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Real-time networks for earthquake observation and structural health monitoring in Sicily

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ABSTRACT: The implementation of systems for Earthquake Observation and Structural Health Monitoring is highly increasing in the last years. In fact, just in recent time, new technologies are enabling low-cost and small-size devices to be installed in large-scale or high-density applications. In this paper we present two case studies where monitoring systems, either for earthquake observation and structural health assessment, have been implemented. The case studies are both based in Sicily (Italy), a region characterized by an elevated seismic hazard and where the buildings are often old and vulnerable. The systems rely on Micro Electro-Mechanical Systems (MEMS) sensors, a triaxial accelerometer which have been specifically selected in order to ensure its suitability for the specific applications (accelerations from 10° to 10^2). We also present the details of the designed monitoring station, of the network architecture and on the devoted managing software.

1 INTRODUCTION

The implementations of systems for Earthquake Observation (EOS) and Structural Health Monitoring (SHMS) are highly increasing in the last years, when the limitations deriving from the traditional systems have been overcome. Such limitations basically consist in the high costs of the traditional instruments and in the difficulty to maintain, in the long-term, monitoring systems for an adequate time span (e.g. a decade or more) after their implementation.

For these reasons, apart from the country-scale networks usually managed by governmental institutions, EOS and SHMS systems are limited to small-scale or low-density application. Inevitably, the technical and scientific results are often poor, but the emerging technologies help to overcome the compromise between technical-scientific needs and the economic affordability. The progresses achieved by the technological development in the last twenty years, have lead to a great advancement of the instrumentation for seismic and structural monitoring in term of miniaturization, sensitivity, and quality of data. In particular, the reduction of dimensions has been so pushed that seismometer passed from bulky and heavy apparatus, to compact, low weight, and manageable devices. Even in more recent years, the Micro Electro-Mechanical Systems (MEMS) also contributed to the growth of the seismology and its applications, further reducing costs and dimensions but sometimes going inevitably to the detriment of sensing capability. However, large-scale and high-density applications can also overlook this unfavorable aspect.

Similarly, advances involved robustness and reliability of the systems, capability of data transmission in terms of frequency rate and amount of information, computational capability for data processing, and also lowering of power consumption. All these new capabilities, through in the integration of different sensors, are enabling applications in the broad fields of seismology and geotechnical monitoring. In particular, MEMS sensor are especially suitable for applications of Early-Warning Systems either for site-specific earthquake alerts or for the assessment of the critical conditions in structures. EOS and SHMS are not only possible and affordable, but in conditions of high seismic risk and high vulnerability should be desirable. In this paper we introduce the realization of two urban-scale, real-time monitoring network designed for EO and SHM in two sites in eastern Sicily (Italy).

2 THE MONITORING SYSTEMS

A monitoring system based on the combination between EO and SHM can sensibly lower the potential impact of a destructive earthquake in an urban context. When a destructive earthquake hits a vulnerable urban area, the prompt assessment of damage is very critical for search-and-rescue operation, and such monitoring systems are able to provide useful information to the emergency management centre addressing timely and targeted actions in the case of emergency (e.g. earthquake). In fact, the shorter the intervention time, the greater will be the opportunity for effective operations minimizing the number of victims. SHM is a fundamental tool to integrate and support conservation strategies of infrastructures and to preserve their strategic function (i.e. security, management, organization) and the architectural heritage. SHM should be considered necessary, at least for public edifices with strategic function, since stress factors acting on the structures (either natural or anthropogenic) lower the resistance properties and induce potential risks in the long-tem. The stress factors acting on the structures can be due to natural or anthropogenic factors: seismic events, atmospheric agents (wind, thermal cycles), vibration due traffic flow, applied loads, lowering of the resistance properties (corrosion, alteration, etc.) which effects are assessed by means of various types of sensors (Moreno-Gomez 2017 for a complete review).

Two prototypal urban seismic network implemented in relevant public buildings are being installed in historical city centre of Catania, and Acireale (Sicily, Italy; Figure 1) (D'Alessandro 2016, 2018a, b). Eastern Sicily is a high seismic risk area. In fact, the area has been struck by strong earthquakes several time during history: 1169, 1542; 1693; 1818 are the dates of the main events which reached Imax up to X MCS causing diffuse damage, victims, and even almost complete destruction (Rovida 2015). According to the seismic hazard map of Italy, eastern Sicily is among the areas where the highest peak ground accelerations are expected in the whole country (Figure 1).

