Self-powered wireless IoT nodes for emergency management

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***Abstract*—Expected and unexpected events affect road infrastructure leading to several issues that require maintenance interventions or prompt actions. In order to face the issues mentioned above, specially designed platforms can be used. Despite the high number of solutions presented in the last decades, it is difficult to find real applications of systems deputed to the emergency management of the abovementioned infrastructures. This paper aims at describing an innovative platform and the results of its first application. The platform consists of a system and algorithms that allow environmental and structural monitoring and emergency management. The proposed system consists of a network of wireless sensor nodes that are self-powered by mean of photovoltaic energy harvesters. Two different types of algorithms were designed to monitor the environmental and structural condition (i.e., the vibro-acoustic signature) of different types of structures and infrastructures, and to display, thanks to a dashboard, several predefined alarms, escape routes, safe place, and gathering points. The results presented in the paper refers to the first application of the platform, here tailored for an Italian theme park in the framework of the project "SICURVIA" funded by Regione Calabria, Italy. These results, presented for the first time, show that the platform is able to extract crucial information about the conditions of the thematic park's assets, and, at the same time, this information are used to recognize an emergency, trigger the related alarm, and provide a plan to manage the extraordinary event happened.**

Keywords*—*emergency management; wireless sensors network; self-powered device; road infrastructure.

I. INTRODUCTION

Road infrastructures have to face problems related to the expected (e.g., aging, crack generation), and unexpected (i.e., accidental and/or catastrophic events, such as vehicle accidents, fires, earthquakes, flash floods, etc.)[1]. To this end, a possible solution is represented by specially designed wireless sensor network. Nonetheless, it is really difficult to find systems deputed to the emergency management of the infrastructures mentioned above. Relevant examples of wireless-sensor-based solutions are reported in the following subsection (see subsection I.A), while subsection I.B provides an overview about energy harvester designed for road-related applications. Section I ends with the objectives and scopes of the paper. Subsequently, in sections II and III, a platform specifically designed as a decision support tool to solve/mitigate the problems stated above and the results of its first application are presented. The results above are followed by conclusions and references.

A. Wireless Sensor Networks and Road Infrastructures

Wireless Sensor Networks (WSNs) enable applications for road and railway state monitoring, traffic safety, traffic congestion control, vehicular warning services, and parking management, especially in urban contexts [2], [3].

WSNs belong to the Internet of Things (IoT) paradigm (technologies-oriented), which is considered as the building block for both future, user-oriented, smart cities and Intelligent Transportation Systems (ITS) [4]. Alavi et al. (2018) [4] presented a literature review about state-of-the-art, trends, and challenges about technologies and worldwide IoT-based projects. In addition, the study above includes an interesting case study in which an IoT-based, low-cost (about $ 46 per node), embedded (the size of a single node is similar to the average aggregate size of the road pavement course), piezoelectric (polyvinylidene fluoride piezoelectric films, PVDF), and wireless prototype of sensor node is used for the real-time monitoring of a road pavement. This latter is able to detect strains induced by axial loading, and the related electrical signals are sent by an IoT board (Arduino) using the Wi-Fi protocol. In particular, a scanning app (Fing) is used to discover all connected devices and to connect the nodes to a web platform (Plotly), which is used to visualize the real-time data.

When sensor nodes are used, the Strip Clustering Scheme (SCS) can be adopted to solve their main drawback, i.e. their limited service life due to the battery power storage [5]. The

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This paper addresses the objectives of both the ongoing Italian project "USR342" (i.e., urban safety, sustainability, and resilience: 3 paving solutions, 4 sets of modules, 2 platforms; reference number: PRIN2017XYM8KC), and the Italian regional project SICURVIA (concluded and patent submitted).

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SCS allows saving energy because of smart data collection that includes data packing (i.e., data from non-head nodes are aggregated before their transmission), region division (i.e. the monitored area is divided into several strip-shaped regions), cluster head node selection (i.e. only one node collects all the data gathered from each node of each strip after their aggregation), link construction (i.e., each non-head sensor node searches for the closest node, and then builds up a link with it, using the PEGASIS protocol and greedy algorithm, until all nodes in the region are linked each other) [5].

