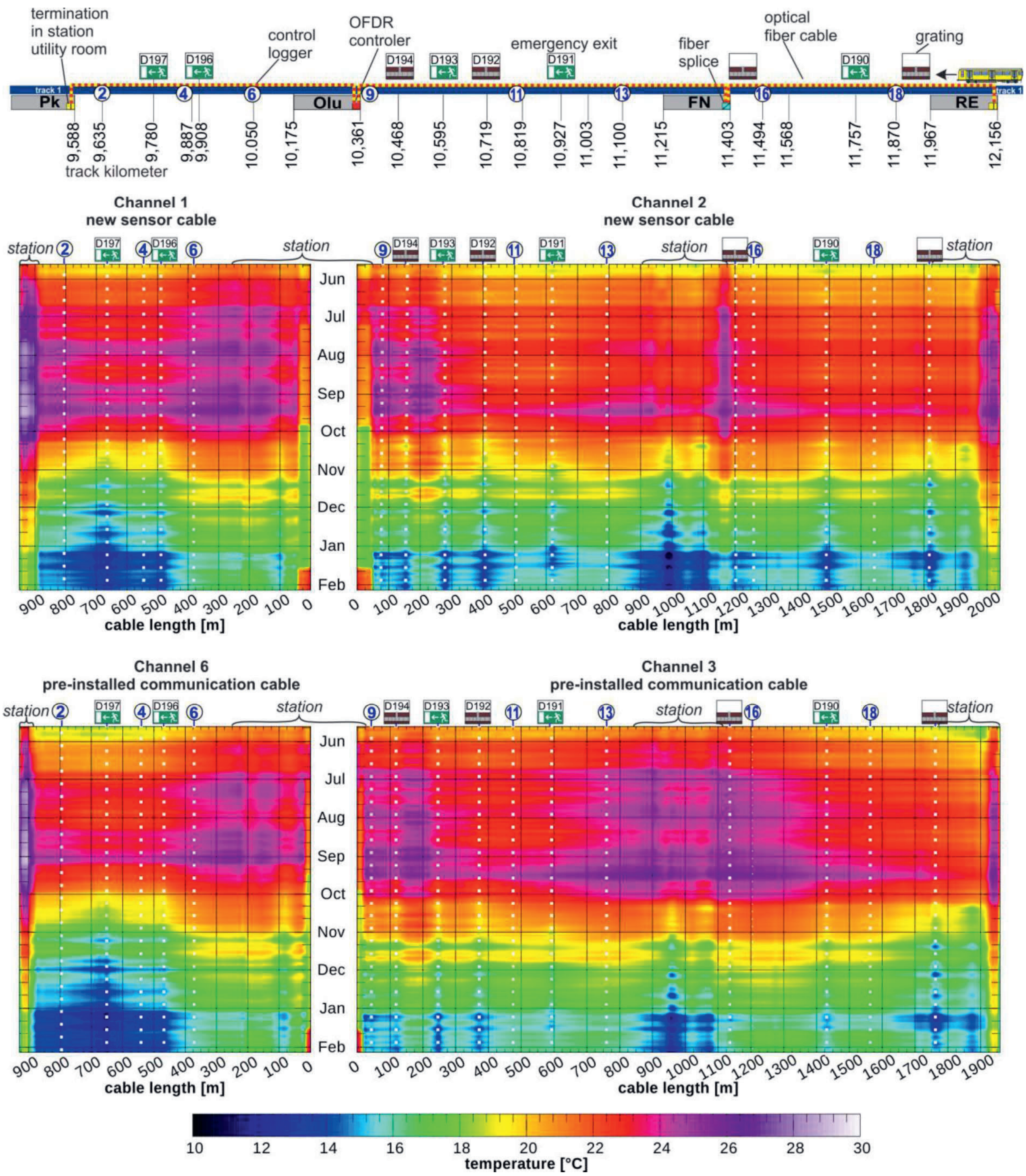

Fig. 1 Set up of measurements (top) and recorded daily mean temperatures by new sensor cables (middle) and pre-installed communication cables (bottom) between June 2016 and February 2017. The observed temperatures of the new sensor cable and the pre-installed communication cable are very similar. Cold spots are clearly associated with the emergency exits and gratings. Channel 1 and 6 showed a relatively cool tunnel section at about 650 m and 700 m, which is related to the above flowing river Panke. Between 100 m and 200 m a warm section was observed in Channel 2 and 3, which is exactly the location auf siding tracks, where trains park during off-peak and cause additional heat transfer. Inside the station, the cable tray is located underneath the platforms (cooler areas) and inside utility rooms (warmer areas).