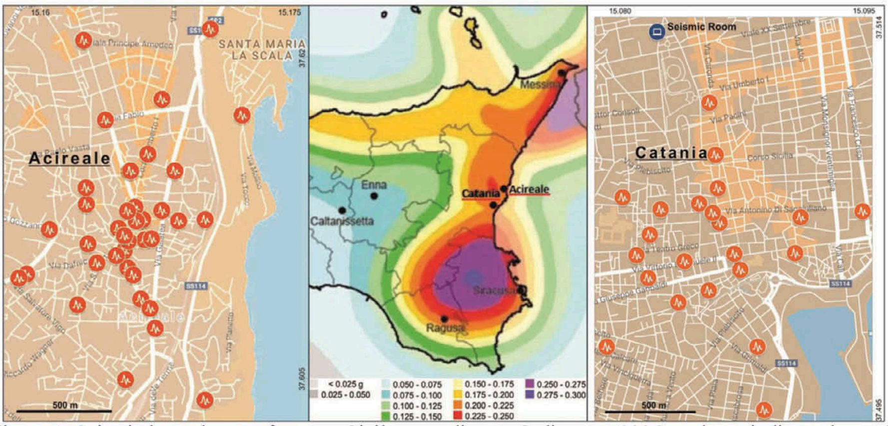

Figure 1. Seismic hazard map of eastern Sicily according to Ordinanza (2006), colours indicate the peak ground acceleration with probability of exceeding equal to 10% in 50 years (centre). On the left and on the right: location map of the monitoring stations in the town of Acireale and in city center of Catania respectively.

The city of Catania counts a population of more than 300,000 people and the town of Acireale about 45,000 people. The Catania network includes 27 nodes represented by relevant public buildings concentrated in the city center; the Acireale network encompasses the installation of about 80 seismic monitoring stations located in likewise high exposure and vulnerability buildings (Figure 1). The installation follows different stages, progressing together with the development of the hardware (i.e. the seismic/monitoring station), with the various versions of the code, and with the building of the transmission network. At present time (February, 2019), the first groups of 15 and 9 stations are operating in the Catania and Acireale networks respectively. AT the same time, is performed the selection of the other sites and their assessment to the suitability to host the monitoring stations.

2.1 *The monitoring station*

The design of a monitoring system is focused on the final objective and consequently the hardware components, the sensors, the code, and the sites, have been accurately selected, designed, and planned. The monitoring stations are based on a suite of MEMS sensors suitable for earthquake strong motion detection and structural monitoring, namely triaxial accelerometers (also integrated with triaxial gyroscope; i.e. IMU) with digital output, and low-noise accelerometer with analog output. Several studies indicate the suitability of such devices for earthquake and structural monitoring systems (D'Alessandro 2013, 2014a, 2014b; Zou 2014; Saunders 2016; D'Alessandro 2017) when they are characterized by flat noise response to acceleration and resolution (smallest detectable acceleration) in the order of 10^{-2} – 10^{-3} m/s^{-2}. (c.f. Scudero 2018).

In particular, the IMU is the model 1044_0 produced by Phidget. This MEMS sensor integrates a three-axis capacitive accelerometer and is also equipped with a gyroscope for angular rate measurements and a magnetometer, both tri-axial. The circuit of transduction is internal to the device and is of the digital type, for which the outputs are already in a digital format. The characteristics of the accelerometer are: measure range of ±2 g; resolution of 76.3 µg, and white noise of 280 µg and is able to measure both static and dynamic accelerations. The low-noise sensor is a MEMS accelerometer produced by TE Connectivity (Model 4630A). It is an analog, ultra low-noise, triaxial accelerometer offering both static and dynamic response and allowing a very good characterization of the ground motion. Its technical specifications are: range of ±2 g, sensitivity of 1000 mV/g, and residual noise of 2 µg/√Hz. A dedicated board can even enhance the bandwidth of the analog output (Vitale 2018). Combining together the accelerometer with an Inertial Movement Unit (IMU) for angular rate measurements, and broadband velocimeter will be possible to reconstruct the full form of all the components of the shaking and explore a larger frequency band.

The core of the station is a Single-Board Computer (SBC; Raspberry Pi3), equipped with an ARM quad-core 64 bit processor of 1.2 GH, and running a devoted code. The Analog-to-Digital Converter (ADC) samples the signals when the analog sensor is embedded. The ADC provides a digital output that can be managed and processed by the SBC. The station carries also a 5200 mAh power bank (UPS) to stabilize the energy supply and to provide power in case of temporary black-out. The working scheme of the station is shown in Figure 2.

