Experimenting an Embedded-sensor Network for Early Warning of Natural Risks Due to Fast Failures along Railways

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Abstract: This paper deals with a project for real-time monitoring of railway tracks to detect events, such as fast failures from natural risks, which may threaten the transit of trains. The paper describes a network of smart sensors for early warning of these endangering events. Three main types of fast-failure events involving railways were identified: sinkhole, rock and debris falls. A case study on a known test site and experimentation with various scenarios were carried out with a view to developing algorithms capable of spotting and localising them. Results demonstrate the good performance of the network in monitoring the investigated events.

1 INTRODUCTION

In the last decade, particular attention was focused on the monitoring of fast to very fast failures, which include landslides from rocky slopes (e.g. falls, topples and wedge sliding), but also sinkholes on plains and debris flows channelled along high-inclination slopes. The relevance of such events is mainly related to the short time available for taking action in case of exposed infrastructures (highways, railways and so on), since no significant displacements are generally detected before failure. In this regard, two are the possible strategies to manage the natural risk: i) monitoring precursors by using micro- or nano-seismometric devices as well as of acoustical emission records (Amitrano et al., 2005; Lenti et al., 2012); ii) monitoring the site as well as the exposed infrastructures, by using optical devices (e.g. cameras, interferometers, videos) capable of detecting fast morphological changes or abnormal and unexpected objects hazardous for the infrastructure (Antonello et al., 2004; Lai et al., 2006; Gaffet et al., 2010; Bigarre et al., 2011; Martino and Mazzanti, 2014).

Integrated monitoring systems should be designed for this purpose and adapted to meet the following requirements: i) investigating or detecting the site at different evolutionary stages (forward prevention), corresponding to different distributions of the landslide hazard; ii) understanding and controlling the parameters for forecasting the short-term evolution of gravitational instabilities (e.g. high-velocity landslides) and for planning alert systems (real-time prevention).

Experiments were conducted on a railway where a Wireless Sensor Network (WSN), with hardware-connected cameras, had been installed. The WSN was intended to detect morphological anomalies, such as rocky slopes prone to falls, and the presence of unexpected objects along the monitored railway track. A WSN, which can transmit real-time data, can provide an early warning system.

The experiments were carried out by artificially causing block falls and localising them along the railway. The experiments were part of a research project, implemented by the Research Centre for Geological Risks (CERI) of the University of Rome "Sapienza". The project will include new sites to be monitored, where natural ongoing processes can be detected. The end goal of the research is to integrate the WSN into a multi-sensor network for detecting natural fast-landslide processes from precursors to failure.

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2 ISSUE AND ANALYSIS

The infrastructure chosen for the project was a railway; in particular, some railway tracks with limited train transit (secondary railways) in Central Italy were selected. The experimental activity consisted in monitoring the railway and the surrounding area, in order to derive a real-time report of obstacles hazardous for train transit. In the selected site, three different types of fast failure may affect the railway:

- Sinkholes: fast vertical collapses generating holes of variable diameter below the railway causing its interruption or flexion. The expected precursor signals are micro- or nano-seismic emissions due to micro-cracks that anticipate the collapse phase and preliminary deformations of the ground surface that may affect the railway track.

- Rock falls: these fast landslides generally occur on cliff slopes (natural or man-made) due to rock mass jointing. They cause the accumulation of rocky blocks of variable size that may occupy and/or damage the railway infrastructure. In this case, the expected precursor signals are micro- or nano-seismic emissions due to micro-cracks that anticipate the collapse phase but rarely are preliminary and detectable deformations observed.

- Debris flows: this phenomenon consists in the fast triggering of a flow-like event due to a mixture of water, air and debris originally accumulated along narrow and deep creeks elongated on high-dip slopes. The velocity and volumes of the flowing debris can produce severe damage to infrastructure due to impact energy as well as debris accumulation. The predisposing conditions for debris-flow triggering are the presence of debris fill along the creek when intense rainfall occurs.

The most suitable site for experimenting a monitoring system meeting the above requirements, i.e. detecting the occurrence of fast failures, should make it possible to:

- detect deformations or abnormal objects along the railway in real time;
- provide multiple points of observation;
- measure the observed objects;
- transmit the detection dataset in real time;
- ensure the interaction between the wireless-connected sensors.

As a preliminary action, the WSN should be calibrated to better identify any “regular” objects statically or dynamically located on the railway, e.g. trains in transit, animals running or existing vegetation. The sensors should also be capable of filtering spurious noise generated by system instabilities, e.g. vibrations induced by regular railway traffic.

