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Early Detection of Pipeline Integrity Threats using a SmarT Fiber-OPtic Surveillance System: The PIT-STOP Project

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ABSTRACT

The preliminary results of a surveillance system set up for real time monitoring activities along a pipeline and analyzing for possible threats are presented. The system consists of a phi-OTDR based sensor used to monitor vibrations along an optical fiber combined with a pattern recognition system that classifies the recorded signals. The acoustic traces generated by the activities of different machines at various locations along a pipeline were recorded in the field. The signals, corresponding to machinery activities, were clearly distinguished from background noise. A threat classification rate of 68.11% with 55.55% false alarms was obtained.

Keywords: Distributed fiber sensing, Acoustic sensing, Vibration sensing, Intrusion monitoring, Pipeline Integrity, phase-sensitive OTDR, Pattern recognition.

1. INTRODUCTION

The transmission by pipeline is by far the most sustainable and safest transmission method in order to transport the energy from the producing facilities to the various end-users. It goes without saying that special attention has to be paid by the system operators with a view to ensuring that these infrastructures are operated safely at all time, particularly when they cross urban areas. Despite all safeguard measures taken by the system operators, energy transmission is an industrial activity, and as such, the zero risk does not exist. It should nevertheless be noted that most incidents involving natural gas transmission infrastructures occur when pipelines are damaged by third party works in their vicinity, some of which unfortunately lead to human casualties. Furthermore, the interruption of energy supply and leaked fuel associated with such pipeline accidents does also lead to high economic losses (as a consequence of supply disruption) and environmental damage.

There is therefore a high demand for cost-effective solutions for continuous monitoring of potential threats to the integrity of pipelines. Considering the size and linearity of these infrastructures, often reaching hundreds of kilometers, distributed optical fiber sensing (DOFS) technology is particularly well-suited for this task, as it allows the monitoring of large distances with a single interrogation unit. Within DOFS, the use of vibration-based sensing to monitor activities near a pipeline represents a promising solution as it can recognize potential threats and alert for a preventive action to be undertaken. In addition, pattern recognition software can be used to distinguish between different activities, thus decreasing the number of false alarms and increasing the cost-effectiveness of the system. Combined with conventional existing pipeline protection activities (such as helicopter flights, foot patrol or monitoring of (un)announced activities), a permanent supervision system for vibration monitoring of localized threat activities can significantly increase the early detection of possible threats and decrease the response time.

In this paper, preliminary results of a pipeline surveillance system are presented. The system is set up for real time monitoring and distinguishing between different types of activities (potentially harmful or not) occurring along a pipeline. It is developed under a GERG (The European Gas Research Group) project entitled PIT-STOP (Early Detection of Pipeline Integrity Threats using a SmarT Fiber-OPtic Surveillance System). This project is supported by three GERG

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The PIT-STOP surveillance system architecture is a combination of hardware and software modules. The hardware side is based on a phase-sensitive optical time domain reflectometer (ΦOTDR) sensor, entitled FIber Network Distributed Acoustic Sensor (FINDAS) [1], used to monitor vibrations in an optical fiber alongside a gas pipeline of Fluxys Belgium S. A.. The software, a threat recognition system (TRS), is used to analyze and classify the recorded vibrations. The TRS performance was evaluated on field recordings of acoustic traces resulting from the activities of several machinery types in different locations along a pipeline.

2. DISTRIBUTED ACOUSTIC FIBER SENSOR

The FINDAS – the hardware of the PIT-STOP surveillance system used to monitor vibrations along an optical fiber – is a ΦOTDR-based sensor. The measuring principle of ΦOTDR relies in sending a highly coherent light pulse into an optical fiber and measuring the Rayleigh backscattering interference pattern at the same fiber input. The measured changes in this pattern can be associated with changes to the state of the fiber at specific positions, thus allowing for distributed vibration sensing [2]. This is a fundamentally different process from conventional OTDR, which uses incoherent light pulses and can therefore only measure intensity variations along the fiber (such as connectors, fiber bends or fiber propagation losses). The sensing range of a ΦOTDR can typically reach several tens of kilometers [2] and even above 100km if distributed optical amplification is used [3]. Using a single interrogation unit, a ΦOTDR sensor is therefore equivalent to thousands of conventional point sensors, making it a well-suited technology for the continuous monitoring of activities along large linear infrastructures, such as pipelines.

