H2IOSC Project: The Italian Federated Cluster for IoT-based Monitoring and Digital Twinning of Cultural Heritage

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***Abstract*—The H2IOSC project aims to create a federated cluster of research infrastructures (RIs) in the domain of Cultural Heritage at the national level in Italy. Through four key Ris — DARIAH-IT, CLARIN, OPERAS, and E-RIHS — the project enables collaboration among researchers with interdisciplinary expertise. Within this context, DIGILAB emerges as a digital access platform for the Italian node of E-RIHS, providing data management, digital tools, and services to boost cultural heritage preservation, fruition, and study. A significant aspect of DIGILAB architecture is its capability to support geo-localization and real-time monitoring of cultural heritage sites in terms of environmental conditions, structural integrity, and diagnostics, leveraging on novel Internet of Things (IoT) systems and large-scale Wireless Sensor Networks (WSNs). By integrating WSNs into DIGILAB framework, the project enhances remote monitoring and control of cultural sites. These networks facilitate the collection of real-time data on factors such as temperature, humidity, and air quality, providing crucial insights for the Cultural Heritage research community. Moreover, WSNs enable proactive measures to be taken in response to emerging threats, mitigating risks and minimizing damage to cultural assets at a national level.**

***Keywords*—IoT, cultural heritage, wireless sensor network, data processing, data management, data visualization.**

I. INTRODUCTION

Humanities and Heritage Italian Open Science Cloud (H2IOSC) [1] is a research project funded by the Italian Ministry of University and Research as part of the National Recovery and Resilience Plan (PNRR). H2IOSC aims to establish a federated and inclusive cluster of Research Infrastructures (RIs) within the European Strategy Forum on Research Infrastructures (ESFRI) domain of Social and Cultural Innovation. This cluster enables researchers from various fields, such as Humanities, Language Technologies, and Cultural Heritage sectors, to collaborate on data and compute-intensive research projects. The involved RIs are four. The first RI is Dariah-IT (Digital Research Infrastructure for the Arts and Humanities), which aims to enhance and support digitally-enabled research and teaching across the humanities and arts. The second RI is CLARIN, which focuses on language data and tools to support humanities and social sciences research. CLARIN provides access to multimodal digital language data (text, audio, video) and advanced tools to explore, analyze or combine these datasets. OPERAS is the third RI and supports open scholarly communication in the social sciences and humanities in the European Research Area. Its mission is to coordinate and federate resources in Europe to efficiently address the scholarly communication needs of European researchers in the field of Social Science and Humanities (SSH). The last RI is E-RIHS [2], the Italian node of the European research infrastructure on Heritage Science. E-RIHS.it offers access to cutting-edge scientific tools and knowledge and organizes research, PhD and training schools on advanced non-invasive diagnostics applied to Cultural Heritage.

DIGILAB aims to become the digital access platform of the Italian node of the European Infrastructure for Heritage Science (E-RIHS). DIGILAB's main challenges are to bring together data, tools, and services into a unique digital environment to maximize access and data interoperability and to provide advanced services for processing, analyzing, and correlating the information. DIGILAB architecture is consistent and aligned with the other European research infrastructure principles defined by the ESFRI [3] and with the cluster project [4] operating in the domain of Cultural Heritage. At the Italian national level, the design of DIGILAB also considers the line guides defined by the National Plan for the Digitization of Cultural Heritage [5] elaborated by the Central Institute for the Digitization of Cultural Heritage - Digital Library of the Italian Ministry of Cultural Heritage. This plan outlines guidelines for the digital innovation process in managing cultural assets. Furthermore, the DIGILAB platform must adhere to EU data management guidelines (FAIR, Open Research Data) and the European Open Science Cloud (EOSC) plan [6].

