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A STRUCTURAL HEALTH MONITORING DATA MANAGING SCHEME WITH RESILIENCY TO SEISMIC EVENTS: IMPLEMENTATION ON A ROAD NETWORK BRIDGE

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Abstract. *The motivation behind this work is the need for a resilient structural health monitoring (SHM) scheme for road network components that will allow for monitoring continuity and efficient data transfer after major seismic events. We have identified the critical specifications, in terms of resiliency, regarding key components of an SHM system, i.e., data transfer from the structure to the remote end user and energy supply of the SHM components. Based on these specifications, we propose an optimal SHM data managing scheme to be implemented on the already instrumented G9 bridge of the Egnatia motorway, in Western Macedonia, Greece, as a case study. The scheme is based on serial/ optical fiber data transfer from the data loggers to a local communication center, hybrid wired/ cellular/ satellite gateways from the local center to the end user, and uninterruptable power supply unit-based back up energy sources. The collected monitoring data will be made available to the end user/stakeholder - in our case, the RETIS-RISK platform for real-time seismic risk assessment- via web access. The innovative elements of the proposed design are the redundant end user gateways and the use of satellite communication that will provide crucial independence from terrestrial telecommunication networks. The proposed data managing approach meets the identified specifications for resilient SHM and minimizes the possibility of data loss in case of major seismic events.*

1 INTRODUCTION

In the past years, advances in technology have lead to the implementation of highly sophisticated structural health monitoring (SHM) schemes towards a more effective remote monitoring of the integrity of structures. Here, the focus is placed on SHM implementations of large structures such as components of road networks, e.g., bridges, which allow for remote access on monitoring data. Besides the ongoing monitoring of the integrity during the service life of a structure, it is evident that SHM data is of crucial importance during or after individual abnormal events, such as earthquakes, that may cause structural damages [1]. Consequently, SHM implementations must, first and foremost, withstand such events in order to allow for post-event monitoring; in other words, they should be resilient.

Key components of an SHM system are the sensors and their deployment on the structure, the way monitoring data are transferred from the structure to the end user, and the energy efficiency of the SHM system. Common practices concerning sensors deployment can be categorized in two classes, i.e., wired and wireless sensors network (SN) [2]. In the case of the wired SN (for a recent proposed design see [3]), cables are used to provide both power and data connectivity, with initial cost, manipulation, and damage risk of such schemes constituting the main disadvantages. However, they are more reliable and the most cost-effective solution for a long service life. On the other hand, wireless SNs (recent implementation in [4]) rely on over the air data transfer and batteries for energy supply. Such systems may be more cost-effective for short service life and easily manipulated, but, potential problems with over the air propagation and battery life limitations render them more unreliable. Either through wires or wirelessly, monitoring data are usually collected to a nearby data center from where they are further communicated to the remote end user. In most cases, there is a single end user gateway, usually, through a wired internet line or a dedicated wide area network. Certain designs have incorporated wireless end user gateways, such as data transfer over the 2G+ [5] or 3G cellular network [6]. Regarding energy supply, the power grid is the most common source, either directly powering devices, or indirectly, recharging device batteries. During recent years, several technologies [7] have been proposed to replace the power grid as the source of recharging batteries, e.g., photovoltaic panels, but, there is no strong evidence of their reliability and effectiveness. In certain cases, e.g., in [1], [4], battery-based uninterruptible power supply (UPS) units serving as backup power sources of certain components are used, in addition to the power grid. In general, the design of the SHM system depends on several factors, such as the structure itself, especially if it is a large scale one, the surrounding area and weather conditions, as well as the available infrastructure [8].

In this context, the present work addresses, initially, the key specifications, in terms of data transfer and energy efficiency, for an outdoor SHM implementation with resiliency to seismic events, and, secondly and more importantly, it presents such an SHM scheme to be implemented on a already instrumented bridge as a small-scale case study. The design of the proposed scheme focuses on data transfer and energy supply, given the available measuring instruments. The work is part of the RETIS-RISK research project and it aims, eventually, at providing real-time measurement data to the RETIS-RISK platform for real-time seismic risk assessment of urban and interurban road networks in the area of Western Macedonia, Greece.