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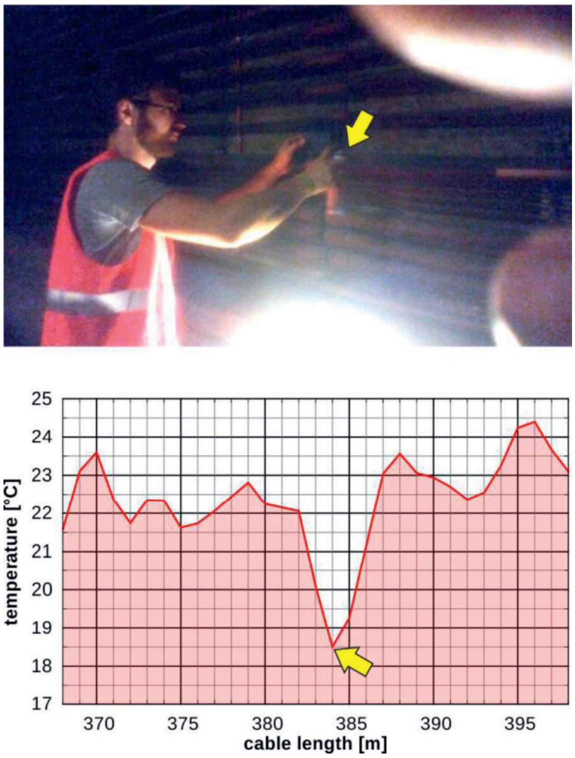

Fig. 2 Localization of exact positions by using freezing spray (top) and the response of recorded temperature of the optic fiber cable (bottom).

Correlations of Measurements

Figure 3 provides an overview of air temperature trends during the measurement period and the correlation between logger data and both sensor and communication cable data.

The temperature was measured at a stand-alone logger of the 1 km route (logger ID 4 – see Fig. 2). The top-left graph in Figure 3 shows clearly that, using OFDR and newly installed fiber optic cables, measuring small-scale changes in the air temperature gives results that are quality-wise comparable to stand-alone logger measurements.

The top-right graph in Figure 3 depicts a comparable situation – but here cable temperature is derived from the pre-existing communication cable. Despite its much larger diameter and, thus, higher temperature damping, the results look promising. Throughout the whole measurement period, the course of the temperature is represented very well by the cable data. In contrast to the dedicated sensor cable, however, attenuation seems to increase with distance in the communication cable.