The code automatically runs when the SBC boots. After checking if the various hardware components are properly connected and working, the software runs the sampling thread from the digital sensor (or from the ADC). The sampling frequency is 200 Hz; the exact absolute time, retrieved from the GPS, is associated to the first datum of each file (5 seconds long), while the time for the following data is calculated on the basis of the sampling frequency. This process runs cyclically in a continuous way (sample loop in Figure 2). The synchronization of the signals between the various stations is fundamental for the determination of the relative position of the earthquake epicenter. In fact, earthquake localization is essentially based on the travel time readings of the seismic phases. Alternatively to the GPS antenna, in particular in the sites where the sky view limited, the connection to a NTP server (Network Time Protocol) provides the desired synchronization.

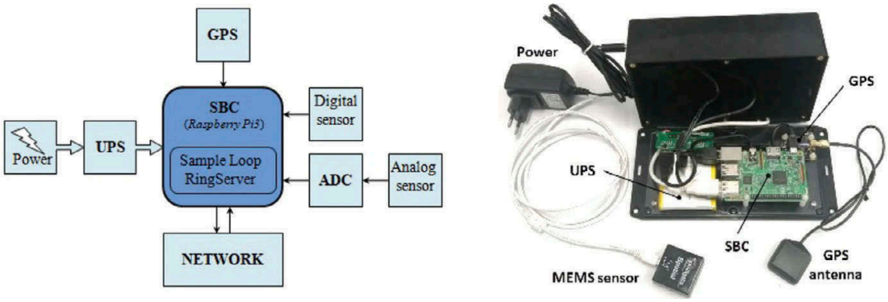

Figure 2. Working scheme of the monitoring station (left) and the assembled station equipped with the digital MEMS accelerometer (right).

The waveform files, one for each component, are written in miniSEED format. This is short version of the SEED (Standard for the Exchange of Earthquake Data) format, primarily intended for the archival and exchange of seismological time series data (Ahern 2007). The reading of the incoming data from the sensor, and the writing of mSEED data files require proper Python API libraries. The data transmission exploits the ring-server conceived by the Incorporated Research Institutions for Seismology (IRIS) for the transmission of mSEED data; it is widely tested and used in the scientific community. The role of the ring server is to connect the sample loop with the software that manages the recorded seismic tracks (Figure 2).

2.2 *The network*

To form a network, very station must be connected to a main hub. Different solutions could be exploited: internet connection, radio bridges, GSM, local area networks, or satellite transmission. The network topology chosen for the project is a star network where each host (spoke) is connected to a central hub with a point-to-point connection (Figure 3). This network has been chosen because it complies with the main needs of our system: flexibility and reliability. From the hub can depart *n* linear connections, therefore further devices (i.e. monitoring stations) can be added or removed without disturbing the network. Moreover, two or more end-points can be merged in a sub-network and, similarly, two or more networks can be

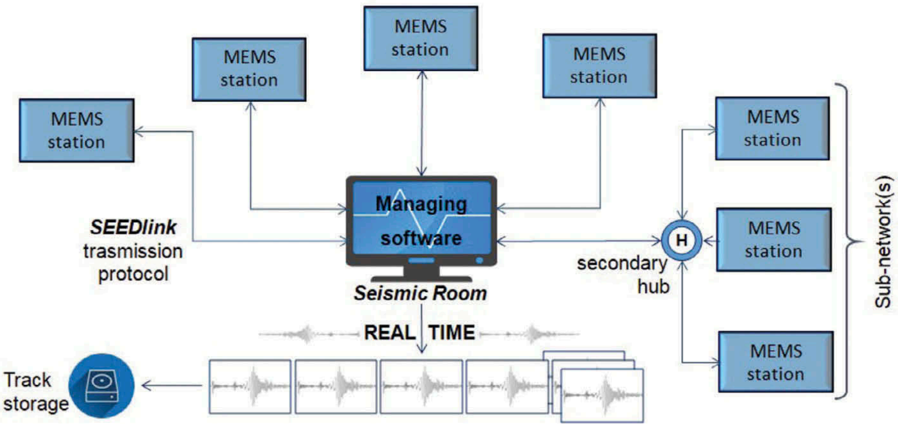

Figure 3. Scheme of the monitoring network. See the text for further details.

Figure 4. Operation of installation and configuration of a monitoring station at the ground floor of the 18th century "Elefanti Palace" located in the main square of Catania. Schemes for the sensors' distribution into edifices: a) minimum necessary requirements for a regular multi-storey building, and b) ideal extensive installations for an irregular masonry building.

merged into a unique network simply connecting their hubs (Figure 3). This is the case of buildings where the structural health monitoring is performed.