In this framework, Wireless Sensor Networks (WSNs) have emerged as a promising technology for real-time monitoring and surveillance of cultural heritage sites, offering advantages such as cost-effectiveness, flexibility, and non-invasiveness. Despite their numerous advantages, implementing WSNs for cultural heritage monitoring also presents challenges, including sensor reliability, energy efficiency, data security, communication protocols, and interoperability issues. Faced with these challenges requires a multidisciplinary approach involving experts from the fields of engineering, computer science, conservation, archaeology, and cultural management. At the state of the art, several IoT platforms are available [7]-[9]. Still, none meet the scalability and national/international interoperability requirements in the context of cultural heritage safeguarding. To face the problem, this paper meets the requirements of the H2IOSC project through the design of a multi-sensor SW/HW platform to support the remote monitoring and the protection of Cultural Heritage assets through the implementation of a multi-technology, large-scale Wireless Sensor Network (WSN). Following the Internet of Things (IoT) paradigm, the proposed framework will rely on integrating a Sensor Network of Smart Objects based on Wi-Fi, Zigbee and Bluetooth Low Power technologies and an online platform for the post-processing and presentation of data. The WSNs gather and transmit measured data on cultural heritage, making them available for remote analysis, post-processing and visualization at the DIGILAB level. From the hardware point of view, microcontroller unit-based modules are in direct contact with the distributed sensors and actuators at different sites on one side and data centers on the other side through wired and wireless communication protocols and standards. The Message Queuing Telemetry Transport (MQTT) protocol [10], offering lightweight and efficient communication mechanisms, has been selected for connecting WSN nodes and facilitating data exchange.

The data acquired by the WSN management middleware platform are sent to an open-source software DIGILAB component that allows the analysis, post-processing and presentation of heterogeneous geolocated data in the domain of cultural heritage. The component will request the data from the WSN using its API and present them through interactive and customizable multi-tenant dashboards. The design of the dashboard will be independent of the WSN implemented and the data collected.

By leveraging the power of Internet of Things (IoT) technologies and the computational power of the DIGILAB, the designed large-scale WSNs can enable remote monitoring and smart control of cultural heritage sites at the national level, reducing the need for physical interventions and enhancing the overall efficiency of preservation efforts. Moreover, the platform will allow the creation of connections between the collected data in several research contexts of the cultural heritage field, promoting their sharing and accessibility.

II. The DIGILAB Architecture

The DIGILAB platform focuses on managing information for the Heritage Science communities. Its architecture must handle both ontologically characterized data (i.e., metadata based on an ontology) and raw data. The reference ontology for DIGILAB is CIDOC CRM (ISO 21127:2006) [11]. The platform is designed to provide advanced services to individual researchers, research and project groups, and the entire scientific HS community. The main DIGILAB services include:

- Catalog of datasets, services, and tools. All resources in the catalog must be public, with different levels of access. Data can be entered directly by a platform user or imported from external sources.
- A single and coherent access point to managed information. Information may be native to DIGILAB (i.e., entered by its members), imported (i.e., imported into the platform from external repositories), or referenced (i.e., using metadata harvesting techniques).
- Knowledge discovery services. DIGILAB has a single semantically referenced repository where all managed information will converge. The repository's uniqueness allows for the creation of a shared knowledge graph accessible to all platform modules.
- Web services for data transformation, reporting, etc. Below is a brief description of the main functionalities to be supported.

In the figure, we report the outline of the DIGILAB software architecture.

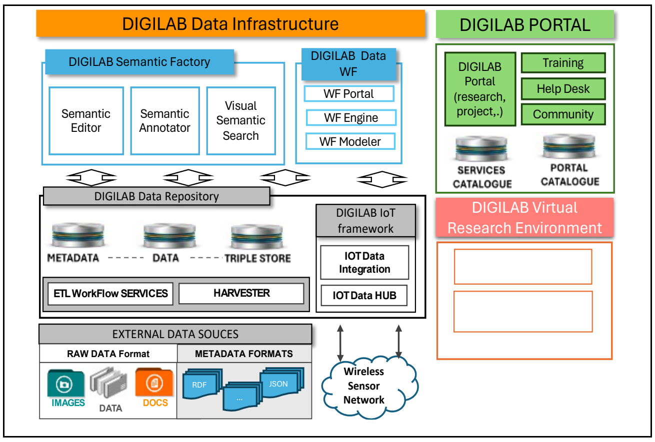

Fig. 1. Outline of the DIGILAB software architecture.