However, it is important to highlight that, the implementation and the use of wireless networks should take into account the orchestration of heterogeneous solutions (i.e., their management, control, connection, integration, coexistence), which can lead to poor resource usage, and, consequently, to decrease service guarantees and performance of the network [6], [7]. Unfortunately, lack of technologies, of intelligent management, and of full acceptance and implementation by industry make the current attempts unsuitable to allow true continuous connectivity for machine-to-machine communication as well as users [6].

B. *Energy Harvesting from Road Infrastructures*

The use of Energy Harvesting Technologies (EHTs) in road-related applications is an acknowledged cleaner and greener alternative to conventional sources, because of the fact that roads are very extensive, are loaded by high traffic volumes of vehicles (especially the heavy ones), and their maximum temperature can reach 60°C [8]. These characteristics allow the implementation of the following classes of EHTs [8]–[15]: 1) Solar-based (i.e., solar pavements, asphalt solar collectors, and photovoltaic thermal hybrid solar collectors); 2) Geothermal; 3) Thermoelectric; 4) Piezoelectric (exploiting traffic-induced vibration and loads); 5) Electromagnetic (based on velocity transducer); 6) Electrostatic (e.g., based on variable capacitors, or on pre-charged or induced charges from an external voltage bias); 7) Wind-based (e.g., turbine); 8) Vehicle-based (i.e., included on tires, or dampers); 9) Pedestrian-based; 10) Micro-Electro-Mechanical Systems (MEMS)-based combined with a super-diode. Among these technologies, solar-based are the most widespread, and their success depends mainly on the level of technology readiness, and on the support from government and industry [9].

Recently, the efforts made in the field of the electric mobility combined with the world of the sustainable energy is going to affect the future road infrastructures by mean of the development of new technologies such as autonomous electric vehicles, contactless/wireless electric vehicle charging, and self-healing asphalt roads (where the latter two are based on inductive coils) [16]. Noteworthy are the emerging concepts of “infrastructure sharing” (i.e., considering an infrastructure as a place where technologies designed for different purposes can coexist and improve each other), and “efficient mosaic integration” (i.e., designing new solutions keeping in mind the already implemented technologies)[16].

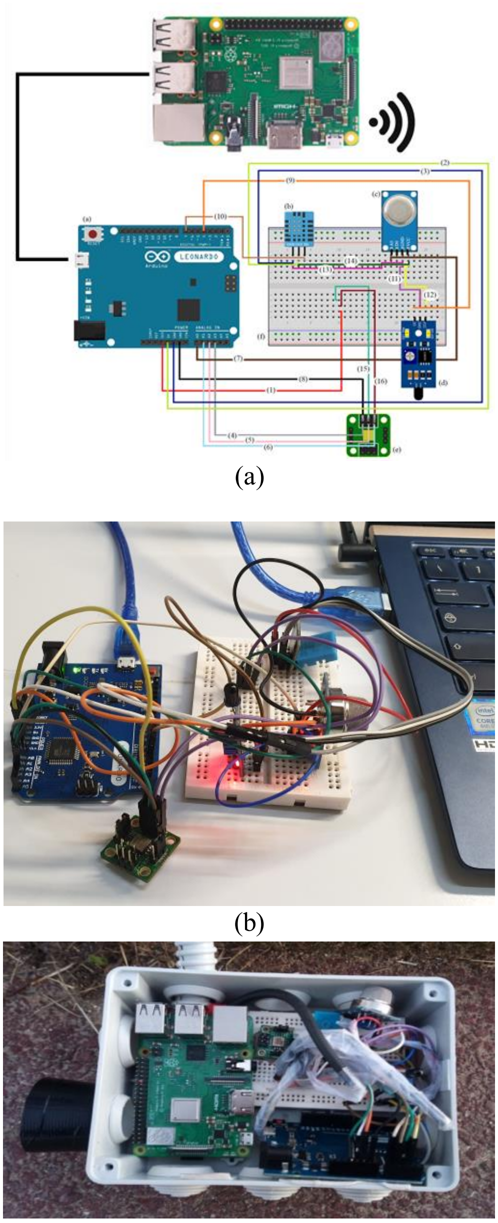
C. *Objectives and Scope*

The main objective of the study described in this paper is the description of an innovative Wireless Sensor Network (WSN) specially designed for monitoring road infrastructure from a structural and environmental point of view. Importantly, this paper reports the main innovations of both the monitoring system (i.e., the proposed sensor nodes), and the monitoring method (i.e., algorithms for emergency management), which are described in section II.A and II.C, respectively, and the results described in section III.