There is no need for two stations to be directly connected, and if one node, or its connection, does not work properly it does not affect the other stations and their connections to the hub. The hub manages and controls all functions of the network and is represented by the seismic room located in the headquarter of our hosting institution. The weak aspect in this kind of networks is that this central hub represents the single point of failure for the network: so it is the only part of the system that, if it fails, will stop the entire system from working. For this reason our network takes advantage from the already existing and reliable seismic room where specialized staff, present 24 hours out of 24 and 7 days a week, can monitor the operation of the system.

Every node (i.e. monitoring station) can be accessed remotely to fix eventual problem and to update the software. The set-up and the arrangement of the monitoring stations at the sites, and within the edifices, have been accurately planned. Considering the scheme of a generic multi-storey building, the literature suggests to install sensors at every level and in correspondence with changes of stiffness (Boscato 2016). The sensors at the base of the building would also provide an almost unaltered record of the input motion. For the masonry buildings, the scheme of a regular multi-storey building (Celebi 2000) can be directly reused taking account of the irregularities in height that often occurs in the historic buildings (Figure 4). Therefore, it is necessary to consider the type and quality of connection between the walls, positioning proper measuring points. All the sensor were levelled on the horizontal plane and the horizontal components accurately oriented along the N-S and E-W directions in order to have a unique reference systems for the signals in every station (Figure 4).

3 CONCLUSIONS AND GENERAL REMARKS

These real-time networks are really pioneering projects and they will enable three main outcomes: i) real-time seismic monitoring and on-site early warning, ii) fast damage assessment of the urban area, and iii) structural health monitoring of the key infrastructures playing the major role during a crisis.

In order to be really useful, the information coming from each monitoring station must be promptly processed. The EEW system is be able to provide an alert in the aftermath of an earthquake; it is based on the automatic earthquake detection and signal processing. In general, the seismic stations devoted to EEW, pick up P-wave arrivals in the proximity of epicentral area and then send the analyzed information to users located in the far-field. In this way the user get information about the incoming earthquake before being reached by the seismic waves (regional EEW). However, for the near-field earthquakes, the EEW information may not reach the user before the S-waves and their strong shaking. This is because the EEW takes several seconds to process and transmit the information (lower than S-waves velocity), so the EEW may be useless for such local events. Conversely, the on-site EEW is specifically conceived for local earthquakes.

Each monitoring station detects the P-wave arrivals using an automatic earthquake recognition procedure (i.e. Allen 1978) and estimate the intensity of impending strong shaking in a few fractions of second. The warning can be issued before S-wave arrival taking advantage of the difference between the velocities of P and S waves and use of relationships between some parameters measured on the initial portion of seismic signal after the onsets (Satriano 2011 for a complete review). Since every small fraction of second is important, the latency of the system (input reading, elaboration, and transmission), should be minimized. The system is based on protocols widely used by the international community of seismologist, and the system has been specifically calibrated for the eastern Sicily region (Tusa 2017).

In case of strong earthquake the damages of the area covered by network are assessed through ground motion maps with the final objective to improve the effectiveness of the rescue operations. Such operations could then be carried out according to a logic of priority on the basis of the highest shaking measured by the seismic network. The automatic earthquake detection allows the rapid data elaboration to produce shake map to be provided to the centers for post-earthquake emergency management. Shake maps provide near-real-time maps of ground motion and shaking intensity following significant earthquakes. They are seismologically based interpolations and combine observed data and seismological knowledge to produce maps of peak ground motion (PGM). The shaking is represented through maps of peak ground acceleration (PGA), peak-ground velocity (PGV), response spectral acceleration (SA), Arias Intensity (AI), Houser Spectral Intensity (HSI), ground-motion shaking intensity, and any other seismological parameter useful to the evaluation of the potential of damage (Faenza 2010). Figure 5 shows an example of a recorded local earthquake. Although the sensibility of the MEMS accelerometer is lower with respect the professional sensor, a local (16 km) 2.8 earthquake has been detected and the waveforms are clearly recognizable. The main limitation of the adopted sensors is represented by the reduced sensing capability, being the noise floor of the best MEMS accelerometer about -100 db. The self-noise of the MEMS accelerometer will be likely reduced in the next generations of sensor, so that even part of the seismic background noise could be assessed. Another disadvantage, but not strictly related to the proposed applications, is the relatively poor response at low frequencies, that is the reason because MEMS sensors are more suitable for strong-motion seismology. A possible solution to partly overcome such limitations is to integrate the station with a compact velocimeter. A velocimeter improves the detection capability for low-energy events and could enhance the detection of the first waves arrivals for EEW purpose (Vitale 2018).

