Synchronization of IoT layers for Structural Health Monitoring

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Abstract—**We spend a lot of time within buildings. The research field of the Structural Health Monitoring (SHM) is aimed to diagnose the state of structures, to prevent that our houses, bridges, offices or other civil infrastructures could become deadly traps as a result of not visible damages. In this paper a SHM system is proposed, that exploits the Internet-of-Things paradigm, to perform in real-time not only the monitoring or damage detection, but also to send a remote notification, finalized to alert the authorities and rescuers, about the potential collapse of the buildings. In this context the timing notification depends both on the ability of the system to detect the invisible damages, using the information collected by several sensors correlated in time, and the delay in the transmission of such information from the building up to the authorities and rescuers offices. Experimental tests highlight the effectiveness of the proposed method to resolve the synchronization problem among sensor signals and to estimate the impact of the data transmission delay on the application logic.**

Keywords— Structural Health Monitoring, Internet-of-Things, Synchronization, Multi-Agent system, Signal Processing, Acoustic Emission.

I. INTRODUCTION

The Structural Health Monitoring (SHM) is a research field aimed to diagnose the state of structures [1]. Events such as earthquakes, aging phenomena or simply excessive loads, can cause internal damage to the concrete piers of houses, bridges or other public infrastructure, which, if not identified, could be dangerous for people's safety.

Recently, technological development has made available a wide variety of sensors useful to monitor different physical quantities related to SHM. Many of them are active sensors and are not suitable for prolonging monitoring [2]. Other needs to be built in the structure during the building, and then are not suitable for the monitoring of existing structures. To overcome such limits, in [3], [4] the design and implementation of a structure monitoring system, based on the Acoustic Emission (AE) is presented. The idea is (i) to identify all the acoustic signals, belonging to the frequency range related to any internal crack produced in the structures concrete [5], then (ii) to select the signal ones related to an important damage, using signal processing techniques [6].

This scenario raises different challenges, concerning the resolution of problems, referred to two distinct levels as described in the follow.

At low level the critical operations involve:

- the efficient management of data generated by the sensing devices;
- the time synchronization and correlation among measurement information, from different sensors.

To handle, store and process a large amount of samples in an efficient way, big data theory can be applied [7]. The use of this information processing methodology improves the system, reducing the computation time and the misalignment delay between the acquisition and processing phases due to the storage operation.

As known in literature [8], [9], to guarantee the synchronization accuracy needed by the particular monitoring purposes, several approach can be used. In wireless sensor network algorithmic approach, based on message passing, are used to synchronize the clock equipping each sensor node, obtaining a synchronization accuracy in the order of clock period.

By using dedicated hardware [4], the synchronization problem moves from the sensors to the dedicated hardware allowing synchronization accuracy typically in the order of some μs. For SHM, the synchronization accuracy of some μs needs for the localization of the crack source.

At a high level, other problems arise. The SHM functioning does not end with the detection of dangerous events. It requires also the implementation of a notification mechanism, that is in charge of sending an alert to the competent authorities (civil protection, police, firefighters). In this paper the system proposed in [4] to easily transfer the information in a wide geographic area, instead

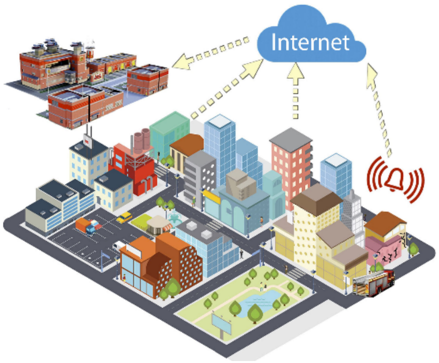

Fig. 1. Example of IoT paradigm applied to SHM.

of radio or ad-hoc wired protocols that covers short distances, is suitably extended according to the Internet of Things (IoT) paradigm [10]. In particular, the system implements a software component, that exploits the use of internet as a connection network. This means that a SHM can be abstracted as a smart object integrated in a domotic system.