II. MONITORING PLATFORM

A. *The Proposed Sensor Units*

The WSN proposed in this paper consists of wireless sensor nodes that contain several sensors, a microcontroller (Arduino), a single board computer with embedded wireless transmitter (Raspberry Pi 3), and a photovoltaic energy harvester. In more detail, each node includes the following sensors: 1) accelerometer; 2) microphone; 3) temperature and humidity sensor; 4) smoke detector; 5) fire detector; 6) air quality sensor. Fig. 1 shows the sketch of the wireless sensor unit used in this study. The cost of each node, for the sensor components, is under 10 $.



(a)

(b)

(c)

Fig. 1. Wireless sensor unit: a) first prototype; b) prototype during in-lab tests; c) first prototype during on site tests.

B. *Energy Balance of the System*

This section of the paper includes the description of the energy harvester system used to power the sensor nodes, and the energy balance of the monitoring system, i.e. the energy consumption of each part of the system. In order to feed each sensor node, an energy harvester consisting of (1) a photovoltaic panel (polycrystalline silicon, 5 W, 18 V), (2) a charge controller (i.e., a dc-dc regulator, 12 V, 20 A), and (3) a battery (12 V, 12 Ah) is used (Fig. 2a). Note that, Fig. 2b shows a preliminary installation of one sensor node with the PV panel in vertical position (inclination = 0°), while during the final installation the PV panels of the sensing nodes were all inclined by 30° and oriented to South.


(a) (b)

Fig. 2. Example of energy harvesting system (a) used to power the sensor node (b) attached on the road pavement.

In previous studies by the same authors of this paper [9], [17], a prototype of the system was described and an estimation of the energy consumption, based on device type (both sensors and wireless transmitters), duty cycle, and sampling frequency was carried out and presented. The first results pointed out that, in given operational conditions (i.e., microcontroller, sensors, and Wi-Fi data transmitter with a duty cycle of operation in sleep mode for 99%, 90%, and 90 %, respectively; a daily solar irradiation of 5.5 kWh/m^2; efficiency of photovoltaic, PV, panel, wires and battery of 14%, 85%, 80%, respectively; a maximum depth of discharge of the battery of 50%; inclination of the PV panel of 36° oriented to south): 1) The energy consumption of each sensing node was about 1 Wh per day; 2) If the WSN consists of 1 sensing node, 12 days of autonomy can be reached using a PV panel of 4×4 cm^2 and a battery of 5Ah (6 V); 3) 20 sensing nodes need about 23 Wh/day; 4) If the WSN consists of 20 sensing nodes, 15 days of autonomy can be reached using a PV panel of 19 × 19 cm^2 and a battery of 7Ah (12 V). Moreover, in another study [18], the system was further tested by mean of a photovoltaic module emulator.

C. *Monitoring Platform*

The platform used to monitor the structural and environmental condition of the road infrastructures is depicted in Fig. 3. In particular, a temperature and humidity sensor, a gas sensor (able to measure both carbon monoxide and liquid petroleum gas concentration, and to detect the presence of smoke), and a flame sensor are used to monitor the environment that surround the assets monitored by the platform. At the same time, the structural conditions of the asset are estimated applying a method that considers the asset as a filter of both the ground borne seismic and sound waves, and aims at deriving the vibro-acoustic signature (i.e., the acoustic response of the asset to a load producing the abovementioned waves) [19]. For this purpose, one 3D accelerometer and one airborne-noise insulated microphone are used. The data gathered by the sensors are read by the Raspberry's serial port and are sent, in real-time (see subsection III.A) and using the Wi-Fi protocol, to an open-source server-side platform (Thingsboard) that allows assessing and controlling IoT devices (see Fig. 3). Note that, the cost of each sensing node can be reduced replacing the Raspberry Pi with cheaper devices (e.g., ESP8266, or Arduino yun), though the Raspberry Pi paves the way to further edge processing on the data (before the transmission to the server), thus reducing the transmission cost, latency and increasing data privacy. At the same time, the MQTT protocol was used (see subsection III.B) to send the data to a web server (e.g., the MQTT broker Eclipse Mosquitto™) seeking to reduce network bandwidth, nodes resource requirements, and, at the same time, improving the data transfer reliability. The data (text strings in JSON format) are stored by the web server and then sent to an authorized (i.e., subscriber to a specific topic) customer of the platform for further analyses (e.g., structural monitoring).