2 RESILIENT SHM SPECIFICATIONS

The term resilient is used here to describe an outdoor and remote SHM implementation that is designed in such a way as to ensure, to a large extent, that the monitoring continues after natural disasters, such as major seismic events, that may cause damages to the infrastructure. Damages to infrastructure refer to deformation of the structure itself, interruptions of telecommunication networks or outages of the power grid [9]. Such an SHM implementation should allow for immediate/ continuous assessment of the structural integrity after the event, serving, in this way, as a decision support system. As far as the crucial specifications regarding such a resilient design are concerned, here, we place the focus on data transfer to the end-user and energy supply of the SHM system, highlighted, also, in [1].

Data transfer refers to the whole process of collecting monitoring data from the structure site and making them available to the remote end user/stakeholder. It usually takes place in two stages. The first stage involves the transferring of monitoring data from the structure to a collecting point, i.e., a small room or a building, near the structure, through a dedicated local area network, while the second stage includes the data transferring from the collecting point to the remote end user via a wide area network. Crucial specifications regarding the data transfer process are:

- d1) Data transfer from the structure site to the local collection point must be efficient and secured from structural damage. To this end, sensors and networking devices should be protected and of industrial specifications in order to withstand weather conditions and minor structural deformation. In addition, lengthy cables for networking, if any, should be installed in such a way as to avoid damage or cuts.
- d2) Data transfer from the collection point towards the end user must be also efficient, in the sense that necessary steps are taken to minimize the possibility of data loss. To this end, availability of redundant end user gateways is considered a good practice. It is of high importance that one of the gateways does not rely on terrestrial telecommunications that suffer from interruptions and congestion in case of emergencies.

In all stages, data transfer speeds, with respect to the monitoring data volume, should suffice for a real-time or on-demand assessment of the structural integrity.

Energy supply refers to the power sources of the individual components that constitute the SHM system. Usually, it takes place through the power grid. However, as local power grid outages are usual in case of seismic events, it is crucial that: e1) every electrical component of the SHM system has a backup power source, and e2) the backup power sources should provide runtimes enough for, at least, an initial assessment of the condition of the structure, immediately after the event.

3 CASE STUDY

Based on the aforementioned specifications, we propose an SHM scheme to be implemented on a part of the road network (Egnatia motorway) that is included in the area of interest, i.e., Western Macedonia, Greece, as a case study. The part of the Egnatia motorway that was selected corresponds to the G9 bridge in the area between Veria city and Kozani city, Greece (Figure 1(a)). The selection was made after the evaluation, in terms of the existing SHM infrastructure, of the road network in collaboration with the motorway administrative body, i.e., Egnatia Odos S.A. (EO S.A.), and it was based on two criteria: 1) it is, currently, the only instrumented part of the road network in the area of interest, and 2) it belongs to second most frequent type of bridges of the Egnatia motorway, built using cantilever construction.

3.1 G9 Bridge Structure and Surrounding Area

The bridge body is T-shaped, consisting of a box-shaped cross-section body with parabolically varying height, which is monolithically connected to the central pier (Figure 1(b)-(c)). The deck has a total length of 173 m. The body is circular in plan view and exhibits a significant slope both along its axis (about 5%) and in the transverse direction due to curvature [5] (Figure 1(d)).

Figure 1: (a) Position of the G9 bridge on the map. (b), (c) Views of the bridge. (d) Overview of the two branches. (e) Abutment of a branch.

On its base, the central pillar is grounded on a compact rectangular box-like foundation socket, and then continues, along its height, as two compact section transverse blades which are monolithically connected to the deck. The connection of the superstructure with the abutments (Figure 1(e)) is made via special type bearings which allow free movement (sliding) along the longitudinal axis of the bridge (for receipt of the temperature expansion and contraction), while functioning as elastomeric in the transverse axis. These bearings operate as elastomeric in the longitudinal axis too, until there is an excess of the static or dynamic (depending on the load) friction between the bridge deck and the Teflon surface of the bearing.

The bridge is situated at an altitude of ~ 600 m (~ 1970 ft) in a rural area. Weather conditions in the area are typical of Northern -Western Greece. Year round, the average lowest temperature is -2 ºC (28 ºF), while the average maximum temperature is 34 ºC (92 ºF). Precipitation ranges from ~60 mm in December (15 rainfall days on average) to ~5 mm in August (five rainfall days on average).