In the presented work, the FINDAS sensor has an (optical) spatial resolution of 5m (readout resolution of 1m) and a typical sensing range of up to 45km, using standard single-mode fiber (SMF). Distributed optical amplification was not used. The FINDAS sensor was connected to a standard SMF, which had been previously installed parallel along the pipeline which was intended to be monitored, and used to continuously monitor vibrations along it. Since the fiber does not always follow on a parallel with the pipeline and in some points there were fiber rolls (for maintenance purposes), the correspondence between fiber distance and pipe length is not consistent. Therefore, a calibration between fiber distance and field location was done before the tests, by applying a known signal at a given field location and matching it with the fiber position of the recorded signal.

If the energy of the vibrations monitored by the FINDAS was higher than a given energy threshold at a certain location, an alarm was raised by the FINDAS, stating that there was activity at that location. At this point, the acoustic samples were recorded and sent to the TRS (described in section 3), which evaluated if the activity was considered a threat or non-threat for the integrity of the pipeline. If the activity was considered a threat for the integrity of the pipeline, an alarm was sent to the end user. The FINDAS energy threshold alarm level is adjustable for each location, thus allowing to take into account factors such as background noise and fiber sensitivity (dependent in the depth of the fiber, type of soil, etc.). The simultaneous detection of multiple activities at different locations is also possible. The general architecture of the PIT-STOP surveillance system is described in Fig. 1.

Figure 1. PIT-STOP surveillance system architecture.

3. THREAT RECOGNITION SYSTEM

The threat recognition system (TRS) – the software side of the PIT-STOP surveillance system - is composed of two different modules: The *feature extraction module*, which extracts the most relevant information from the acoustic traces, and stores that in feature vectors; and the *classification module*, that assigns each acoustic trace the most likely class, usually by comparison with a set of previously trained patterns, according to a certain algorithm.

The feature extraction is based on the spectral content of the acoustic traces, which are analyzed by sequentially splitting them in acoustic frames of a given length. This spectral information is computed using the Short Time Fast Fourier Transform (ST-FFT), and is then integrated as the energy of a set of frequency bands. The values of the spectral energy in bands constitute the final feature vector components that represent each of the acoustic frames of the input signal. The relevant parameters to perform the ST-FFT are the acoustic frame size (which in the system is set between 1 and 20 seconds long), the acoustic frame overlap (set to a fraction of the frame size), and the number of FFT points (set to achieve a spectral resolution below the Hz scale). The number of frequency bands finally defines the number of components in the feature vectors, and is set between 20 and 100.

The classification process is based on a Gaussian Mixture Model (GMM) recognition module that comprises two different stages: training and recognition. The training stage builds a GMM for each of the defined classes (threat and non-threat), using sample data from a set of field recordings belonging to the corresponding class, and it just needs to be run once. The well-known Expectation-Maximization algorithm [4] is used for the GMM training. The recognition stage carries out a threat/non-threat classification of the input acoustic frames, assigning each of them the class with the highest probability, given all the GMMs.

The acoustic signal recordings comprise 4 machines carrying out different activities, leading to a total of 8 machine+activity pairs (see description of Fig. 2). These machine+activity pairs were further classified as being a "threat" class (4 machine+activity pairs), or a "non-threat" class (4 machine+activity pairs), in order to carry out the TRS experiments. The total recorded time for these 8 machine+activity pairs amounts to about 10 hours, recorded with a sample frequency of 1085Hz in six different geographical locations.

The TRS performance evaluation experiments were conducted by cross-validation (CV) [5] on the recorded data. This approach is required to obtain a reliable estimation of the actual classification accuracy. The evaluation uses a six-fold CV, where each fold contains the data from five locations for the GMM training, and the data belonging to the other location are used for actual testing. The final results are calculated averaging the performance of each of the six-fold results, according to the frame-based classification strategy.