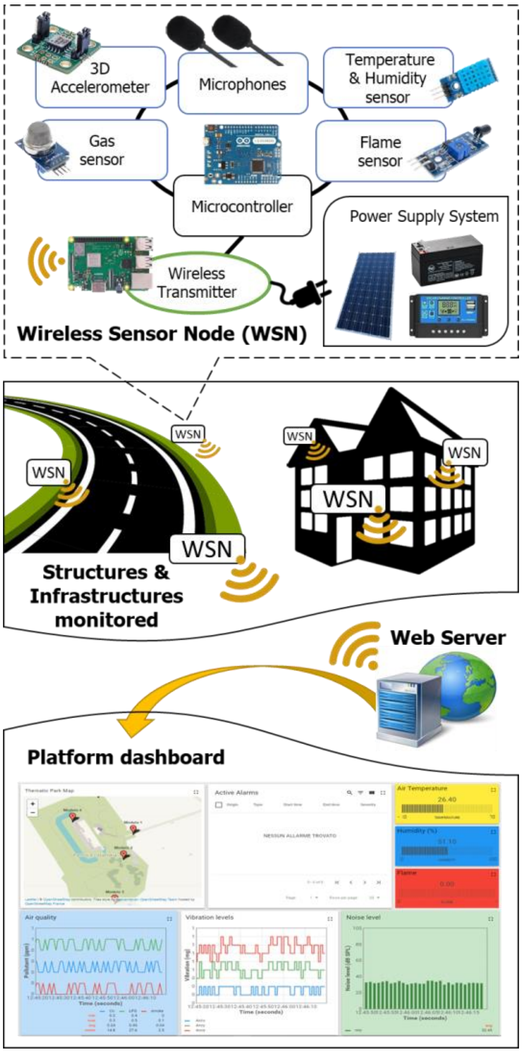


Fig. 3. Schematic representation of the monitoring platform.

For instance, as described in previous studies [17], [20] specific features can be extracted from the vibro-acoustic signals and can be used to detect damages occurred on/inside road pavements. In particular, the following nine features, extracted from both time, frequency, and time-frequency domains of analysis, and were used for the derivation of the vibro-acoustic signature of a road pavement: 1) the differences between absolute maxima and absolute minima of the signal's amplitudes (time domain); 2) the differences between the arrival times of the absolute maxima and absolute minima (time domain); 3) the standard deviation of the signals (time domain); 4) the absolute maxima of the power spectral density in the frequency range 20–500 Hz (frequency domain); 5) the spectral centroid (i.e., the "center of mass" of the spectrum) in the frequency range 20–500 Hz (frequency domain); 6) the slope of the linear regression of the spectrum in the frequency range 20–500 Hz (frequency domain); 7) the Shannon's entropy of the of the Continuous Wavelet Coefficients (CWCs) calculated applying the Continuous Wavelet Transform (time–frequency domain); 8) the pseudo-frequency associated with the wavelet ridge of the scalograms (i.e., graphs that show, in the time–frequency domain, the variation in the CWCs' amplitudes with a color scale that ranges from 0 to 64); 9) the maximum energy of the CWCs associated with the highest values of the CWCs (time–frequency domain). The nine features listed above, derived from a data set consisting of 4000 signals related to 4 different structural condition opf the same road pavement, were used as input of a Convolutional Neural Network (CNN, with two fully connected hidden layers, one convolutional layer, and one pooling layer). The CNN was able to identify the level of damage of the road pavement with an accuracy of 99.6% [10].