2.1 Methodology

The pilot sites were selected after field surveys aimed at assessing their suitability for the planned experiments in terms of both expected failure occurrences and adequacy for the installation and calibration of the WSN. For each of the main events (sinkholes; debris flows; falls) in all the selected sites, the monitoring and early warning network was designed with specific sensors.

On the selected sites, the activity was carried out in the following steps:

- preliminary geological and geomorphological field survey on longer railway tracks and surrounding areas, in order to check the existence of slopes prone to fast-landslide events;
- selection of shorter railway tracks to be monitored;
- planning of the WSN installation;
- setting of sensor resolution;
- evaluation of alarm thresholds.

The monitoring and early warning system designed for the sinkhole consisted of two sensors, detecting any railway deformation with high accuracy and in real time. The two wireless sensors covered the same portion of land from different points of view. This type of installation allows individual cameras to better define the objects and to communicate useful information to better identify the phenomenon on a wider scale. For the monitoring of rock falls and debris flows, the system was configured with one or multiple wireless sensors with multiple points of observation based on both the “background target” (i.e. the static regular scene) and the object to be detected. The number of sensors was also dependent on the monitoring accuracy of the expected railway deformations, as well as of the expected abnormal object along the railway track. For all the investigated phenomena, the definition of the WSN parameters was fundamental to perceive and then process only the differences between a step of the background and the next disturbance, so as to minimise false alarms and optimise data collection and transmission. This optimisation procedure contributes to providing more efficiency to the management process.

2.2 Materials

This section of the paper presents the design and development of a sensor prototype based on the

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previously defined WSN concept. This prototype was particularly suited for the investigated scenarios. In particular, the prototype was a sensor node having enough computational power to accomplish the computer vision task envisaged for the railway monitoring scenarios, as described in the previous section. In the design of the prototype, an important requirement was the use of *low-cost* technologies. The node uses sensors and electronic components of low cost so that, once engineered, the device can be manufactured at low cost in large quantities. In the design and planning of the architecture, an important consideration was the ease of installation of the device: the protective shield used for the sensor nodes was compact but capable of accommodating all components of the device. A WSN having its nodes so engineered was called Smart Camera Network (SCN).

Going into detail, the single sensor node had a main board that managed both the *vision* tasks and the *networking* tasks thanks to an integrated wireless communication module (RF Transceiver).

Other components of the sensor node were the power supply system that controlled charging and permitted to choose optimal energy-saving policies. The power supply system included the battery pack and an optional module for harvesting energy, e.g. photovoltaic panels (Figure 1).

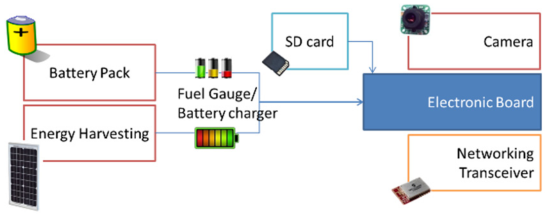

Figure 1: Architecture of the sensor node.

For building the vision board, an embedded Linux architecture was selected in the design stage, so as to provide enough computational power and ease of programming. A set of ready-made Linux-based prototyping boards was evaluated in terms of computing power, flexibility/expandability, price/performance ratio and technical support. They were all found to have common disadvantages: high power consumption and electronic components not suitable for the tasks of a smart camera node.

It was thus decided to design and build a custom-made vision component, by designing, printing and producing a new PCB. The new PCB (see Figure 2) was conceived to have maximum flexibility of use while maximising the performance/consumption ratio. A good compromise was achieved by using a *Freescale* CPU based on the ARM architecture, with support for MMU-like operating systems GNU/ Linux.

This architecture had the advantage of integrating a Power Management Unit (PMU), in addition to numerous peripheral interfaces, thus minimising the complexity of the board. In addition, the CPU package of type TQFP128 helped us to minimise the layout complexity, since it was not necessary to use multilayer PCB technologies for routing. Thus, the board could be printed also in a small number of copies. This choice had the further benefit of reducing development costs: the CPU only needed an external SDRAM, a 24MHz quartz oscillator and an inductance for the PMU.

It had an average consumption, measured at the highest speed (454MHz), of less than 500mW.

The system included an on-board step-down voltage regulator, type LM2576, featuring high efficiency to ensure a range of voltages from 6 to 25V, making it ideal for battery-powered systems, in particular for power supply by lithium batteries (7.2 V packs) and lead acid batteries (6V, 12V, 24V packs).