4. FIELD TESTS AND RESULTS

For the field tests, a gas transmission pipeline operated by Fluxys Belgium S. A., was used, thus aiming to operate in a real case scenario. Activities of different machinery were recorded near the pipeline by monitoring an optical fiber cable installed at about 0.5m from the pipeline (see left inset figure of Fig. 1) and parallel to it along several kilometers. The FINDAS was placed in a telecom room and activity was recorded at six different locations at an (optical fiber) distance from the FINDAS of 22450m, 22700m, 23950m, 27650m, 27800m, and 34500m.

Four different machines were used, as presented in Fig. 2, to build 8 different machine+activity pairs: a 5ton Kubota KX161-3 (moving, hitting the ground, scrapping the ground); a 1,5ton Kubota KX41-3V (moving, hitting the ground, scraping the ground); a pneumatic hammer (hitting the ground); and a plate compactor (hitting the ground). These machine+activity pairs were labeled as "threat" or "non-threat" depending on whether they were considered potentially harmful to the integrity of the pipeline. Four pairs were classified as "threat" (Kubota KX161-3 –hitting and scraping the ground); Kubota KX41-3V (hitting and scraping the ground). The remaining 4 pairs were classified as "non-threats".

a)  b) c) d)

Figure 2. Machines used for the fields tests: a) Kubota KX161-3 (~5000kg; 5.54x2.53x1.96m length/height/width), b) Kubota KX41-3V (~1500kg; 3.66x2.28x0.99m length/height/width), c) Pneumatic hammer, d) Plate compactor

An unprocessed sample of one of the recorded signals, corresponding to a Kubota KX161-3 hitting the ground, is presented in Fig. 3. The variations in the acoustic signal over time, monitored at the location where activity was performed, are presented in Fig. 3a. The corresponding spectrum of the acoustic signal as a function of time, which would be used by the TRS, is shown in Fig. 3b. The signal corresponding to the different machine+activity pairs was clearly distinguished from background noise, recorded when no activity occurred, as seen in Fig. 3.

The initial results, with respect to threat classification, are promising, given the high complexity of the task. They obtain a true alarm classification rate of 68.11% (i.e., "threat" activities correctly classified as "threat" activities) with a 55.55% rate of false alarms (i.e., "non-threat" activities being classified as "threat" activities).

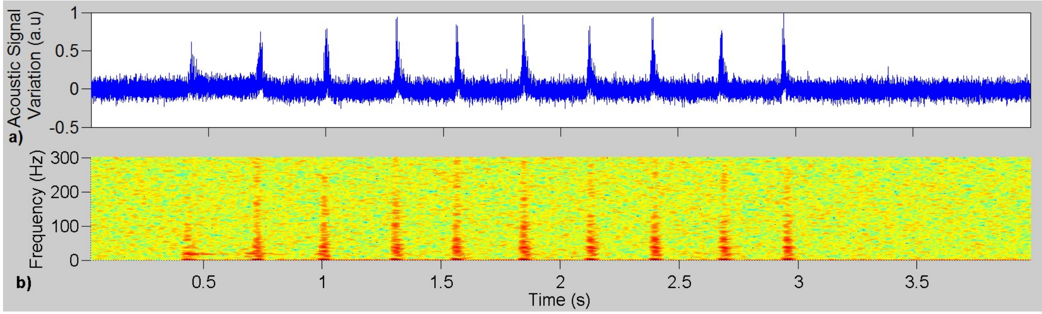

Figure 3. Acoustic signal of a Kubota KX161-3 hitting the ground: a) Signal variations over time b) Corresponding spectrum

5. CONCLUSIONS

The preliminary results of the PIT-STOP surveillance system (hardware+software), installed along an operational industrial gas transportation pipeline, have been presented. The hardware system was able to detect and record specific activities along the pipeline. Furthermore, the software system is able to distinguish different activities and evaluate whether they represent or not an actual threat to the integrity of the pipeline. A classification rate of true alarms of 68.11% with 55.55% of false alarms was obtained.

These results are promising and proof the feasibility of the system. Future work will focus on noise reduction techniques aiming at extracting a more robust set of feature vectors, new strategies to deal with the non-linear behavior of the sensing system, and on new classification algorithms, aiming at improving the TRS classification accuracy.

6. ACKNOWLEDGMENTS

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