D. *Algorithm for emergency management*

The platform proposed in this paper was designed to carry out emergency management using the real-time data (gathered as described above). Fig. 4 shows the algorithm that is implemented in the platform dashboard.

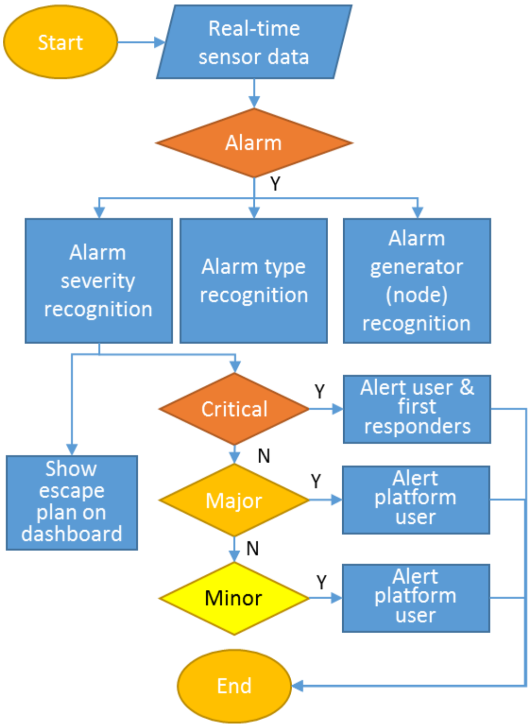


Fig. 4. Algorithm for the emergency management.

The above mentioned algorithm is used to carry out the following tasks: 1) identify an emergency; 2) recognize the emergency's severity; 3) trigger an alarm; 4) point out the area where the emergency occurred; 5) find and point out the quickest and safest path for the crowd to reach the meeting points or an available exit; 6) send messages to platform's user, or to first responders (based on the alarm type and severity, and indicating the available access route).

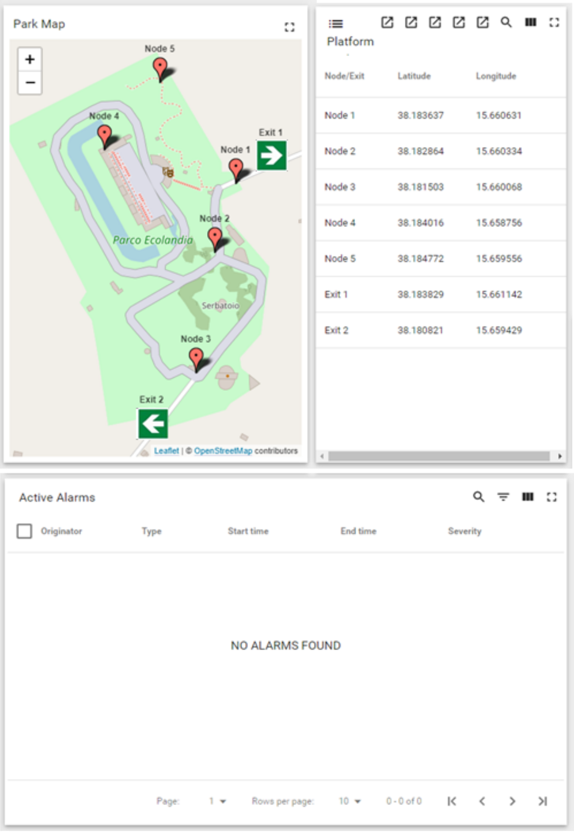
Based on the number of the physical nodes of platform and on the possibilities offered by the server-side platform (that allows designing the dashboard), it is possible to determine (permutations) the number of alarm combinations (e.g., 31 if the platform consists of 5 nodes, see Fig. 5). Furthermore, both different alarms (e.g., temperature alarm) and several severities (e.g., minor, major, critical) can be defined. In addition, the alarm's severity can be automatically recognized using a specific index (e.g., if no alarm = 1, minor = 0.75, major = 0.5, critical = 0).

III. RESULTS AND DISCUSSIONS

In this section are reported the results derived from the real-time data. These results are related to the dashboard shown in the figures included in the following subsections.

