Towards detection of Pipeline Integrity Threats using a SmarT fiber-OPtic surveillance system: PIT-STOP project Blind Field Test results

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ABSTRACT

This paper presents the first report on on-line and final blind field test results of a pipeline integrity threat surveillance system. The system integrates a machine+activity identification mode, and a threat detection mode. Two different pipeline sections were selected for the blind tests: One close to the sensor position, and the other 35 km away from it. Results of the machine+activity identification mode showed that about 46% of the times the machine, the activity or both were correctly identified. For the threat detection mode, 8 out of 10 threats were correctly detected, with 1 false alarm.

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

1. INTRODUCTION

There is a high demand for cost-effective solutions for continuous monitoring of potential threats to the integrity of pipelines to avoid potential incidents, some of which unfortunately lead to human casualties. Current pipeline integrity prevention systems combine distributed acoustic sensing technology and a pattern recognition system for continuous monitoring of potential threats to the pipeline integrity [1].

In previous works [1, 2], we presented the preliminary results of the PIT-STOP (Early detection of Pipeline Integrity Threats using a SmarT fiber-OPtic surveillance system) project, where data used for experimentation were recorded under a thorough recording methodology (i.e., different machines were carrying out certain activities in different soil conditions, pipeline sections, and days). In this work, we present the final results of this project, which correspond to the on-line, final blind field tests carried out in two different pipeline sections (one section spreads 400 meters of pipeline and was set near the sensing system, while the other spreads 5 kilometers of pipeline and was set 35 kilometers far from the sensing system) employing unknown machinery in unknown times and a priori unknown locations during three different days by the GERG (The European Gas Research Group) partners. In addition, two post-processing methods that make the system fully-functional as an on-line production system are also presented.

The PIT-STOP surveillance system, whose architecture is presented in Figure 1, consists of a combination of hardware and software modules. The hardware side refers to the distributed acoustic sensor used to record the data, which is based on phase-sensitive optical time domain reflectometer (ϕ-OTDR) technology, entitled “FIber

Figure 1. PIT-STOP surveillance system architecture.

Network Distributed Acoustic Sensor (FINDAS)" [3]. The software module classifies the acoustic data recorded by the FINDAS in a machine+activity pair or threat/non-threat depending on the system mode.

To the best of our knowledge, this is the first report that presents on-line, blind field test results of a fiber optic surveillance system that aims to pipeline integrity threat detection and employs distributed acoustic sensing for signal acquisition. The full system was continuously operating during different days to detect every possible activity occurring in the different pipeline sections.

2. DISTRIBUTED ACOUSTIC FIBER SENSOR

The FINDAS has an (optical) spatial resolution of 5 meters (readout resolution of 1 meter) and a typical sensing range of up to 45 kilometers, using standard Single-Mode Fiber (SMF). A sampling frequency of $f_s = 1085$ Hz was used for signal acquisition. When the energy of the vibrations monitored by the FINDAS in a certain location is above a predefined threshold, the acoustic samples are recorded to form a 20-second length acoustic trace. This acoustic trace is then sent to the software module (described in the next section). The threshold for each location was set by comparing the acoustic sample recordings corresponding to real activity in the given location with recordings corresponding to background noise (i.e., when no activity was being conducted) in the same location. To do so, machine+activity recordings belonging to the training data (see Section 4) and 5-minute length background noise recordings were employed. The simultaneous detection of multiple activities at different locations is also possible, by placing a different threshold for each location, in case it is needed. More information about the distributed acoustic fiber sensor can be found in [1, 2, 4].

3. PIPELINE INTEGRITY THREAT DETECTION SYSTEM

The pipeline integrity threat detection system - the software part of the PIT-STOP surveillance system - integrates two different modules: the *feature extraction* module and the *classification* module. The feature extraction bases on the spectral content of the acoustic traces, for which the Short Time Fast Fourier Transform (ST-FFT) extracts the spectral content of each acoustic frame, which is then employed to compute the energy of a set of frequency bands (100 bands in our case) that finally composes the feature vector components. The classification process is based on Gaussian Mixture Models (GMMs) and classifies each acoustic frame into a predefined class (the class corresponding to the machine+activity pair or threat/non-threat with the highest probability) from a previously trained set of GMMs, with a single GMM component each. More information of these two modules can be found in [1]. To make the system fully-functional as an on-line production system, two post-processing methods have been integrated in the classification module, which are presented next.

3.1 Majority voting decision

The FINDAS records 20-second length acoustic traces, and the GMM-based classification process outputs one classification per acoustic frame, which is 1-second length. Given that the acoustic frame overlap in the feature extraction module was set to 950 milliseconds, there are 415 acoustic frames in each 20-second length acoustic trace. Therefore, to classify each acoustic trace into a machine+activity pair or threat/non-threat, a method to combine the 415 individual frame classifications into a single class is needed. We have adopted a simple majority voting decision. Therefore, each acoustic trace is assigned the class to which more frames are classified.