The board had several communication interfaces including an RS232 serial port for communication with the networking board, SPI, I2C and USB.

For radio communication, a transceiver compliant with IEEE 802.15.4 was integrated, in line with modern approaches to the Internet of Things applications. Appropriate glue was used to integrate the transceiver into the IPv6 stack, also containing the 6LoWPAN header compression and adaptation layer for IEEE 802.15.4 links. Therefore, the operating system was well capable of supporting ETSI M2M communications over the SCN.

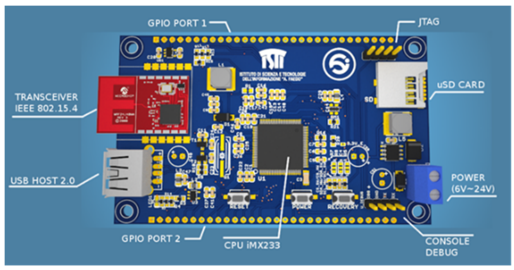

Figure 2: Design of the PCB and main features.

For integration of a camera sensor into the vision board, some specific requirements were defined in the design stage: ease of connection to the board and of management through it, and minimum performance under difficult visibility conditions, i.e. night vision. Thus, the minimal constraints were: compliance with USB Video Class devices (UVCs)

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and possibility to remove the IR filter or capability of Near-IR data acquisition. Moreover, the selection of a low-cost device was an implicit requirement considered for the whole sensor node prototype.

The previously described boards and camera were housed into an IP66 shield. Another important component of the node was the power supply and the energy harvesting system that controlled charging and permitted to choose optimal energy-savings policies. The power supply system included the lead (Pb) acid battery pack and the optional module for harvesting energy through a photovoltaic panel.

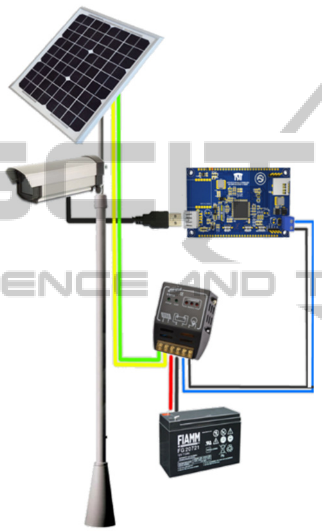

Figure 3: General setup of the monitoring node.

Figure 3 shows the general setup of a single node with the electrical connections of the related components.

2.3 Image Analysis

Sample applications based on computer vision for monitoring railways via the SCN are described below. They concern the detection and real-time alert of dangers strictly related to the flow of trains on the railway, and are based on a lightweight computer vision pipeline different from the one used in standard architectures.

More precisely, the analysis of the railway scene status and the estimation of the level of service were usually carried out by collecting data about the railroad track in terms of events occurring, their type and extension in space and time. Conventional pipelines start with i) background subtraction and move forward to ii) object detection, iii) object classification, iv) object tracking and v) final data extraction. On the SCN, instead, it is convenient to adopt a lightweight approach; in particular, processed data reside only in the Region of Interest (RoI), where the presence of an obstructing object needs to be detected. On the basis of these detections, then, flow information is derived without making explicit use of classical tracking algorithms.

More in detail, background subtraction is performed only on convex quadrangular RoIs. Such shape is sufficient for modelling physical rectangles under perspective skew. In this way, when low vision angles are available, it is possible to manage a skewed scene even without performing direct image rectification, which can be computationally intensive on an embedded sensor. The quadrangular RoI can be used to model lines on the image (i.e. a 1 pixel thick line) as well.

On such RoI, lightweight detection methods are used to classify a pixel as *changed* (in which case it is assigned to the foreground) or *unchanged* (in which case it is deemed to belong to the background). Such decision is made by modelling the background. Several approaches are feasible. The simplest one is represented by straightforward *frame differencing*. Under this approach, the frame before the one being processed is taken as background. A pixel is considered to be changed if the frame difference value is higher than a given threshold. Frame differencing is one of the fastest methods but has some limitations; for instance, a pixel is considered to be changed twice: first, when an object enters into and, second, when it exits from the pixel area. In addition, the RoI is placed in an area of train transit; thus, when an event of transit occurs, and if the object (i.e. the train occluding the RoI) is homogeneous and imaged in more than one frame, it might be not detected in the frames after the first. Another approach is based on the *static background*. Under this approach, the background is taken as a fixed image without objects, possibly normalised to factor illumination changes. Due to weather, shadows and light changes, the background should be updated to yield meaningful results in outdoor environments. However, strategies for background update might be complex; indeed, it should be guaranteed that the scene is without objects passing through when updating. To overcome these issues, algorithms featuring *adaptive backgrounds* are used. Indeed this class of algorithms is the most robust for use in uncontrolled outdoor scenes. The background is constantly updated by merging the old background model with the new observed image. There are several ways of obtaining adaptation, with different levels of