The architecture of DIGILAB is reported in Figure 1. Three distinct modules can be identified: DIGILAB Data Infrastructure (DIGILAB-DI), DIGILAB portal, and DIGILAB Virtual Research Environment. DIGILAB Data Infrastructure is the main module. Its main goal is the management of data. The data model of DIGILAB includes information and metadata based on CIDOC-CRM. Thus, DIGILAB-DI includes semantic management systems that allow data correlation and metadata enrichment. DIGILAB-DI enables the creation of workflows for data manipulation and consists of an ETL module for data import and a metadata harvesting module. To support the Wireless Sensor Network, DIGILAB-DI integrates the DIGILAB IoT semantic framework (described below) that allows the import and metadata enrichment of raw sensor data. The DIGILAB Portal module focuses on making DIGILAB services available to the research community. It integrates a series of support portals: training, helpdesk, and Community. DIGILAB Virtual Research Environment provides researchers with advanced data analysis services, allowing them to use metadata to correlate data and, thus, discover new specific knowledge.

A. *DIGILAB Computational Capabilities and Datacenter*

The DIGILAB platform will be hosted inside the E-RIHS node that will be located in Lecce, Italy. Some services will be managed in conjunction with other federated national nodes.

The Datacenter is a Hyper-Converged HPC (High-Performance Computing) composed of 12 compute nodes that deliver different services based on CPU and GPU processing. It is accompanied by different storage tiers to handle hot, warm, and cold data. These components let us manage the services and the entire data life cycle efficiently and flexibly.

The hardware equipment available includes the 12 HCI nodes, each with a 2x32-core Xeon Gold with 1TB of RAM, 4x25GbE Optical network ports, 25TB of Tier 1 storage on NVMe HDD, and NVIDIA A40 GPUs. The tier 2 storage system comprises 4 Storage Array Nodes of 320TB each, which will be integrated by a cloud backup (Tier 3) to store cold data on other federated Datacenters that participate in the distributed infrastructure.

The internal networking infrastructure is based on a high-speed spine-leaf architecture to increase east-west traffic performance and let the cluster's nodes communicate faster with each other, thus giving optimal conditions for the Software-Defined Infrastructure (SDI) scalability. There is also a strong focus on system security, enforced by both appliances and software platforms for monitoring and active response. However, specific security measures will be implemented to manage the sensor's connection and the collected data.

The Wireless Sensor Network will be managed by an IoT Management platform for data collection, processing, visualization, and device management configured as orchestrated containers that will handle MQTT message queues, to achieve high scalability and fault-tolerance. This is needed to let the system handle many concurrent connections to remote sensors to cover the requirements related to Cultural Heritage monitoring at a national scale. The collected data will be published inside the DIGILAB platform and associated with the Digital Twin, part of the internal multidisciplinary knowledge base. The stored information will become accessible to researchers, enabling possible data processing with AI/ML algorithms, among other things, through the platform's services on the distributed infrastructure.

DIGILAB IoT framework and Wireless Sensor Network for Cultural Heritage Sensing and Monitoring

The proposed system gathers data from various sensors located in different historical and culturally valued sites. These sensors collect sensory data such as temperature, humidity, exposure to direct light, ultraviolet exposure, air quality, vibrations, and degrading agents. To achieve this, we need hardware-software middleware to ensure that the sensors can interface with the DIGILAB infrastructure (see system architecture in Fig. 2). To do this, we designed wireless-enabled nodes to host the distributed sensors. The nodes' hardware is centered around microcontroller units (MCU) that manage the node's entire operation cycle. The MCU performs three primary tasks: data capture from the distributed sensors, initiating actions on the actuators' circuits, and communicating with the data center. The interaction between the distributed sensors and the MCU will depend mainly on the sensor setup. In some cases, an extra interfacing circuit may be required to intermediate between the MCU and the sensor for signal conditioning. This configuration allows a versatile and adaptable setup for low-level communication with a wide range of sensors. We consider several communication buses and protocols to secure communication between nodes and the gateway. These include CANbus, Bluetooth, Wi-Fi, serial communication (USB, SPI, I2C), and Ethernet. Additionally, there will be a microSD port for data logging when communication means are hindered. Due to the variety of sites that need to be covered by the DIGILAB platform, the power consumption of the distributed nodes will be critical. Some nodes can be implanted in off-the-grid sites, which raises the necessity to explore alternative powering options, for instance, lithium rechargeable batteries. Since the alternative energy sources are unstable or limited, careful consideration of the power consumption at the firmware and hardware levels is essential.