3.2 Current SHM Status and Nearby Infrastructure

The current SHM status of the bridge includes a measuring system that records ambient vibrations on the ground near the bridge. The system consists of triaxial accelerometer that is connected on sight to a GeoSIG GSR-24a data logger (GeoSIG Ltd, Switzerland) with a 24 bit high resolution digitizer [10] (Figure 2(a)). The data logger is also connected to a GPS device and, via a serial RS232 cable, with a Siemens TC35i GSM (Global System for Mobile telecommunications) modem (Siemens A.G., Germany) that is equipped with a SIM card and allows for the remote access to the measurement data over the 2G+ cellular network [11]. Data can also be accessed locally by connecting a laptop via a serial cable to the data logger. The measuring system is powered through the power grid (220 V AC), while, the data logger is also equipped with a battery that offers several hours of system functionality in case of power

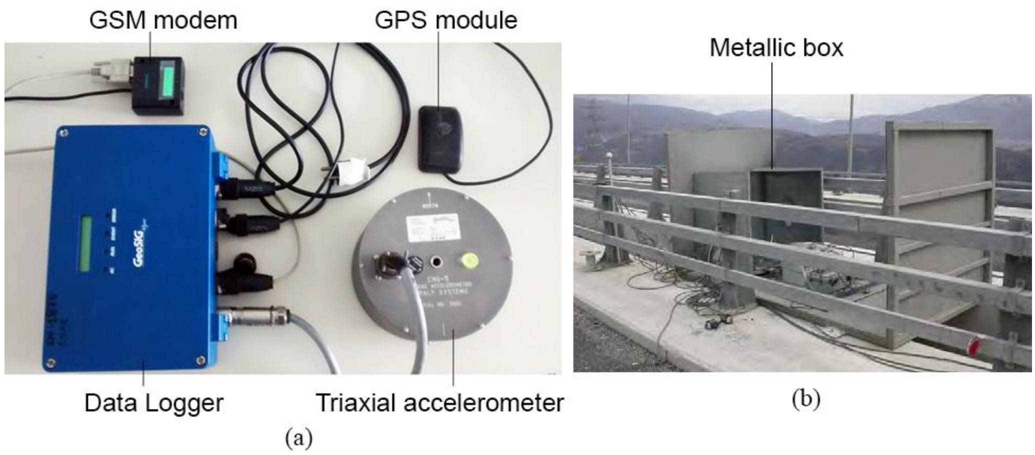

Figure 2: (a) Measuring system of ambient vibrations consisting of a triaxial accelerometer, a data logger, a GPS module, and a GSM modem. (b) Metallic box/ container where the measuring systems are /will be installed.

grid outage. The system is enclosed in a metallic box (Figure 2(b)) that lies on the ground, 62 m away from the bridge entrance lane, with direction from Kozani city to Veria city, Greece, on the right side (Figure 3). According to EO S.A., a second identical measuring system will be installed in a metallic box located midway of the bridge deck, on the right side of the traffic lane with direction from Veria to Kozani, which will record structural vibrations (Figure 3).

In the following, a short presentation of the available infrastructure in the area surrounding the bridge will be given that is not directly related to its current instrumentation, but, it will be taken advantage of during the case study (Figure 3). In particular, on the right side of the exit of the traffic lane with direction from Veria to Kozani, there is a variable-message sign (VMS) on the base of which lies a metallic container where the message routing system is located. The routing system mainly consists of an Ethernet (VMS side) -to-Optical Fiber converter, i.e., a Siemens optical switch module (OSM) (Siemens A.G., Germany) that allows for connection, via an optical fiber, to the nearby traffic control centre (TCC). The TCC building is located on a hill, at a distance of about 1 km from the bridge and within sight of it. There, the optical fiber is converted back to an Ethernet interface that leads to the network switches that constitute the local gateway to the EO S.A. computer network. It must be noted that, from the TCC building, there is visual contact with two nearby villages, the importance of which will be highlighted in a following section. The TCC infrastructure is powered from the grid, while there is also a diesel generator and UPS units that function as backup power sources.