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3.2 Temporal and spatial analysis procedure

Since the pipeline integrity threat detection system is run continuously in field conditions, methods to 1) avoid classifying *spurious* acoustic traces and 2) generating many continuous alarms (due to continuous threats detected in nearby temporal or geographical positions) in a given location are needed.

Spurious acoustic traces refer to those detected by the FINDAS that do not have a minimum time duration along near positions (40 meters). This time duration was set to 80 seconds. These spurious acoustic traces are removed from the system (i.e., as if their energy was not above the predefined threshold).

For the second issue, acoustic traces classified as threat that are separated up to 80 seconds and less than 40 meters from the previous threat are grouped in this same threat.

4. EXPERIMENTAL PROCEDURE

The database used for training in the GMM-based classification comprises acoustic traces corresponding to machine+activity pairs that are potentially identifiable. These include different kinds of excavators and drilling machines, hammer, plate compactor, and pneumatic hammer, carrying out several activities such as moving, preparation, removing trees, scrapping, hitting, digging, compacting, etc. Activities such as people walking and people fencing were also included in the database since these may occur in the pipeline vicinity as well. There are 45 machine+activity pairs, with 22.5 hours of acoustic traces in total, which derives in 45 GMMs for the machine+activity identification mode. The machine+activity pairs were recorded from 22 kilometers to 35 kilometers far from the FINDAS. Each of these machine+activity pairs is next labeled as threat or non-threat to train the 2 GMMs for the threat detection mode. There are 30 and 15 machine+activity pairs used to train the threat and non-threat GMMs respectively.

The evaluation metric used in this work is the accuracy in terms of machine+activity classification (i.e., the percentage of machine+activity pairs for which the machine, the activity or both are correctly identified) and threat detection (i.e., the percentage of threats that are correctly identified), and the number of false alarms for threat detection (i.e., the number of non-threats that are classified as threat).

5. BLIND FIELD TESTS AND RESULTS

Blind field tests were conducted in two different pipeline sections, and results are presented in Table 1 where the machine+activity classification (MAC) rate, the threat detection rate (TDR), and the number of false alarms (#FA) are presented: The first section (SEC1 in Table 1) comprises a 400-meter pipeline section, in which the sensor is placed at the beginning (i.e., in the first meter), and different machines carried out different activities. These include work preparation, fiber touching, unloading of different tools, unloading of excavators, excavator moving/hitting/digging/filling, drilling, and plate compactor. There are 15 machine+activity pairs in total, with 6 of them labeled as threat and the other 9 labeled as non-threat. This blind field test spreads 8 hours of a single day in a priori unknown location. The second section (SEC2 in Table 1) comprises a 5-kilometer pipeline section and is 35-kilometer far from the sensor. New machines carried out certain activities such as excavator moving/digging/hitting, truck moving, shovel digging, unloading of drilling, drilling, drill compactor, and plate compactor. There are 13 machine+activity pairs in total (4 threats and 9 non-threats). This blind field test spreads 2 full days in a priori unknown location.

A same activity may occur more than once in any section in the blind field tests. The SEC1 section obtains better results than SEC2. We consider that this is due to SEC1 is *easier* than SEC2 in terms of experimental conditions. In SEC1, the FINDAS is placed in the blind field test location and the blind field tests employed much less time than for SEC2 (8 hours vs. 48 hours). Since the distance to the FINDAS is just a few meters, a better signal acquisition is obtained so that the classification system obtains better performance. However, when the distance to the FINDAS grows (as is the case of SEC2), a worse acoustic signal is acquired (about $3dB$ of decay every 7.5 kilometers), which affects the final classification performance. The performance in the machine+activity identification mode is worse than that of the threat detection mode for both sections. This is reasonable, since more confusability exists in the classification process. In addition, the 33% and 31% of the machine+activity pairs in SEC1 and SEC2 respectively correspond to classes for which no training data exist. This makes impossible the system can detect them, hence contributing to lower figures.

Table 1. Blind field test results of the PIT-STOP surveillance system. 'Average' refers considering both sections as a single one.

Pipeline section	MAC	TDR	#FA
SEC1	53%	100%	0
SEC2	38%	50%	1
Average	46%	80%	1

6. CONCLUSIONS

We have presented the PIT-STOP surveillance system results when this is evaluated on-line with blind field tests. Two post-processing methods needed for an on-line production system have also been presented. The system is able to identify the machine and the activity conducted in the pipeline, and to detect threats to the pipeline integrity. Considering the complexity of the task (classifying unknown machinery/activity in unknown times and locations), blind field test results show quite good performance: 8 out of 10 threats were correctly detected, while generating a single false alarm during 3 different days. These results were quite above our estimations, since the blind field tests employed machine+activity pairs for which no training data exist.

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