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 a 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

Events such as earthquakes, aging phenomena or simply excessive loads, can cause internal damage to the concrete piers of houses, bridges or other infrastructure, which, if not identified, could be dangerous for people's safety[1]. Buildings are subjected to inspection, monitoring [2],[3] and maintenance programmes that may be regulated by law, depending on importance, ownership, use, risk and hazard[4],[5]. The usefulness of these security measurements depends on the timeliness with which they can detect hazards [6]. To improve human safety, the research in Structural Health Monitoring (SHM) is devoted to develop new systems for the real-time and automated monitoring of buildings [7]. Such systems aid the competent authorities in the scheduling of the inspections on the basis of the structure health status and of the occurrence of events of interest pointing out danger.

Generally, a SHM deploys wired or wireless sensor technologies to detect event of interest. Such sensor are typically based on the fiber Bragg gratings [8] or MEMS (Micro-Electro-Mechanical- Systems) sensors [3]. Both them estimate the impact of static and dynamic loads on building pillars and columns, measuring the structural vibration response. Recently, accurate, reliable and cost-effective methods for structural monitoring have been developed exploiting the measurement of the Acoustic Emissions (AEs) [9]. AEs are elastic radiations generated by the release of energy within the material [10]. Through the use of piezoelectric sensors, applied on the surface of the buildings, these elastic waves are detected and converted to voltage signals. The perceived acoustic emissions include information about fracture and plastic deformations, impacts, friction, corrosive film rupture, and other damage or aging processes [11],[12].

In this paper an AEs-based SHM system is proposed. Its development starts from author's previous work [13], improving the sensing layer and introducing new notifications mechanism that supports the possibility to exchange information locally among the different components located in the structure, or remote to alert the authorities of the occurrence of some critical event [14].

According to the Internet-of-Things (IoT) paradigm [15]-[17], the proposed SHM system is designed as a distributed measurement system, that follows a layered implementation, shown in Fig. 1. Each layer has a specific role and requires specific temporal constraints and robustness [18] depending on the goals that it has to achieve [19]. The lowest layer is constituted by the so called *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. Going up in the hierarchy the highest levels are grouped in the so-called *cyber-part* that implement the application logic, including all the algorithms finalized for structural damage detection, and all the mechanisms needed to propagate such information.

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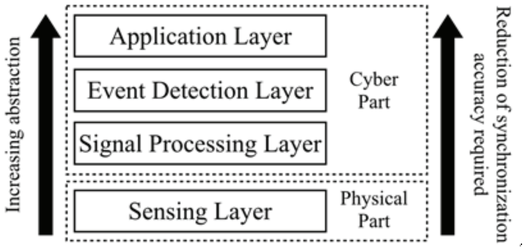

Fig.1 Hierarchical layered implementation of a SHM system.

Fig.2. Example of IoT paradigm applied to SHM.

The proposed SHM system is made by a set of Smart-Object (SO) [20] each of them responsible to monitor, for example, a pillar or a beam of the structure. Internet is used as communication network to exchange information among SOs that are reachable by an IP [21],[22]. In particular, as shown in Fig. 2 if a dangerous event is detected, a local alarm through the LAN is sent locally from one SO to the others to start the evacuation of the building, then through the WAN a remote notification is sent to the competent authorities to alert them.

The different layers have different time-synchronization issues, and imposes different time constraints to work properly [23]-[25]. In particular, to correlate the measurement information coming from different sensors of a same SO, the dedicated hardware proposed in [13] is used allowing a synchronization accuracy in the order of some μs.

Moving to the next layer, to send a local alarm notification to SOs within the same structure, for example to launch the evacuation alert, IoT communication protocol guarantying delays in the order of ms is used.

Finally, to notify the alarm to competent authorities, a message is sent through internet. In this case, moving on a WAN the delivery delay is unpredictable, but in this layer it is important to prevent the packets loss. This goal can be achieved using appropriate protocol. In any case, compatibly with the Ethernet functioning the upper bound of the delay can be estimated in the order of hundreds of ms [26]-[28], that is negligible with respect to the time needed by the authorities to take a decision and intervene.

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. THE MULTI-AGENT IOT-BASED SHM

The goal of the proposed paper is to offer a methodology useful to develop an agent-based architecture for a IoT based SHM system (ISHM). As shown in Fig. 3, according to the IoT paradigm a ISHM can be considered as the interconnection of a set of SOs, spread in the building, that exploit Internet for the data exchange. Each SO is in charge of:

- acquire the signal associated to an event;
- process each signal acquired and then to extract any useful information;
- send data (alarm) through the network to others SO or outside the building.