Fig. 1 shows an example of IoT paradigm applied to SHM. According to IoT the proposed system is designed as a stack of layers, each one with a specific role. In the proposed architecture the lowest layer is constituted by the physical-part, which includes the physical components, such as sensors and actuators (alarm), and manages the basic operations aimed to acquire, pre-process and perform the digital conversion of the signals. The highest levels are grouped in the so-called cyber-part of the system. They implement the logic of the structural application to detect the structural damage, and all the mechanisms needed to propagate such information. The use of Internet as a communication channel introduces a random transmission delay, that in the worst case is in the order of seconds. However, since the system reaction concerns interventions estimated at least in the order of minutes, the transmission delay overhead is acceptable.

The paper is structured as follows. Section II presents an overview on the concrete structure monitoring system. Section III details about the methodology and new features introduced in the proposed SHM system. Section IV shows the experimental test results, with indication of further work. Finally, the conclusions are drawn.

II. CONCRETE STRUCTURE MONITORING SYSTEM

The development of cracks plays an important role in concrete's response to load in both tension and compression [9]. Fig. 2 shows a crack through calcium silicate-hydrate and calcium hydroxide in cement paste [7]. The earliest studies of the microscopic behavior of concrete involved the response of concrete to compressive stress. Different early works conducted for the realization of USA standard (ACI) [13] showed that the stress-strain response of concrete is closely associated with the formation of micro-cracks. In recent years, many researchers have been studying the issue of the damage in the concrete through the use of Acoustic Emission (AE). AE is a naturally phenomenon that occurs when there is a crack, or dislocation source, in a material. A significant amount of energy is released due to a loss of cohesion and changes in the internal-structure of the crack. Part of the energy released is transformed into an acoustic wave, i.e. the AE signal.

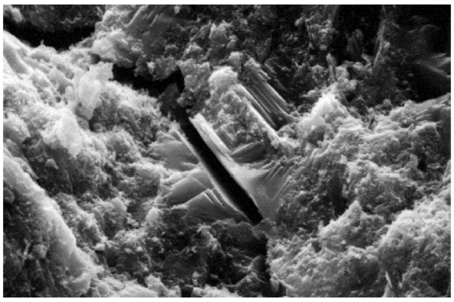

Fig. 2. Crack through calcium silicate-hydrate and calcium hydroxide in cement paste [7].

The signal is recorded by AE sensors that operate in ranges from 50 to 400 kHz.

Different methods for studying and analyzing AE signals are presented in the literature. In [5], [6] a new method to detect the state of damage of the concrete by analyzing the AEs is presented. This method takes into consideration the b-value [11], a figure of merit depending on the amplitude and the number of significant peaks in the signal. It is based on the Gutenberg Richter (GBR) law, typically used in seismology for study of earthquakes [12]. This approach has been possible because there are strong analogies between AE waves and seismic waves. In fact, both the typologies of the waves can be classified as damped waves characterized by a highest peak and a progressive damping of the signal.

The GBR law defines the relationship between the magnitude and total number of earthquake events recognized in a region during a pre-established time interval. In the framework of the GBR law, the b-value parameter is used to select the most important and dangerous events. In the study of the concrete damage, the b-value is used to identify the development of critical cracks. In particular, the critical cracks are selected under the condition that the b-value evaluated on the associated AE signals has the value in the neighborhood of 1. The amplitude of such neighborhood is experimentally evaluated in [5], [6].

The AE signals can be attenuated respect to their original amplitude due to the propagation in the concrete. The signal attenuation causes difficulties in the detection and increases the probability to lose AE signals. This problem can be reduced using multiple transducers deployed on the surface of the structure. In this way it is increased the probability that an AE is generated near a transducer, and then acquired with reduced attenuation. To overcome the problems coming from the high dimension of the memory needed to store the signals acquired by multiple transducers, in [5] is proposed the triggering acquisition modality. Propagation can attenuate the AE signal below the trigger level causing signal loss, while the occurrence of multiple AE events can cause the loss or partial acquisition of signal due to the unpredictability of the Acquisition Time Interval (ATI). To overcome these problems in [4] a new hardware has been proposed allowing the multi-triggering acquisition modality and the adaptive evaluation of the ATI: the Logic Flat Amplifier and Trigger (L-FAT) generator block. Fig. 3 shows the hardware architecture of L-FAT.