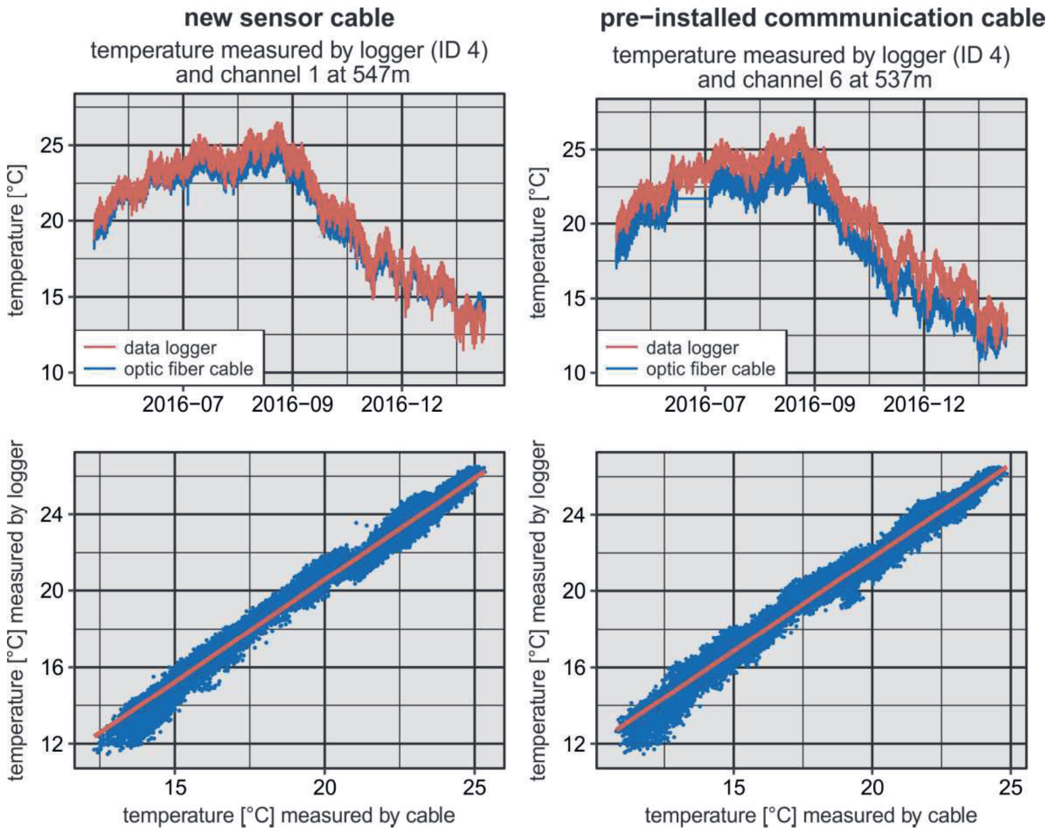

Fig. 3 Comparison of measured temperatures by new sensor cable (left) and pre-installed communication cable (right) with stand-alone control temperature loggers loggers at the same position (top), and their correlations (bottom).

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This results in slightly lower temperatures derived with growing distance from the controller module.

When taking the correlation between stand-alone logger and cable measurements into account, the offset differences between dedicated sensor cable and communication cable nearly disappear. The lower part of Figure 3 depicts the correlation between temperature data gathered by the stand-alone logger and the optic fibers. The bottom-left graph shows a correlation with the coefficient of determination (R^2) being 0.985, which is another sign that the sensor cable seems to be able to measure the air temperature with a very high accuracy. The bottom-right graph now shows the possibilities of using existing communication cables for OFDR measurements. Here too, a very high coefficient (R^2 = 0.984) confirms the potential of this technique.

Figure 4 is intended to clarify, whether there are any changes of the correlation's goodness of fit appearing with growing distance from the controller unit. As it can be seen, constantly high values prove the usability of this approach even in longer parts of tunnel systems. With growing distance from the controller unit no degradation of the correlation can be observed.

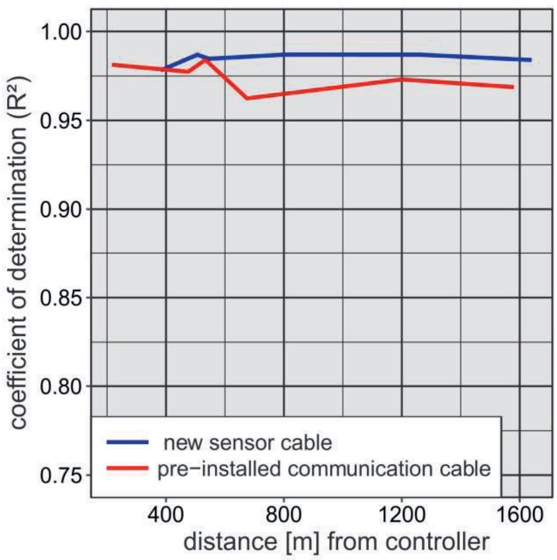

Fig. 4 Correlation coefficient between stand-alone temperature loggers and distributed temperature sensing.

Conclusion

The comparison of the temperature data from the dedicated fiber-optic sensor cable and the existing communication cable showed very high correlation thus confirming the eligibility of communication cables for temperature monitoring (see Fig. 4). Therefore using pre-installed optical fiber-optic cables for temperature sensing is possible at least up to cable lengths of some kilometer. Available OFDR devices are able to monitor cable lengths of up to 30 km, but it has to be proven, which cable length can be reached with pre-installed fiber optics. Furthermore, future work has to be done to show which temperature resolution is needed in order to derive the airflow inside subway tunnels.

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