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Original
Early-warning debris flow and avalanches detection system based on optical fiber polarization sensing / Rizzelli, Giuseppe; Pellegrini, Saverio; Lacidogna, Marco; Aiassa, Santina; Antolini, Francesco; Insana, Alessandra; Barla, Marco; Gaudino, Roberto. - ELETTRONICO. - (2023), pp. 1-4. (Intervento presentato al convegno 2023 23rd International Conference on Transparent Optical Networks (ICTON) tenutosi a Bucharest, Romania nel 02-06 July 2023) [10.1109/ICTON59386.2023.10207193].

Availability:
This version is available at: 11583/2981378 since: 2023-08-29T15:13:55Z

Publisher:
IEEE

Published
DOI:10.1109/ICTON59386.2023.10207193

Early-warning debris flow and avalanches detection system based on optical fiber polarization sensing

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ABSTRACT Landslides, avalanches and debris flows are the main hazards in the mountain environment, endangering people and infrastructures. The existing monitoring systems in the geotechnical field are often unsuitable for real-time applications, such as early-warnings of the aforementioned events. We present an optical fiber system able to give an alarm when some anomalous event is detected. Experiments have been carried on a reduced scale model of a slope of a mountain, showing that state of polarization monitoring is a reliable way to early-detect anomalous vibrations.

Keywords: Rockfalls, monitoring system, optical fibers, optical switch, polarization.

1. INTRODUCTION

Mountain regions are often affected by destructive events such as snow avalanches, landslides, rockfalls and debris flows. Due to the high velocities, large impact forces and long runout distances involved, these phenomena can be potentially dangerous for people and infrastructures. In this scenario, very important goals are the timely detection of catastrophic events (within a few seconds), the dispatch of an alarm signal to the local authorities and the subsequent restriction of the access to the endangered area. Currently, the solutions of choice are usually installed at specific discrete positions along the gullies formed on the mountain slope and have several drawbacks such as low reliability, limited coverage of the monitored area and high maintenance needs in hard-to-reach locations [1], [2]. In this paper, we propose an optical fiber-based detection and early warning system that can overcome the limitations of the sensors traditionally used in the geotechnical sector, typically based on mechanical solutions, [3], [4], while still providing simplicity of use at a reduced cost, especially compared to more advanced and costly distributed fiber sensing options [5] or less sensitive interferometric techniques [6], [7], [8]. The system is based on the deployment of buried SMF cables across or close to the mountain gully to be monitored and on the observation and processing of the output state of polarization (SOP) change rate, induced by the strong mechanical and vibrational stresses associated to the movement of massive mixtures of water, soil and snow. Our solution is able to provide quasi-distributed sensing over vast mountain areas, since the deployed SMF can be several km long along the gully and offers, as we will show, very fast real-time response to catastrophic events. If coupled to radio nodes and actuators (e.g. traffic lights, automatic barriers, sirens, etc.) whenever a dangerous event is detected, the system is in principle able to promptly alert and secure the area where the falling material might endanger people, for instance a road at the bottom of the gully.

We developed an algorithm to process the optical signal received by a polarimeter (Novoptel PM1000) and extract information on the SOP variation speed. We tested its use on a reduced scale model of a mountain slope and show that, regardless of the optical fiber path and depth of installation (up to 9 cm underground), there is always a configuration of the algorithm parameters that allows to correctly detect all the generated rockfall events. Moreover, we show potential for improved reliability and cost-effectiveness by using an optical switch in order to monitor more than one fiber simultaneously, with the same hardware. This configuration can also give a rough estimation of the velocity of the debris if two (or more) fibers are placed at different altitude of the mountain gully.

2. EXPERIMENTAL SETUP AND ALGORITHM VALIDATION

A block diagram of the proposed sensing system is shown in Fig. 1a in the “single fiber” configuration. The interrogator includes a CW laser at 1550 nm, a polarimeter that detects the optical signal and returns the instantaneous SOP with a sampling frequency f_s, and a personal computer (PC) running a Matlab script with our digital signal processing (DSP) algorithm. The optical signal propagates along optical fibers installed in a reduced scale experimental setup based on a slide emulating the slope of a mountain, as shown in Fig. 1b. The slide is a 3 m long and 0.7 m wide plane inclined by 30° and filled with a 10 cm thick mixture of sand and soil. A total of nine single mode fibers (SMFs) are buried in three configurations at 1 cm, 5 cm and 9 cm into the soil along the slope length: in the middle (Uc, green); along the left side of the slope (Ul, yellow); in a serpentine layout, with six transversal crossings of the slope longitudinal section (T, red). For each of the nine fibers we generated a total of 30 events releasing from the top of the slide a single rock about 5 cm wide (SR), a test cylinder 15 cm long and with a diameter of 5 cm (C) and a debris flow made of 25 rocks (DF), 10 times each. A USB connection between the PC and the polarimeter allows to read data from the device registers and apply the following algorithm:

i) at each sampling instant k the SOP Stokes vector $\vec{S}^k$ is acquired;
ii) the SOP angular speed (SOPAS) in radians/sec is then computed as: $\omega(k) = \arccos\left[\frac{(\vec{S}^k, \vec{S}^{k-1})}{\|\vec{S}^k\| \|\vec{S}^{k-1}\|}\right] \cdot \frac{1}{T_s}$ where $T_s = 1/f_s$ is the sampling period;
iii) a FIR-based moving average filter with duration T_{mov} is applied to the SOPAS samples $\omega(k)$ to reduce the impact of system background noise;
iv) the averaged SOPAS $\overline{\omega}$ is compared to a threshold ω_{th} and an alarm is generated if $\overline{\omega} > \omega_{th}$.

We started our algorithm optimization by selecting the proper sampling rate f_s: in Fig. 1c, we report the spectrogram of the resulting $\omega(k)$ evolution during a single rockfall event happening about 7 seconds after the beginning of the acquisition. The graph clearly highlights that the relevant spectral information is below 40 Hz, a value that was confirmed also for the other rockfall acquisitions [9], [10]. Consequently, a sampling frequency $f_s = 95.4\ Hz$ was found to be sufficient: such a low value allows to greatly limit the amount of data to be processed and stored in an application where constant endless monitoring is needed. As clearly outlined in [11], reducing the overall size of the dataset is crucial in these applications that should run 24/7.

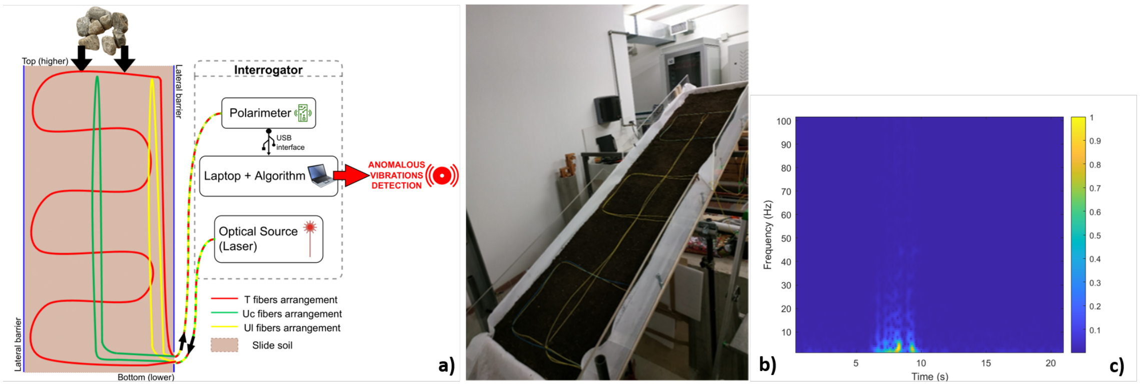


Figure 1: a) Block diagram of the system, b) picture of the slope scale model, c) spectrogram of the resulting $\omega(k)$ evolution during a single rock fall event (linear spectral amplitude normalized to 1).

Fig. 2 shows how the algorithm behaves as a function of the two main parameters T_{mov} and ω_{th} for each of the three fiber configurations. The green area represents the parameter space where the algorithm is able to correctly detect 100% of the events (i.e. 30 events on each fiber at the three depths). Conversely, the red area is where the threshold ω_{th} is below the noise floor level and no event can be correctly distinguished from the noise (thus giving false alarms), or it is higher than all of the SOPAS curves and no event is detected (thus giving missing detection events, which are the most dangerous in our application area). For all the three fiber configurations, the graphs shows that there always exists a large parameters T_{mov}, ω_{th} area that yield full correct detection. After these initial parameter setting optimization, we then developed an hardware real-time implementation (we can't show here its details due to space limitations) able to run 24/7 and having a delay between the rockfall events and the alarm generation (a red semaphore) of the order of T_{mov}, i.e. in the 1-2 seconds range. We conclude this Section by mentioning that our reduced scale model is somehow more critical