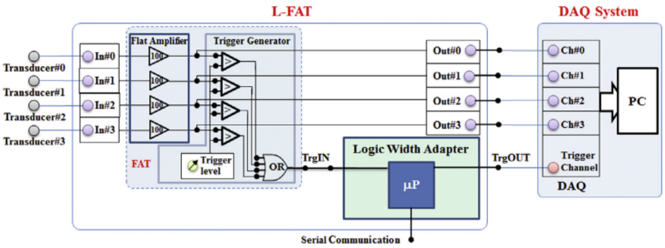

Fig. 3. L-FAT hardware schema.

The acquired signals are amplified by the cascade of two Burr-Brown INA 111 [14], for each channel. It allows amplification of 10 ± 0.01% in the range [1, 1000] kHz [14]. The triggering section is constituted by two comparators ADCMP563BRQZ [15] and OR logical port MC10EL01/D [16]. A micro-processor adapts the ATI on the basis of an internal timer that is reset at each event. Once the timer expires, the acquisition stops. The timer value is established on the basis of the AE time span.

III. THE MULTI-AGENT IOT-BASED SHM

Following a hierarchical approach, based on the schema in Fig. 4, the overall system is developed as a stack of layers, each one with an associated growing level of abstraction. To model the application logic and to encapsulate the different features and sub-goals, the programming agent paradigm is used.

The main advantages deriving from these procedures are:

- facilitate the addition of new features to the application (extensibility) or the update of the technologies used, avoiding any redesign cost;
- isolate the problems, detecting any malfunctions easily;
- possibility of being able to scale the system without additional computational cost.

A. *Physical-Part*

The lowest levels in the hierarchy are occupied by two tiers which constitute the so-called physical part. As shown in Fig. 5 they include all the hardware and software finalized to the raw-data acquisition.

To carry out the structure monitoring operations and to detect the AEs, each sensor has been applied on a specific point on the concrete structure. Several problems arise during the acquisition phase concerning with:

- identification of the signals of interest, distinguishing among environmental noise and sounds produced by mini-crack;
- the limited computational resources, which also requires the identification of the signals of interest, not being able to process any type of signal acquired;
- the synchronization of the measurements coming from the different sensors, in order to ensure their time correlation.

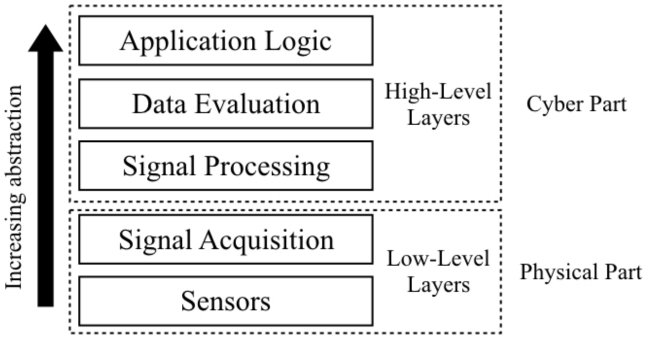

Fig. 4. System Architecture Logic. Aggiungere s a layer

To overcome this issues, the proposed architecture includes the L-FAT. This acts coupled with the Data AcQuisition (DAQ) system and guarantees no loss of signals and no waste of storage memory. The PSs are connected directly to the L-FAT through different channels.

The trigger is generated if one or more of the signals, coming from the channels, exceed experimentally fixed threshold level, identified by the amplitudes of signals associated to events of interest.

In order to move the synchronization problem among the acquired signals from the sensors to the DAQ, L-FAT is designed to supports the parallel acquisition (Fig.5). Each channel of L-FAT introduces a propagation delay in the order of 20 ns, with an uncertainty of few ns due to the components. As a consequence, the delay among the amplified signals is in the order of some ns. This synchronization delay can be considered negligible, because the sampling frequency used in the DAQ is in the order of MHz, according to the frequency range of the AEs.

Also the trigger signal is subject to a propagation delay, which is estimated in the order of hundreds ns. The elapsed time between the input signals and the trigger signal, both received by DAQ, constitutes the part of the signal crack not acquired. To avoid the loss of the information, the DAQ board allows to acquire a fixed number of samples before the trigger occurrence. To evaluate the number of pre-trigger samples compatible with the AEs dynamics, the Hsu-Nielsen test is used [17].