A. *Results from Realt-Time data*

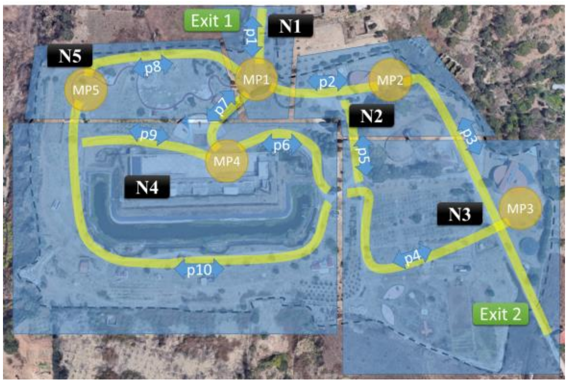
Several simulations were carried out to test the performances of the dashboard. In particular, a fire was simulated in order to verify if: i) the alarms are correctly triggered; ii) the escape plans are properly designed; iii) the related alert is sent to users/first responders. Fig. 5 shows the main page of the dashboard without active alarms.



Node/Exit	Latitude	Longitude
Node 1	38.183637	15.660631
Node 2	38.182864	15.660334
Node 3	38.181503	15.660068
Node 4	38.184016	15.658756
Node 5	38.184772	15.659556
Exit 1	38.183829	15.661142
Exit 2	38.180821	15.659429

NO ALARMS FOUND

Fig. 5. Main page of the dashbord displaying map, node/exit positions, and active alarms.



Legend:
Polygons = areas monitored by the nodes;
Stripes = escape routes;
Circles = Meeting Points;
N_n = Points where the Nodes are installed;
$Exit_n$ = Access routes (with n = 1, 2);
p_m = Escape routes' name (with m = 1,.., 10);
MP_i = Meeting Points (with i = 1,.., 5).

Fig. 6. Graph that shows the position of the nodes of the platform, of the escape routes, of the meeting points, and the areas monitored by each IoT node.

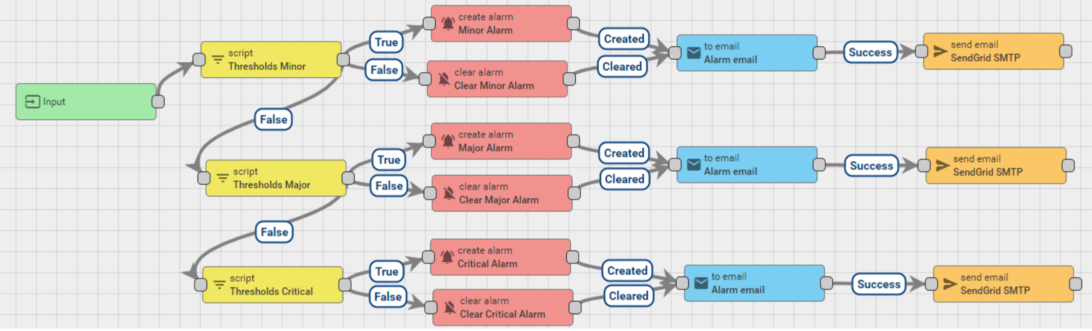


Fig. 7. Algorithm that allows alarm generation and message sending to the dashboard.

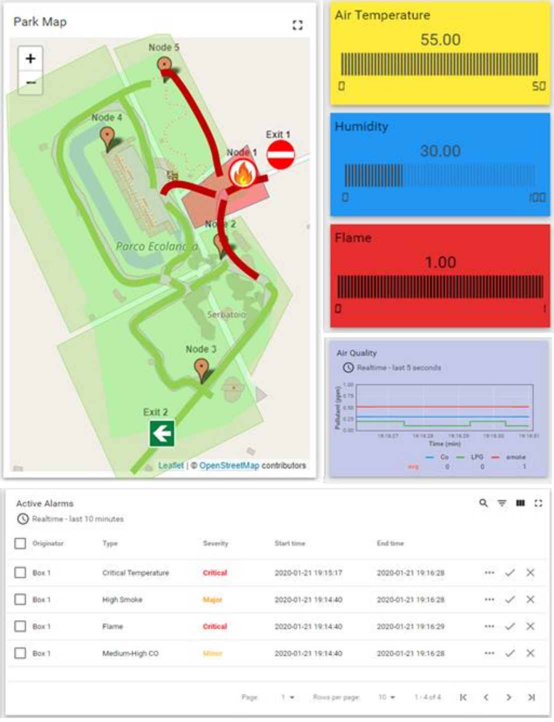
Fig. 6 shows positions of the nodes of the platform, of the escape routes, of the meeting points, and the areas monitored by each node. Meanwhile, Fig. 7 represents the algorithm that was implemented in the server-side platform (Thingsboard), and that allows the dashboard to (1) generating three levels of alarm (i.e., Minor, Major, and Critical) when sensor data are in three predefined intervals (thresholds), (2) sending email to the user of the monitoring platform whenever the alarm is created, (3) clearing the active alarms when sensor data returned under the thresholds.