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computational complexity. The simplest is to use an *average image*. In this method, the background is modelled as the average of the frames in a time window. Online computation of the average is performed. Then a pixel is considered to be changed if it exceeds a given threshold of the corresponding pixel in the average image. The threshold is uniform on all the pixels. Instead of modelling just the average, it is possible to include the standard deviation of pixel intensities, thus using a statistical model of the background as a single *Gaussian distribution*. In this case, both the average and standard deviation images are computed with an online method on the basis of the frames already observed. In this way, instead of using a uniform threshold on the different image, a constant threshold is used on the probability that the observed pixel is a sample drawn from the background distribution, which is modelled pixel by pixel as a Gaussian. *Gaussian Mixture Models* (GMMs) are a generalisation of the previous method. Instead of modelling each pixel in the background image as a Gaussian, a mixture of Gaussians is used. The number k of Gaussians in the mixture is a fixed parameter of the algorithm. When one of the Gaussians has a marginal contribution to the overall probability density function, it is disregarded and a new Gaussian is instantiated. GMMs are known to be capable of modelling changing backgrounds even in cases where there are phenomena such as trembling shadows and tree foliage (Stauffer and Grimson, 1999). Indeed, in those cases, pixels clearly exhibit a multimodal distribution. However, GMMs are computationally more intensive than a single Gaussian. *Codebooks* (Kim et al., 2004) are another adaptive background modelling technique presenting computational advantages for real-time background modelling with respect to GMMs. In this method, sample background values at each pixel are quantified in codebooks, which represent a compressed form of background model for a long image sequence. This makes it possible to capture even complex structural background variations (e.g. due to shadows and trembling foliage) over a long period of time under limited memory.

Several ad-hoc procedures can be envisaged starting with the methods just described. In particular, one important issue concerns the policy by which the background is updated or not. In particular, if a pixel is labelled as foreground in some frame, we might want this pixel not to contribute to updating the background or to contribute thereto to a lesser extent. Similarly, if we are dealing with a RoI, we might want to fully update the background only if no change has been detected in the RoI; if a change has been detected instead, we may decide not to update any pixel in the background.

3 RESULTS

This section reports the preliminary results for the identified case study site, where the experimental activity was performed in order to monitor the railway and derive a real-time report of obstacles endangering train transit. The main objective was to define the scenarios and set-up for the above-mentioned three different types of fast-failure events that might locally involve the railway.

3.1.1 Case Study

The selected pilot site for the first test was located close to Terni, Central Italy, along a secondary line of the Italian railway network. The site of Terni is subject to rock falls and is characterized by a narrow man-made trench cut in intensely jointed limestones. From the trench walls, which are partially bounded by wire mesh, stones of a size from few centimetres to about one meter may fall onto the railway. In this site, several tests were carried out for analysing and verifying the installation's positions and the data acquisition methods to monitor the railway tracks.

The tests were also aimed at verifying the SCN suitability for field acquisitions in case of real running trains as well as in case of artificially caused rock falls.

Some video sequences were recorded including the following scenes:

A. sideway scanning of tracks to catch events;
B. semi-perpendicular scanning to catch the rails to detect any changes;
C. railway scanning without trains, representing the "background scene";
D. scanning steps with trains in both directions;
E. scanning during vibration generated by train transit;
F. scanning of simulated anomalous transits as well as of artificially caused falls of "objects" on the railway.

It was possible to record and quantify image artefacts induced by vibrations and air movement. The collected data enabled to estimate the possible consequences on the image analysis algorithms and, therefore, to improve a software solution for reducing disturbances.

If compared with the static background image, the recorded noise is very low and can be directly managed by the acquisition software.

However, the reduction of noise via specifically-implemented tools should be encouraged in order to further optimise the performance of the device.