After the evaluation of the current SHM status, the following key conclusions were drawn:

- The measuring instruments that are/ will be installed provide adequate and quality measurements for the assessment of the condition of the bridge. Image monitoring of the bridge would have been useful.
- The way measurement data are accessed remotely, i.e., via the GSM network only, is insufficient and ineffective for two reasons: 1) download speeds of the 2G+ service are low (of the order of 100 Kbit/s, for data the size of several megabytes) [11], and 2) the cellular network suffers from congestion, especially, in cases of emergency, and as a result, it becomes unreliable for data transfer.

3.3 Proposed Data Managing Scheme

Based on the aforementioned conclusions and by taking into consideration the identified specifications, the intervention to the current SHM status of the bridge was designed with the

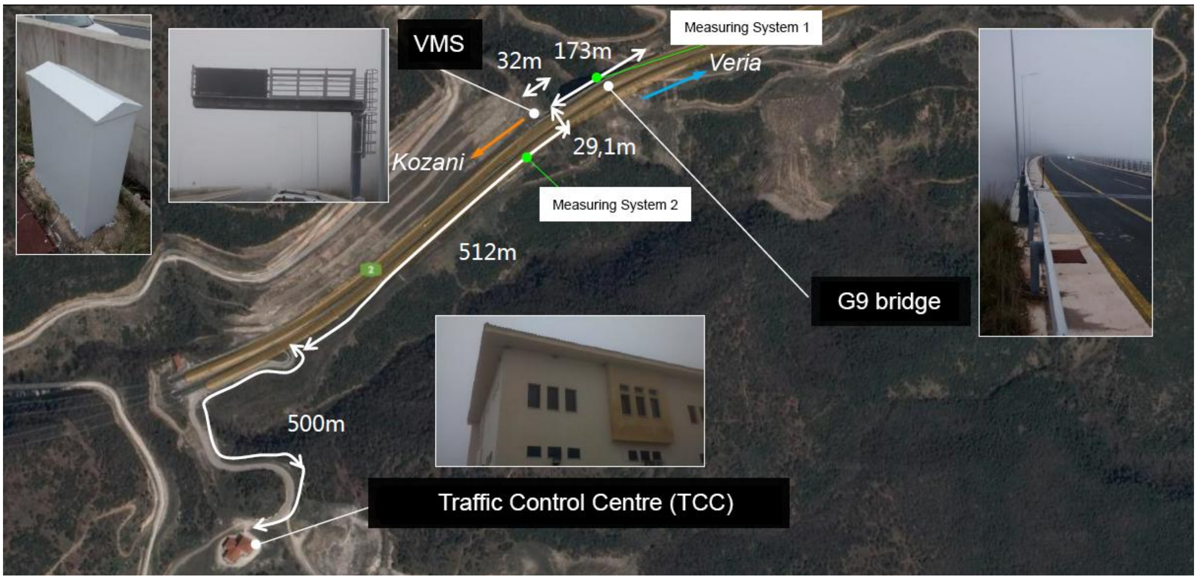

Figure 3: Critical points in the area surrounding the G9 bridge, i.e., the VMS and the metallic container on its base, the TCC, and locations of the two measuring systems.

focus placed on data management that is currently problematic. An overview of the proposed scheme includes the addition of image monitoring, the routing and collection of bridge monitoring data in the TCC (local communication centre), their transfer to the end user through multiple gateways, as well as the efficiency of the whole system in terms of energy supply (Figure 4(a)).

In particular, acceleration data recorded by the two accelerometers will be carried by foil screened twisted pair (FTP) cables, over the RS485 serial protocol, and routed through a local network switch that will be added in the metallic container on the base of the VMS and it will be connected to the OSM. A monitoring camera will be installed on the VMS and connected via Ethernet cable to the network switch. The switch, as well as the OSM system, will be connected to a UPS unit that will be also added to the container and it will serve as a backup power source. The data (accelerations and image) will be carried by the optical fiber to the TCC, where, via optical fiber-to-Ethernet interface conversion, they will be forwarded from the existing EO S.A. network switches to a desktop personal computer (PC) that will be installed and it will serve as a data router to three planned end user gateways: 1) the existing EO S.A. network, 2) an upgraded connection to the 3G cellular network, and 3) a satellite link. Specifically:

1. Data transfer through the EO S.A. network will be realized by routing monitoring data back to the network switches that will then forward them through the EO S.A. computer network to the end user.
2. Connection to the 3G UMTS (Universal Mobile Telecommunications System) cellular network will be realized by forwarding monitoring data to an Ethernet-to-3G converter that will be connected to a UMTS antenna. The latter scheme will allow for significantly higher transfer 3G speeds (of the order of 1 Mbit/s) [11] as compared to the 2G+ service currently used.
3. As far as the satellite link is concerned, data from the PC router will be forwarded to a satellite system that will provide access to fast satellite internet. In this way, monitoring data will be made available through the internet to the end user; there is no need of satellite equipment to be installed to the end user's side.

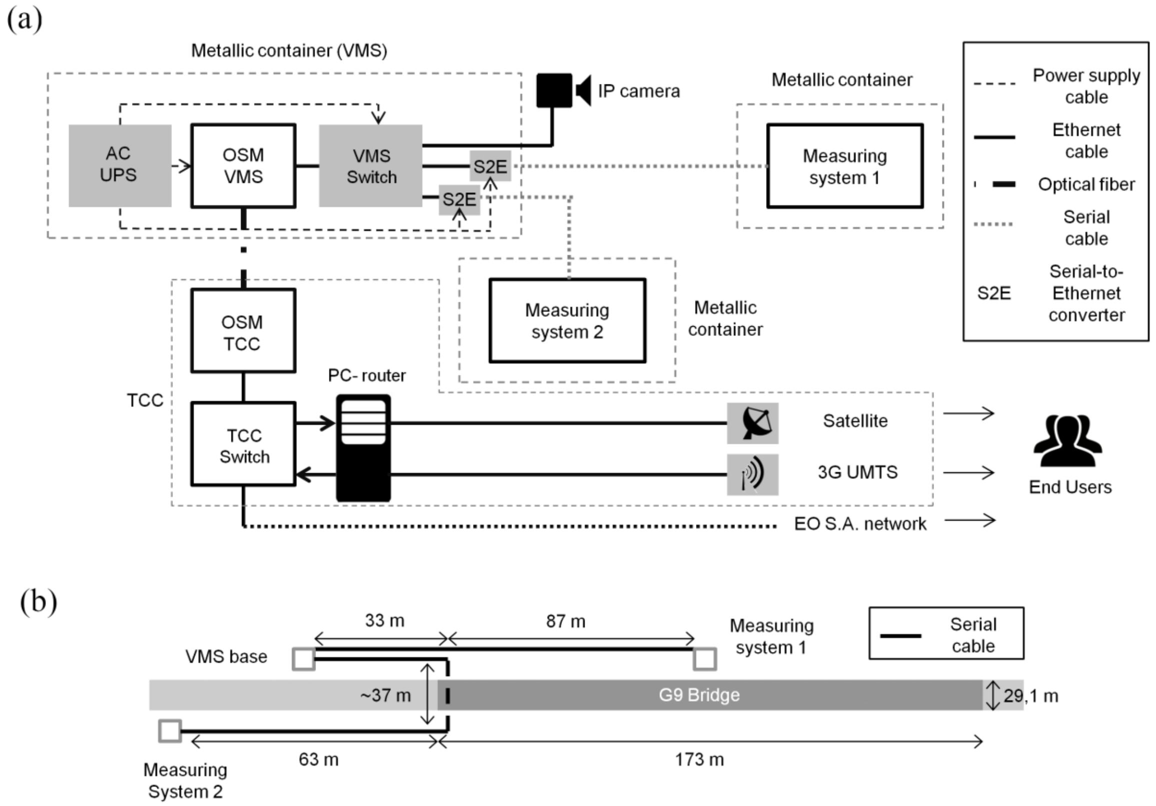

Figure 4: (a) Schematic of the proposed data management scheme. (b) Ethernet cable deployment from the two measuring systems to the metallic container at the VMS base. Dashed line denotes the part of the cabling that will pass under the bridge.