The following thresholds were defined to trigger the three levels (Minor, Major, Critical) of alarm: i) medium-high temperature: ≥ 30°C and ≤ 40°C, high temperature: > 40°C and ≤ 50°C, critical temperature > 50°C; ii) medium-high humidity: ≥ 70% and ≤ 80%, = high humidity: > 80% and ≤ 90%, critical humidity: > 90%; iii) medium-high Carbon Monoxide (CO; parts-per-million, ppm; [21]): > 0 ppm & ≤ 25 ppm, high CO: > 25 ppm & ≤ 35 ppm, critical CO: > 35 ppm; iv) iv) medium-high Liquefied Propane Gas (LPG; [22]): > 0 ppm & ≤ 5000 ppm, high LPG: > 5000 ppm & ≤ 10000 ppm, critical LPG: > 10000 ppm; v) flame: 1, no flame: 0; vi) smoke thresholds are the same of LPG; vii) medium-high vibration (1 g ≈ 9.81 m/s^2): < 1.5 g and ≥ -2r > 1.5 g and ≤ 2 g, high vibration: < 2 g and ≥ -3 g, or > 2 g and ≤ 3 g, critical vibration: < -3 g, or > 3 g; viii) medium-high noise (Sound Pressure Level, SPL, dB): ≥ 50 dB and ≤ 60 dB, high noise: > 60 dB and ≤ 70 dB, critical noise: > 70 dB.

Fig. 8 refers to the first simulation, i.e., a fire occurred near the node 1. Note that, the node 1 is the node deputed to the monitoring of one of the two thematic park's access routes (herein called Exit 1), and that the meeting points are highlighted by the dashboard if both the exits are closed because of alarms active around node 1 and 3.

Fig. 8. Dashboard of the system that shows the environmental conditions before a fire.

Fig. 9 refers to the first simulation, i.e., a fire occurred near the node 1, and shows the ability of the dashboard to recognize the presence of fire, to trigger the alarms (i.e., fire, smoke, temperature, CO), and to provide a map for the emergency management, which shows safe and unsafe paths colored in green and red, respectively.



Active Alarms

Realtime - last 10 minutes

☐ Originator	Type	Severity	Start time	End time
☐ Box 1	Critical Temperature	Critical	2020-01-21 19:15:17	2020-01-21 19:16:28
☐ Box 1	High Smoke	Major	2020-01-21 19:14:40	2020-01-21 19:16:28
☐ Box 1	Flame	Critical	2020-01-21 19:14:40	2020-01-21 19:16:29
☐ Box 1	Medium-High CO	Minor	2020-01-21 19:14:40	2020-01-21 19:16:28

Page 1 Rows per page: 10 1 - 4 of 4

Fig. 9. System's dashboard that shows the emergency plan after a fire.

IV. CONCLUSIONS

In this study, a platform consisting of a system and algorithms that allow environmental and structural monitoring and emergency management is presented. For the first time, the results of the real-time application of the platform, here tailored for an Italian thematic park in the framework of the project "SICURVIA" funded by Regione Calabria, Italy, are discussed. These results show that the platform is able to extract crucial information about the conditions of the thematic park's assets, and, at the same time, this information is used to recognize an emergency, trigger the related alarm, and provide a plan to manage the extraordinary event happened.

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