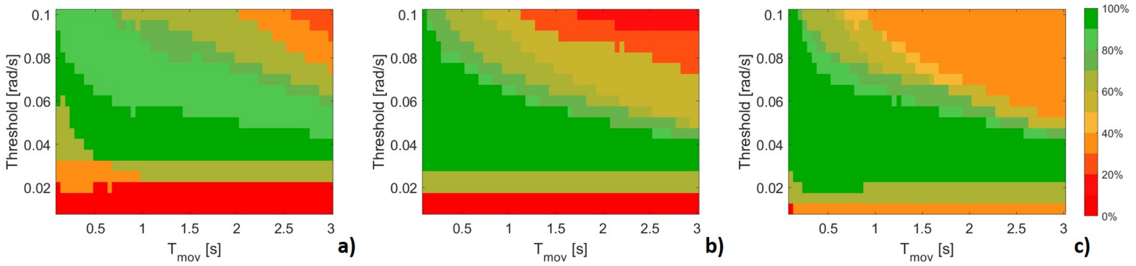
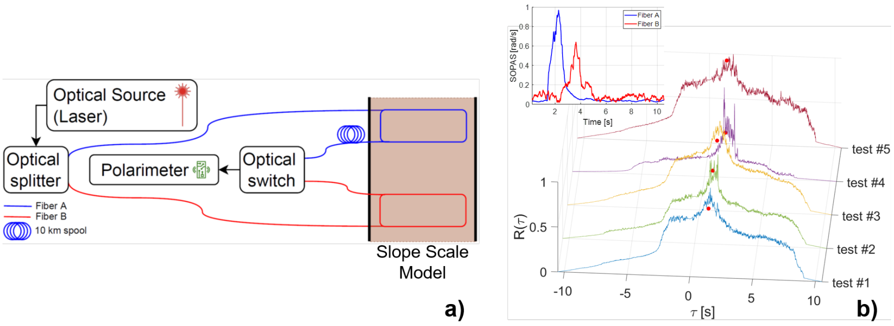


Figure 2: Algorithm results for the three different deployed a) Uc, b) Ul and c) T fiber configurations. The colormap indicates the percentage of correctly detected events (30 iterations per fiber and depth).

from the DSP point of view than an actual deployment in a real large scale gully. In fact, in real world situation the rockfall events would be much longer in time (tens of seconds at least) and much stronger in intensity. To have an indication of the time constants involved in a real scenario, we can consider these realistic values: a typical rockfall or debris speeds of about 10 m/s and a sensing fiber crossing the gully, for instance, 400 meters above the traffic road to be closed. In this simplified example, given the 40 seconds that the rockfall would approximately take to run along the 400 meters and the previously mentioned 1-2 second delay in DSP processing, the alarm semaphore would turn red 38 seconds before the rockfall hits the road, a reasonable warning time lag for this specific scenario.

2.1 TWO-FIBER DETECTION SYSTEM

In Section 2 we demonstrated that by properly setting the two main parameters of the algorithm, our system can detect all our generated rockfall events. However, the proposed single fiber system may be prone to false alarms if an occasional non-dangerous event occurred (e.g. animals walking in the area, tree falling, etc.) in the vicinity of the fiber. In this Section, we present an improved setup based on deploying (at least) two fibers in different positions of the gully, and on the proper post-processing of the two resulting $\omega(k)$ SOP evolutions with the goal of reducing false alarms. In our reduced scale setup, a two-fiber system was thus implemented by splitting the optical signal at the laser output and installing two fibers at 5 cm depth covering two separate sections about two meters apart, one at the top and one at the bottom of the slope (see Fig. 3a). At the polarimeter input, an optical switch is used to alternatively select each of the two fiber outputs, with a switching period of 5 ms. By doing so we measure the SOP on each fiber with nearly the same f_s of the previous single-fiber system configuration, i.e. $f_s = 100\ Hz$ per fiber, but on two fibers simultaneously. To test the performance of the system on even longer fibers (i.e. wider monitored areas, or remotely located interrogator) we also inserted a 10 km spool of SMF on one of the two optical signal paths. The inset of Fig. 3b shows the averaged SOPAS evolution on the two fibers when a SR event was generated. It can be noticed that the SOPAS traces have a relative delay around 1.5 seconds, which is approximately the time that the rock takes to roll down between the two fibers. Fig. 3b shows the normalized SOPAS cross correlation for five different SR events, and their centroids (red dots): the τ-axis coordinate of these points corresponds to the delay estimate between the two SOPAS traces. All of them produce a cross correlation centroid at about 1.5 seconds delay, consistently with the SOPAS evolution. The centroid of the cross correlation curve in the 5 cases is reported in the table in Fig. 3c, confirming an average estimated delay of 1.48 seconds between the two fibers and sligth variations due to the different shape of the used rocks and, consequently, their falling speed variation.



