Leveraging the Edge-Cloud Continuum in Structural Health Monitoring Applications

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***Abstract*—In this paper, we present the reference architecture developed and its deployment for the long-term monitoring of a viaduct located in Naples, Italy, as part of the MAC4PRO and DS2 projects funded by INAIL under the BRIC initiative. These projects aim to develop adaptable cyber and physical components for efficient Structural Health Monitoring (SHM). We demonstrate the architecture's versatility by deploying it in a real-world scenario, showcasing its ability to integrate various sensors and computing stages.**

I. Motivations

The safety of critical infrastructures, such as those used in transportation systems, is paramount to protecting individuals and advancing towards a safer society. This goal aligns with the objectives of various national and international research funding programs. Structural Health Monitoring (SHM) is a burgeoning field of research that supports this vision by assessing the structural integrity of civil buildings and industrial infrastructures. While the primary focus is on civil engineering aspects, the design and development of real-world SHM systems necessitate interdisciplinary contributions from various research domains. Modern data-driven SHM applications rely on the capability to monitor the behavior of civil structures in real-time through IoT sensors that support different types of analyses and vary in type and measurement capabilities, such as vibration and acoustic emission.

Significant research has been dedicated to designing effective sensing strategies that integrate data processing capabilities at the edge. However, the end-to-end design of SHM applications also requires robust data management systems capable of gathering, processing, and integrating the IoT data collected by the sensors. Despite its importance, data management in SHM has received relatively little attention in the research literature, even though it presents substantial challenges. Indeed, most SHM deployments on literature focus on the sensing or civil-engineering aspects while overlooking the computer science ones. Consequently, the software stack developed are often ad-hoc to the specific monitored structure and not easily applicable to other scenarios. This leads to high cost and time requirements to monitor new structures. Additionally, real-world SHM applications can generate massive amounts of data over time, especially when high-frequency sensors are used. For example, monitoring a bridge with a single span using 10 accelerometers at a sampling rate of 200 Hz can produce up to 15 GB of data per day, considering 10 minutes of continuous acquisition. Twofold objectives arise:

- **Efficient data management and processing strategies**: are critical to reducing the amount of data transferred to the cloud, ensuring the system's scalability. Edge computing presents a viable solution by offloading computation closer to the monitoring site, such as a bridge. However, the computational resources of edge nodes must be carefully considered.
- **General-Purpose Platform for SHM**: A platform is needed for adaptable SHM deployments that leverages modern technologies from information, software, and industrial engineering communities. Its design should be modular and customizable. Based on the scenario requirements, components could be included to support a given feature, such as a specific interoperability integration or a latency requirement.

Based on these considerations, SHM systems can benefit from edge-cloud continuum architectures that intelligently allocate services and tasks across available computational units. This approach can ensure scalability, performance, and adaptability to scenarios with varying requirements.

II. SHM Data Management in MAC4PRO and DS2 BRIC Projects

In this paper, we review the SHM data management strategies developed by the UNIBO team within the MAC4PRO and DS2 projects, both founded by INAIL under the BRIC founding scheme. The projects aimed at developing innovative solutions for civil structure monitoring, safety assessment and prognostic by leveraging cutting-edge technologies for sensor design, IoT data acquisition and processing. Such tecnologies

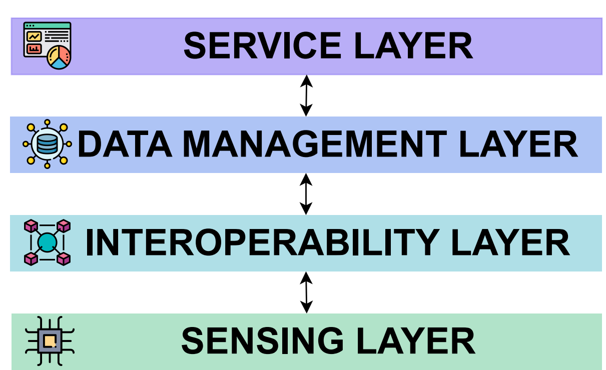

Fig. 1. MAC4PRO-DS2 IoT Architecture for IoT (adapted from [1])