B. *Processing signals*

Going up into the abstraction hierarchy, the higher levels in Fig. 4 constitute the so-called cyber part. They include all the algorithms and protocols, needed to develop and achieve the application business logic goals.

The Signal Processing Layer is in charge of to extract the information from the data available. It implements all the mathematical operations and the procedures finalized to:

- realize a low-level processing of the acquired signals, in order to identify if they represent a potentially dangerous crack;
- make available to the higher software levels, the information about the number of the dangerous crack that has occurred.

To determine if a crack represents a dangerous structural damage, it needs an analytic evaluation.

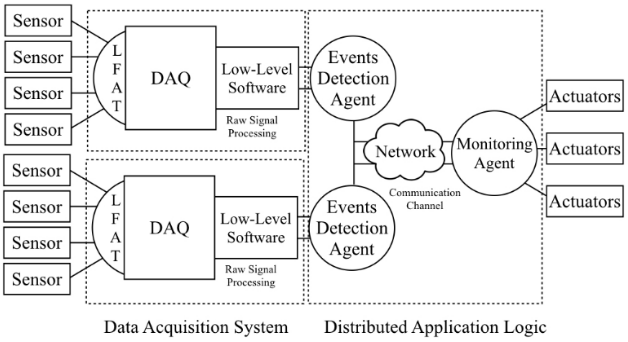

Fig. 5. Distributed Structural Health Monitoring Architecture.

The mechanism implemented, is based on the assumption that the AEs generated by the crack are similar to the waves generated during an earthquake [19]. Therefore, in order to estimate if the damage level associated to a crack is critical, the AEs are analyzed using a variant of the GBR law [12]:

$$Log(N) = a - b \cdot A_{dm} \qquad (1)$$

The N parameter represents the number of the hits higher than the threshold noise, fixed at 40dB. The A_{dm} variable represents the maximum amplitude peak of AE signal. The a and b parameters are two constants fixed experimentally. In particular, a can be obtained imposing b equal to 1 and analyzing some signals characterized by an amplitude of 12 V, as described in [6]. After that all acquired signals are processed using equation (1), obtaining the relative values of b. Critical cracks are characterized by a value of b in the neighbor of 1, the range is now established experimentally [6]. During the monitoring, each acquired signal is processed and the b value is evaluated. If it is recognized as critical, a Counter Variable (CV) is incremented.

As shown in Fig. 5 the overall system can be considered as the composition of:

- the Acquisition Block (AB), whose cyclic operations end with the update of the CV;
- the Distributed Application Block (DAB), that evaluates CV and implements the notification and alarm mechanisms.

These two subsystems are asynchronous and since they follow different goals, they need to read or write CV with different time constraints. Therefore, AB does not send the CV update to the DAB, but it makes the data available to the higher software levels, storing it in a shared location memory. This solution fully supports the a-synchronicity and, compared to other solutions such as sockets, reduces the data transmission delay between different software architecture. It exploits the native storing mechanisms of the operating systems (such as the dynamic-link library in Windows) and it costs one memory access. To avoid any concurrency problems, the operations on CV are handled using Dekker's mutual exclusion algorithm [20].

C. Multi-agent operations

The highest levels in the abstraction hierarchy evaluate the information coming from the underlying levels, in order to complete the monitoring operations, notifying any dangerous situations associated with the state of a structure to the competent authorities.

To develop the business application logic, the agent programming paradigm is used. Agents are chosen because offers proprieties such as reactivity, proactiveness and social ability [21], useful to model the functioning and the dynamics of a distributed system. Each agent has assigned a specific task to perform. Consequently, the whole application can be split in the design of the individual agents and their interactions. The main advantages concern not only the modularization, but also the extensibility of the software. In fact, adding a new feature in the application implies the design and the implementation only of a new agent, which will cooperate with others.

The proposed SHM system use a lightweight version of the multi-agent architecture in [22].

According to Fig. 5 each structural monitored component is supervised by an Events Detection Agent (EDA). It explains the operations of the Data Evaluation layer, that determine if the associated structure has a critical damage.

The EDA monitors CV according to its observation period T_O, settled according to the specific task of the monitoring. Recent literature [23] assesses that if in a time interval fixed to 60s there are at least 3 events of interest, the structure can be considered damaged. Therefore, if during the last 60s of monitoring, EDA detects a CV variation equals to 3, it notifies the alarm to the Remote Monitoring Agent (RMA)according to the operations of the Application Logic layer. When RMA receives the alert, it starts the set of operations required for the rescue and the inspections, that in Fig. 5 are represented as actuators.