The different tasks of each SO suggests to develop the system following a hierarchical approach, based on the schema depicted in Fig. 1. All the features are encapsulated in a stack of layers, each one with a growing abstraction level and specific time constraints.

The algorithms finalized for structural damage detection and all the mechanisms needed to propagate such information, are grouped in the cyber-part layers, implemented using the agent programming paradigm. An agent, as defined in [29], is a computer system capable of autonomous operation to meet an established behavioral goal. Each SO is equipped with an agent that, through its properties such as reactivity and proactiveness [30], supervises and manages its operations. Agents can be assembled as an interactive societal group, called multi-agent systems (MAS), and support the *message passing protocol* to communicate each other for the achieving of specific application goals. Furthermore, their use introduces these advantages:

- high computational throughput due to concurrent data processing;
- 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, due to role decomposition.

In the following sub-section are shown the implementation details and synchronization issues related to the developing of a single SO of the proposed ISHM.

Physical-Part

As shown in Fig. 1 the lowest level of the hierarchy is occupied by the tier that constitute the so-called physical part. It acts as a sensing layer, aimed to carry out a continuous real-time monitoring of the structure using piezoelectric sensors (PSs) and to start the data acquisition operations when a potential dangerous event is detected.

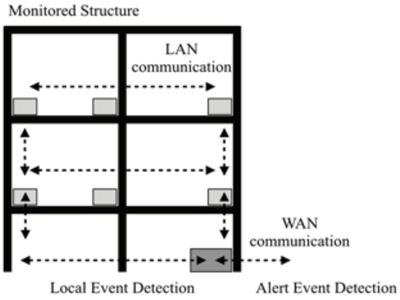

Fig.3. Example of communication network for a ISHM system.

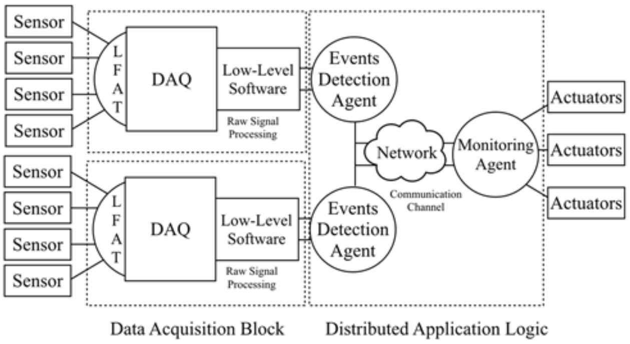

Fig.4. Distributed Structural Health Monitoring Architecture.

The main problems of this layer concern:

- the identification of the signals of interest, distinguishing it among environmental noise and sounds produced by mini-crack;
- the storage only of signals associated to potentially critical events, in order to save computational resource;
- the synchronization of the measurements coming from the different sensors, in order to ensure their time correlation, so as to have ensured that the identified phenomenon is the same.

As shown in Fig. 4, to overcome these issues, the proposed architecture includes in the data acquisition block a specific hardware, the Logic Flat Amplifier and Trigger (L-FAT), whose implementation details are described in [13]. It extends the capability of traditional Data AcQuisition (DAQ) systems allowing to perform the triggering acquisition modality, guaranteeing no loss of signals and no waste of storage memory. The trigger signal starting the DAQ acquisition operations occurs if one or more signals of interest reach any of the PSs. Since the trigger generated by L-FAT needs some ns to reach the DAQ, the sensing layer may lose information about the the early samples of the signal of interest. To avoid the loss of the information, the DAQ board allows to acquire a fixed number of samples before the trigger occurrence, functioning in a pre-trigger modality. To evaluate the number of pre-trigger samples compatible with the AEs dynamics, the Hsu-Nielsen test is used [31].

The acquisition of the signals made by sensors, is time-critical because the data coming from the different PSs positioned on the same pillar, need to be synchronized with an accuracy of the µs, to establish if they are related to the same event/phenomenon. Such accuracy is guaranteed by the L-FAT hardware characteristics. L-FAT introduce a propagation delay among the acquired signal in the order of 20 ns, with an uncertainty of few ns [13]. That delay can be considered negligible, owing the frequency range of the AE signals that are in the order of a hundred of kHz.