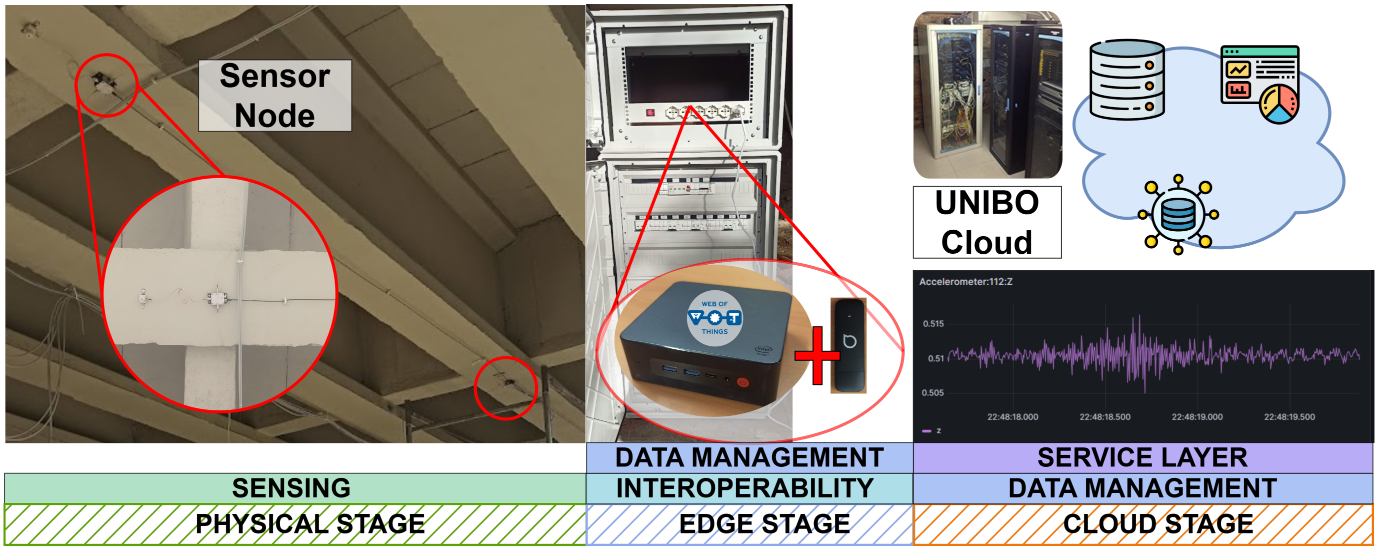

Fig. 2. The deployment of the MAC4PRO-DS2 IoT Architecture in the Volto-Santo viaduct in Naples, Italy.

were demonstrated on real-world pilots and installations on existing structures, such as the Volto Santo viaduct located in the Naples metropolitan area. Regarding the UNIBO team contribution, we proposed in Gigli, et al [1] a generic and modular architecture for IoT-SHM scenario, depicted in Figure 1. It consists of four layers:

1) *Sensing* layer, consisting of the sensing units necessary to acquire the physical phenomena to be monitored and the physical communication medium of the network stack – e.g., LTE, Wi-Fi, LoRa.
2) *Interoperability* layer, offering a uniform and standardized Application Programming Interface (API) for two-way interaction with the *Sensing* Layer devices through homogenization tools (e.g., the WoT standard [2]) and communication-enablers (e.g., MQTT Broker, LoRaWAN server).
3) *Data Management* layer, working as data lake and enabling SHM data acquisition, aggregation, storage and processing via SHM anomaly detection algorithms;
4) *Service* layer, including user applications able to query the *Management Layer* for custom data visualization and processing, being them built-in services or third-party applications.

The architectural design is independent of the deployment plan. Depending on requirements and available resources, software components can be configured and deployed across the edge-cloud continuum in diverse ways, as illustrated in the following Section.

III. SHM Pilot Case Study

We deployed the aforementioned architecture for the long-time monitoring of the Volto Santo viaduct in the city of Naples. The Fig. 2 illustrates the cyber-physical components utilized in the scenario. Specifically, there are three computing stages spread over the distributed IoT infrastructure: (*i*) *the physical stage*, where triaxial accelerometers and acoustic emission sensors are located; (*ii*) *the edge stage*, represented by an mini-pc (Intel Celeron N5105 and 8 GB RAM) equipped with a 4G LTE USB Dongle that operates as a network gateway for the sensors and initial computation unit, performing preprocessing data homogenization operations; and (*iii*) *the cloud stage*, which is represented by a private data center where data is stored and computationally demanding tasks such as visualization and data analysis are performed.

Figure 2 illustrates the architecture layers deployed at each computing stage, demonstrating that the architectural layers are independent of the location of the computation node. This flexibility allows us to make custom decisions based on the requirements of each deployment. In this case, we applied data preprocessing, a *data management* task, on the acquired signals (using Fast Fourier Transform-based compression) at the edge. This approach reduces both the processing burden on the cloud and the amount of data transmitted from the edge to the cloud.

Acknowledgements

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References

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[2] M. Kovatsch, R. Matsukura, M. Lagally, T. Kawaguchi, K. Toumura, and K. Kajimoto, “Web of things (wot) architecture,” W3C Recommendation, Apr. 2020, https://www.w3.org/TR/wot-architecture/.