D. Remote trasmission protocol

If all the agents are on a same machine, they can exchange information locally exploiting their sociality propriety, through the message passing. Instead, if the agents are deployed on different machines, they require mechanisms that support the message delivery in a distributed environment.

The architecture described in [22] includes the Gateway component. It exposes to the agents the basic read and write operations, to interact with physical devices, hiding all the details about the communication protocols used. In the proposed SHM system, the Gateway component has been enriched with a communication channel, that enables the data exchange through the internet network. In particular, according to the IoT paradigm, the acquisition and event detection components of the SHM system can be assumed as Smart Object that send the information to the RMA. To avoid the active waiting due to the polling cycle, the Message Queue Telemetry Transport protocol (MQTT) is used [24]. It does not

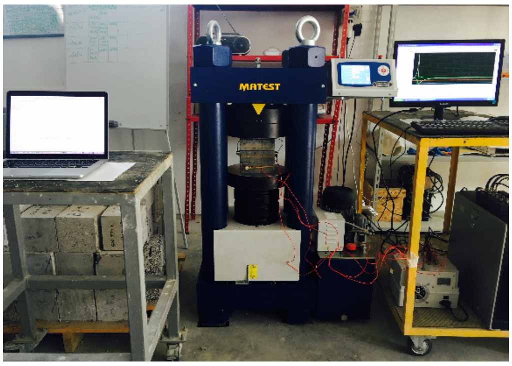

Fig. 6. Overall System Configuration.

require that sender and receiver are synchronized, because it is based on the publish-subscribe communication paradigm. In order to implement this paradigm, the MQTT architecture has an entity called broker, which acts as a mediator. All data transit from the broker and are labeled with a topic string, that summarizes their content. Subscribers register themselves to the broker, specifying the topic of the data that they want to receive. When the publisher makes available to the broker a data with a specific topic, the broker forward it to all subscribers interested. In this way there are not constraints that bind subscriber to publishers, guaranteeing the a-synchronicity in the operations.

MQTT was also chosen because it is designed for networks with low bandwidth, high latency and because it offers mechanisms that ensure the data delivery. It uses also reduced header and payload that estimate the transmission upper bounds delays in the order of 56ms as reported in [24].

When the alarm notification is received, the reaction requires few minutes, because it consists in the arrival of a rescue team at the required point. So, the transmission delay introduced by the network is acceptable.

IV. EXPERIMENTAL RESULTS

The experimental test aims to verify the functioning of the proposed SHM architecture and to validate the solutions proposed for the highlighted synchronization problems. At a low level LabVIEW was chosen as a software to manage and supervise the acquisition phase, while all the cyber part has been implemented using Java.

The tests were carried out in a certificated laboratory located in Catanzaro, using a set of cubic concrete specimens. When the specimen crack is detected, a remote alert is sent to another computer, that represents the civil protection resources.

A. *Measurement stand*

The measurement stand configuration in Fig. 6 is composed by:

- four AE transducers R15α, operating in the frequency range [50, 200]kHz, with peak sensitivity of 69V/(m/s), resonant frequency 150kHz, and directionality ±1.5 dB;
- the L-FAT component with four input channels;

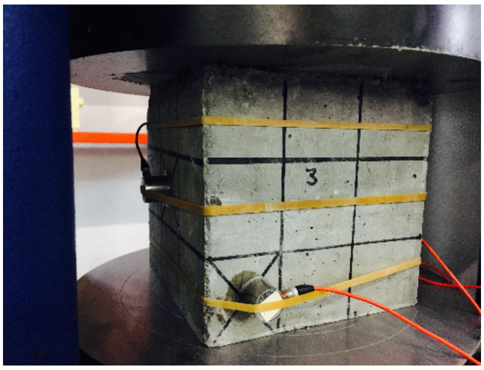

Fig. 7. Piezoelectric Sensors on the specimen.