Fig. 3 exhibits a generic prototype for a setup that can serve as a gateway or a node. The prototype comprises the Nucleo-F767ZI development board from STMicroelectronics, which is connected to the ESP32 NODEMCU module Wi-Fi development board via the UART port, which enables serial data communication between the two boards. This setup utilizes the high computational power of the Nucleo's primary microcontroller, the STM32F767ZI, based on a high-performance Arm Cortex-M7 32-bit RISC core that operates up to 216 MHz. The microcontroller is ethernet-enabled, and to provide wireless connectivity, we have plugged in the ESP32-WROOM-32, a generic microcontroller that supports Wi-Fi and Bluetooth. In Fig. 4, we demonstrate a prototype of a wirelessly connected node that hosts several sensor and actuator interfacing circuits. Wireless communication enables bi-directional communication for sensors` data capturing and action execution through the interfacing circuit.

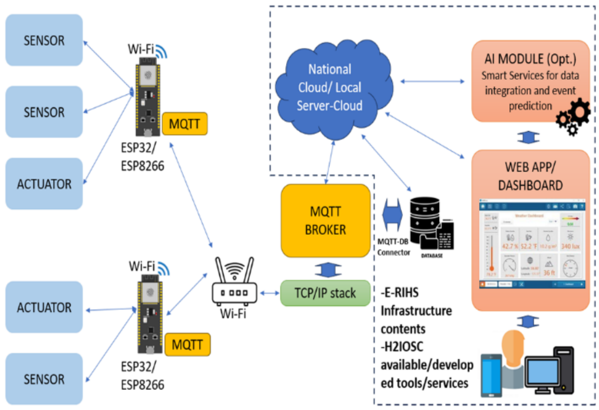

Fig. 2. Architecture of the proposed large-scale H2IOSC Wireless Sensor Network for cultural heritage monitoring.

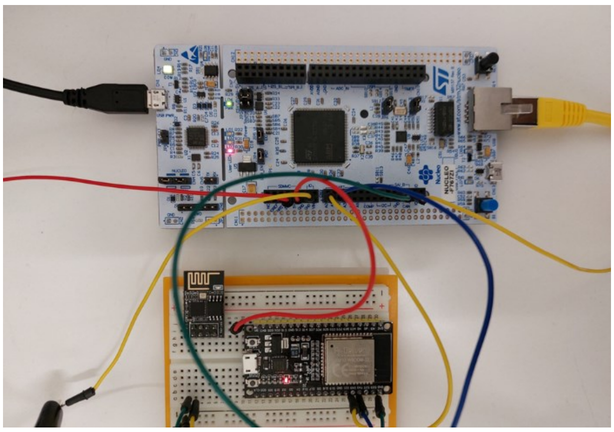

Fig. 3. Gateway/node prototype. In this configuration, the prototype is capable of communicating with the external world through various wired and

wireless communication protocols and standards: USB, I2C, SPI, CANbus, Ethernet, Wi-Fi, and Bluetooth.

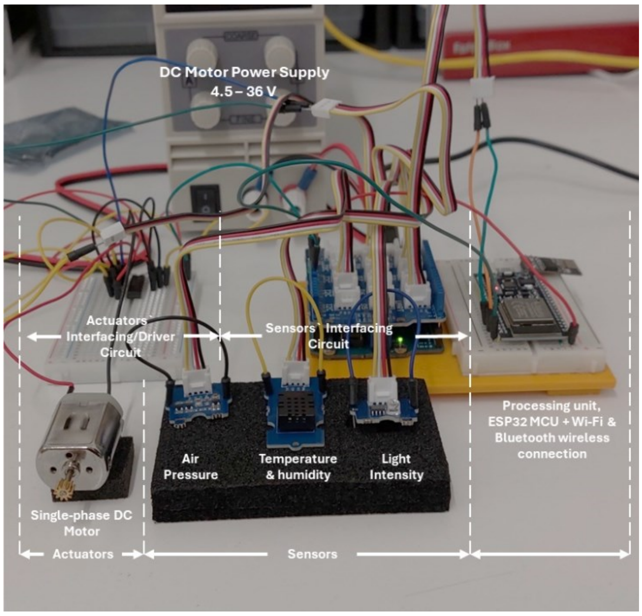

Fig. 4. Node module. In this prototype of a wirelessly connected node, the platform hosts the following sensors: an air pressure transducer, a temperature and humidity sensor, and a light intensity sensor. In this setup, the actuator's interfacing circuit is practically a driver circuit for a single-phase DC motor.