Finally, the real-time networks enable to remotely monitor the edifices, to compile a register of historical data, and to create files for post-processing. Apart from the above-mentioned benefits in case of strong earthquake, the monitoring stations allow to study the site response due to local geological conditions and also to assess the structural health and the characteristic features of the buildings. In fact, the analysis of the recorded signals enables to characterize the input signal (e.g. the earthquake) and the output signals (i.e. the edifice shaking) allowing, in a successive phase, to describe the relationship between the shaking level at the site and the variation of the equivalent structural modal parameters, while keeping into account the effects of soil–structure interaction.

Such designed networks (real-time and urban-scale) represent powerful tools for several tasks in the post-earthquake scenario, but also some future developments can be implemented. The shake maps allows a rapid disaster assessment of the stricken area and could also represent the base for an automated visual inspection system and survivors research relying on

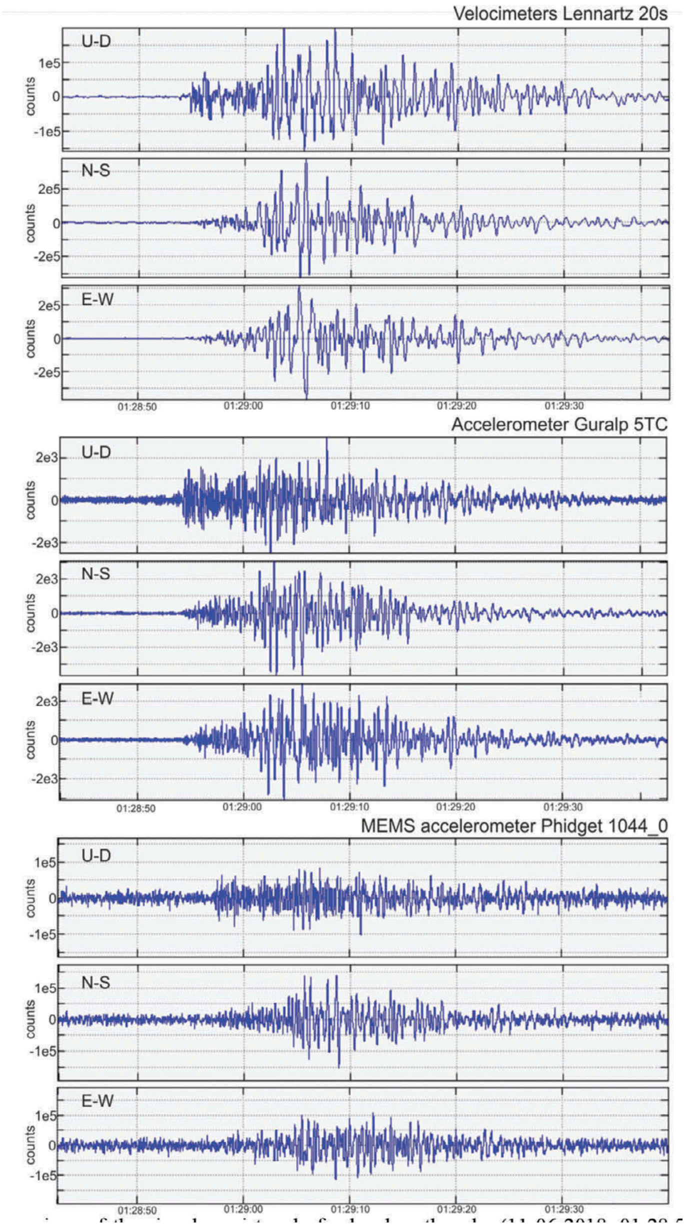

Figure 5. Comparison of the signals registered of a local earthquake (11-06-2018, 01:28:52, depth=2.2 km; M=2.8) located at about 16 km from the site (Catania network).

remotely operated vehicles (Cannioto 2017). The recorded signals could represent a great source of information for seismic microzonation studies. All the earthquakes recorded, even the low magnitude ones, will be used to identify site effects by direct comparison between the waveforms at the recorded station and at the reference site. Such microzonation approach is more reliable with respect the model obtained with empirical methods. Even new techniques and new approaches to the assessment of the site effects could be developed and validated.

The network are further expandable either within the same building and also towards other critical buildings or infrastructures in the city of Catania and in the town of Acireale. The flexibility of the designed network makes also exportable to all other areas of high seismic risk and high vulnerability of buildings.

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