- the data acquisition board DAQ is the NI 6110 PCI, allowing a sampling frequency of 5MS/s for each input channel and a resolution of 12-bit;
- Matest high stiffness compression machines with load control (Mod. YIMC109NS, Serial N. YIMC109NS/AE/00225);
- Hp PC-Desktop, 2Gb, Windows XP, equipped with the DAQ;
- Macbook Pro Intel Core i5, 2.9GHz, 16GB, OS High Sierra.

B. *Results*

To perform the tests, the four sensors were placed in different points, each one located on a face of the specimen, as shown in Fig. 7. The b-value acceptability parameter, for the detection algorithm, is in the range [0.9-1.2].

The threshold of the L-FAT to send the acquisition trigger is 0.7V, established with the Hsu-Nielsen test. The number of pre-trigger samples settled in the DAQ is 1000.

By considering the particular application, in the cyber part the EDA uses a TO equal to 1s, while the RMA does not need for settings because it is advised by the EDAs.

Tests were conducted on 6 specimens. The results show that the three dangerous crack in the time interval of 60s have been detected around the 80% of the maximum load curve (Fig. 8). In two cases, however, the operations did not end as expected, because the SHM system identified only 2 crack, instead of 3. This may be due to the fixed values of *a* and *b* used in the equation (1). Their values may depend on the resistivity of the specimen. Indeed, the test failed with specimen with resistivity higher then average one.

This suggests that the experimentation has not ended. As future work, further tests will be carried out, in order to draw up a look-up table, containing the pairs of parameters *a* and *b* depending on the resistance of the specimen.

By analyzing the delays among all the acquired signals related to the same event (100 events were detected), all them result compatible with the specimen dimension and the positioning of the sensors. This confirm that the delay among

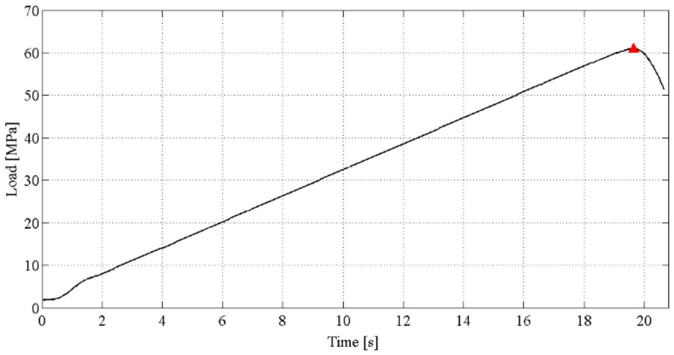

Fig. 8. Load vs Time. In red the maximum value of the compressed strenght.

signal is only due to the propagation of the AE in the specimen and not to the L-FAT architecture.

In order to evaluate the delay between the sending and the receiving of the alert message exchanged in the cyber part, the WireShark open source network analyzer tool is used to time stamp the packets [24]. Such solution allows to time stamp all the packets according to the same clock, i.e. the one of the network analyzer, avoiding the problems introduced by the synchronization between the clocks of EDAs and RMA computers. In all cases the propagation delay of the packets is less than 60ms.

V. CONCLUSION

In this paper a SHM system is proposed, that computes an on-line detection of the structural damage events. The overall architecture exploits the IoT paradigm and it is structured according to a layered hierarchy. The system automatically sends a remote alert to the authority, when detects the occurrence of a potential collapse.

The paper highlights the importance of the synchronization among signals and the impact of the data transmission delay on the application logic. Experimental tests were executed to assess the correct functioning of the system and the respect of the synchronization and timing constraint by the proposed SHM system.

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REFERENCES

[1] G. T. Webb, P. J. Vardanega, and C. R. Middleton, "Categories of SHM deployments: Technologies and capabilities," J. Bridge Eng., Vol. 20, n. 11, Nov. 2015.

[2] W.J. Staszewski, B.C. Lee, L. Mallet and F. Scarpa, "Structural health monitoring using scanning laser vibrometry: I. Lamb wave sensing," Smart Materials and Structures, 2004.

[3] F. Lamonaca, A. Carrozzini, D. Grimaldi, R.S. Olivito, "Improved monitoring of acoustic emissions in concrete structures by multi-triggering and adaptive acquisition time interval," Measurement , Vol. 59, Jan 2015, pp. 227-236.