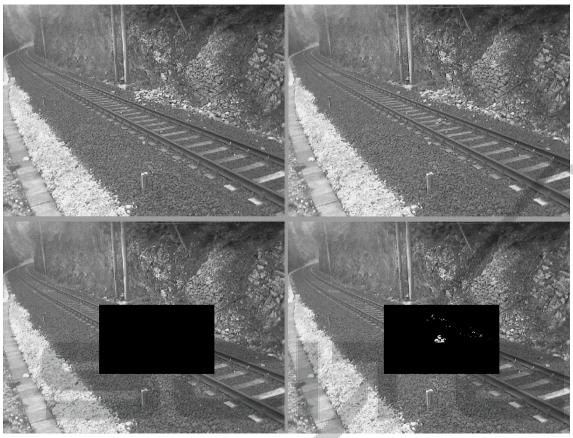

Figure 4: Example of event detected in a RoI over the tracks (e.g. falling debris).

A final test was performed by recording videos during train stops along the railway, a type of disturbance due to the specific event expected to occur along the railway track. This final test demonstrated the excellent performance of the implemented algorithms: once the directional parameters referred to the monitored scene have been defined, the software only processes the camera records that express differences between the background scenario and the changed one, minimizing false alarms and optimising data collection and transmission.

More in detail, scenarios were defined for training and testing the implemented algorithm to be robust and satisfy the specific requirements defined for the case study application. In particular, the robustness of the image analysis algorithm was tested under scenarios such as the management of false alarms due to train transit, coherence in case of vibrations caused by train transit, adequacy of detection of debris passing by the rails but not impeding subsequent train transit, capability of detecting early signs of sinkholes.

In Figure 4, an example of a detected event (falling debris) is shown (right), in comparison with the normal situation (left). The amount of the detected change in the scene is above the threshold fixed as definition of an endangering situation.

Moreover, Figure 5 shows the amount of maximum displacement (in pixels) during the transit of a train causing vibration to the installation; such amount was quantified to be less than 1% with respect to the image size, thus a very limited and manageable difference.

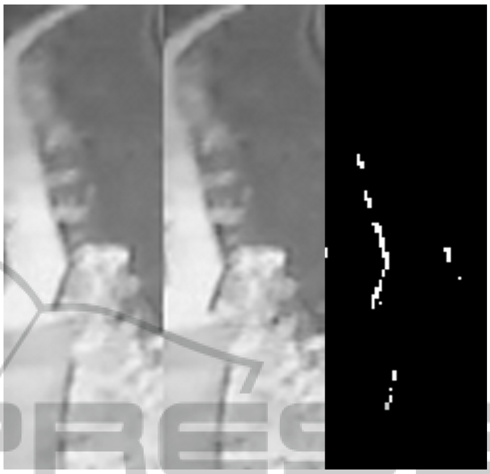

Figure 5: Details (zoom 400%) of the maximum displacement between two frames during vibration due to train transit.

With regard to the capability of detecting early signs of sinkholes, a different scenario was set up with the SCN device placed perpendicularly over the train tracks. With this set-up, it was possible to define the limit of distance from the railway and the limit of movement in the parallelism of the rails. The set-up is shown in Figure 6, with a highlighted area indicating the distance representing the limit of the detection capability of the sensor (i.e. around 150 pixel size) for determining discrepancies in the parallelism of the rails.

4 CONCLUSIONS

In order to monitor railway tracks in real time and detect fast failures occurring and threatening train transit, a Smart Camera Network was put in place. Three different types of fast-failure events, involving the railway, were identified with the goal of developing algorithms capable of spotting and localising them. Furthermore, scenarios were defined to experiment, in the case study site, the capability of the SCN to successfully monitor the various events. While the simulation of some events was feasible (e.g. debris falling onto the railway), the simulation of other events was not feasible due to risks for safety (e.g. early signs of the sinkhole). Therefore, the latter events were only simulated through software changes, but the results were good and promising in both cases.

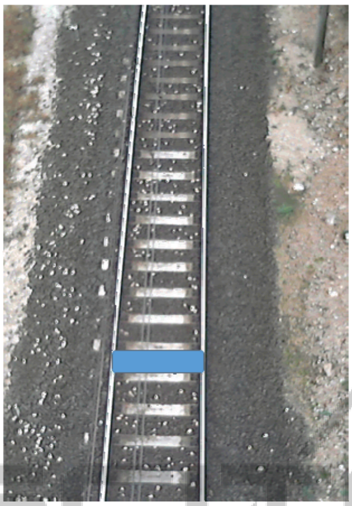

Figure 6: Sinkhole detection set-up highlighting the detection area.

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