Cyber part

Going up into the abstraction hierarchy, the higher levels in Fig. 1 constitute the so-called cyber part. They include all the algorithms and protocols, needed to develop and achieve the application logic goals.

1) Signal Processing layer

The Signal Processing Layer is in charge of extract the information from the acquired signals. In particular, while the Sensing Layer acts acquiring all potential cracks, this layer aims to process them estimating the crack intensity, so as to decide whether or not if can be considered as a dangerous event. To achieve this goal, 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 crack identified as dangerous.

The analytical evaluation of the crack signal is based on the assumption that they are similar to the waves generated during an earthquake [32]. 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 [33]:

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

The *N* parameter represents the number of the hits higher than the threshold noise, experimentally 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, using the techniques reported in [9]. Critical cracks are characterized by a value of *b* in the neighbor of 1 [9]. If an acquired signal is recognized as critical, a Counter Variable (CV) is incremented.

The Signal Processing Layer operations are executed in the Data Acquisition Block, and are finalized to:

- update the CV value;
- make CV available to the upper layers for the subsequent operations.

To decouple the layers and increase the parallelism of the operations, instead of the data exchange mechanisms based on techniques such as sockets, the CV variable is stored in a shared memory location. Such shared variable imposes the synchronization among agents using it, to coordinate the access for reading and writing operations. Such synchronization, in Windows, is achieved by using the dynamic-link library. In this way the software related to the Signal Processing Layer and the other implemented in the Event Detection Layer, can work according to their specific timings constraints. Since the CV value can be read at any instant, even when the variable is going to be updated, to avoid any concurrency problems, the access is handled using Dekker's mutual exclusion algorithm [34].

2) Event Detection Layer and Application Layer

The highest levels in the abstraction hierarchy are the Event Detection Layer and the Application Layer, that are respectively in charge of:

- evaluate the information coming from the underlying levels, in order to complete the monitoring operations, relating the identified cracks with a possible structural collapse;
- notifying any dangerous situations associated with the state of a structure to other SO of the ISHM and to the competent authorities.

These layers are developed using the agent-based programming paradigm, because it offers properties useful to model the functioning and the dynamics of a distributed system [29].

Each agent is designed to work:

- alone, trying to achieve individual specific sub-goals (behavior);
- together with other agents of a same platform, exploiting its social abilities (message passing techniques), to achieve a more general application goal.

As show in Fig. 4 the algorithmic details of the remaining layers of the proposed ISHM system, can be modelled through agents and their interactions.

The implementation of the lightweight multi-agent framework used, are summarized in [35].

To determine if a detected crack represents a dangerous event, which announces a damage that could lead to the structure collapse, each SO is equipped and supervised by an Events Detection Agent (EDA). This agent, which carries out the Event Detection Layer operations, monitors the CV value according to its observation period T_O settled to 1s. This periodicity is acceptable and the layer do not require a greater granularity, because T_O is compatible with the time requirements of the higher layer to perform its operations. Recent literature [36] assesses that if in a time interval fixed to 60s are detected at least 3 events of interest, the structure can be considered dangerously damaged. Therefore, if during the last 60s of monitoring, EDA detects a CV variation equals to 3, it sends a message to to the Remote Monitoring Agent (RMA). According to the operations of the Application Logic layer, when RMA receives the message, it starts the notification operations required, to propagate the alarm to other SO and to the the authorities, modelled in Fig. 4 as actuators.

The notification mechanism introduces a propagation delay estimated in the order of ms. Using Internet as a communication network both locally, via LAN, and globally, via WAN, ensuring better performance is impossible without using particular router ensuring privileges in the scheduling of alert messages [37]. By the way, also using internet, a delay in the order of ms can be tolerated, because the Application Layer of ISHM does not require hard real-time operations. In particular, to activate the alarm, no strict temporal correlations between the measurements coming from different SOs is needed, also if they are related to the cracks of a same pillar. Since the reaction is completed with the evacuation of the building or authorities' arrival, which are operations that require times in the order of seconds and minutes respectively, a propagation delay bounded in the order of hundreds of ms can be considered acceptable. According to these considerations, the only critical constraint introduced to guarantee the reliability of the overall system and the correct functioning of the layer is the ensuring of no loss of packets in sending data, for alarm launch. To this aim, the remote transmission protocol is implemented.

Remote trasmission protocol

If all the agents are on a same SO, they can exchange information locally exploiting their sociality propriety, through the local message passing. Instead, if they agents are deployed on different SOs, the data exchange requires the use of the network and mechanisms that support the correct message delivery in a distributed environment.