[4] F. Lamonaca, A. Carrozzini, D. Grimaldi, R.S. Olivito, "Improved monitoring of acoustic emissions in concrete structures by multi-triggering and adaptive acquisition time interval," Measurement, Vol. 59, 2015, pp. 227-236

[5] D.L. Carnì, C. Scuro, F. Lamonaca, R.S. Olivito, D. Grimaldi, "Damage analysis of concrete structures by means of acoustic emission technique," Composite Part B: Engineering, Vol. 115, April 2017, pp. 79-86.

[6] D.L. Carnì, C. Scuro, F. Lamonaca, R.S. Olivito , D. Grimaldi, "Damage analysis of concrete structures by means of b-Value Technique," International Journal of Computing, 2017, pp. 82-88.

[7] S. J. Samuel, K. RVP, K. Sashidhar, and C. R. Bharathi, "A survey on big data and its research challenges," ARPN J. Eng. Appl. Sci., Vol. 10, no. 8, May 2015, pp. 3343–3347.

[8] Y. Lei, A. S. Kiremidjian, K. K. Nair, J. P. Lynch, and K. H. Law, "Algorithms for time synchronization of wireless structural monitoring sensors," Earthquake engineering & structural dynamics 34.6, 2005, pp. 555-573.

[9] N. Kaempchen, and K. Dietmayer, "Data synchronization strategies for multi-sensor fusion," In Proc. of IEEE Conference on Int. Transportation Systems, 2003, pp. 1-9.

[10] L. Atzori, A. Iera, and G. Morabito, "The internet of things: A survey," Computer networks, 2010, pp. 2787-2805.

[11] M. E. Zitto, R. Piotrkowski, A. Gallego, F. Sagasta, and A. Benavent-Climent, "Damage assessed by wavelet scale bands and b-value in dynamical tests of a reinforced concrete slab monitored with acoustic emission," Mech. Syst. Signal Process., Vol. 60, 2015, pp. 75–89.

[12] B. Gutenberg and C. F. Richter, "Magnitude and energy of earthquakes," Science, Vol. 176, 1955.

[13] ACI 224R-01: Control of Cracking in Concrete Structures. Reported by ACI Committee 224. ???

[14] Burr-Brown Corporation, "High Speed FET-Input INSTRUMENTATION AMPLIFIER, 1992.

[15] "Dual, High Speed ECL Comparators ADCMP563/ADCMP564", Rev.5, 2005 Analog Devices.

[16] "MC10EL01/D", Rev.6, Semiconductor Components Industries, LLC, 2008.

[17] A. Anastasopoulos, D. Kourousis, S. Botten, and G. Wang, "Acoustic emission monitoring for detecting structural defects in vessels and offshore structures", Ships and Offshore Structures, 2009, pp. 363-372.

[18] G. Lacidogna, F. Accornero, M. Corrado, and A. Carpinteri, "Crushing and fracture energies in concrete specimens monitored by Acoustic Emission," In VIII International conference on fracture mechanics of concrete and concrete stru ctures, 2013, pp. 1726–1736.

[19] M. V. M. S. Rao and K. J. Prasanna Lakshmi, "Analysis of b-value and improved b-value of acoustic emissions accompanying rock fracture," Vol. 89, 2005, pp. 1577–1582.

[20] F. Cicirelli, L. Nigro and P.F. Sciammarella, "Model checking mutual exclusion algorithms using Uppaal," Software Engineering Perspectives and Application in Intelligent Systems, Springer, 2016, pp. 203-215.

[21] M. Wooldridge, "An introduction to multi-agent systems," Second edn., John Wiley & Sons, 2009.

[22] F. Cicirelli, L. Nigro, and P.F. Sciammarella, "Model continuity in cyber-physical systems: A control-centered methodology based on agents," Simulation Modelling Practice and Theory, 2017.

[23] C. Grosse, H. Reinhardt, and T. Dahm, "Localization and classification of fracture types in concrete with quantitative acoustic emission measurement techniques," NDT & E Int., Vol. 30, 1997, pp. 223–230.

[24] L. De Vito, F. Lamonaca, G. Mazzilli, M. Riccio, D.L. Carnì and P.F. Sciammarella, "An IoT-enabled multi-sensor multi-user system for human motion measurements," In Medical Measurements and Applications (MeMeA), 2017, pp. 210-215.