Test #	τ [s]
#1	1.49
#2	1.44
#3	1.4
#4	1.68
#5	1.39

c)

Figure 3: a) Simplified block diagram of the two-fiber system. b) Cross correlation curves and centroids (red dots) between SOPAS on fiber A and B for five SR events. The inset shows the SOPAS curves for one of the five SR events. c) Table of delays τ of the five cross correlation curves.

The use of two (or possibly more) geographically separated fibers has several potential advantages:

- it can greatly reduce false alarms by allowing to activate the alert only when an above threshold SOPAS is detected on both fibers. Monitoring multiple fibers placed along the slope, as Uc and Ul configurations in Fig.1a, and not at different depth as in our experiments, can even be more suitable for this purpose;
- it reduces cost by reusing the most expensive hardware components (i.e. the laser and the polarimeter, while the very low target f_s allows to use low-cost optical switches): a single interrogator could be reused to monitor different portion of one gully or even different gullies, and also to mitigate false alarms;
- it enables event time localization as it allows to identify which fiber was hit first, and the delay measured on the different fibers;
- it helps to analyze the dynamics of mass movements by enabling an estimate of rockfall time and speed.

3. DISCUSSIONS AND CONCLUSIONS

We presented a novel optical fiber sensing system based on SOP tracking for the monitoring and early warning of dangerous mass movements in mountain regions, with the goal of mitigating the risk associated with the ever increasing human and infrastructure presence in these areas. The main advantages of the proposed system include: i) the possibility to monitor a vast geographical area, limited only by the cost of burying the fiber along the gully; ii) the possibility to put the interrogator at a large distance from the gully (for instance in a central office in a mountain village in the region of the gully): we showed detection at 10 km distance, but the fiber length can be much longer and only limited by its attenuation and sensitivity of the polarimeter; iii) real-time early warning alarm generation is possible, limited only by the averaging stage of the signal processing that, however, can be as short as 1-2 seconds; iv) sensitivity: in our small-scale setup, we were able to detect even the fall of a single small rock, much more moderate than the destructive phenomena to be detected in a realistic mountain environment; v) reliability: the use of two (or more) fibers and an optical switch can remove the false alarms and enable event localization and tracking; vi) cost-effectiveness: in our experiment we used costly laboratory devices (cooled laser, fast polarimeter, PC) that can easily be replaced by low-cost ad-hoc counterparts in a commercial version of the system. Moreover, the hardware can be shared among different monitoring sites in the two- (or more-) fiber configuration; vii) Simplicity: the low required sampling frequency f_s allows the use of simple electronics: the algorithm can easily run on a hardware DSP platform, such as a small and slow FPGA, and is totally automatic once the optimal parameters pair is set. The above mentioned characteristics describe a monitoring system which can represent a beneficial alternative with respect to already existing mountain engineering techniques available on the market, which are often expensive, difficult to install and with limited reliability. For instance devices such as geophones, accelerometers and seismometers are easy to install but require calibration and interpretation; remote doppler sensors can detect the initiation of avalanches in wide areas but are very expensive and need a line-of-sight condition; ultrasonic doppler radar sensors, pendulums and impact sensors have high reliability but require to hang sensors over the gully and have a high environmental visual impact; photocells and infrared cameras rely on visual acquisition and but have limited accuracy, especially at night and with bad weather conditions. These solutions require some form of power supply on site, in areas where electricity is not present and hard to be made available. Furthermore, most of the aforementioned devices would need to be serviced after each alarm-generating event, whereas our system would require fiber replacement only after the occurrence of an extremely intense rockfall phenomenon causing a fiber break. However, in this case only the portion of the fiber actually installed in the gully would have to be replaced, with considerable savings in terms of time and cost.

ACKNOWLEDGMENTS

The authors would like to acknowledge the OPTIALP project funded by the Piemonte regional Government and the PhotoNext Center at Politecnico di Torino.

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