At a given period, monitoring data will be forwarded through one of the aforementioned gateways according to a priority protocol and their availability that will be monitored by the PC-router. Devices that will be added in the TCC will be powered from the grid, and, additionally, they will be connected to the backup power sources that are available, i.e., the diesel generator and the UPS units. Collateral advantages of centralizing the three user gateways in the TCC are the facilitation of network monitoring and the protection of the associated equipment.

3.4 Equipment and Implementation Issues

This section summarizes the required equipment and the implementation issues for the proposed scheme to be realized. On the bridge side, the serial ports on the two data loggers will be connected to RS232-to-RS485 serial protocol converters (Figure 5(a)) in order to allow for long distance transfer [12]. Via FTP cables, data will be transferred to the VMS base, where, via serial-to-Ethernet converters (Figure 5(b)) and Ethernet cables, they will be forwarded to the network switch that will be installed on site. FTP cable deployment is illustrated in Figure 4(b). Since, the distance between both the data loggers and the VMS is long enough, conversion from RS232 to RS485 serial protocol transfer is mandatory in order for satisfactory data transfer rates to be achieved [12]. In particular, a ~120 m-long cable will be used for the data logger that will be installed midway of the bridge, and a ~133 m -long cable will be used for the data logger located on the ground near the bridge. In the case of the latter, part of the cabling will go under the bridge. Rugged foil screened twisted pair (FTP) cables of

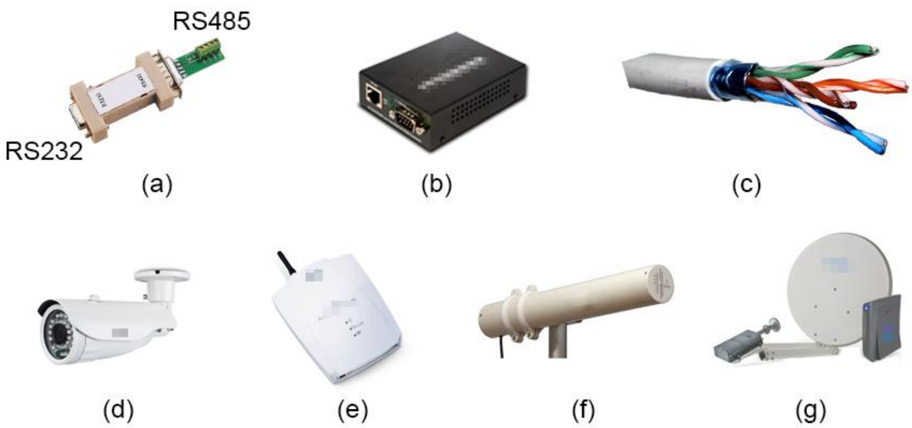

Figure 5: Representative images of parts of the equipment that will be used: (a) RS232-to-RS485 serial protocol converter, (b) Serial-to-Ethernet converter, (c) FTP cable, (d) Day/night IP surveillance camera, (e) Ethernet-to-3G router, (f) directional UMTS antenna, (g) satellite dish.

Category 5e (Figure 5(c)) will be used for both serial and Ethernet-based cabling, which provide insulation from noise interference and allow for outdoor deployment. The day/night monitoring camera will be installed on the top of the VMS scaffolding and it will be IP and PoE-based (Figure 5(d)). It will be connected to the network switch on the base of the VMS via a ~10 m Ethernet cable. The switch will have 5 ports (two ports for the connection with the data loggers, one for the monitoring camera, one for the connection to the OSM and a spare port) and it will be of industrial specifications to withstand weather conditions in the area and with PoE injecting capability to power the IP camera. PoE is a technology, under the IEEE 802.3a(f, t) standards [13], that allows for both data and power to be transferred through an Ethernet cable, and as a result, the main advantage of using PoE-enabled devices is the elimination of additional power sources that would be required to power individual components. A 220V alternating current (AC) UPS unit will be installed that will serve as the back-up power source for the network switch, the OSM, and the serial-to-Ethernet converters with external battery that will provide two hours of runtime.