The architecture described in [35] includes the Gateway component, which has the task of managing the distributed data exchange, exploiting different protocols. In particular, it exposes to the agents the basic *read* and *write* operations needed to interact with physical devices or other remote cyber components, hiding all the details about the communication protocols used. In the proposed ISHM system, the Gateway component has been enriched with a communication channel, that enables the data exchange through Internet.

According to the IoT paradigm, to avoid the active waiting due to the polling cycle between sender and receiver agents (i.e. RMA), the Message Queue Telemetry Transport protocol (MQTT) is used [38]. MQTT does not require that sender and receiver are synchronized, because it is based on the publish-subscribe communication paradigm. A subscriber client registers itself to the publisher server specifying the topic of the information that it is interested to receive. After the registration the subscriber could continue its other operations. When the publisher has available the requested data, it checks their topic and it forwards them asynchronously to all registered and interested subscribers. It is worth to note that the MQTT protocol does not allow a direct data exchange between publisher and subscriber, but requires that the transmission would be mediated by an entity called *broker*. The broker acts as a mediator to dispatch the messages; all data sent on the network are managed by it and are labeled with a topic string, that summarizes their content. Subscribers register themselves to the broker, specifying only the topic of the data that they want to receive. When the publisher makes available a data with a specific topic, sends it to the broker that forward the received data to all interested subscribers. Through the use of the broker, all publishers ignore any details related to the subscribers and vice-versa, guaranteeing the operations asynchronicity.

MQTT was also chosen because it is designed for networks with low bandwidth and high latency. It uses reduced header and payload for the packet transmission, estimating the transmission upper bounds delays in the order of 56ms as reported in [39]. Furthermore, MQTT offers also three Quality-of-Service (QoS) levels for the reliability of message delivery [40], summarized as follow:

- Level 0: it guarantees a best effort performance, because a message is delivered at most once and no acknowledgement of reception is required. This level ensures lower transmission times, but no reliability on delivery;
- Level 1: every message is delivered at least once to the receiver and confirmation of message reception is required. This level ensure that the message arrives to the receiver but duplicates can occur;
- Level 2: through a four-way handshake mechanism this level guarantees that each message is received only once by the receiver. It is the safest and also the slowest quality of service level and ensures that delivery occurs avoiding network congestion and packets duplication.

To ensure that the notification alarm produced but a SO of the Application Layer reaches the recipients, the proposed ISHM implementation uses the QoS level 2, ensuring the delivery and reducing the network traffic at the cost of a slightly longer transmission delay, but still acceptable if compared with the timing of reactions.

III. EXPERIMENTAL VALIDATION

The experimental test aims to verify the functioning of the proposed ISHM architecture by testing the functioning of a single SO and its notification mechanism. 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 NGT test laboratory, 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.

Measurament stand

The measurement stand configuration in Fig. 5 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;
- 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.

Results

To perform the tests, the four sensors were placed on a face of the specimen, as shown in Fig. 7. According to [13][32], the b-value acceptability parameter, for the detection algorithm, is selected 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 [31]. The number of pre-trigger samples settled in the DAQ is 1000.

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. 6). In two cases, however, the operations did not end as expected, because the ISHM 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 about double than the one typically used in building construction.

Fig.5. Overall System Configuration.

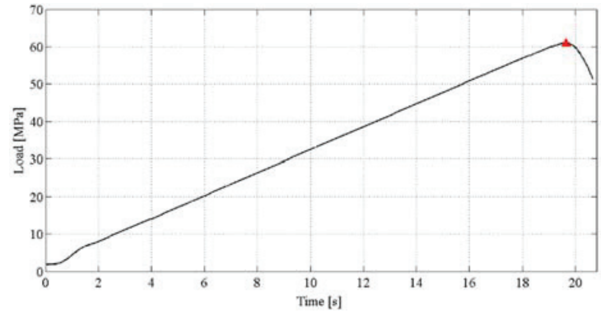

Fig. 6. Load vs Time. In red the maximum value of the compressed strenght.

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 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 locally in the cyber part, the WireShark open source network analyzer tool is used to time stamp the packets [39]. 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 lower than 60ms.

IV. CONCLUSION

In this paper a SHM system based on IoT paradigm is proposed (ISHM). ISHM 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 local alert to each other component of the SHM to starts the evacuation operations of the building and a remote alert to the authority, when the occurrence of a potential collapse is detected.

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 constraints.

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