Fig. 2 illustrates the architecture of the large-scale WSN proposed at both the physical and software levels. Each node within the hardware subsystem collects data from various sensors. The sensor node performs preliminary data processing on board and subsequently transmits the results to the MQTT broker using appropriate wireless technologies.

In the proposed architecture, the element capable of interconnecting the physical part with the software part is the MQTT broker. The feasibility of adopting an IoT architecture based on the MQTT protocol hosted in the cloud has been considered and is being evaluated. MQTT is regarded for its ability to provide lightweight and efficient messaging services between sensor nodes and the application layer. The choice included an assessment of MQTT's suitability to handle the expected data volume, meet latency requirements and address security considerations. At the software level, the output of each sensor node will be information in JSON format encapsulated in MQTT messages and available for possible storage in a database or for direct processing by the software interface. The speed of data coming from the sensors and collected by the MQTT system depends on the dynamic variation of the specific monitored parameter. It can vary from a few seconds (in real-time) to several hours.

Fig. 2 demonstrates the architecture of the software platform for data collection, storage, analysis, transformation and representation of acquired. The architecture comprised of three main logical components:

1. **Central MQTT Broker:** The central server is equipped with an MQTT broker responsible for managing messages from sensor nodes. The central MQTT broker interfaces via a specific "connector" with the central database. The connector allows the transmission of sensor data to the database and the reception of the sensor node configuration information from the database. The connector acts in a bidirectional mode to align the state of the "variables" of the central MQTT system with the configuration of individual sensor nodes. The central MQTT server is robust and could support the connectivity of at least 100,000 sensors distributed throughout the country. The maximum size of the message sent to the MQTT broker for each single sensor is approximately 1.5 KByte.
2. **Local Database/Repository:** The central server has a central database/repository that collects all the data from the sensor nodes via an MQTT "connector." The database saves the user's main configurations and parameters sent to the sensor nodes, as well as user information and accessibility levels for their system information.
3. **Software system for configuration and management of Backend services:** The central server is equipped with a backend software system for the management and configuration of the primary services, such as the overall backup of system data, the timing for managing updates and data storage, management of database level synchronizations and, in general, all the necessary configurations for the complete execution of server-side services to guarantee the overall functioning of the central software infrastructure and complete interfacing with the frontend described below.

The developed WSN system enables several functions at the user level, allows the individual sensor nodes to be associated with the specific cultural "object" or monitored environment, provides analysis tools, monitoring, and configuration functions of the particular sensor nodes (enable the individual sensor, setting the monitoring time intervals, alert thresholds and other parameters) as well as guaranteeing security in access for users who can log in with different profiles.

The user interface and indicators relating to the individual values detected by the sensors will be completely customizable. The interface will provide a graphic-scale representation of the sites of interest with icons that allow access to the sensor monitoring page associated with the selected site. APIs will be provided to interface with optional artificial intelligence modules.

In case of limited or absent connectivity, a backup function will be added for the data coming from the local sensors. Furthermore, the system will be able to provide for the automatic or manual realignment of the sensor data of the individual local site with the data of the central system.

III. Results

The proposed IoT platform aims to implement a multi-sensor SW/HW network (WSN) at the national level that allows real-time monitoring of cultural heritage assets in a cost-effective, flexible, and non-invasive way. The WSN supports an open-source web-based component of the DIGILAB platform that will contribute to collecting and disseminating heterogeneous data on cultural heritage. This component will be one of the first implemented pilots in the DIGILAB and will be used to show the potential and functionalities of the platform. The element represents the upper level of the IoT system, and it will use the computational power of the data center to manage and process the data.

One of the component's main features is the possibility of having dashboards that the user can customize based on the scenario and information to be represented. Multiple users can share and manage the dashboards, encouraging collaboration and information sharing. Furthermore, creating and managing dashboards will not depend on the type of WSN or the sensors used.

For the component's implementation, ThingsBoard [12] has been decided upon. This open-source IoT platform includes tools for collecting, presenting, and processing data. In particular, the Community Edition is used, allowing the ability to add new features and custom tools.

As previously mentioned, the component's main target is the representation and processing of heterogeneous data coming from different interest areas relating to the conservation and study of cultural heritage. Some use cases could be the monitoring of historic buildings to plan structural and systems maintenance or the check of environmental parameters in a museum.