On the TCC side, the desktop PC serving as a router will be equipped with four Ethernet adapter cards (one for the input data and three for the planned gateways to the end user) and a special version of Linux operating system ('Clear OS', Clear Foundation, New Zealand) that allows for easy configuration of the routing functionality. Regarding the 3G-based end user gateway, an Ethernet-to-3G router (Figure 5(e)) will forward the Ethernet data to a 3G antenna (Figure 5(f)). A directional UMTS antenna with 16 dBi gain, functioning in the 1.9-2.1 GHz range, will be installed on the facade of the TCC building and it will be pointed to one of the nearby villages in order for access to be gained on the 3G enabled-base stations that are located there. The latter configuration is necessary as in the surrounding area of the bridge there is no 3G service (2G+ only). For the satellite-based user gateway, a satellite dish (Figure 5(g)) will be used that will be also installed on the facade of the TCC building in a precisely selected position (elevation and geographical azimuth) in order for a proper pointing and connection with the satellite to be realized. All connections from the PC-router to the three planned end-user gateways will be done via Ethernet cables that will not exceed 30 m in total.

4 MEETING THE SPECIFICATIONS

In the following, the ways that the proposed scheme addresses issues regarding the identified data transfer and energy supply specifications are discussed.

4.1 Data Transfer Efficiency (d1-d2)

On the bridge side, data transfer from the monitoring instruments to the TCC will take place through cabling that is unfolded in such way that the risk of suffering damage due to a seismic event is minimized. In particular, the largest part of outdoor cabling is unfolded on the ground alongside the bridge, rather than on the structure itself, minimizing in this way the possibility of being damaged or cut due to structural deformation. Furthermore, the optical fiber that will carry the data to the TCC is buried deep into the ground and, as a result, it is nearly impossible to suffer catastrophic damage due to a seismic event. It must be also noted that most of the equipment will be installed in metallic boxes that offer protection from extreme weather conditions or/and will be of industrial specifications (e.g., weather proof, wide range of operating temperatures) in order to operate in such conditions.

Regarding the gateways to the end user, the scope of the proposed scheme is to provide redundancy, i.e., multiple ways for the end user to have access to the monitoring data, an issue that is often neglected in SHM designs. In this vein, in case of damage or network congestion, there will be alternative ways to access the monitoring data. Especially in the case of the satellite link, the technology allows for independence from the terrestrial telecommunication networks that can suffer damages from a major seismic event. To the authors' knowledge, this is the first SHM design that incorporates such a number of user gateways and intends to take advantage of satellite communication as one of the means to transfer data to the end user.

4.2 Energy Efficiency (e1-e2)

The proposed design ensures that every component in the network will have backup power sources in order to continue operation in case of power interruption. Specifically, the two measuring instruments have batteries that offer several hours of functionality, while the IP camera is powered over Ethernet. The latter combined with the fact that the serial-to-Ethernet converters and the PoE injecting network switch will be connected to the AC UPS unit ensures that the bridge-side network will continue to function for two hours after a power grid outage. The UPS unit will also serve as a backup power source for the OSM. Finally, on the TCC side, all the devices that will be installed will be connected to the existing backup power sources, i.e., the diesel generator and the UPS units. Consequently, a remote and detailed assessment of the structural integrity of the bridge over a sufficient two hour-interval will be possible, in case of a seismic event that will lead to grid power outage in the area.

5 CONCLUSION

The present work addressed the key specifications regarding an SHM design with resiliency to seismic events and proposed such a scheme to be implemented on a road network bridge as a case study. We consider the proposed data management scheme as an optimal solution for the G9 bridge that not only meets the identified specifications for resilient SHM monitoring, but it also takes advantage of the existing infrastructure in the area, eliminating, in this way, the cost of additional equipment and installation. Apart from the bridge-side data transfer scheme that depends on the structure and the surrounding area, the TCC side data management design, i.e., the three proposed end user gateways, can be applied in most SHM implementations, existing or future, which include a monitoring data collecting point.

Following the implementation of the SHM scheme, acceleration data being acquired from the bridge will be integrated, as additional input, with the novel RETIS-RISK software platform for seismic risk assessment of urban and interurban road networks. Hence, besides statistical data, the platform will be capable of updating models and providing risk assessment feedback for the G9 bridge, based, partially, on valuable real-time measurements.

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