Since the variety of fields in which the component finds application, the figures involved are not only those closely linked to cultural heritage, such as archaeologists, museologists, and museum curators, but also researchers in geophysics, engineering, architecture and chemistry. For these reasons, the customizable dashboard is one of the key points in creating a proper workspace for each type of user. Moreover, the open-source feature of the platform will allow the creation of customized widgets and new components to enhance the data representation. So, based on the field of interest, each user can see only the categories of data of interest represented in such a way as to highlight the aspects relevant to his research field.

Because of this heterogeneity of users and needs, using a multitenancy system makes it possible to create different tenant accounts working on the same platform. These accounts could be assigned to institutions, research centers and companies working in various fields of cultural heritage. Each tenant could have users to whom it will offer the service, choosing which type of data and widget it will show. For example, a tenant working in the architecture could decide to get access to building data, and he will show only these data to his users, while a tenant working in the chemistry field could choose to get access only to diagnostic data that he will make available for his users. This feature, together with the chance to customize the dashboard and tools, is a remarkable aspect that makes this component the reference point for collecting and accessing cultural heritage data.

Regarding real-time monitoring, an alert system is used to monitor and forecast risk cases and maintenance and restoration interventions. The monitoring and alert settings can report when values are below or above the threshold, and they can also provide statistics about collected data.

Finally, thanks to the geolocalization system, it is possible to identify the geographical position of the assets and the location of sensors monitoring it. If possible, it will be integrated with a 3D representation of the site or the asset in line with HBIM and digital twin applications [13][14]. Using the mapping of data on the 3D model, it is possible to give a new knowledge dimension, showing the temporal evolution of the asset and enhancing the data presentation (for example, a 3D representation of the interior of a museum showing the position of the assets and of the sensors that carry with the detected data in real-time as showed in Fig. 3 and 4).

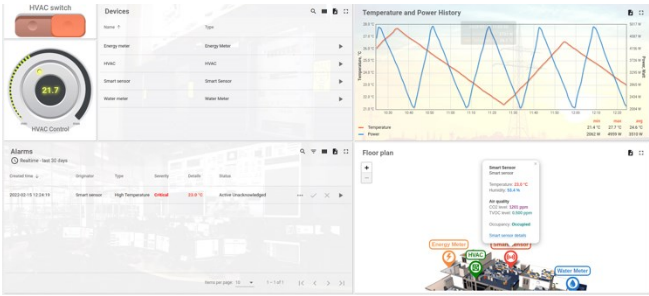

Fig. 5. Example of a customizable dashboard layout form [12]. It will include several data representations of the hetereogeneus cultural heritage context.

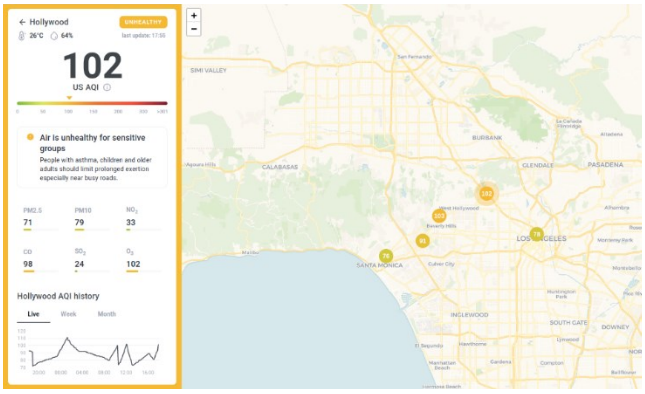

Fig. 6. Example of geolocalized data acquired by sensors (image from [12]).

IV. Conclusions

The Humanities and Heritage Italian Open Science Cloud (H2IOSC) project aims to establish a federated cluster of Research Infrastructures (RIs) within the ESFRI domain of Social and Cultural Innovation, facilitating collaboration among researchers across various fields. The project includes RIs such as DARIAH-IT, CLARIN, OPERAS, and E-RIHS. DIGILAB represents the digital access platform for the Italian node of the European Infrastructure for Heritage Science (E-RIHS), addressing challenges in data interoperability and providing advanced services for processing and analyzing information. Leveraging Wireless Sensor Networks (WSNs), the platform enables real-time monitoring and protection of cultural heritage assets. By integrating IoT technologies, DIGILAB enhances remote monitoring, reducing the need for physical interventions and promoting data sharing and accessibility across research contexts at national and international levels.

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